

SEDIMENTS ON THE CONTINENTAL MARGIN OFF

SOUTH WEST AFRICA BETWEEN LATITUDES

17° AND 25°S

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ABSTRACT

The study area lies on the north-central part of the South West African continental margin. It covers approximately 57 000 n.miles², and extends from 2 n.miles offshore to a depth of about 1 500 m. Four cruises of the R.V. THOMAS B. DAVIE were undertaken over a two year period (May, 1972 to May, 1974) to collect 555 sediment samples, 38 rock samples, and bathymetric data. The main effort of the study has been directed at the unconsolidated sediments of the continental margin, and particular emphasis was placed on the authigenic mineral deposits.

On sedimentological grounds, the continental margin is divided by a latitudinal boundary at 18°40'S. This boundary coincides with the northern flank of the Walvis Ridge Abutment, and separates the morphologically distinct Kunene and Walvis Continental Margins. To the north, the Kunene Shelf is narrow (~24 n.miles) and breaks at about 200 m depth whereas in the south, the Walvis Shelf is wide (~64 n.miles) with a poorly defined shelf break at about 360 m depth, and features an inner shelf break over most of its length.

Stiff muds of Miocene to Quaternary age crop out intermittently on the outer part of the continental margin, and consolidated bedrock is occasionally exposed on the inner shelf. Most of these rocks are poorly fossiliferous quartzose limestones, and, together with unconsolidated deposits of pelletal phosphorite on the shelf, are assigned a Middle to Late Miocene age. On the mid shelf, borings in the limestones are filled with phosphorite rock, which by analogy with similar material to the south of the study area, is tentatively dated as pliocene.

The inner shelf is blanketed over most of its surface by unconsolidated diatomaceous mud. The seaward flank of this deposit is rich in organic matter and CaCO₃, and its landward flank contains concretionary phosphorite and terrigenous quartz and mica. The relict terrigenous sand deposits reflect regions where biogenic sedimentation is minimal, and the most common textural component of this material is fine-grained quartz. This also constitutes the mean size of sediment composing the Namib Desert dunes.

The mid shelf is covered by gravelly and sandy sediment of a variety of compositions. Patches of relict Mollusca and modern benthic foraminifera occur on the landward side of the inner shelf break, and on the seaward side, faecal pellets and planktonic foraminifera predominate. Authigenic minerals are most common in two mineralized provinces on the mid shelf adjacent to the exposures of stiff pre-Holocene mud. The Northern Province is rich in glauconite and glauconitized pelletal phosphorite, and the Southern Province contains an extensive deposit of pelletal phosphorite.

The outer margin consists of muddy sediment that becomes progressively finer with increasing depth. On the Walvis Margin it is predominantly calcareous and derived from planktonic foraminifera, whereas on the Kunene Margin, it consists chiefly of very fine sand-size and silt-size quartz.

Clay-size sediment introduced into the marine environment by the perennial Kunene River is rich in montmorillonite and kaolinite, both minerals being deposited in greatest concentration on the Kunene Margin and on the Walvis Upper Slope. However, the dominant clay mineral on the continental margin is illite, and it, together with vermiculite, reaches maximum concentrations on the Walvis Shelf adjacent to the Namib Sand Sea. The Kunene River clay mineral assemblage is strongly correlated with the elements Mg, Mn, Fe, Al, K and Rb. Cu, Ni and Zn correlate with diatomaceous organic matter, Cd with opal, Ca, Sr and Co with planktonic foraminiferal tests, and Pb with the coarse fraction of the sediments irrespective of their composition.

Concretionary phosphorite consists almost entirely of carbonate-fluorapatite, and, compared to the other phosphorite minerals, it contains a high proportion of Mg. Pelletal phosphorite is abnormally rich in C_{org} and S, and glauconitized pelletal phosphorite in Fe. Both of the last-named minerals are contaminated by an abundance of terrigenous silt and clay. The glauconites all contain more than 8% K_2O , and are therefore chemically mature. Only a few trace elements are selectively enriched in the authigenic minerals relative to sea water - Sr in the three phosphorite minerals, Y in the two pelletal varieties and Cr in glauconite.

Concretionary phosphorite grows authigenically in the diatomaceous mud by seeding of P-supersaturated interstitial fluids with phosphatic solids such as fish scales. Pelletal phosphorite and glauconitized pelletal phosphorite on the other hand were formed by direct inorganic precipitation from sea water in semi-restricted shallow lagoons. Nutrient-rich waters drawn into the lagoons through estuarine circulation were warmed by solar radiation, and their concentration of Mg was lowered by ion exchange with river-borne terrigenous mud. Glauconitized pelletal phosphorite precipitated close to the river mouth in relatively well-oxygenated water, whereas the pelletal phosphorite formed under strongly reducing conditions. Glauconite originated from K-rich clays filling planktonic foraminiferal tests on the upper slope, and from alteration of faecal pellets on the continental shelf.

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Chapter 1. INTRODUCTION

1.1 THE CONTINENTAL MARGIN PROJECT

In January 1967, a Marine Geology Programme was initiated in the Geology Department at the University of Cape Town by the South African Committee for Oceanographic Research (SANCOR). The aims of the programme were to investigate the nature of sediments mantling the South African and South West African continental margins, and also, to determine the distribution and composition of phosphorite and glauconite deposits on the continental shelves. In April 1972, financial responsibility for supporting the programme was transferred from SANCOR to the Geological Survey Branch of the Department of Mines, and direction of the Unit became a joint undertaking of the Geological Survey and the University of Cape Town.

1.2 THE PRESENT INVESTIGATION

The present investigation represents the last of three West Coast projects that fall under the Continental Margin Project. The first to be completed, by Birch (1975), covered the area between Cape Point and latitude 30°S , and this was followed by a study of the area between latitudes 30°S and 25°S (northern Cape Province and southern S.W.A.) by J. Rogers (1977). The present study area extends from 25°S to 17°S and covers the central and northern parts of the continental margin off South West Africa. The main effort in all three areas has been directed towards understanding the regional aspects of modern and relict sedimentation. However, each of the studies has been expanded in varying degrees, to account for some of the special geomorphic or geochemical properties of the three different regions.

The purpose of the present investigation is: (i) to examine the textural, compositional and geochemical character of continental margin sedimentation in a region of strong coastal upwelling, and (ii) to investigate the geochemistry and possible modes of origin of various authigenic mineral deposits on the continental shelf.

The study area has attracted scientists of many disciplines and nationalities over the past 50 years, the main interest being centred on the upwelling of nutrient-rich waters within the Benguela Current system, and on the intense primary productivity of the surface waters. Geologists and geochemists have been attracted by a thick belt of diatomaceous mud on the inner shelf, mainly from the point of view of its unusually high organic carbon content, and also its association with contemporary phosphorite concretions. A rich pelletal phosphorite deposit on the mid shelf off Sylvia Hill, and a glauconite occurrence on the upper slope near the Kunene River mouth have received less inter-

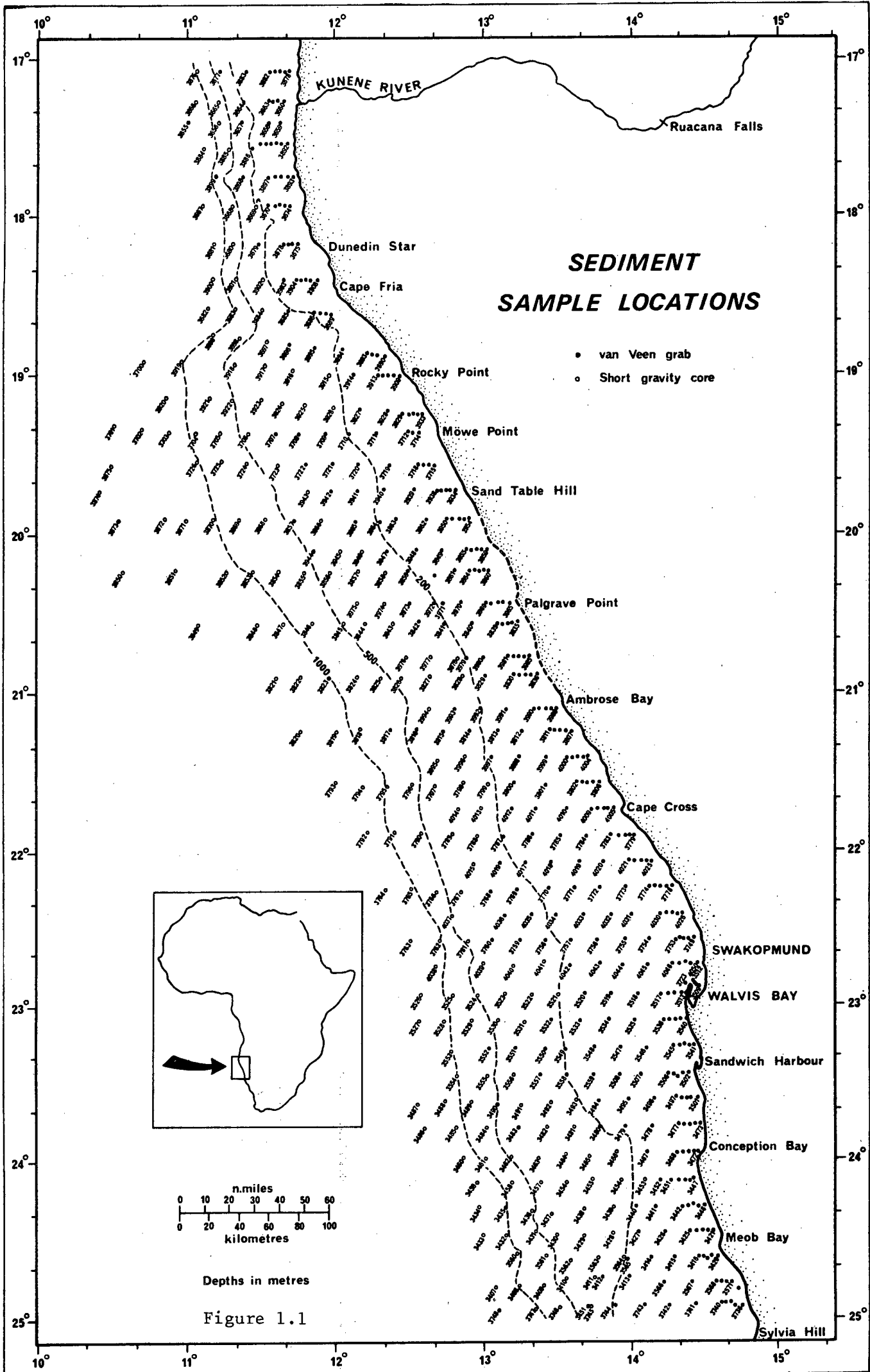
national attention, mainly because of their relict origin. Appropriate reference to all these investigations is made throughout the body of the present study.

In serving as a general introduction to the thesis, the first Chapter is used to provide synoptic background information on the geology and geomorphology of the hinterland, as well as to give a brief outline of the meteorological aspects governing erosion and supply of terrigenous detritus to the continental margin. The second Chapter is a short review on the hydrology of the south-east Atlantic with particular emphasis on the waters overlying the continental margin, and serves to establish a perspective for the many complex sedimentological processes discussed later on. Chapter three is a description of the continental margin morphology, and some reference to its structure is drawn from published geophysical data. In Chapter four, lithified basement rocks underlying the sea floor are discussed, and a few exotic fragments recovered during dredging operations in the area are also described. One of the main objectives of the thesis is covered in Chapter five, which undertakes to examine in detail the textural and compositional properties of the sediment mantling the continental margin. Chapter six is a brief description of some chemical variations of the sediment that occur in depth as indicated by 27 short gravity cores collected from the continental shelf. In Chapter seven, the clay fraction of the sediment is described in terms of its mineralogy and geochemistry, and the relationship between these parameters is examined by means of factor analyses. Chapter eight is a presentation of the results obtained from a study of the trace and major element compositions of phosphorite and glauconite, and drawing on this and previous findings, various models are proposed for the genesis of these authigenic minerals. The last Chapter, Chapter 9, is a brief synthesis of the main conclusions of the entire investigation.

Experimental information is organized into two Appendices, A and B, and the contents of each are ordered sequentially. Appendix A involves a brief description of all the various analytical techniques utilized in the study, and Appendix B is a presentation of the results.

1.3 SAMPLE RECOVERY

The study area covers some 57 000 n. miles², and extends from about 2 n. miles offshore to the 1 500 m isobath. In all, 555 sediment samples were collected from the shelf and upper slope using a modified van Veen grab in shallow water (usually less than 100 m), and a short gravity corer in the deeper regions (Fig. 1.1). Once recovered, the samples were stored in plastic tubs of 2 litre capacity. The sampling pattern was based on a rectangular 10



n. mile grid, with reduction of the line spacing to 2 n. miles in the near-shore zone, and expansion to 20 n. miles in deep water over the Walvis Ridge abutment. A total of 46 sample lines were needed to cover the area, and this was achieved in three sedimentological cruises of 2-4 weeks duration each. Subsequent to these cruises, a dredging cruise was undertaken to obtain samples of consolidated basement material. Dredging stations were located on a 20 n. mile rectangular grid oriented to coincide with the sediment-sampling grid, but because of generally poor recovery, the spacing of these stations was often increased to 2 n. miles around sites of successful dredge hauls (Fig. 1.2).

A summary of the samples collected during the four cruises is presented in Table 1.1, and a complete listing of them together with other geographical data, are given in Appendix B.1. Their geographic locations are illustrated in Figs. 1.1 and 4.1.

Table 1.1 Sample recoveries from four cruises to the study area.

Cruise number	Duration	Unsuccessful stations	Successful stations			
			Sediment			Rock
			G	SGC	LGC	D
273	8 May-26 May, 1972	3G, 1D	102	65	4	1
279	19 Nov-15 Dec, 1972	-	49	26	-	-
283	13 Mar- 8 Apr, 1973	3G, 5SGC	208	94	1	2
300	15 May-31 May, 1974	97D, 1LGC	-	-	6	35
TOTALS		110	359	185	11	38
RECOVERY			98%	97%	92%	27%

G = grab, SGC = short gravity core, LGC = long gravity core, D = dredge.

1.4 THE HINTERLAND

1.4.1 Geology

Precambrian basement is extensively exposed between the regional watershed and the coast, whereas Phanerozoic rock exposures are rather limited in their distribution (Fig. 1.2). Granite-gneisses and metasediments of Archaean to late Proterozoic age crop out along the Skeleton Coast north of Sand Table Hill, and constitute the watershed for most of the area east of there. These basement rocks are overlain unconformably by Middle to Late Proterozoic strata of the Damara Supergroup, together with a number of less important formations that include undersaturated intrusives, acid porphyries and various metasediments. A large exposure of Damara sediment in the Kaokoveld north of Sand

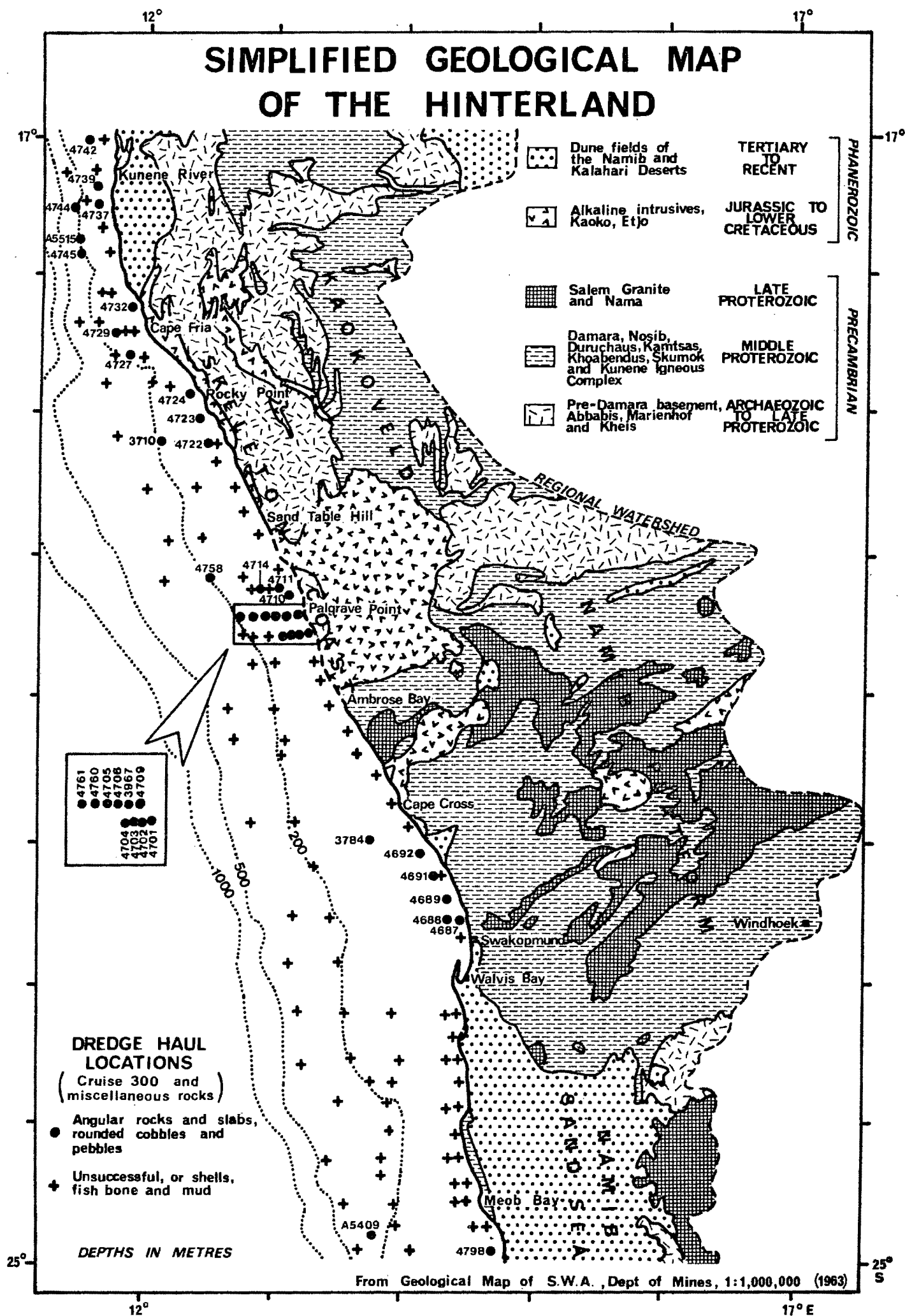


Figure 1.2

Table Hill forms part of the miogeosynclinal Outjo Facies (Martin, 1965), and consists predominantly of massive dolomites and limestones. The eugeosynclinal Swakop Facies (Martin, *op.cit.*) occupies the Namib Platform between Ambrose Bay and the Namib Sand Sea, and consists on the whole of muscovite and biotite schists, sandstones and conglomerates, all thoroughly traversed by quartz veins, and strongly folded about an east-northeast axis. They have undergone considerable granitisation and intrusion by late Proterozoic Salem Granite, which is typically grey to pink in colour, biotitic, and contains large phenocrysts of orthoclase and microcline. In the southeastern corner of the area, a small exposure of Nama Group sediments occurs, which is believed by Martin (1965) to be an unmetamorphosed equivalent of the Damara Supergroup.

Etjo sediments, considered by Martin (1973) to be of Jurassic age, underlie the Kaoko Lavas around Palgrave Point, and along the regional watershed east-southeastwards of there. They consist of conglomerates, arkoses, sandstones, siltstones and shales. Lower Cretaceous Kaoko Lavas exposed along the Skeleton Coast, particularly just north and south of Palgrave Point, are predominantly tholeiitic in composition, but do include some rhyolites and andesites. They are correlated with the Drakensberg volcanics, and are considered to be the product of volcanic activity which accompanied continental breakup of west Gondwana (Dingle, 1977). Of roughly similar age (± 127 m.y.), a belt of alkaline intrusive plugs, which follow the Damara lineation east-northeast of Cape Cross, have been shown by Marsh (1973) to lie along an active transform fault that offsets the Mid-Atlantic Ridge.

Tertiary Kalahari Beds (Haughton, 1969) occur only in the north-eastern corner of the drainage area, and are thus of minor significance in the total contribution of terrigenous sediment to the continental margin. The Cenozoic Namib dune fields, however, cover extensive regions of the coastal platform, and occur as two main deposits. The smaller of the two extends from Cape Fria to Mocamedes in Angola, and the southern deposit stretches from Walvis Bay to Lüderitz. Material composing these unconsolidated migrating dunes added significantly to sedimentation on the inner shelf during the Pleistocene, and at the present time, it is an important aeolian source of terrigenous detritus on the continental margin (see Chapter 5). A few small Tertiary and Pleistocene terrace deposits occurring along some of the rivers are remnants of formations that previously were more widespread.

1.4.2 Morphology

The desert can be subdivided physiographically into a number of distinct regions based on the amount of sand cover, the nature of the bedrock, and the erosional effectiveness of ancient river systems. Broadly speaking, the desert consists of a wide pediplain surmounted abruptly in places by ranges of

inselbergs, and variably dissected by dry river courses. Hinterland relief is illustrated by means of 46 traverse lines between the regional watershed and the coast in Fig. 3.3.

The two dune fields mentioned above, the Kunene Sand Sea and the Namib Sand Sea, both owe their origins to extremely strong southerly winds at the southern boundaries of the two deposits, and also, to the north-south orientation of the coastline along their western extremities. Where the coast swings in a northwesterly direction, as between Swakopmund and Cape Fria, unconsolidated coastal sand is blown northwards into the moister interior, and accumulation along the arid coast is thereby prevented. Nourishment for these sand seas is partly obtained from mechanical exfoliation and granular disintegration of the bedrock and, in the case of the Namib Sand Sea, its western edge receives considerable input from detritus unloaded on the banks of the Orange River through northward littoral and aeolian drift (Rogers, pers. comm.).

South of the Kunene Sand Sea, between Lines 41 and 25 (Fig. 3.3) the Skeleton Coast is made up of rocky platforms and gravelly desert pavements (Logan, 1972). Further inland, the Kaokoveld presents an entirely different morphological character, with rugged mountainlands strongly dissected by numerous short rivers and tributaries between Lines 46 and 32, and wide plateaus built of Kaoko Lavas between Lines 32 and 25 (Martin, 1965). Although the latter area is gentler in relief than its northern counterpart, it is distinguished by very widely spaced and deeply incised river channels.

The Namib Platform covers the entire region south of Ambrose Bay (Line 25) and consists of a wide featureless coastal plain broken in places by long north-east-southwest trending ridges, and isolated volcanic peaks like Brandberg and the Erongoberg. Rivers are fairly well incised, but very long, and near the Great Escarpment have carved a maze of intricate canyons into the Damara basement.

East of the Namib Sand Sea, the escarpment is composed of the rugged Naukluftberge, from where short river courses drain towards the coast, but eventually become blocked by the 300-metre high dunes of the desert, which are said to be the highest in the world (Seely, pers. comm.).

The central Namib Platform is the most elevated part of the regional watershed, and near Windhoek, it attains a height of 2 484 m. Brandberg, an isolated volcanic peak midway between the watershed and the coast (Fig. 3.3) however, is fractionally higher, and reaches up to an elevation of 2 606 m.

1.4.3 Drainage

The catchment areas of all rivers west of the regional watershed have been measured with a polar planimeter, and are shown in Table 1.2. Apart from

the perennial Kunene River at the northern boundary of the study area, they are all episodic. The larger ones, which drain from the Highland Plateau, flow at least once a year, and reach the sea, on average, once every three years (Sandelowski, pers. comm.). Exceptional flooding once every 50 years exerts a pronounced influence on the geomorphology of the normally arid hinterland, and Stengel (1964) for instance, has described the 1934 floods, when the Swakop River transported $35 \times 10^6 \text{ m}^3$ of sediment to the coast, and advanced the coastline by more than 1 km into the sea. Annual 'flushing' of the Kuiseb River furthermore, inhibits northward migration of the Namib Sand Sea except at its 'inland delta' at Walvis Bay. Here, sediment deposited after flooding is blown northwards as far as Swakopmund in the form of fast-moving barchanoid dunes.

All the longer rivers, although dry for most of the year, transport water within their bedloads from the Highland Plateau to the sea. Even where they are completely blocked by dunes, brackish water can generally be found just above sea level at some of the river mouths, for example, at Reutersbrunn and Fischersbrunn near Meob Bay, at Conception Water inland from Conception Bay, and at several places at Sandwich Harbour (Figs. 1.1 and 3.3).

The Kunene River is approximately 700 km long, and rises in the sub-tropical highlands of southern Angola where rainfall exceeds 100 cms/year (Bornhold, 1973). Upstream from the Ruacana Falls (Fig. 1.1), the river flows in a broad marshy valley with low banks, and during the annual summer floods, its southern bank is invariably burst with the result that excess water finds its way eastward to the Etosha Pan. Uplift of the area towards the end of the Tertiary, coupled with Pleistocene pluvial episodes, led to the rapid incision of westward-flowing rivers (Haughton, 1963). Headward erosion of one of them in particular is believed to have been responsible for the capture of an originally southeastward flowing Kunene drainage system (Wagner, 1916). West of Ruacana, the river exhibits immaturity by being confined to a steep rocky gorge with several large rapids, and only near the coast does its course again open into a broad shallow valley. The annual water discharge of the Kunene River is $5 \times 10^9 \text{ m}^3$ (Capstickdale, 1976), and the annual sediment discharge, both suspended and bedload, is estimated at $5,8 \times 10^6 \text{ m}^3$ (Senin, 1970).

Table 1.2. Catchment areas of rivers west of the regional watershed

River system	Physiographic Regions	Catchment area (km ² x 10 ³)
Kunene **	Angolan plateau, Kaokoveld	106,4
Natas	Skeleton Coast	1,2
Sekomib	" "	2,3
Kumib	" "	2,0
Hoarusib	Kaokoveld, Skeleton Coast	16,0
Hoanib*	" " "	17,7
Uniab	" " "	8,6
Koichab	" " "	2,5
Huab	" " "	15,6
Ugab*	Namib Platform	23,1
Messum	" "	2,2
Omaruru	" "	13,1
Swakop*	" "	34,1
Tubas	" "	3,6
Kuiseb	" "	22,5
Tsondab	" "	5,6
Sossus	" "	5,9

* Rivers examined for their clay mineralogy and geochemistry (Chapter 7).

+ Of the total catchment area, $13,3 \times 10^3 \text{ km}^2$ lies within S.W.A. territory.

1.5 METEOROLOGY

1.5.1 Rainfall

Rainfall over the hinterland is very scant, increasing slightly from south to north across the study area, and decreasing from the Highland Plateau towards the sea. Isohyets for the territory closely parallel the coastline; the 100 mm isohyet coinciding approximately with the Great Escarpment. As relatively moist air from the east drops over the escarpment, it heats up adiabatically and thereby prevents precipitation. Another reason for the lack of rainfall along the coast, is that cold air is imported from the sea surface during the afternoons by a sea breeze, thereby establishing a strong temperature inversion (Logan, 1969). Rainfall measurements at Swakopmund show that since 1899 the average rainfall has been 14 mm/annum, but some years are completely dry, and others experience flash flooding e.g., in 1934, Swakopmund received 156 mm of rain (Logan, 1960). Of relatively greater importance are the fogs that shroud the coast during the mornings for most days of the year. They form from advection of warm air over the cold Benguela Current (Anonymous, 1944) and precipitation from them in the form of fine drizzle, occurs on average 60 days/annum. Swakopmund receives an estimated 35-45 mm/annum (Goudie, 1972), which is three times higher than the average rainfall.

1.5.2 Temperature

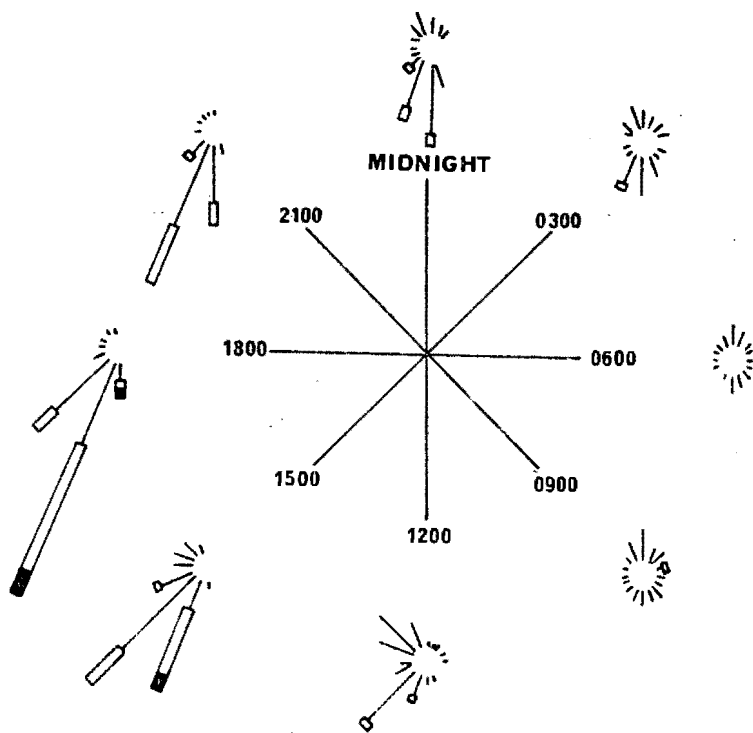
Compared with other deserts of similar latitude, the Namib is classified as a cool humid desert due to the influence of cold Benguela waters offshore. The temperature range is less extreme along the coast than farther inland, and the summer months reflect a smaller temperature range than the winter viz., 18° - 24° and 10° - 38° respectively (Anonymous, 1944). The high winter maxima are due to easterly 'berg' winds, which bring hot dry air from the interior to the coast.

1.5.3 Wind

Wind and water circulation patterns off S.W.A. are intimately linked, both being governed by a sub-tropical high pressure cell located over the mid South Atlantic. In summer this anti-cyclonic system lies at latitude 28° S, and with the approach of winter, it migrates approximately 4° to the north (Bornhold, 1973). This gives rise to the southeasterly Trade Wind system over the eastern South Atlantic, which blows with remarkable regularity at 6-11 m/sec, and according to Schell (1968) is the principal driving force behind the Benguela Current. The interior of South West Africa is also subjected to a high frequency of southeasterly winds during the summer, but this is due to a well-developed low-pressure cell over the sub-continent. During late autumn and early winter, this continental pressure system is replaced by a weak high-pressure cell, but over Angola and the northern part of South West Africa, a low-pressure region persists throughout the year (Schell, op.cit.). The late Autumn months are also marked by the highest frequency of berg wind conditions, and these may last from a few hours to several days in length. The berg winds are hot, dry, gusty and laden with dust; they reach velocities of 11-14 m/sec, and transport significant amounts of fine-grained sediment from the desert onto the continental shelf (Chapter 5).

The coastal region lies in a transitional zone between the oceanic and continental pressure systems, and as such, is influenced by both. Southeasterly winds along the coast are rare because the temperature differences established between land and sea surfaces during the afternoons result in a strong sea-breeze from the southwest. By far the most important feature of these coastal winds is their regular diurnal variation, which is much more pronounced in summer than during the winter (Anonymous, 1944). In the early hours of the morning, light north to easterly winds generally blow over the coast (Fig.1.3), and as the temperature effect comes into play, the wind backs with slightly increased force to the northwest. Finally, the southwesterly sea-breeze sets in between noon and midnight, and at Walvis Bay, it reaches a force of 6-14 m/sec. Berg wind conditions, when they exist at the coast, are usually overpowered by the sea-breeze during the afternoons, but farther inland, they may persist

DIURNAL VARIATION OF WIND AT WALVIS BAY



Scale : Frequency 1mm = 2%

Speed: — 0-25 Km/hr
 — 26-50 Km/hr
 — 51-75 Km/hr

After Anonymous (1944)

SAND ROSES FOR COASTAL WINDS

MÖWE POINT

ANNUAL

SUMMER

AUTUMN

WINTER

SPRING

PELICAN POINT (WALVIS BAY)

Dec

Jan

Feb

Mar

Apr

May

June

July

Aug

Sept

Oct

Nov

Scale : 1mm = 50 vector units

Data from Schaik et al. (1970) and N.C.C., U.S.A (1978)

throughout the day. The hot, less dense berg wind diverges to higher elevations over the coast, and its load of terrigenous detritus is thus carried high into the atmosphere over the continental margin.

The strongest winds along the west coast of Southern Africa occur between Lüderitz ($26^{\circ}40'S$) and Bogenfels ($27^{\circ}30'S$) (Rogers, 1977), and the latitude of this region coincides roughly with that of the South Atlantic high pressure cell in summer. These winds, with a resultant drift potential (RDP) of 2065 vector units (Appendix A.1), far exceed the strengths reported by Fryberger (in press) for other deserts, viz. Chinese 81, Indian 82, Kalahari 191 (low energy deserts), most 200-399 (intermediate energy deserts), and Saudi Arabia 458, Libya 431 (high energy deserts). The RDP and other wind parameters have been calculated, using the methods of Fryberger (in press), on a monthly basis for Pelican Point (Walvis Bay) and on a seasonal basis for Mõwe Point. Graphic portrayal of these results is given in Fig. 1.3, and comparisons between them are drawn in Table 1.3. The immediate impression gained from these presentations is the higher wind strength (higher RDP) at Mõwe Point relative to Pelican Point, despite the fact that the Trade Winds decrease in strength from south to north (Anonymous, 1944; Hart and Currie, 1960). Furthermore, the annual resultant drift direction (RDD) at Mõwe Point is practically due north, whereas at Walvis Bay it lies between north-northeast and north.

These changes in direction and velocity of the wind along the coast, together with the coastline orientation, are, as mentioned earlier, important factors controlling the location where sand is able to accumulate, e.g. at the Kunene and Namib Sand Seas. The reason for the differences in wind character along the coast probably stems from a regional interplay between the oceanic high pressure cell, and the two continental pressure systems.

From a geological point of view, two important facts emerge from the nature of the winds along the coast. Firstly, the frequency of berg wind conditions which are almost entirely responsible for the transport of terrigenous detritus onto the shelf, are insignificant in relation to the frequency of the prevailing southerly winds, however, when they do occur (mostly in autumn and winter) they are very strong. Secondly, the increased wind speed at Mõwe Point relative to that at Pelican Point tends to promote nourishment of the Kunene Sand Sea, not only from the greater competence of the aeolian processes, but also from accelerated littoral drift.

Table 1.3 Wind Parameters* along the coast of South West Africa

Season	Location+	DP/ ₄	RDP/ ₄	RDP/ _{DP}	RDD
Summer	Möwe Point	126,03	123,36	,98	7,59°
	Pelican Point	52,91	49,17	,93	40,55°
Autumn	Möwe Point	192,02	189,96	,96	,15°
	Pelican Point	99,49	73,08	,84	33,77°
Winter	Möwe Point	220,22	209,49	,95	1,44°
	Pelican Point	114,94	89,03	,72	17,79°
Spring	Möwe Point	191,50	187,01	,98	4,20°
	Pelican Point	214,95	202,91	,94	33,28°
	Location	DP+	RDP	RDP/ _{DP}	RDD
Annual	Möwe Point	729,58	714,45	,98	3,73°
	Pelican Point	492,25	455,82	,93	30,80°
	Bogenfels ^x	2252,00	2065,00	,92	342,30°

* See Appendix A.1 for explanation of terms.

+ High energy winds are indicated by $\frac{RDP}{DP} > 0,8$, or $DP > 400$.

x J. Rogers (pers. comm.)

Chapter 2. HYDROLOGY

2.1 INTRODUCTION

The high productivity of shelf waters off north-central South West Africa is well known (Brongersma-Saunders, 1949, 1967a; Copenhagen, 1953; Hart and Currie, 1960; Stander, 1964; Senin, 1970; Calvert and Price, 1971b, and others) and sediment presently accumulating on the sea floor south of the Walvis Ridge abutment contains, on average, more than 50% biogenic detritus (Chapter 5). This feature of the sediments is reflected by an almost continuous deposit of diatomaceous mud on the inner shelf south of Rocky Point (19°S), and a blanket of foraminiferal muddy sands and sandy muds on the outer shelf.

A brief review of the water properties and current systems is presented here to provide background for discussing the composition and distribution of these unusual sediments in subsequent chapters. Also, an analysis of average and storm-wave conditions has been made in an attempt to understand the textural distribution of unconsolidated sediments on the continental shelf.

// 2.2 WATER MASSES OF THE EASTERN SOUTH ATLANTIC

South Atlantic Subtropical Surface Water forms the eastern arm of the South Atlantic anticyclonic gyre to a depth of about 400 m (Pickard, 1966), and flows in a northwesterly direction at about 4 cm/sec (Shannon and van Rijswijk, 1969). The average temperature and salinity of this water is 18°C and $35^{\circ}/\text{oo}$ respectively, and its average oxygen content is 5,4 ml/l (Shannon and van Rijswijk, op.cit.). Below this water mass, the South Atlantic Central Water flows at about the same velocity, and in the same direction, down to a depth of approximately 600 m, and reflects a very broad temperature and salinity range of 6°C to 16°C and 34,4 to $35,4^{\circ}/\text{oo}$ respectively (Shannon and van Rijswijk, op.cit.). The oxygen content is also highly variable, averaging about 4,8 ml/l (Hart and Currie, 1960), and the upwelled water along the coast of south-central South West Africa is apparently derived from this layer (Hart and Currie, op.cit.; Ledenev, 1963; Stander, 1964). Clowes (1950) considers the South Atlantic Central Water to be the product of simple mixing between Surface Water and the Antarctic Intermediate Water, which lies immediately below it. The latter forms by sinking of cold, poorly saline water at the Antarctic Convergence (50°S), and flows in a general northwesterly direction (Kirwan, 1963) between 600 and 800 m depth (Standar, 1964). Its most distinguishing features are a salinity minimum of 34,3 to $34,4^{\circ}/\text{oo}$, and a temperature of $4,4^{\circ}$ to $4,5^{\circ}\text{C}$. Its oxygen content is about 4,4 ml/l (Standar, op.cit.).

Antarctic Deep Water, with a core at about 2 000 m depth, is identified by a salinity maximum of $34,9^{\circ}/\text{oo}$ (Standar, op.cit.; Dubravin and Navrotskaya, 1972) and average temperature and oxygen contents of $3,1^{\circ}\text{C}$ and 4,7 ml/l re-

spectively. It is a southward moving water mass of considerable thickness, known to originate in the North Atlantic with a contribution from the saline Mediterranean (Dubravin et al., 1972). At abyssal depths, Antarctic Bottom Water forms from the sinking of very cold and poorly saline water in the region of the Weddell Sea. It spreads slowly northwards but is effectively blocked from entering the Angola Basin by the Walvis Ridge. In the Cape Basin, it has temperature and salinity values of about $1,5^{\circ}\text{C}$ and $34,78^{\circ}/\text{oo}$ respectively (Dubravin et al., 1972).

The northern part of the South West African continental margin is not affected by South Atlantic Central Water, but rather by an oxygen-poor layer that extends over the eastern tropical South Atlantic between 50 m and about 900 m depth (Visser, 1970). This water is introduced to the area through a cyclonic gyre off Angola, that reaches from just below the surface to a depth of about 300 m (Moroshkin, Bubnov and Bulatov, 1970). In the north, the gyre is bounded by the South Equatorial Counter Current, to the south and west by streams of the Benguela Current, and its eastern arm forms the narrow and fast Angola Current (Fig.2.4).

2.3 NON-CONSERVATIVE PROPERTIES OF THE SHELF WATERS

2.3.1 Oxygen

The vertical distributions of dissolved oxygen shown in Figs.2.1 and 2.2 demonstrate the presence of the oxygen-poor layer mentioned above. At its core, it contains less than 0,5 ml/l oxygen, and occurs on the Kunene Shelf at a depth of approximately 300 m depth. Stander (1964) has found it to be very wide off the Kunene River mouth, tapering in towards the coast near Walvis Bay, and usually disappearing south of Sylvia Hill (Fig.2.3). De Decker (1970) has obtained evidence indicating that in abnormal years, it is able to penetrate as a narrow coastal current as far south as Cape Town. In general however, its southward penetration is greatest in autumn and winter when the frequency of calm wind conditions is at a maximum. The phenomenon occurs only once every several years, and the introduction of warm, oxygen-poor water into southern latitudes results in massive mortalities of fish and other marine organisms (Stander and de Decker, 1969). Disruption of the normal circulation system here may be the equivalent of 'El Niño' found periodically off Peru.

The oxygen minimum layer is believed to form in response to three main factors (Visser, 1970): large amounts of oxidisable organic matter sinking through the water column (dead plankton and planktonic excretions), respiration of large quantities of zooplankton, and bacterial/chemical decomposition of organic-rich sediments on the continental shelf. Hart and Currie (1960) were the first to recognise it as an oxygen-deficient, southward moving, water mass, and re-

OCEANOGRAPHIC PARAMETERS BETWEEN THE KUNENE RIVER AND SYLVIA HILL

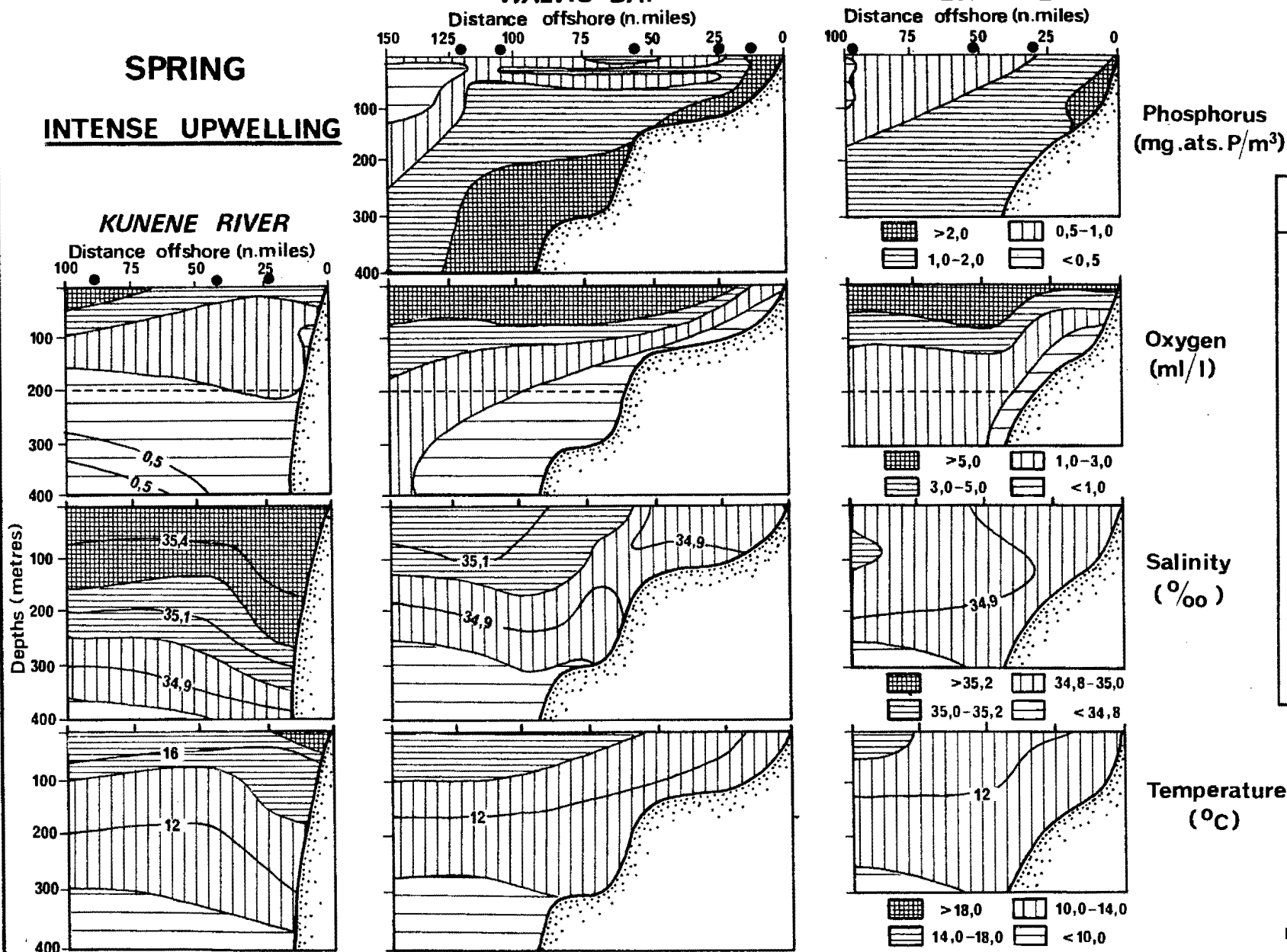
WALVIS BAY

SYLVIA HILL

SPRING

INTENSE UPWELLING

KUNENE RIVER



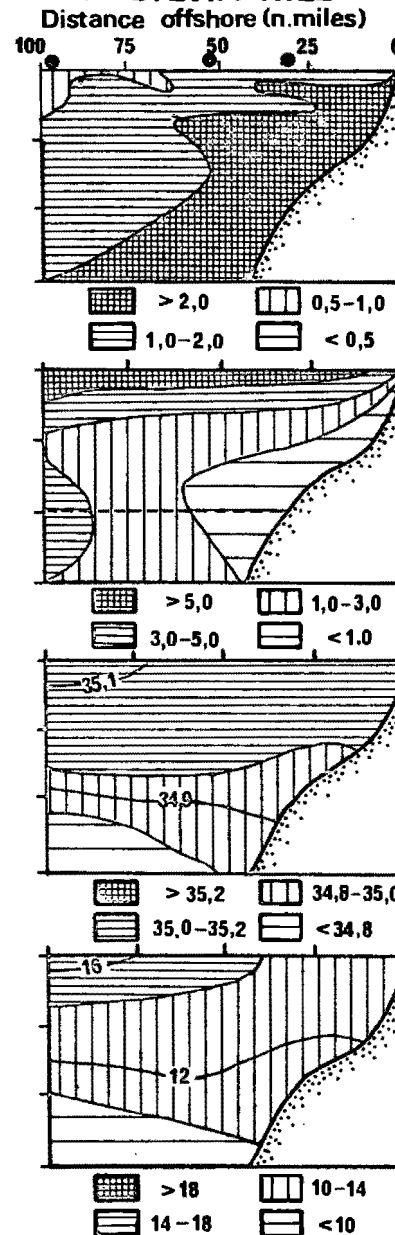
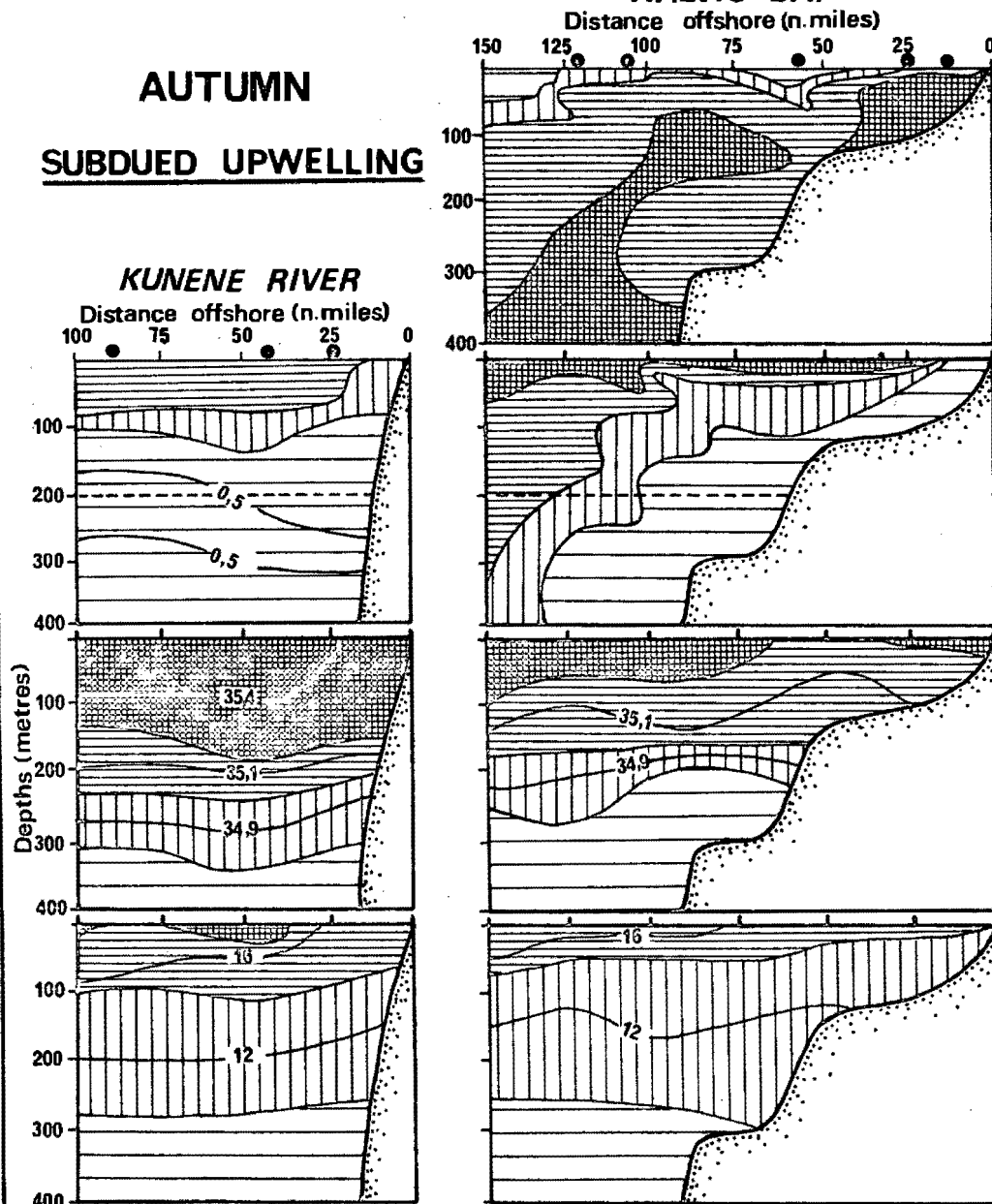
Modified after Hart and Currie (1960) and Stander (1964)

OCEANOGRAPHIC PARAMETERS BETWEEN THE KUNENE RIVER AND SYLVIA HILL

WALVIS BAY

SYLVIA HILL

AUTUMN SUBDUED UPWELLING



Phosphorus
(mg.ats. P/m³)

Oxygen
(ml/l)

Salinity
(‰)

Temperature
(°C)

LOCATION MAP

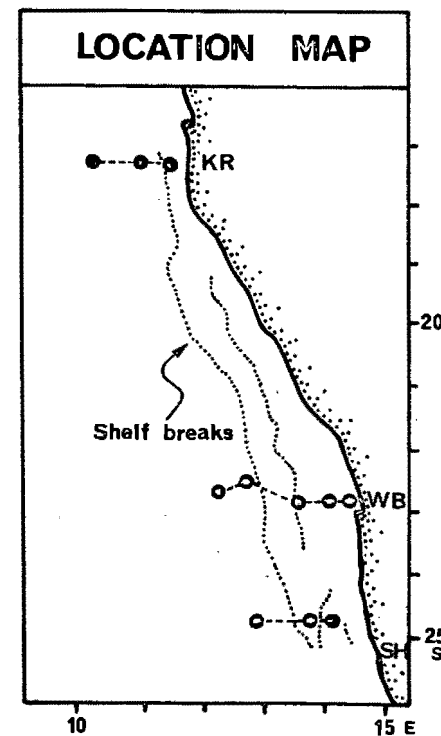


Figure 2.2

Modified after Hart and Currie (1960)
and Stander (1984)

DISTRIBUTION OF OCEANOGRAPHIC PARAMETERS BETWEEN THE KUNENE RIVER AND SYLVIA HILL

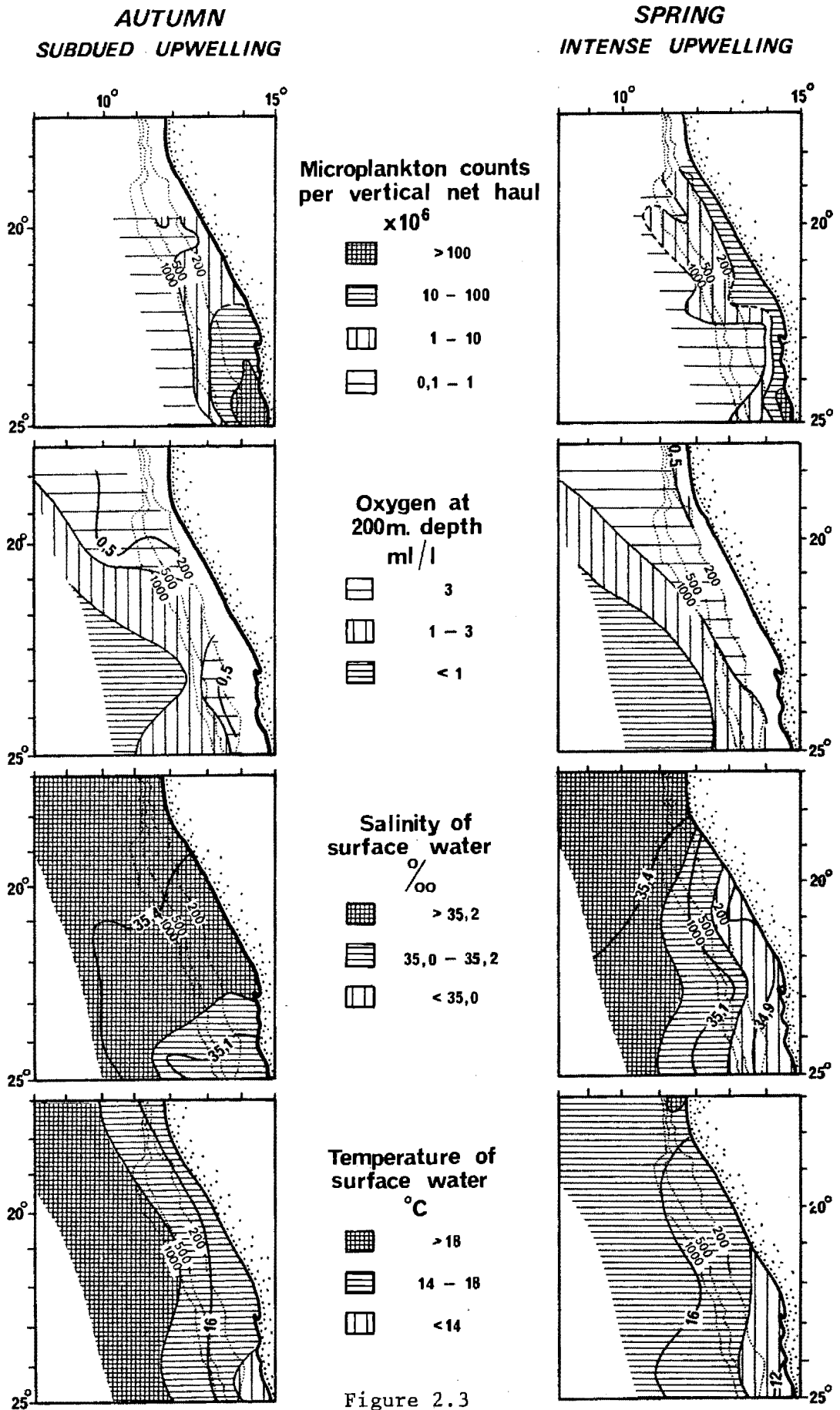


Figure 2.3

ferred to it as the 'Compensation Current'.

2.3.2 Nutrients

The concentration of phosphate in the shelf waters off South West Africa are the highest that have been measured for the Atlantic Ocean (Senin, 1970). Maximum concentrations of 2 mg. at. P/m³ are found in the bottom waters during autumn when stable thermoclines develop and upwelling is reduced to a minimum. The Walvis Bay profiles shown in Figs. 2.1 and 2.2 illustrate the utilization of phosphate by phytoplankton at various levels during spring when the intensity of upwelling is greatest, and general suppression in the intensity of coastal upwelling during autumn.

The extremely high nutrient values of the shelf waters are attributed by Hart and Currie (1960) to regeneration from organic matter accumulating there, and in this connection Calvert and Price (1971a) have found that a progressive change from normal, deep, oceanic nutrient ratios (N:Si:P = 16:16:1) is obtained on moving shorewards into the region of upwelling. Near the shelf break off Sylvia Hill they recorded a Si:P ratio of 5:1, while close inshore, where active upwelling existed at the time of their survey, the ratio changed to 95:1. Similarly, the N:P ratio varied from 12:1 near the shelf break to 40:1 in the inshore waters. Based on laboratory culture experiments of Grill and Richards (1964), they reasoned that phosphate was released more readily than either ammonification of organic nitrogen, or silicate solution of diatom frustules. Where vertical stability of the water column existed, they found that the surface waters reflected low nutrient levels because of phytoplankton utilization; the bottom waters at these locations were nutrient-rich, but oxygen depleted.

Calvert and Price (op.cit.) detected no H₂S in the shelf waters because their investigation was carried out in spring. Baturin (1976) however has reported values of 7,0 ml/l, and Copenhagen (1953) found 5,9 ml/l H₂S for water immediately above the sea floor off Walvis Bay. Copenhagen (op.cit.) states that when H₂S is released from the anaerobic diatomaceous mud, it first changes to colloidal sulphur which turns the sea milky, and subsequently, it becomes oxidized to SO₄²⁻. From a number of mud samples which he submitted to K.R. Butlin, a viability count of 10⁷/gm was obtained for the halophilic sulphate-reducing bacterium Desulphovibrio desulphuricans. Baturin (1974b) found the number of sulphate-reducing bacteria to be 7 x 10⁶/gm and H₂S, 790 ml/Kg.

2.3.3 Productivity

The introduction of nutrient-rich water to the euphotic zone through upwelling is the principal reason for the exceptional productivity of shelf waters off South West Africa. Plankton densities of 2 - 3 grams/m³ exceed tenfold the densities found in open ocean waters (Emilionov and Senin, 1969; Senin,

1970), and near Walvis Bay, primary productivity reaches the highest values for the Atlantic Ocean, viz., 3,8 grams/m³ (Steeman-Nielsen and Jensen, 1957). Hart and Currie (1960) are of the opinion that the annual production of phytoplankton in the Benguela Current may equal or even exceed the Antarctic coastal waters at certain times of the year, and find that the densest populations of these organisms lie along the coast between Lüderitz and Sylvia Hill (Fig. 2.3). This part of the coast is immediately north of the area of strongest southerly winds (Chapter 1) and also, of maximum upwelling (see next section). Prominent amongst the large number of different diatom species recovered by Hart and Currie (op.cit.), 95 in all, were Chaetoceros sp. and Fragillaria karsternii, both of which are commonly found preserved in the diatomaceous muds (Chapter 5). The abundance of large populations of pelagic fish, seals, and birds, and the occurrence of rich guano islands along the coast reflect the intense primary productivity of the nutrient-rich waters that are upwelled along the coast (Hart and Currie, op.cit.; Summerhayes, 1974).

2.4 CURRENTS OVER THE CONTINENTAL MARGIN

2.4.1 Upwelling

Upwelling along the coast of South West Africa is brought about by frictional stress of the Southeast Trade Wind on the sea surface which, combined with the effect of the Earth's rotation, causes the surface waters to move northwestwards away from the coast. Water from below then 'upwells' to replace it in an estuarine-type of circulation (Brongersma-Saunders, 1968). The intensity of upwelling is seasonally dependant, being least intense during the winter months, and strongest in spring when the velocity and frequency of southeasterly winds are at a maximum (Hart and Currie, 1960; Stander, 1964; Schell, 1968). In summer and autumn, the intensity of upwelling is considerably weakened, and stable thermoclines become established in the water column (du Plessis, 1967; Stander, 1960). The rate of upwelling in spring averages 1,9 m/day (Stander, 1964), but south of the study area, 20-30 m/day may be attained (Bang, 1976). The distribution of conservative properties of the water, as shown in Figs.2.1 and 2.2, gives a good account of the variation in the upwelling intensities during the various seasons. It is noticeable in Fig.2.3 however, that the isohalines tend to bend in toward the coast much more rapidly than the isotherms in either spring or autumn, and this suggests that salinity may be a more sensitive parameter for determining the trajectory of upwelled cells of water (Schell, 1968).

Although common along the entire coast of South West Africa, upwelling is usually stronger and more persistent at some locations than at others. Generally, it is most conspicuous south of the study area, and decreases in intensity

towards the Kunene River. The locus of maximum upwelling is situated between the Orange River and Lüderitz, where Bang (1971) has been able to define a 'pivot' or 'point of little change' at $27^{\circ}30'S$, $15^{\circ}00'E$. The position of this stable, active, centre of upwelling coincides latitudinally with the region of strongest southerly winds (Chapter 1), and also with the South Atlantic Gyre in summer.

The depths affected by upwelling are greatest south of the study area, and decrease progressively towards the north. Between the Orange River and Lüderitz, the maximum depth of upwelling is 350 m, between Sylvia Hill and Walvis Bay it is 300 m, and at Sand Table Hill, only 200 m (Hart and Currie, 1960; Stander, 1964). Stander (op.cit.) has found that with the onset of upwelling in late winter, uplift commences from shallow depths e.g., at Walvis Bay, 100-150 m, but as the process intensifies, water is gradually drawn up from increasing depths.

The phenomenon of shelf-break upwelling in these waters has been mentioned by a number of workers (Hart and Currie, 1960; Stander, 1964; Bang, 1971) and is clearly in evidence on the Walvis Bay phosphate profile shown in Fig.2.1. Further evidence of this may be the occurrence of sand-size glauconite and quartz along the shelf break south of Walvis Bay (see Chapter 5). Presumably, the intensity of shelf break upwelling in this region is sufficiently strong to prevent the settling of silt- and clay-size sediment on the sea floor.

2.4.2 The Benguela and Angola Currents

The Benguela Current is a sluggish body of water, with maximum velocities north of the Orange River of approximately 25 cm/sec ($\frac{1}{2}$ knot) (Standar, 1964; Senin, 1968). It is thought to originate entirely from southeasterly wind stress on the sea surface, and its greatest velocities are therefore recorded in spring (Schell, 1968; Bang, 1971). Moroshkin et al. (1970) describe the Benguela Current as a broad (200 to 360 n.mile wide), meandering, northwesterly to westerly moving current that leaves the coast at about $23^{\circ}S$. They state furthermore, that the main stream of the Benguela Current, which flows westwards at latitude $23^{\circ}S$, reaches velocities of 15-20 cms/sec. between the surface and 100 m depth, and 5-10 cms/sec. between 200 and 300 m depth. Aside from this, they maintain that three narrow ancillary branches of the current flow parallel to the coast in a northerly direction. The most easterly of these penetrates as far north as $18^{\circ} - 19^{\circ}S$ (Cape Fria), and in the upper 150 m layer, has velocities of 5-10 cms/sec.; the middle branch reaches velocities of 35 cms/sec. in the upper 100 m layer, and penetrates northwards as far as $13^{\circ} - 15^{\circ}S$ (Angola) between longitudes 10° and $11^{\circ}E$; and the most westerly of the three branches moves slowly northwards as a broad stream to $13^{\circ} - 14^{\circ}S$ (Angola) between longitudes 8° and $10^{\circ}E$. These and other currents are shown

diagrammatically in Fig.2.4.

In the northern part of South West Africa, a southward-setting current named the Angola Current by Moroshkin et al. (1970) converges with the eastern branch of the Benguela System, and exists as a narrow, stable and fast stream reaching velocities in excess of 70 cms/sec. at the surface off Angola. Along the outer margin in the vicinity of the Kunene River, this southward flow decreases to 5-8 cms/sec., penetrates at least as far south as 23°S (Moroshkin et al., 1970), and has its origin in the oxygen-poor layer of the eastern tropical South Atlantic (Visser, 1970).

The interaction between the Angola and Benguela Currents has as yet not been rigorously studied, but the intrinsic weakness of both systems, where they converge and intermingle on the continental shelf, is given expression by the presence of a thick deposit of diatomaceous muds on the inner shelf. The undisturbed nature of sediment on the sea floor is also clearly apparent from bottom photographs, where animal trails and markings are well preserved in the soft muddy sands and sandy muds (Plate 2.1).

Direct current measurements in the region are few in number, but those that have been made tend to emphasize the variability of current strengths and directions with time (Table 2.1).

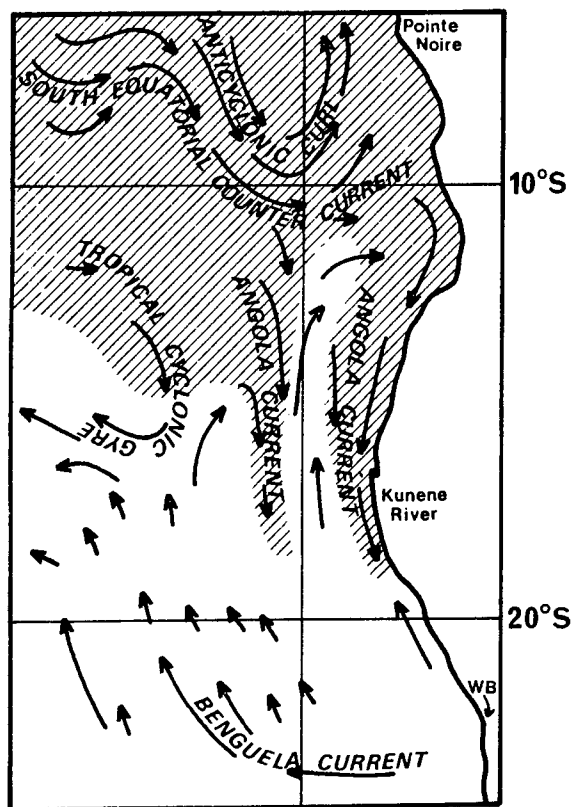
Table 2.1 Current measurements on the South West African shelf
(After Kuderiskiy (1962), in Baturin (1971))

Location		Bottom Depth (metres)	Date	Duration (hours)	Current		
Coords	Vicinity				Depth (metres)	Direction (degrees)	Speed (cm/sec)
17° 20'S 11° 40'E	Kunene River	90	27 - 28 Jan.1961	13	5 10 25 50 85	341 8 89 319 172	28,0 8,8 3,0 3,8 11,0
23° 08'S 13° 40'E	Walvis Bay	155	9 Feb.1961	24	10 50 100 150	31 49 316 311	7,1 3,0 3,3 3,3
23° 08'S 13° 40'E	Walvis Bay	155	11 Feb.1961	24	100 150	123 172	2,0 2,8

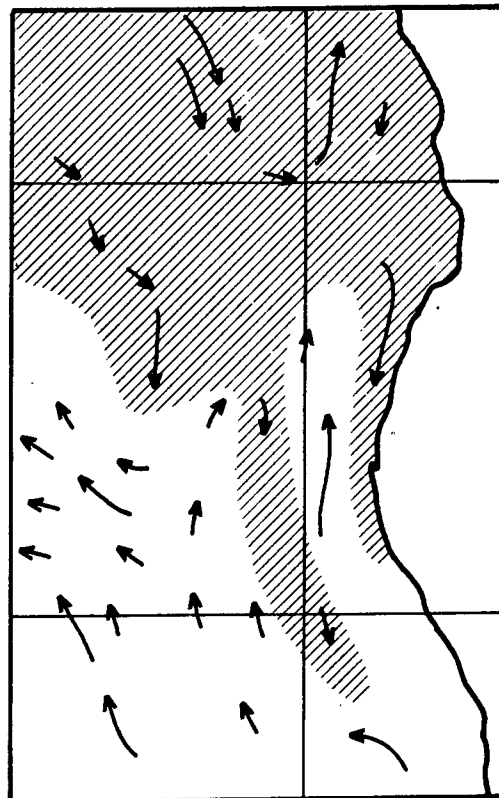
2.4.3 Tidal and inshore currents

Tides off South West Africa are semidiurnal with a maximum range of 1,42 m between mean low water and mean high water springs at Walvis Bay (S.A. Tide Tables, 1976). In view of the small range, and also because the co-tidal lines are roughly parallel to the coast (Harris, pers.comm.) tidal currents are not considered to

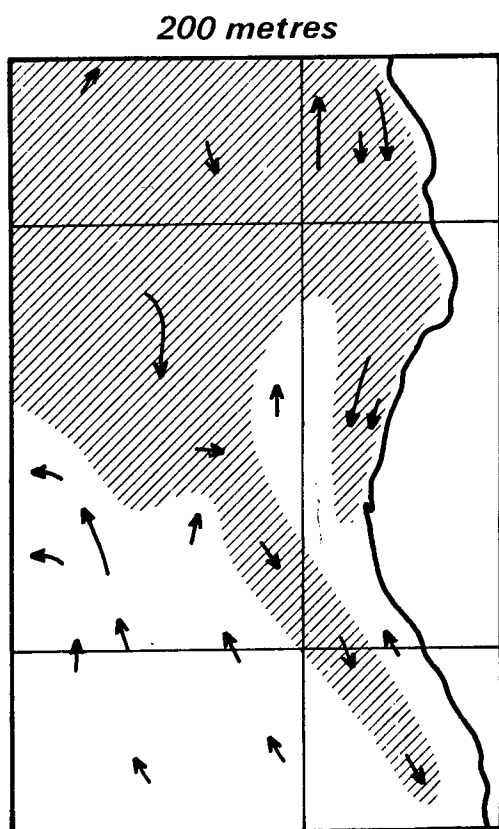
SURFACE CURRENTS OFF S.W.A. AND ANGOLA



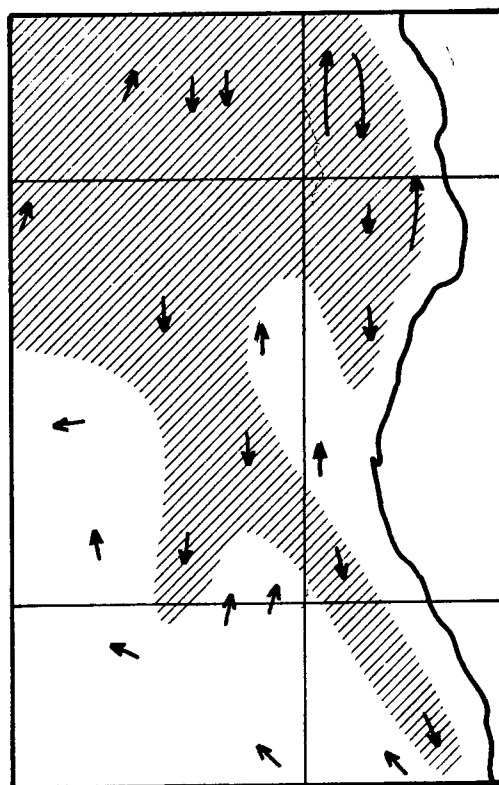
10°E
SURFACE



100 metres



200 metres



300 metres

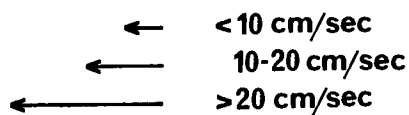
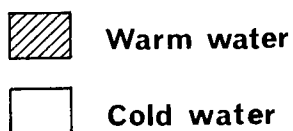


Figure 2.4

Modified after Moroshkin, Bubnov, Bulatov (1970)

be a major factor in distributing sediment across the continental shelf. Kuderskiy (1962) in Baturin (1971), and Senin (1968) however, have reported fairly high overall tidal current speeds viz. 25-30 cms/sec., but they give no indication of the methods used for determining these velocities. When spring tides coincide with the arrival of long wave-length storm waves, their combined effect may perhaps become significant.

A weak, narrow and shallow, southward setting inshore current has been described by Visser et al. (1973) as an intermittent stream occurring when northerly winds or extended periods of calm prevail. They have found that pilchard shoals congregate at or near this 'counter current' during the spawning season, and utilize it for migrating to their traditional spawning grounds off Walvis Bay. Whether it is related in any way to the oxygen-poor Angola Current is not known.

Longshore drift resulting from the large angular incidence of groundswell along the coast is strongly towards the north, and this is testified by the many northward-growing sand spits adjacent the shore, and by the recovery of diamonds as far north as Mbe Point (Maree, 1966). Two main sets of swell impinge along the coast, one develops locally from the southeasterly Trade Winds, and the other originates from storms in the 'Roaring Forties'. Their periods are 4-7 sec. and 6-9 secs. respectively (Emery, Milliman and Uchupi, 1973).

2.4.4 The Ekman Friction Layer

Although suitably detailed measurements are lacking in the study area, theoretical considerations (O'Brian, 1975) and measurements in the southern Benguela system (Bang and Andrews, 1974) make it clear that some velocity enhancement occurs at the shelf break and that this intensification extends to the sea floor. Near the bottom, an Ekman friction layer develops with net transport towards the right of the flow higher up (Ekman, 1905; Bang, pers. comm.), and this is of particular importance with regard to the stability of the diatomaceous mud belt lying on the landward side of the mid shelf break.

It is anticipated that the strength of the Ekman 'pumping' effect would be somewhat weaker than that occurring at higher latitudes (Bang, 1976), but its existence, particularly south of Walvis Bay, may be an important factor in explaining the discrepancy between the predicted and actual dispositions of sediment texture (see Fig.2.6).

2.4.5 Wave-induced Bottom Currents

An attempt is made in this section to relate the textural properties of the unconsolidated shelf sediments with the average wave parameters published for the study area. In addition, two storm-wave conditions have been examined

to assess their capacity for generating bottom currents capable of dispersing sediment on the deeper parts of the continental shelf (Swift, 1970). These are locally produced storms, most common in spring and typified by large-amplitude short-period waves, and distant storms, most common in winter as low-amplitude, long-period waves (van Schaik et al., 1970; Emery et al., 1973).

The wave data utilized are based on ship-board observations made every three hours over a one year period (Appendix A.2). Mass transport velocities at a number of different water depths have been calculated for each of the three sea states mentioned above, and the results of this work are listed in Appendix B.1, and shown graphically in Fig.2.5. In order to ascertain the water depths at which mud and very fine sand would settle from suspension for each of the sea states, two critical mass transport velocities, at 3 cms/sec. and 16 cms/sec. respectively (Allen, 1965, Fig.10), were plotted against the curves of Fig.2.5, and the results are shown in Table 2.2.

Table 2.2 Approximate sediment settling depths for three different sea states

Mass transport velocity	Settling components	Settling depths (metres)		
		1	2(a)	3(b)
16 cms/sec.	v.f. sand	15	30	100
3 cms/sec.	mud	30	45	200

1 = average waves; 2(a) = local storm waves and 2(b) = distant storm waves.

From Fig.2.5 and Table 2.2, it is apparent that average waves and local storm waves are restricted in their influence to the nearshore zone (<50 m), although the latter are capable at $U_m = 200$ cms/sec., of transporting very coarse sand and fine gravel as bedload (Allen, 1965) in water shallower than 10 m. Distant storm waves generate weak, deep currents that are capable of keeping very fine sand and mud in suspension to a depth of 100 m, and mud alone to a depth of 200 m. These settling depths have been plotted in Fig.2.6 adjacent to a map of the actual distributions of very fine sand and mud, and the differences between the two diagrams are quite striking. The reasons for these differences are now briefly considered.

In early spring, distant storm waves arriving in the area may coincide with a local storm condition, in which case the potential transfer of considerable fine sediment from the nearshore zone to greater depths is possible. At $U_m = 45$ cms/sec., which is attained by local storm waves at 22 m depth, erosion of the sea floor begins with very fine and fine sand being transported in suspension in a seaward direction (Cook and Gorsline, 1972), and medium and

MASS TRANSPORT VELOCITY CURVES FOR DEEP WATER WAVES OFF S.W.A.

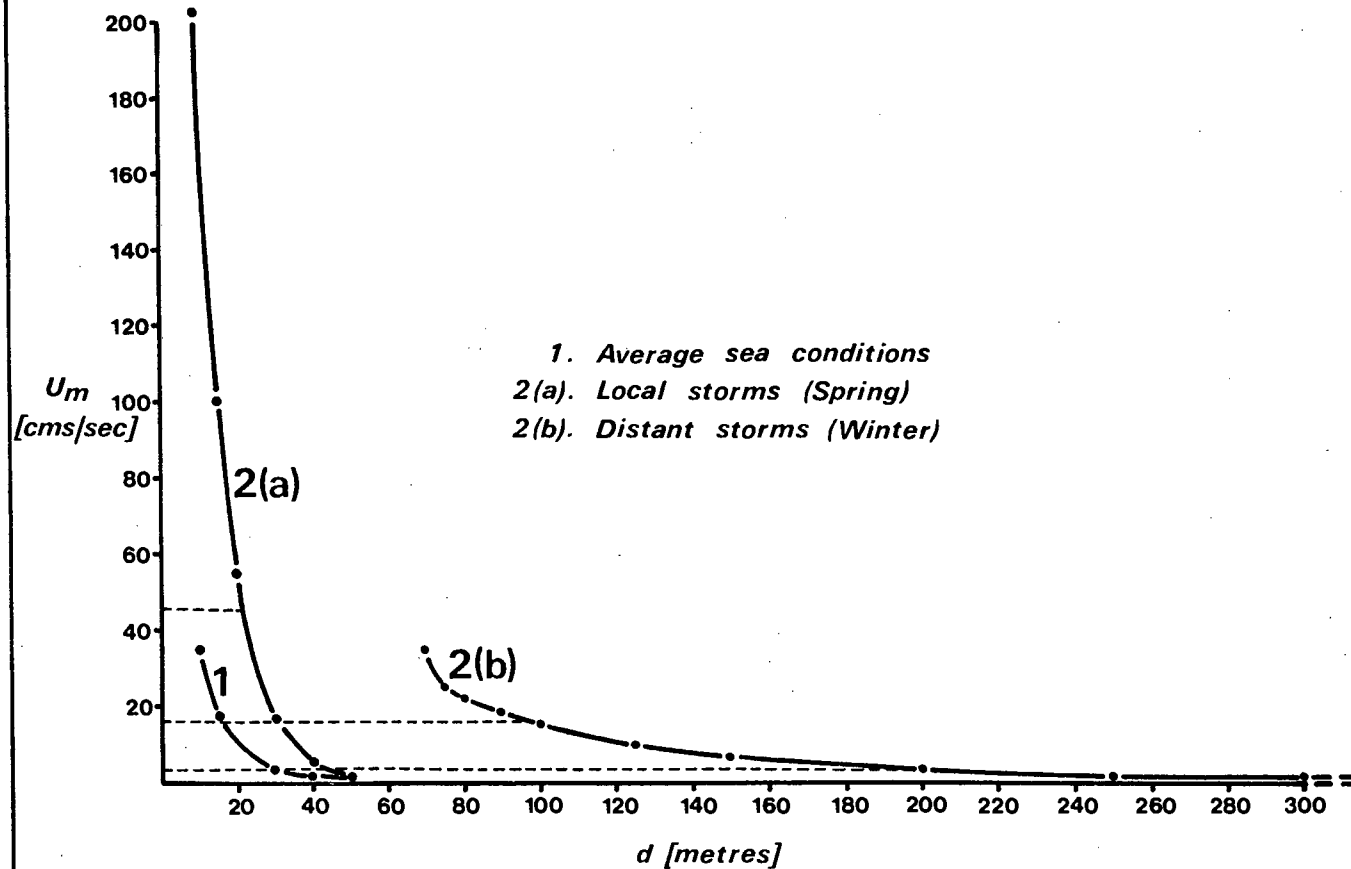


Figure 2.5

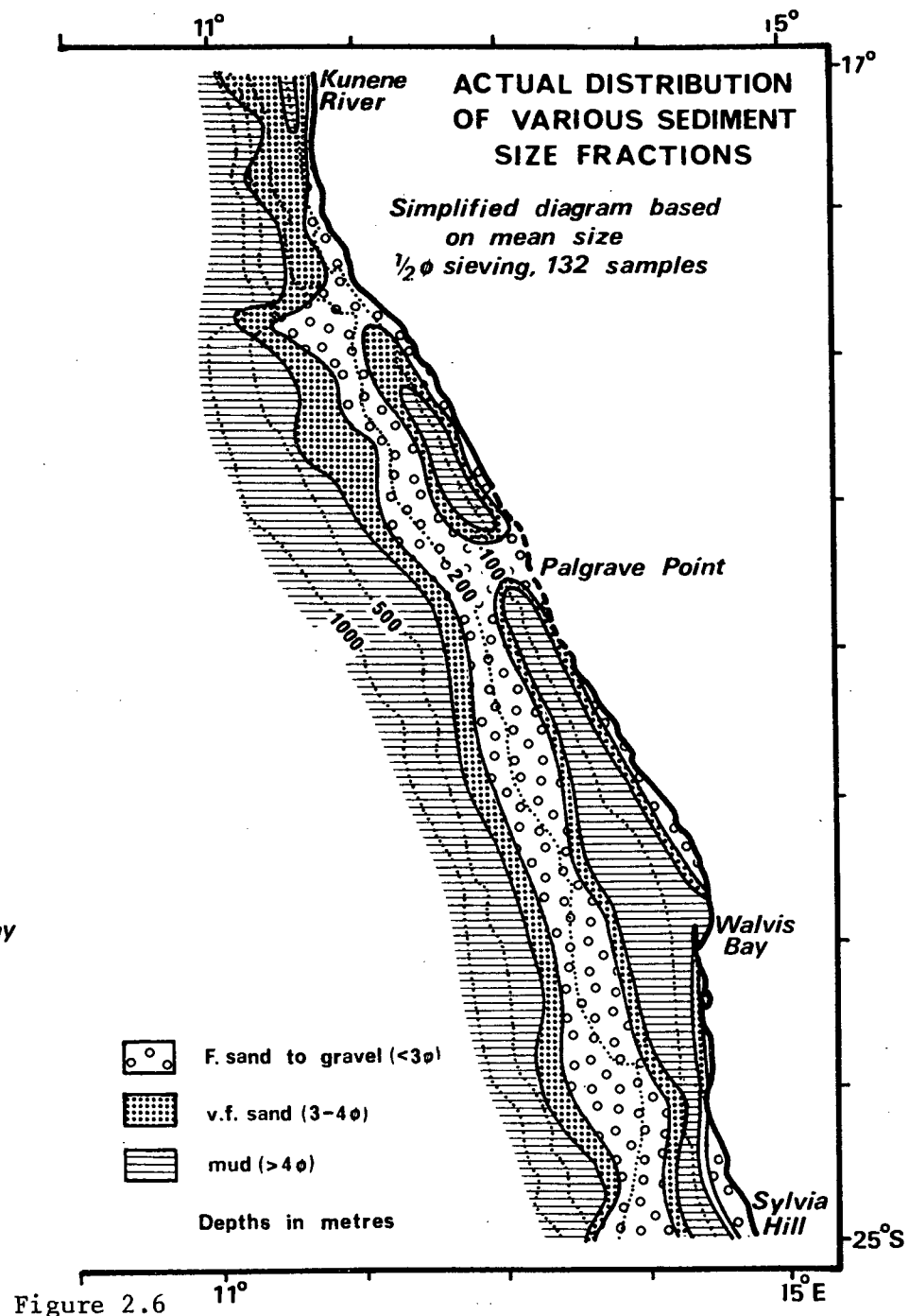
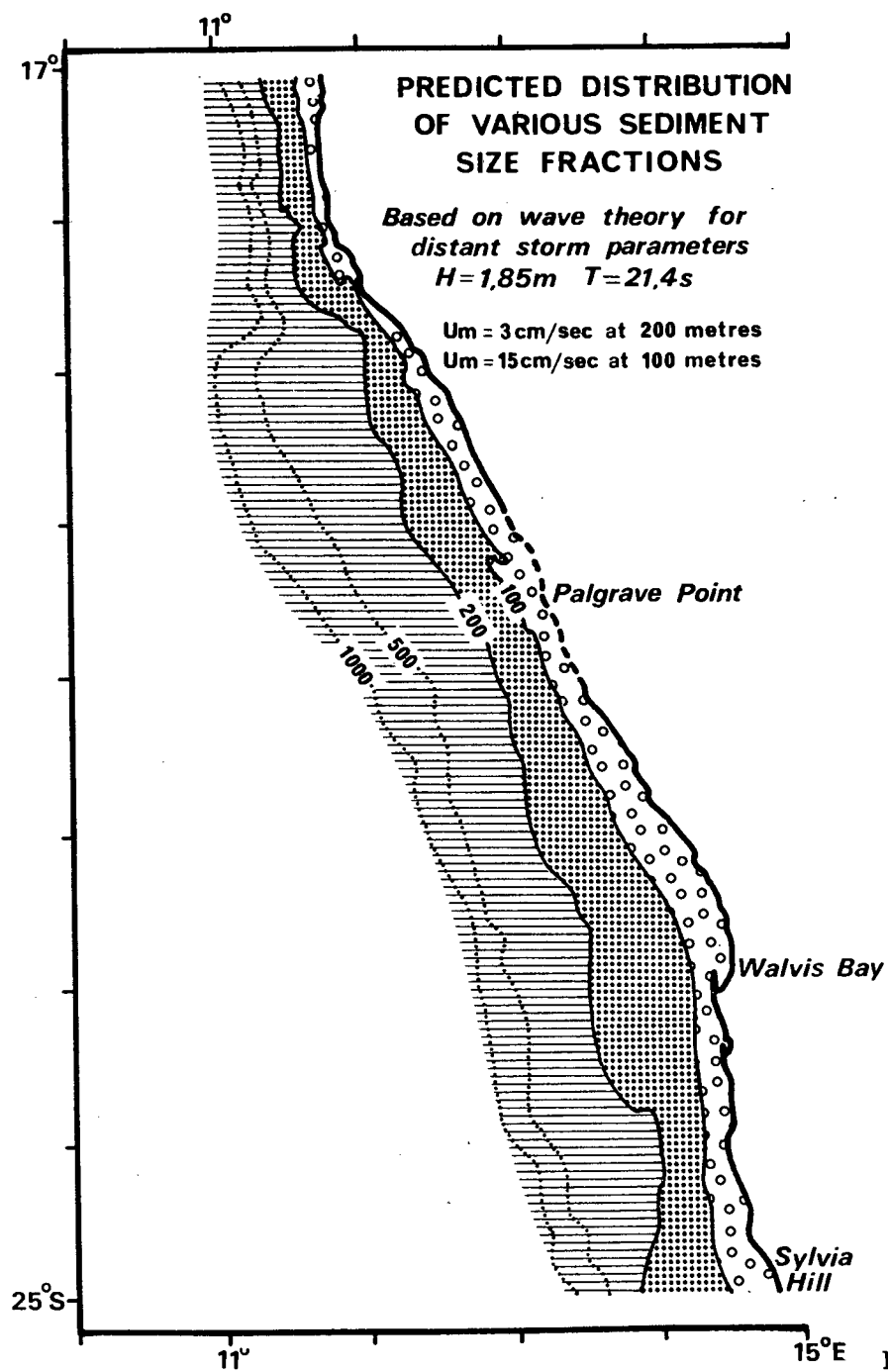


Figure 2.6

coarse sand being moved as bedload in a landward direction (Allen, 1965). Another reason for the differences exhibited by the two diagrams of Fig.2.6, is that benthic infauna in the sediments of the mid shelf transform vast quantities of mud to sand-size faecal pellets (see Figs.5.13 and 5.14). Finally, one of the reasons for apparent stability of the diatomaceous mud belt on the inner shelf, aside from the Ekman 'pumping' effect described earlier, may be due to its density. Surface waters above the mud belt contain 3,8 mg plankton/litre (Steeman-Nielsen and Jensen, 1957), and near the bottom, no clear sediment-water interface has been found in attempts to obtain underwater photographs of it. McCave (1971) considers that where suspended sediment concentrations reach about 100 mg/l, mud deposits will result irrespective of the wave activity at the bed.

2.5 SUMMARY

In the northern part of the study area, warm, highly saline, oxygen-poor waters of the Angola Current invade the continental shelf from the north, and in the southern part of the study area, cool, nutrient-rich, relatively well-oxygenated waters of the Benguela Current sweep along the continental shelf from the south. Between these two regions, the current systems converge and intermingle in a complex series of eddies and minor streams. Their relative strengths are a function of the seasonal intensity of the southeasterly Trade Winds, the Benguela Current penetrating farthest north in late winter and early spring when the winds are at their height, and incursion of the Angola Current southwards toward Sylvia Hill in summer and autumn when the winds are at their weakest.

The intensity of upwelling is also directly proportional to the wind strength, being most vigorous south of the study area in the vicinity of Lüderitz. During the summer and autumn months, the rate of upwelling diminishes, and stable thermoclines become established in the water column. The availability of upwelled nutrients in the surface water layer then causes massive phytoplankton blooms, many of the more robust species of which accumulate on the sea floor. Entry of the oxygen-deficient Angola Current during these seasons furthermore, aids in the preservation of associated organic matter.

Wave-induced bottom currents do not account satisfactorily for the textural distribution of unconsolidated sediment on the continental shelf. This is attributed to periodic abnormal storm conditions, reworking of the sediment by benthic infauna, and the great density of the mud deposits on the inner shelf.

Plate 2.1

Photographs of the sea floor^{*}

A. 35 n.miles SW of Ambrose Bay, 183 m depth.

(i) and (ii) Smooth, firm sediment, consisting of relict mollusc shells intermixed with modern, foraminiferal, faecal pellet, muddy sand. The shelly material is exposed as whitish patches where coelenterates have scoured the mud with their tentacles.

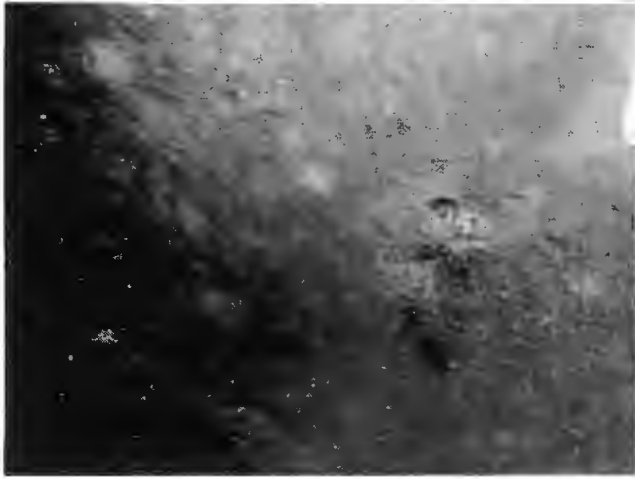
(iii) Enlargement of bottom right-hand corner of photograph (ii). Visible are two sea anemonies, a crab, a gastropod shell, and other molluscan debris.

B. Upper slope W of Conception Bay, 2078 m depth.

(i) and (ii) Smooth soft sediment consisting of foraminiferal sandy muds extensively reworked by benthic organisms. Visible in (i) is a sea cucumber, and in (ii), numerous depressions and trails.

* These photographs were taken by Dr. C.P. Summerhayes from aboard the R.V. CHAIN. (Cruise 115, Leg 2, December 1973-January 1974).

A(i)



(ii)



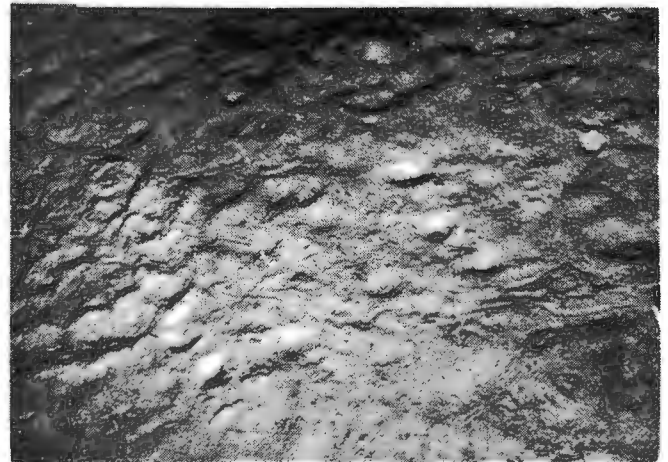
(iii)



B(i)



(ii)



Chapter 3. STRUCTURE AND PHYSIOGRAPHY OF THE CONTINENTAL MARGIN

// 3.1 INTRODUCTION

The junction between the Walvis Ridge and the South West African continental margin occurs at the Walvis Ridge Abutment. The northern edge of the abutment separates two distinctly different structural and morphological styles of continental margin and, for purposes of description, these regions have been called the Kunene and Walvis Margins, respectively. The boundary between them is defined explicitly at 18° 40'S. by a dramatic change in the composition of the overlying Holocene sediments. //

In this chapter, the structure of the continental margin is first briefly reviewed from published geophysical data to aid in the later interpretation of its morphology. This is followed by a discussion of broad regional trends exhibited by different segments of the margin, and by a physiographic description of the large-scale features present there. The effects of sea level and climatic change on the development of the continental margin are then considered, and finally, these evaluations are used to assess the origin of the inner shelf break.

Two regional maps have been compiled to show the physiographic character of the continental margin. One of them is a bathymetric map drawn at 10 m contour intervals on the shelf and 100 m contour intervals on the slope (Fig.3.2). The other one is a block diagram, which is used to contrast the physiography of the hinterland with that of the margin using 46 transverse profiles (Fig.3.3). Most reference to the latter map is made in Chapter 1, but its inclusion here is to facilitate correlation of place names with river names in the subsequent discussion.

Methods employed for the acquisition of bathymetric data are described in Appendix A.3, and the techniques used to compile the two maps are given in Appendix A.4. A list of Quaternary and Neogene stiff muds recovered from the outer margin is presented in Appendix B.3.

3.2 CONTINENTAL MARGIN STRUCTURE

3.2.1 Pre-Pliocene Continental Margin Development

Results from the Deep Sea Drilling Project (DSDP) Leg 40 (Bolli et al., 1975) indicate that both the proto-Cape and Angola Basins were occupied by stagnant euxinic waters during Early Cretaceous times. Terrigenous sediment was supplied to the southern part of the Cape Basin at a very rapid rate (38 m/m.y., Siesser (in press b)), whereas in the Angola Basin, a thick evaporite body was being deposited (40 m/m.y., Siesser (op.cit.)). Dingle (1973) has proposed that upbuilding of the continental margin was the dominant accretionary

basement (Scrutton, 1973; Barnaby, 1974). The thickness of this sediment wedge has been estimated from seismic evidence to be at least 1,5 km (Rabinowitz, 1972).

On the Walvis Margin, Goslin and Sibuet (1975) have detected a basement high on the inner shelf off Walvis Bay, and another beneath the Walvis Ridge Abutment. These two regions produce high amplitude, short wave-length, magnetic anomalies (Fig.3.1) which Goslin and Sibuet (op.cit.) have interpreted as being due to rises in the magnetic basement layer. Rapidly deepening seismic refraction equal-velocity lines between them are similarly taken to indicate a steep descent of the basement layer, and a thick prograding sediment wedge (Fig. 3.1). Of all the published seismic profile lines in the study area (van Andel and Calvert, 1971; du Plessis et al., 1972; Goslin et al., 1975; Emery et al., 1975), only one shows acoustic basement exposed at the surface. This steep-sided volcanic peak, which protrudes through the sediment wedge on the southern side of the Walvis Ridge Abutment (van Andel and Calvert, 1971; profile A, p. 592), lies due west of Sand Table Hill (Fig.3.2). These authors have estimated the thickness of the sediment wedge on the Walvis Margin to approximate 4 km.

The Kunene and Walvis Continental Margins also differ in structural style from the margins north and south of the study area. Scrutton and Dingle (1975) have described the Cuanza Basin off central Angola where sedimentation was controlled by a marginal basement plateau, a number of basement highs, and salt tectonism, and Bolli et al. (1975) note that at least 2 km of salt are reported to have accumulated in this area. South of the study area, in the vicinity of the Orange River delta, Scrutton and Dingle (op.cit.) have outlined a very thick sedimentary wedge that progrades over oceanic basement to a thickness of about 5 km. Bryan and Simpson (1971) have identified a number of intra-Cretaceous unconformities from seismic refraction work, but structures within them are only poorly known.

3.2.3 Shallow structures within the sedimentary wedge

Four or five individual sedimentary units are recognisable in the upper portion of the sedimentary wedge (van Andel and Calvert, 1971; du Plessis et al., 1972; Emery et al., 1975), and all of them are apparently built in similar fashion. They start with a transgressive onlap sequence that covers a pre-existing erosion surface, and end with a regressive sequence containing beds which parallel the angle of the slope (van Andel and Calvert, op.cit.). Barnaby (1974) and du Plessis (pers.comm.) are able to correlate each of the sedimentary units between individual seismic reflection profile lines, and their dispositions on the continental margin are illustrated in Fig.3.1 by means of single line off Walvis Bay. Du Plessis et al. (1972) have interpreted the

SOME GEOPHYSICAL AND GEOLOGICAL FEATURES OF THE CONTINENTAL MARGIN AND ADJACENT HINTERLAND

DSDP Site 362/362A

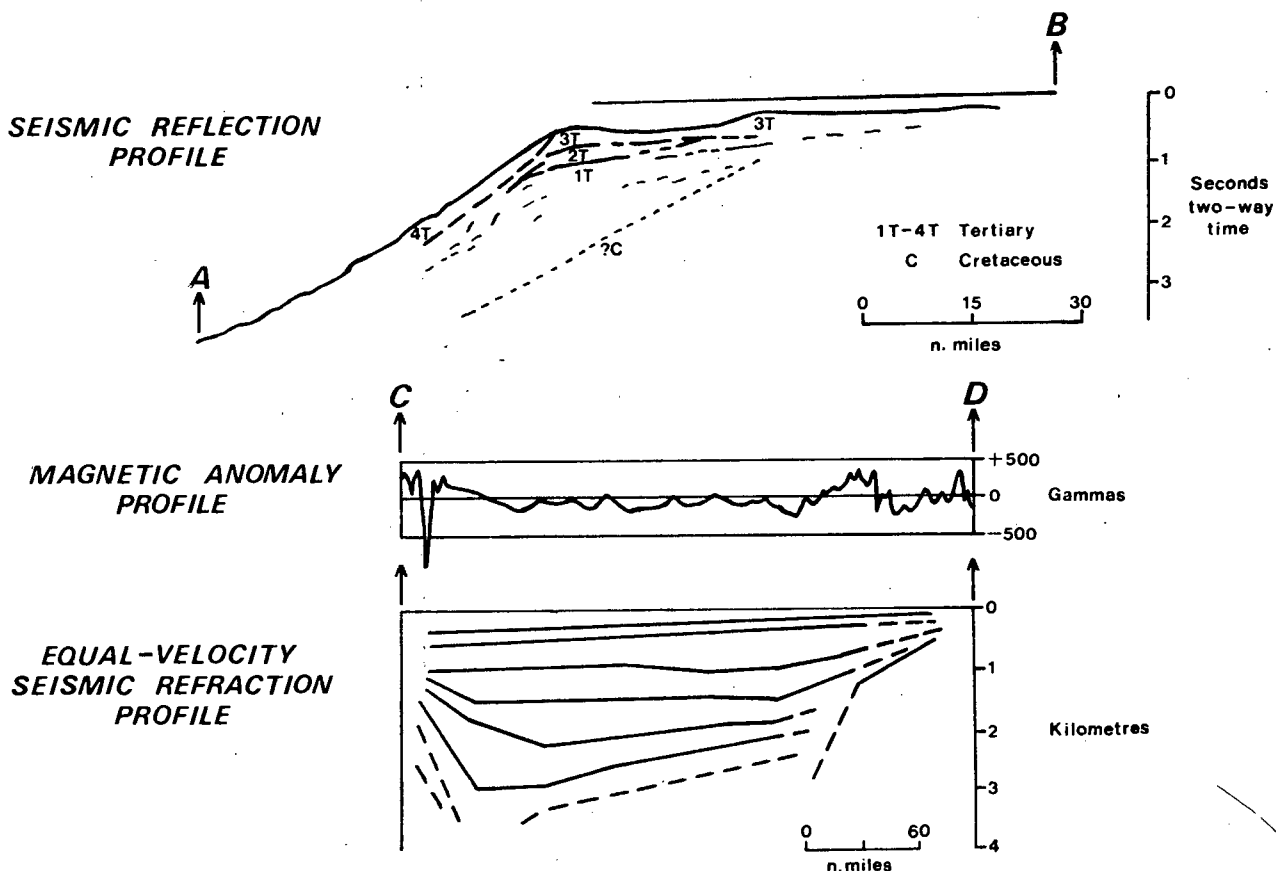
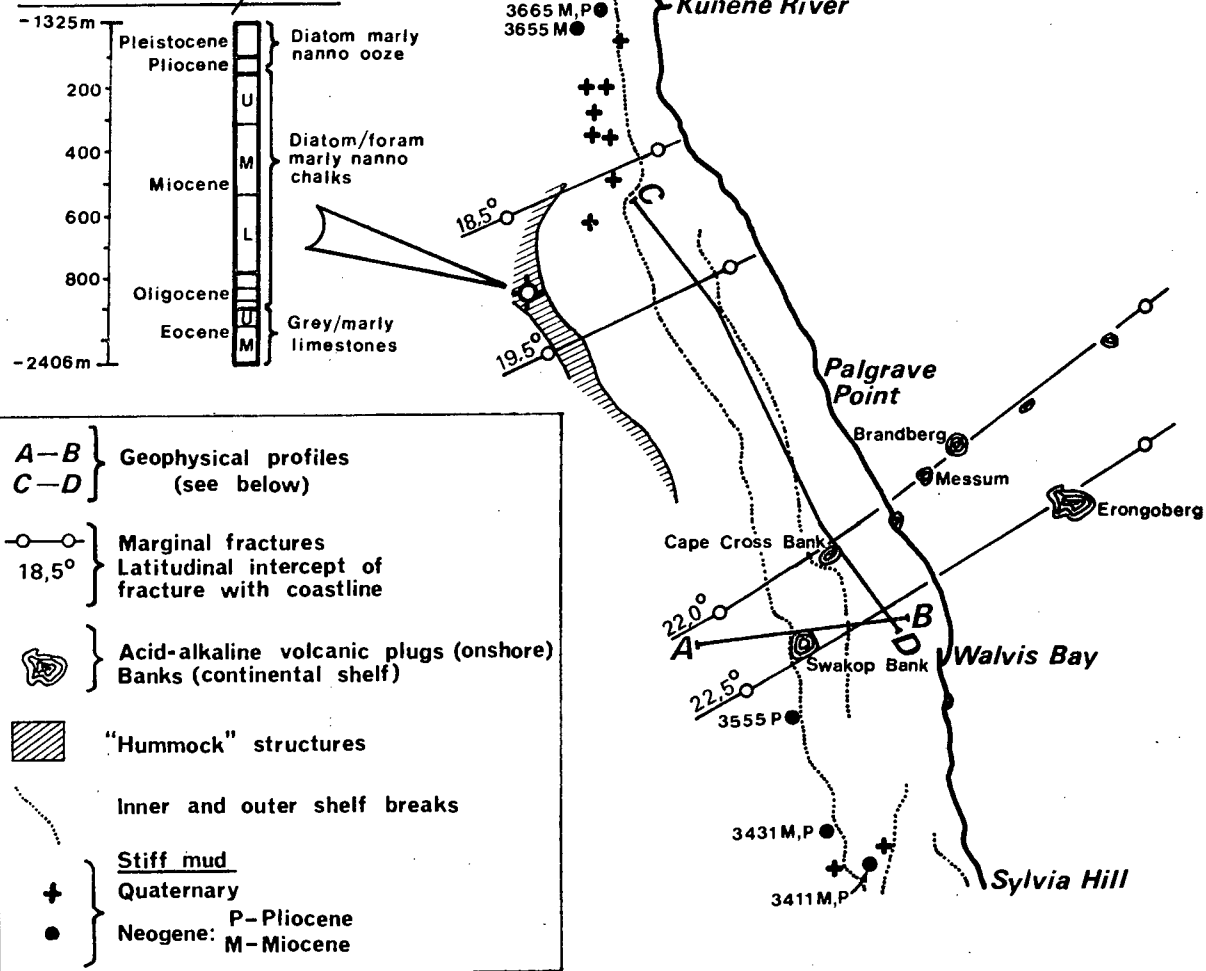


Figure 3.1

Modified after Barnaby(1974), du Plessis et al (1972) and Goslin et al (1975).

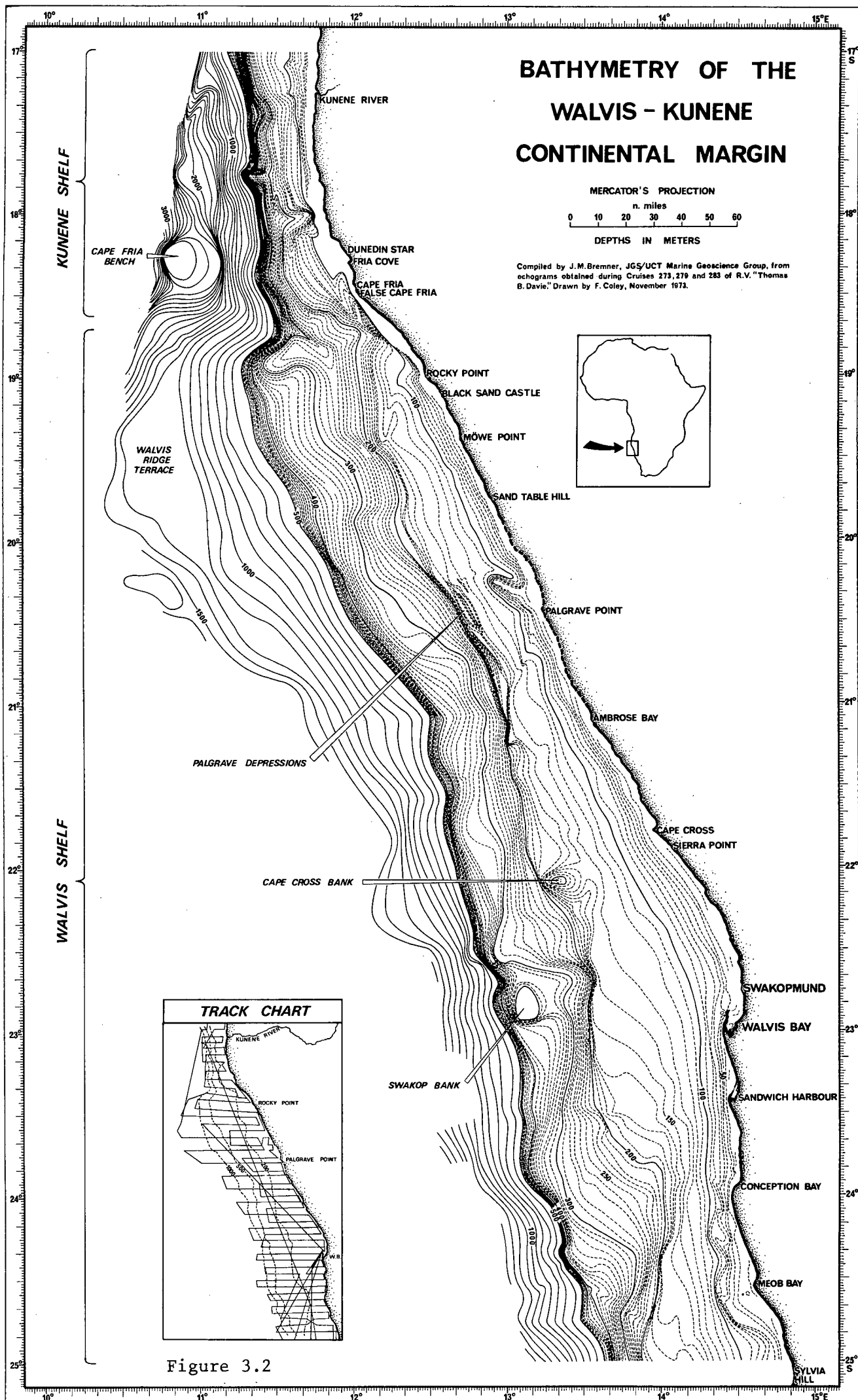


Figure 3.2

succession as being a reflection of mass sediment transport from the inner shelf to deeper water with each sea-level regression in Post-Cretaceous times.

Small-scale normal faulting, although a common feature of the sedimentary sequence, rarely gives expression to the present sea floor. Van Andel and Calvert (1971) consider the faults to be the effect of gravitational settling of the sediment, rather than to deep-seated crustal adjustments, since their downward displacements to the west decrease upward and often terminate within a single unit.

3.2.4 Continental flexure and marginal fractures

In general, continental interiors tend to rise due to net erosion, and continental margins tend to subside as a result of net deposition (Lewis, 1975). Although evidence for these isostatic adjustments of the crust are often masked by eustatic or tectonic events, isolated remnants of once widespread marine formations on the coastal platform of South West Africa may perhaps be indicative of continental uplift. For example, south of the study area, Haughton (1931) has described a small exposure of marine Cretaceous rocks near Bogenfels at an elevation of 60 m, Stocken (1962) has found littoral Lower Tertiary beds in the same vicinity at 160 m, and Carrington and Kensley (1969) have studied Pleistocene warm-water molluscs from raised beaches near the Orange River at an elevation of 25 m. Thus, although high marine deposits do not provide unequivocal evidence for continental uplift, acceptance of the tenet is generally widely accepted (du Toit, 1954; Haughton, 1969; King, 1951, 1962). On the other hand, irrefutable evidence for offshore subsidence is provided by the massive accumulation of continental shelf sediments since the breakup of West Gondwana 110-140 m.y. B.P. (Larsen and Pitman, 1972; Le Pichon and Hayes, 1971). Van Andel and Calvert (1971) have estimated the thickness of Tertiary strata on the shelf to be roughly 1 200 - 1 300 m.

Continental flexure necessitates the existence of an axis about which the rate of tilting can change. The concept of a 'zero isobase' close to shore (Lewis, 1974) satisfactorily accounts for this tilting of the continental margin - onland coastal belt, and defines the zero isobase as a line of no vertical movement, and an isobase as a line joining points of equal movement (de Geer, 1892, in Lewis, 1974). The isobase of maximum epeirogenic uplift on the southern African landmass was apparently located on the seaward side of the Great Escarpment (Truswell, 1970; Siesser, in press b), and gradual backward erosion has brought the escarpment to its present site.

The sediment wedge, although surprisingly thick (van Andel and Calvert, 1971), is not uniformly massive over its whole length because of differential subsidence of the crust between marginal fractures. These fault zones are

aligned along small circles of opening of the South Atlantic Ocean and are believed to be extensions of oceanic transform faults (Le Pichon and Hayes, 1971; Francheteau and Le Pichon, 1972). A number of attempts have been made to correlate onland lineaments of several ages to established offsets on the Walvis and Mid-Atlantic Ridges (Fuller, 1971, 1973; Marsh, 1973; Barnaby, 1974), as well as with boundary lines defining large sedimentary basins on the Brazilian and Argentinian continental shelves (Scrutton and Dingle, 1975). Barnaby (1974, Fig.1) has presented geophysical and bathymetric evidence for no fewer than seven marginal fractures within the study area. Three of these, which in the writer's opinion have most evidence to support them, are shown in Fig.3.1, and one additional one at $22,5^{\circ}$ is proposed based on parallelism of a Swakop Bank-Erongoberg lineament with the others (Fig.3.1). The importance of these fractures in the evolution of the continental margin has probably waned since Cretaceous times when crustal instability beneath the proto-margin would have been most profound (Siesser, Scrutton and Simpson, 1974).

3.3 REGIONAL TRENDS IN CONTINENTAL-MARGIN MORPHOLOGY

The regional trends of four continental-margin parameters, shelf-break depth, shelf width, shelf gradient, and the upper slope gradient have been plotted as a series of longitudinal curves in Fig.3.4, and a summary of these data is given in Table 3.1. The Walvis Ridge Abutment acts as a transitional zone between the morphologically distinct Kunene and Walvis margins, and for this reason, is expressed separately from the latter in Table 3.1 instead of as part of it.

Table 3.1 Average values for four morphological parameters of the continental margin

Parameter	Kunene Margin	Walvis Ridge Abutment	Walvis Margin south of the Abutment	World average*
Shelf break depth (metres) [Inner Outer]	- 196	140 305	155 361	- 132
Shelf width (n.miles) [Inner Outer]	- 24	25 42	36 64	- 40
Shelf gradient (degrees)	0,31	0,23	0,16	0,12
Upper slope gradient (degrees)	2,06	0,80	1,27	4,28**

* From Shepard (1963)

** Gradient of entire slope.

The physiographic regions shown in Table 3.1 and Fig.3.3 are: Kunene Margin - between survey lines 46 and 37; Walvis Ridge Abutment - between survey lines 37 and 31; and Walvis Margin - between survey lines 37 and 1.

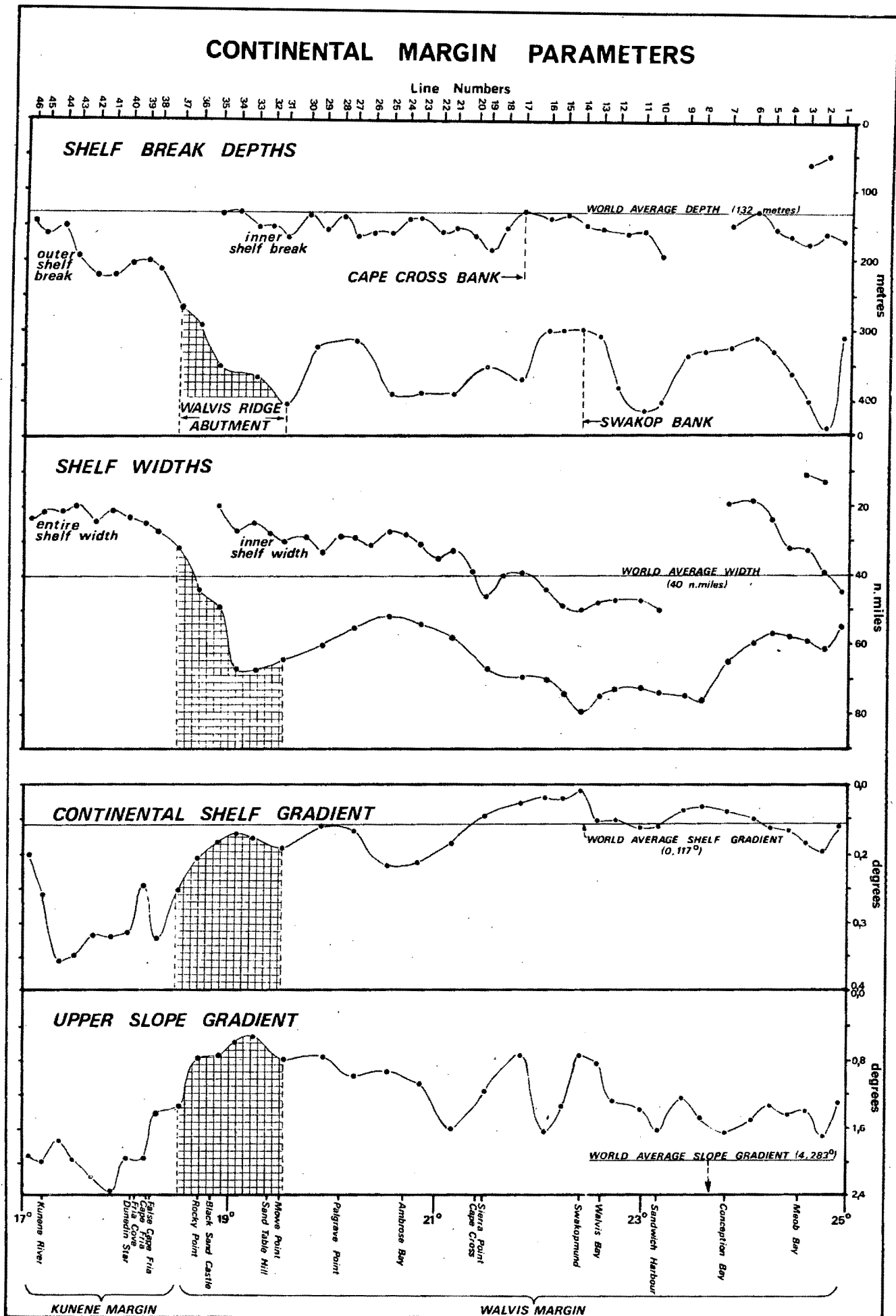


Figure 3.4

The shelf break off South West Africa has been commented on by Shepard (1963) as being one of the deepest in the world. On the Walvis Margin, the depth varies dramatically between 300 and 440 m, some of the shallower regions as off Swakopmund and Conception Bay being correlatable with major slumps on the upper slope, and generally showing better definition than the more broadly convexed deeper parts. From the southern end of the Walvis Ridge Abutment towards the north, the shelf break rises comparatively smoothly to about 150 m off the Kunene River mouth. This is the depth of the inner shelf break on the Walvis Shelf which is only fractionally deeper than the world average value for shelf break depths (Table 3.1). The inner shelf break extends from the northern edge of the Walvis Ridge Abutment to Sylvia Hill and, except for a 30 n.mile gap between Sandwich Harbour and Conception Bay, constitutes an unbroken and relatively well-developed feature of the Walvis Mid Shelf (Fig.3.1).

The widest part of the continental shelf is off Walvis Bay where a width of 80 n.miles is recorded. Although significantly wider than the world average for continental shelves (Table 3.1), it fades in comparison with the 125 n.mile shelf width measured in the vicinity of the Orange River delta (Rogers, pers.comm.). Northwards from the Walvis Ridge Abutment, the shelf decreases rapidly in width with the Kunene Shelf possessing a dimension equivalent to the northern part of the Walvis Inner Shelf. A gradual increase of the inner shelf width is evident on moving southwards from the Walvis Ridge Abutment to the Sandwich Harbour-Conception Bay gap, and south of the gap, a similar gradation is apparent towards Sylvia Hill (Fig.3.4).

The gradient of the Walvis Continental Shelf is, with minor variations, comparable with that of the world average value (Table 3.1). From the northern end of the Walvis Ridge Abutment however, it steepens sharply towards the north only to incline more gently again off the Kunene River mouth. The upper slope gradient is considerably less than the world average value for continental slopes (Table 3.1), and apart from a general sympathetic relationship to the shelf gradient, the upper slope exhibits somewhat greater fluctuations.

3.4 MORPHOLOGICAL REGIONS

The major geomorphic features of the continental shelf and upper slope are described in the following section, and where possible, they are related to the geophysical findings of other workers. The Kunene and Walvis continental margins are discussed separately, in each case starting with the shelf areas and ending with the slopes. Regarding the Walvis Shelf, the region between the coast and the inner shelf break is defined here as the 'inner shelf', and the region between the inner and outer shelf breaks as the 'outer shelf'. An additional region sometimes referred to is the 'mid shelf' which refers

to the central part of the continental shelf lying astride the inner shelf break. The nearshore zone is defined as a region adjacent the coast not exceeding a depth of 50 m.

3.4.1 The Kunene Margin

(a) Shelf

Ten n.miles north of the Kunene River mouth and also due west of it, two gentle ridges, composed at least in part of limestone (see Chapter 4), have caused slight seaward flexure of the isobaths down to a depth of 100 m. The latter ridge forms the northern flank of a shallow, westward-broadening valley that crosses the shelf to constitute a gentle indentation of the upper slope. Based on sedimentological evidence, this valley must have served to channel the Kunene River during periods of lower sea level since on either side of it, relict glauconite deposits of identical colour and morphology exist (see Chapter 5). The Kunene River has therefore not developed an extensive delta similar to the Orange River farther south, and this is probably due to the relative youth of the Kunene drainage system (Chapter 1).

Twenty n.miles south of this broad 'Kunene Valley', the shelf break is marked by a spur that protrudes out over the slope for about 5 n.miles. The general shape of this structure suggests that it probably formed through faulting as opposed to the more frequent slump structures which are evident in this region.

In the vicinity of Dunedin Star, two large assymmetric valleys head towards the coast but are traceable only as far as the 100 m isobath due to the lack of soundings landward of there. One of these valleys lies 10 n.miles north of Dunedin Star and the other roughly 10 n.miles to the south near Cape Fria. The Dunedin Star valley is a bifurcate feature that extends to a depth of 240 m and at its landward end, rises precipitously by at least 80 m. The Cape Fria valley strikes obliquely to the coast from a depth of 170 m and possesses a landward flank-wall at least 70 m in height. As with the Kunene Valley described earlier, these two valleys separate identical deposits of authigenic minerals, but this time, of relict pelletal phosphorite (see Chapter 5). Fluvial erosion must therefore have played a part in their formation, when sea level was lower and the climate more humid.

(b) Upper Slope

Due west of the Kunene River mouth, a deep valley cuts diagonally across the slope in a north-easterly direction and opens onto a gently sloping terrace between 1 800 and 2 100 m depth. The floor of this valley consists of stiff Miocene mud (sample 3655) whereas the slope immediately above it is composed of stiff muds of both Miocene and Pliocene age (sample 3665). Farther south, the slope has yielded several samples of stiff mud of Quaternary age. These and other pre-Holocene samples from the outer margin are listed in

Appendix B.3 together with their respective ages (Siesser, pers.comm.), and their locations are shown pictorially in Fig.3.1. In view of the age distribution of these stiff mud samples, together with apparent continuity of the slope above the valley and the terrace (Fig.3.2), it would seem that both structures resulted from a single large slump that occurred some time during the Quaternary. Several small dislocations near the shelf break are visible on the profiles of Fig.3.3 in this area, thus giving credence to the contention that large-scale slumping has been a feature on the relatively steep gradient of the upper slope (Fig.3.4).

At the southern end of the terrace, and in slightly deeper water, a semi-circular bench-like feature, called the Cape Fria Bench (Fig.3.2), constitutes the largest single geomorphic feature on the Kunene Upper Slope. Immediately above it, the slope plunges steeply to 2 300 m depth after which the bench rises to a 12 n.-mile-wide plateau at 2 100 m. Below the seaward edge of this plateau, the slope dips steeply again to 2 900 m after which the isobaths assume normal spacing. The southern edge of the Cape Fria Bench is bounded by the 18,5⁰ marginal fracture (Fig.3.1), and it is therefore tempting to speculate that tectonic seismicity along it may have been the agent responsible for triggering dislocation of the Cape Fria Bench from the upper slope. Moreover, it is possible that the valley and terrace features described earlier were also part of the same event.

3.4.2 The Walvis Margin

(a) Inner Shelf

South of Black Sand Castle (Fig.3.2), the morphology of the nearshore zone and large parts of the inner shelf, are masked by a thick cover of Holocene diatomaceous muds. However, a few isolated inliers that stick through the mud and a fairly large 'window' at Palgrave Point, have provided a number of clues, particularly on the bedrock composition and, to some extent, the morphology. The main source of information on bedrock morphology has been the high-resolution daughter-set echograms, which show very rough topography over large areas beneath the acoustically transparent diatomaceous mud (Fig.3.5, Plate 3.1, B and C). In general, it appears that the inner shelf dips relatively steeply down to a depth of about 90 m after which it flattens out as far as the inner shelf break (Fig.3.2).

Starting in the north of the area, the first geomorphic feature of interest is a shallow valley that strikes northeastwards towards Black Sand Castle from a depth of 150 m. This valley, as with the two already described on the Kunene Shelf, the Dunedin Star and Cape Fria valleys, caused dissection of a once widespread deposit of unconsolidated pelletal phosphorite

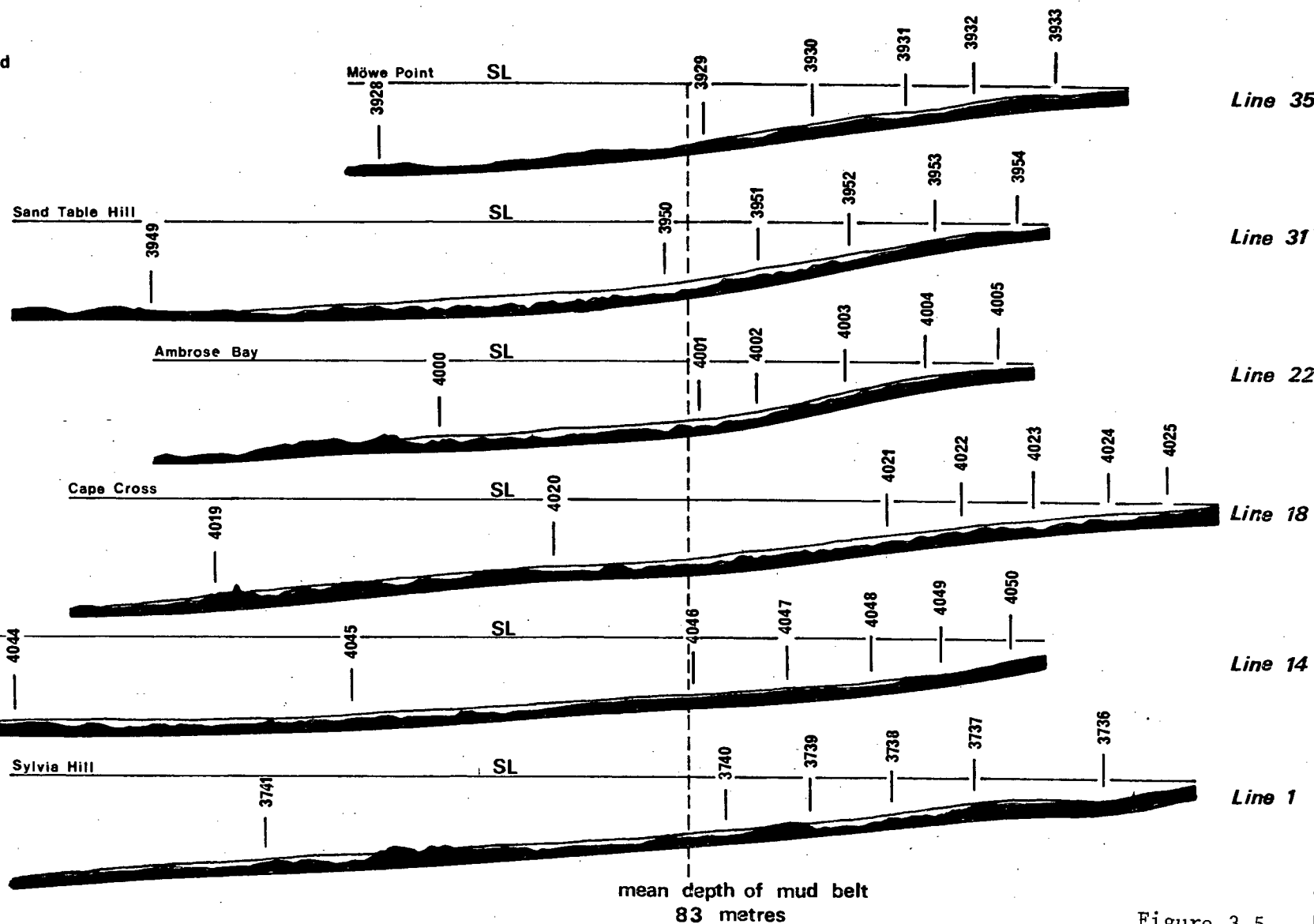
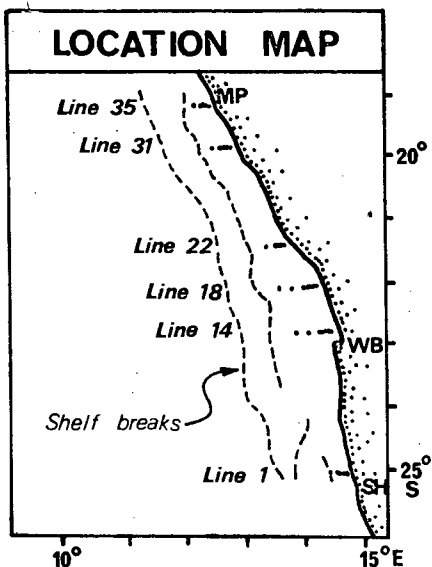
ECHOGRAMS ACROSS THE DIATOMACEOUS MUD BELT

3928 station numbers

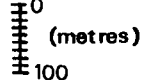
 acoustically transparent mud

 acoustic basement

LOCATION MAP



approx vertical scale



approx horizontal scale



Figure 3.5

that now exists as four, small, discrete bodies (see Chapter 5). It follows that fluvial erosion during lower sea level times must have played a part in the formation of this valley as well. The Hoarusib River, which reaches the coast directly onshore from this valley (Figs.3.2 and 3.3), drains a considerable catchment area, and would have been quite capable of eroding the sea floor during pluvial episodes that coincided with sea level regressions. Subsequent drowning of the river channel with terrigenous sediment presumably accounts for its shallowness.

At Palgrave Point, a northwest-trending shoal at 50 m depth, extends out to a point approximately 15 n.miles from shore. The crest of the shoal, as defined by the 50 m isobath, is separated from the nearshore zone to the north by a relatively steep-walled re-entrant, which strikes roughly parallel to the lineation of the Palgrave Depressions (Fig.3.2). Based on this evidence, it is tentatively suggested that the shoal originated through basement faulting. Two shallow valleys south of the shoal, one lying due west of Palgrave Point and the other 15 n.miles to the south, may also be related genetically to the tectonic framework of the area, but certainly provided channel-ways for the Koichab and Huab Rivers respectively during lower sea level times. The genetic explanations proposed for geomorphic features of the inner shelf are speculative, but lack of geophysical work in this area has made positive identification of their structures difficult.

An interesting aspect regarding Holocene sedimentation in the vicinity of the Palgrave Shoal deserves brief mention. This involves the previously mentioned 'window' in the diatomaceous mud belt off Palgrave Point. In this area, turbulence created by wave-induced bottom currents is sufficiently strong at the depth of the shoal (50 m), to prevent diatom frustules from settling (Chapter 2). Dissipation of some wave energy over the shoal, and the presence of deeper water in its lee, has resulted in accumulation of a small body of diatomaceous mud offshore from Sand Table Hill (see Chapter 5).

Due west of the 'Palgrave Shoal', and extending southwards for 60 n.miles, are the longitudinal troughs and ridges of the Palgrave Depressions (Figs.3.2 and 3.3). They lie immediately above, and up to 10 n.miles landward of the inner shelf break, and measure up to 20 n.miles in length, 3 n.miles in width, and 35 m in depth. The region is underlain by limestones (see Chapter 4) that have suffered extensive recrystallization, and dating them from nanno- and microfossils has not been possible (Siesser, pers.comm.). The area is unique however, in that it represents the only region where geophysical evidence points to faulting as the controlling factor in determining sea floor topography (van Andel and Calvert, 1971; profile B, p. 592). Six depth profiles across the Palgrave Depressions are shown in Inset A of Fig.3.3, and a daughter-

set echogram across the rugged topography is shown in Plate 3.1, D.

Fifty n.miles south of the Palgrave Depressions is the Cape Cross Bank (Fig.3.2). It is a cone-shaped feature which rises 40 m on its landward side to a fairly sharp peak at 90 m depth, and then drops off steeply on its seaward side to merge with the gradient of the inner shelf break. The geographic location of the bank is coincident with a 22° onshore lineament which is defined by a string of acid-alkaline volcanic plugs (Fig.3.1) of Jurassic to early Cretaceous age (Scrutton and Dingle, 1975). This 22° lineament has been interpreted by Marsh (1973) as being the continental expression of an oceanic transform fault, and Fuller (1971) and Barnaby (1974) have suggested that a marginal fracture occurs at this latitude. The overall shape of the Cape Cross Bank, and its geographic position in relation to the 22° marginal fracture, both suggest that it may be volcanic in origin, and furthermore, that it may be genetically related to Brandberg and the other onland volcanic occurrences (Fig.3.1). A profile across the feature is shown in Inset B of Figure 3.3.

The nearshore zone off Meob Bay is a region of fairly rugged relief (Plate 3.1, A) that probably reflects an offshore extension of Damara metasediments. These rocks crop out intermittently along the coast farther to the north (Fig.1.2), and a nearshore break in slope at 50 m depth south of Meob Bay (Fig.3.2) may indicate the boundary between these basement rocks and younger marine limestones.

(b) Outer shelf

The outer shelf 10 n.miles north of Rocky Point is marked by a large west-southwest pointing spur (Fig.3.2), beneath which lies the basement high shown on seismic-refraction, magnetic, and gravity maps of Goslin et al. (1973, 1975), and reproduced in section C - D of Fig.3.1. This basement high, lying immediately south of the $18,5^{\circ}$ marginal fracture, represents the landward termination of the northern flank of the Walvis Ridge, and according to Goslin (1975), it is probably basaltic in composition.

Sixty n.miles south of the spur-like feature on the Walvis Ridge Abutment, the southern flank of the Walvis Ridge terminates at the shelf break just north of the $19,5^{\circ}$ marginal fracture (Fig.3.1). Although not discernable on the bathymetric map of Fig.3.2, a steep-sided volcanic peak is exposed on the sea floor here, due west of Sand Table Hill (van Andel and Calvert, 1971). An extremely high Neogene sedimentation rate of 35 m/m.y. has been measured for the Walvis Ridge Abutment (DSDP site 362; Siesser, in press b), and the difference in slope gradients north and south of the Walvis Ridge Abutment (Fig.3.2) is therefore possibly related to differing seismicities of the $18,5^{\circ}$ and $19,5^{\circ}$ marginal fractures.

Forty five n.miles south of the Cape Cross Bank, another feature with positive relief and even larger dimensions lies on the outer shelf due west of Swakopmund. Called the Swakop Bank, it rises 25 m on its landward side to a 10 n.-mile-wide plateau at 300 m depth, and then drops off steeply at its seaward side in continuation with the gradient of the upper slope. The Swakop Bank is located south of the $22,0^{\circ}$ marginal fracture by approximately the same distance as the onshore Erongoberg massif (Fig.3.1), and therefore suggests the presence of a lineament parallel to the $18,5^{\circ}$, $19,5^{\circ}$ and $22,0^{\circ}$ marginal fractures. Based on this meagre evidence, it is postulated that this lineament represents an additional marginal fracture at $22,5^{\circ}$. Lack of information on the age and composition of the Swakop Bank make this hypothesis highly speculative, especially in view of the sedimentary bedding evident beneath its plateau-like summit on a shallow seismic profile (van Andel and Calvert, 1971; profile 2, p. 590). However, the pattern of isobath flexuring in the neighbourhood argues against an erosive origin whether by currents or wave-action, and the attractive symmetry of its disposition in relation to the Erongoberg does favour the concept of a marginal fracture there. The sediments at the crest of the feature may, furthermore, just be a thin cover overlying a large acid-alkaline volcanic plug.

On the outer shelf off Conception Bay, the isobaths are deflected from a northerly to a northwesterly trend, and in this general area the inner shelf break disappears. Shallow seismic profiles published by van Andel and Calvert (1971) and by Emery et al. (1975) do not expose any structural changes in the sediment bedding there, and the bathymetry may therefore be an expression of some deep-seated basement phenomenon. This aspect is discussed in Section 3.7.

(c) Upper slope

West of the Walvis Ridge Abutment between 1 200 and 1 300 m depth lies the Walvis Ridge Terrace which reaches a maximum width of 30 n.miles and an arcuate length of about 80 n.miles. An extremely gentle slope gradient immediately above the terrace would appear to preclude the possibility of it having formed through sediment slumping, and other hypotheses, such as current action or differential sedimentation rates, are very unlikely. However, continuous seismic profile records in the vicinity of the terrace indicate a thick sedimentary sequence between the two basement ridges flanking the Walvis Ridge (Goslin and Sibuet, 1975). It may therefore simply reflect infilling of a basin-like depression in the basement by oceanic sediment such as is deposited there today (see Chapter 5).

Another feature of the slope in this vicinity is the presence of a long narrow field of what have been called 'hummock structures'. Similar features have been reported from a number of other places in the world, and several theories have been proposed for their origin. For this reason, the non-genetic term 'hummock' has been coined to describe them. In general, hummocks appear on the echograms as a series of pseudo-symmetrical, overlapping hyperbolae that range in wavelength from 400 to 850 m, and in amplitude from 10 to 15 m (Plate 3.1, E). The distribution of the hummock field is shown in Fig. 3.1, and more explicitly, they fringe the outer edge of the Walvis Ridge Terrace, extending westwards to unknown depths. They do not, however, occur below the southern edge of the Walvis Ridge Terrace between 1 280 and 1 520 m depth. Shepard et al. (1975) have reported the presence of 'sand waves' on the west coast of Mexico at depths ranging between 320 and 770 m, with a maximum wave length of 750 m and an amplitude of 65 m. In profile they appear very similar to those on the Walvis Ridge Terrace, but are somewhat more peaked, and are thought to have originated from seasonal oscillations of a strong sub-surface current. Belderson et al. (1972) have obtained similar echograms from the Mediterranean Ridge using a conventional wide-beam echosounder, and refer to them as 'cobble stones' despite their heights of 100 m. Through use of a narrow-beam echosounder however, they were able to discern their true forms as angular, blocky, rock-structures. Krause and Kanaev (1973) have shown from theoretic considerations, that trapeze-shaped, trough-like depressions can, from the multiple echos of a wide-beam echosounder, produce hyperbolic traces. For this reason, the hummocks on the Walvis Ridge Terrace are envisaged as being a series of parallel troughs that may have been formed from down-slope gravity sliding of sediment in a highly hydrogenous state.

South of the Walvis Ridge Terrace, some large embayments on the upper slope have been found to have originated from slumping with concomittent translation of sediment onto the continental rise (Summerhayes, pers.comm.). Two very large slump structures were discovered during Cruise 115, Leg 2, of R.V. CHAIN, one from the slope embayment adjacent to Swakop Bank, and the other from an embayment just south of Conception Bay (Fig.3.2). Both of these slumps, together with others, are evident as regions of steepened upper-slope gradient in Fig.3.4.

Stiff mud samples recovered from the Walvis Margin are limited in number, but identical in appearance and texture to the stiff mud samples from the Kumene Margin (Fig.3.1). Unlike the latter however, no sequential order in the regional distribution of the Walvis Margin stiff muds is apparent (Fig.3.1), and Quaternary samples occurring at both greater and shallower depths than Miocene/Pliocene samples, probably indicate their presence as isolated thin outliers. The

semi-consolidated nature of these mud occurrences indicate a very slow sedimentation rate on the outer margin, or alternatively, that erosion of overlying younger sediment occurred during periods of sea-level regression. Both processes would indicate that upbuilding of the outer margin due west of the Kunene River, and due west of Sylvia Hill, ceased to be a phenomenon in post-Miocene times. The absence of stiff mud in the region between the Walvis Ridge Abutment 'spur' and the Swakop Bank (Fig.3.1) suggests that this is the only region where thickening of the sediment wedge has occurred to any extent since the Miocene.

3.5 EFFECT OF SEA LEVEL AND CLIMATIC CHANGES ON CONTINENTAL MARGIN SEDIMENTATION

Holocene sedimentation on the continental margin has been most pronounced on the inner shelf as indicated by the relative thickness of diatomaceous mud on the Walvis inner shelf (Fig.3.5). During eustatic lowerings of sea level, this zone of maximum sedimentation would have shifted to the outer shelf or upper slope depending on the magnitude of the regression. An increased precipitation rate at this time, as is suggested by Guilcher (1971), would have resulted in unconsolidated sediments on the inner shelf, such as diatomaceous mud, being eroded subaerially, and mass transported to a new depocentre on the outer margin. Under this set of conditions, the Kunene and Namib Sand Seas would conceivably have become vegetated and largely stabilized, and the net effect on the inner shelf would have been a reversion to its pre-transgression state through mass sediment transport onto the outer margin. On the other hand, if sea-level regression was accompanied by a continuation of the arid climatic conditions, as is suggested by van Zinderen Bakker (1975) for the Würm II pleniglacial, the highly mobile coastal parts of the Kunene and Namib Sand Seas would have migrated onto the inner shelf by aeolian processes, and burial and preservation of unconsolidated sediment there would have been assured. A probable corollary to this migration concept would be the development of lagoons and estuaries in the lee of barrier beaches, numerous relict examples of which exist along the coast in the form of salt pans today. The net effect of this set of conditions would therefore be significant upbuilding of the inner shelf, which contrasts strongly with the high precipitation situation when inner shelf erosion and outer margin upbuilding would have occurred.

Biological evidence suggests that at several times in the past, subtropical conditions must have prevailed along the west coast of southern Africa. In particular, Barash (1974) has found that a subtropical climate extended as far south as Múwe Point (20°S) during the last stadial, and Tankard and Rogers (in prep.) have obtained evidence that summer-rainfall conditions may have existed as far south as Saldanha Bay (33°S) during the Pliocene. A northward shift

of the climatic belts during the Pleistocene Würm II pleniglacial however, is suggested from the following diverse lines of evidence:

- A thick deposit of diatomaceous mud exists beneath Holocene foraminiferal muddy sands on the Walvis Ridge Terrace (DSDP hole 362/362A; Siesser, pers. comm.) implying a northward shift in the region of maximum upwelling.
- An endemic biome common to both the Kunene and Namib Sand Seas (van Zinderen Bakker, 1975) suggests that the two sand deposits were at one time unified.
- Fluvial silt beds, occurring high above the present channel of the Kuiseb River at Homib (Mueller, 1974), indicate that the floor of the valley was at some stage dammed by northward migrating dunes of the Namib Sand Sea.

3.6 DEPTH OF SEA LEVEL DURING THE WÜRM II REGRESSION

Evidence of a Würm II sea-level lowering to -110 m along the west coast of southern Africa has recently been obtained from vibro-coring work in the vicinity of the Orange River delta (Rogers, 1977). Further evidence for a still-stand at this depth has been found by van Andel and Calvert (1971) who, from shallow-seismic work in the study area, detected a low but consistent escarpment which they referred to as the 110 m notch. Finally, during the course of routine sediment sampling on the inner shelf, the writer recovered a number of well-rounded pebbles and cobbles from probable relict storm beaches. The frequency of these gravel sample recoveries plotted against their respective depths indicate that, although the total number of samples is small (21), peaks between 40 and 60 m, 100 and 120 m, and 180 and 200 m depth occur (Fig.3.6). The last-named peak may be a reflection of a major Pleistocene sea-level regression, and the first one may have been formed during a short-lived still stand of the Flandrian transgression. The 100-120 m peak supports previous evidence of sea-level reaching -110 m during the Würm II pleniglacial, and based on this premise, the depths at which sediment of various textural sizes would have settled from suspension at that time, have been calculated using wave parameters descriptive of 'distant' storm waves that impinge along the coast today (see Appendix A.2). The results are plotted in the form of a regional distribution map in Fig.3.6 from where it appears that the maximum depth at which fine sand (2-3 ϕ) (the mean size of sediment composing the dunes of the Namib Sand Sea) would have settled from suspension, is 210 m. Dispersion of terrigenous sediment during the Würm II pleniglacial would therefore have been largely restricted to the inner and mid shelves.

3.7 ORIGIN OF THE INNER SHELF BREAK

Shallow seismic work in the area has thrown little light on the internal structure of the inner shelf break, and most profiles across it show a simple

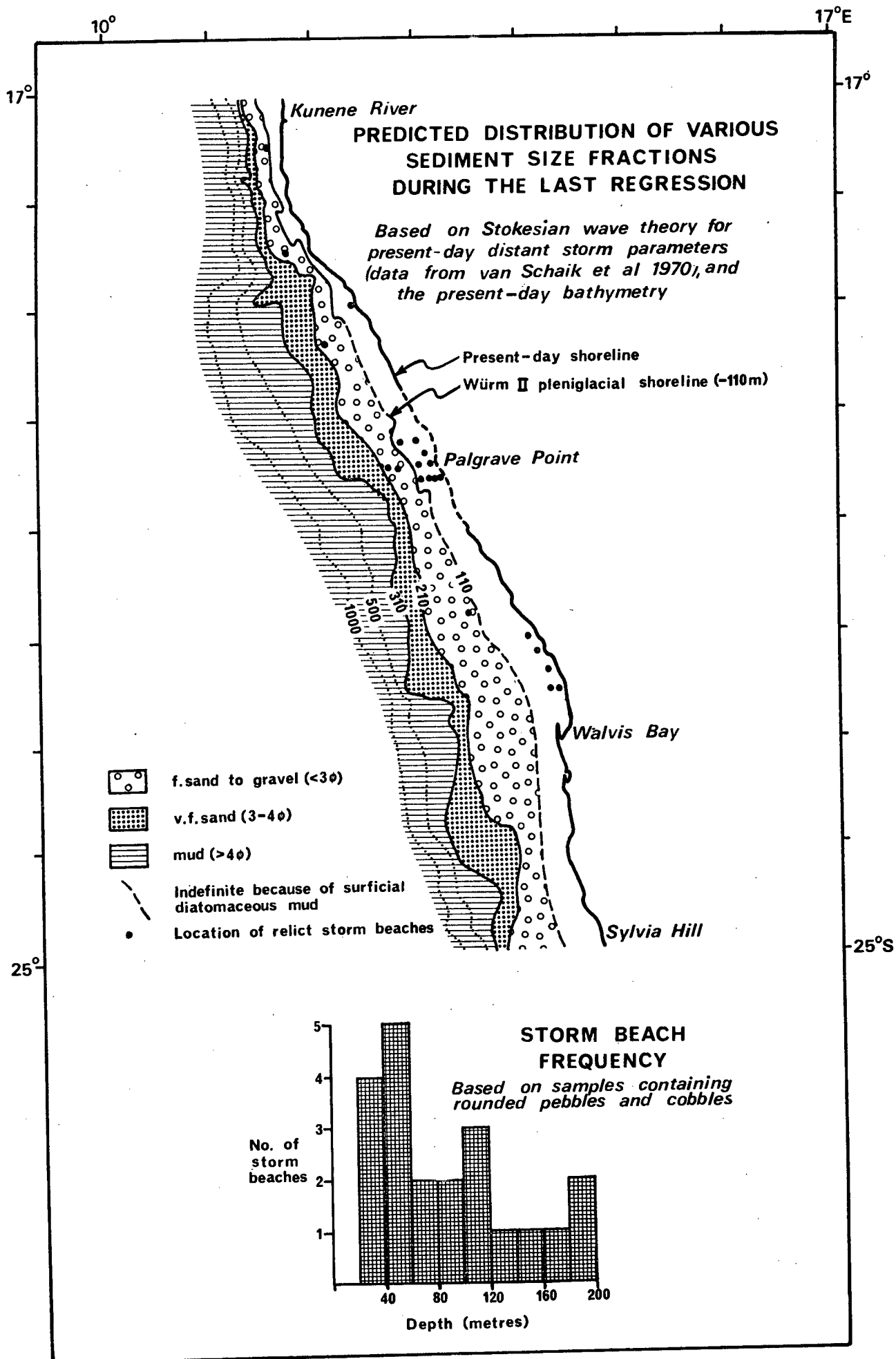


Figure 3.6

thickening of the underlying sedimentary unit 3T (Fig.3.1). Only south of the study area between the Orange and the Olifants Rivers has it been studied to any extent, but even here its origin is not properly known. Dingle (1971, pers.comm.) considers that a lower Upper Tertiary shelf-bar complex on the seaward side of a sub-bottom anticlinal arch in this area may perhaps be related to the development of the inner shelf break. Within the study area however, the inner shelf break appears to be totally unrelated to basement structure (except for the Palgrave Depression and Cape Cross Bank areas), and is simply defined by a gentle convexity of the sea floor. In addition, despite the presence of several small declivities on either side of it, the uniqueness of its virtual unbroken continuity and its regular depth (Figs.3.2, 3.4) make it a singularly important geomorphic feature on the Walvis Continental Shelf.

The average depth of the inner shelf break (155 m, Table 3.1) is 45 m below the depth of sea level during the Würm II pleniglacial (110 m). This difference is roughly equivalent to the depth of wave base ($L_0/2$) for material coarser than very fine sand using wave parameters of 'local' storm conditions existent today (Table 2.2). In other words, fine-grained terrigenous sediment of the Namib Sand Sea would have been stable at the top of the inner shelf break (155 m) during the Würm II sea-level lowering, and as shown above, wave-induced bottom currents from 'distant' storms would have been able to transport this material in suspension to the bottom of the inner shelf break (~ 210 m). Based on this and previously listed evidence, it is postulated that the inner shelf break dates from the Würm II pleniglacial and formed through migration of coastal parts of the Namib Sand Sea onto the Walvis Inner Shelf. Other indications of this event having occurred are obtained from studies on the terrigenous fraction of the sediments in this region (see Chapter 5).

The discontinuity of the inner shelf break between Sandwich Harbour and Conception Bay may be related to the northwest orientation of isobaths in the area. During Würm II, the strike of this part of the mid shelf would have been at a fairly wide angle to prevailing southerly winds, and terrigenous sand accumulating on the beach foreshore would have been blown inland rather than trapped, as elsewhere, along the coast.

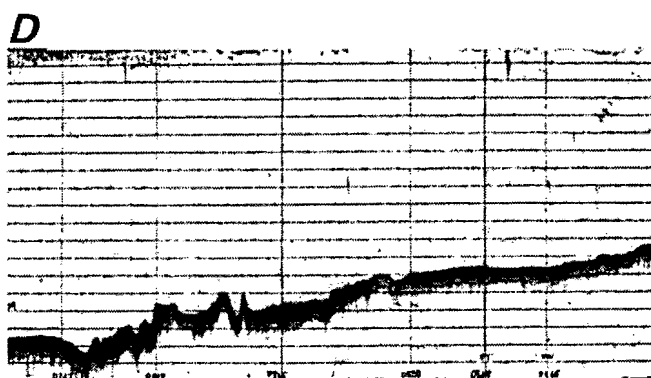
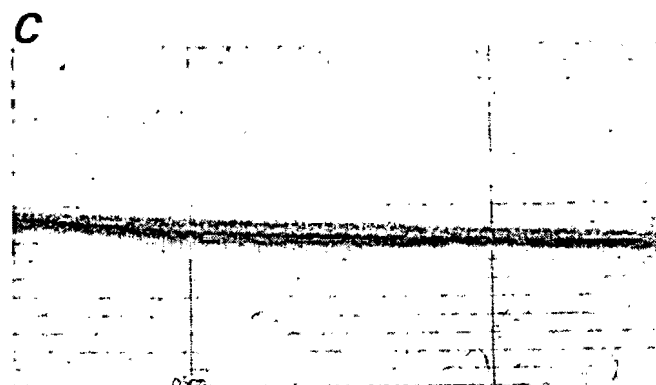
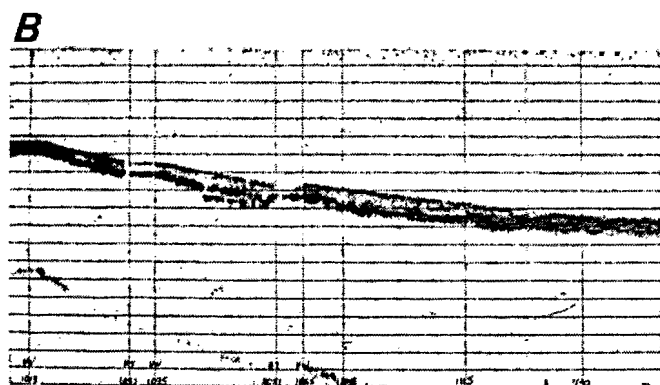
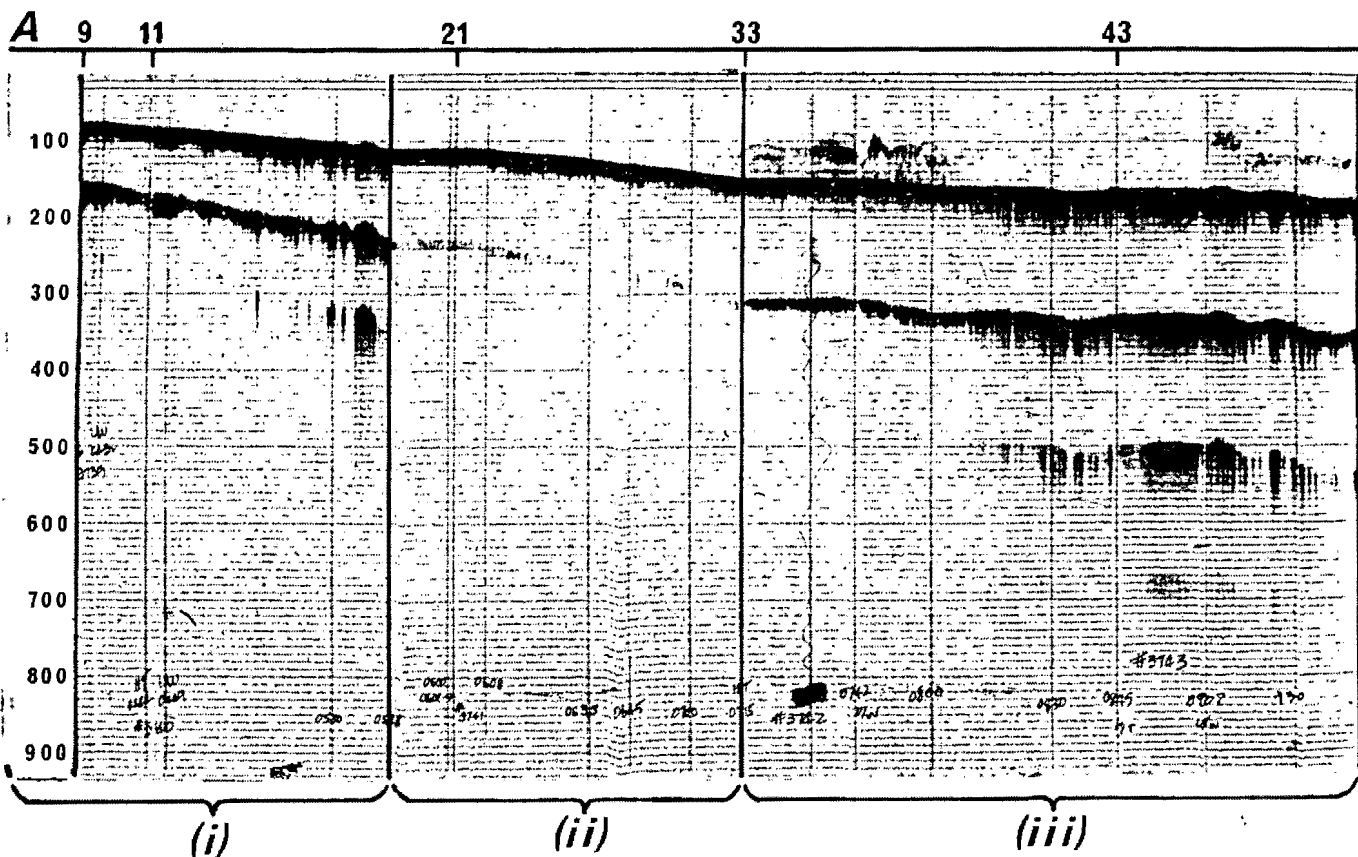
The outer shelf, in contrast to the inner shelf, is an ancient geomorphic feature supporting only a thin veneer of Holocene sediment over much of its surface. The apparent concavity of its profile need not be attributed to strong current scour as has been proposed by van Andel and Calvert (1971) but rather, to an expression of the upbuilding that occurred on the inner shelf during Würm II.

Plate 3.1

Echograms of the sea floor

- A. Master set echogram across the continental shelf showing typical variations in the intensity of sea floor reflectiveness (20 n.miles south of Meob Bay).
- (i) Rugged bedrock topography overlain by patches of terrigenous sand and diatomaceous mud.
 - (ii) Smooth-surfaced, firm, sediment, composed mainly of relict mollusc-shell debris and pelletal phosphorite.
 - (iii) Undulating surface topography with strong reflectivity.
- The sea floor is stiff pre-Holocene mud capped by a thin layer of relict pelletal phosphorite and quartz, and modern planktonic foraminifera.
- B. Daughter set echogram (10 n.miles south of Cape Cross). Rough topography overlain by acoustically transparent diatomaceous mud (cf. Fig. 3.5).
- C. Daughter set echogram (off Swakopmund). Smooth topography overlain by acoustically transparent diatomaceous mud (cf. Fig. 3.5).
- D. Daughter set echogram (30 n.miles south of Palgrave Point). Rugged bedrock topography of the Palgrave Depressions (cf. Fig. 3.3).
- E. Master set echogram (145 n.miles west-northwest of Palgrave Point). "Hummock" structures in smooth soft sediment.

Distance from shore in n.miles



HORIZONTAL SCALE

2.6 cm = 1 n. mile

VERTICAL SCALE

1 interval = 10 metres

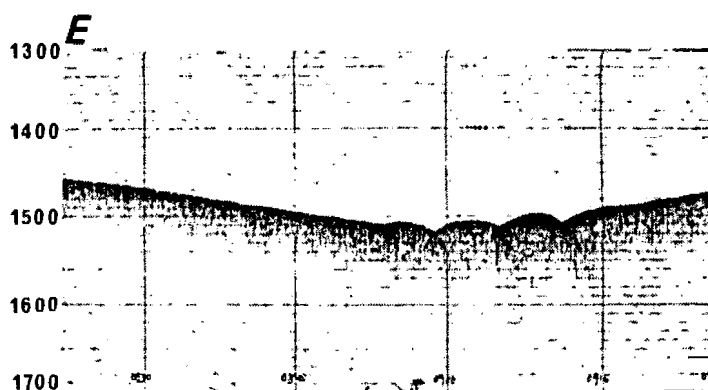


Plate 3.1

Chapter 4. PETROGRAPHY OF SEA-FLOOR BEDROCK

4.1 INTRODUCTION

This Chapter gives the results of a petrographic study on bedrock samples recovered during Cruise 300 to the study area. The methods employed in recovering these samples were described in Chapter 1, and the stations occupied during the cruise are listed in Appendix B.1 and shown graphically in Fig.1.2.

The relatively low success rate of bedrock sample recoveries (Table 1.1) is due to a thicker and more extensive apron of Holocene sediments here than south of the study area, and this in turn reflects the greater productivity of these shelf waters compared to the study areas in the south (Chapter 1). Almost all the samples were obtained from depths of less than 200 m, and the Kunene Shelf, which lacks a modern biogenic sediment cover equivalent to that of the Walvis Shelf, yielded proportionately a much greater number of samples. In general, the rocks recovered can be grouped into four main areas viz. the Kunene River - Rocky Point area (13 samples), the Palgrave Point area (14 samples), the Cape Cross - Swakopmund area (6 samples), and the Meob Bay area (2 samples). Total recovery from these 35 successful stations include 42 pre-Jurassic terrestrial rocks, and 53 Tertiary marine sedimentary rocks. Whereas the former have simply been identified (Appendix B.4) and correlated with the onland geology, the latter were examined petrographically (Appendix B.6) and classified (Appendix B.5) in an effort to evaluate their petrogenesis.

One of the rock facies found on the continental shelf is phosphorite, and in this Chapter, its age and depositional environment, as well as that of associated pelletal phosphorite, is briefly examined. In Chapter 5, the concentration and regional distribution, and in Chapter 8, the major and trace element compositions and modes of origin of these lithofacies are considered.

4.2 CLASSIFICATION AND NOMENCLATURE

4.2.1 Terrestrial rocks

Almost all rocks recovered from the continental shelf that were correlatable with the onland geology, occurred either as well-rounded pebbles, or cobbles, thus indicating some transport from their places of origin. Their study has therefore been confined to a rapid thin-section examination, simply in order to assign petrographic names to them (Appendix B.4). However, their depths of occurrence have been utilized for determining still-stands of late-Pleistocene sea-level regressions by assuming that they represent sites of relict storm beaches (Fig.3.6).

4.2.2 Limestones

Dunham's (1962) classification of carbonate rocks has been effectively used by Siesser (1971) and Rogers (1977) on the Agulhas Bank and Orange Shelf areas respectively, and for the sake of consistency, this system is used here as well (Appendix B.5). It entails a textural subdivision of the rocks based on the abundance of lime mud, and the packing style of the granular fabric. For example, 'lime mudstones' and 'lime wackestones' contain <10% and >10% grains respectively, 'lime packstones' consist of a grain-supported framework with subordinate amounts of lime mud, and 'lime grainstones' contain no lime mud at all. Moreover, the grain-size scale of Grabau (1913, in Siesser, 1971) is employed to qualify more precisely the textural character of the carbonate rocks. For example, 'calcilutite', 'calcarenite' and 'calcirudite'. Regarding the composition of the granular fabric, minerals exceeding 10% of the rock have been named from left to right in decreasing order of abundance (Appendix B.5). An important sub-group of the limestones from the study area are those containing gravel-size particles as a distinctive component of the granular fabric. These calcirudites are classified separately from the other limestones by use of the prefix 'pebbly'. Thus, a large amount of information on the texture, composition and origin of the rocks is provided in the nomenclature. For example, sample 4714A is a 'Very fine sand size calcarenite: pebbly quartzose glauconitic lime wackestone'.

Finally, an apparent disparity between the P_2O_5 content of some of the limestones and the petrographic estimates of their phosphorite contents, is due to the fact that the phosphorite occurs most commonly as infillings in limestone borings, and the chemically and petrographically analysed material from the same samples were sometimes quite different. These rocks are qualified by the prefix 'bored'. For example, sample 4798B is a 'Bored calcilutite: lime mudstone' ($P_2O_5 = 7.26\%$).

4.2.3 Phosphorites

Following the approach of Rogers (1977), Dunham's (1962) classification for limestones has simply been extended to include the phosphorites by replacing the terms 'lime' and 'calc' with 'phosphate' and 'phos' respectively. For example, sample 4727B is a 'Cast - very fine sand size phosarenite: quartz phosphate wackestone' (Appendix B.5).

Parker (1971) and Rogers (1977) adopted the classification of Bushinsky (1966) for defining the boundary between limestones and phosphorites viz. 18% P_2O_5 . Chemical analyses of marine rocks from the study area are misleading however, because the dominant mode of occurrence of phosphorite, as mentioned earlier, is in the form of infillings. Also, most of the samples recovered were very small in size and after cutting thin-sections from them, not much

material remained for analysis. It was therefore decided to use visual estimates for classification purposes, and this was based on a total apatite content of 50% (Bushinsky, 1966) using the percentage charts of Terry and Chilingar (1955). Those samples composed of two different rock types have been classified individually in Appendices B.5 and B.6 and are indicated by means of a slash (/).

Diagnostic information on the origin of some phosphorite samples was obtained from the morphology of the hand specimens e.g., mollusc casts and bones, and this evidence has been incorporated into the classification of the phosphorites as well e.g., sample 4744D is a 'Bone - fine sand-size phosarenite: quartz phosphate wackestone'. One of the samples from the vicinity of Cape Fria (sample 4727A/) consisted of several thin layers of lime wackestone the top member of which was eroded and capped by phosphate wackestone; it is therefore prefixed by the adjective 'lamellar'.

Attention should be drawn to the fact that the vast majority of phosphorite samples are small in size and occur most commonly as infillings in cavities e.g., in limestone borings, in haversian canals of vertebrate bones, and as mollusc casts. They are therefore generally referred to as 'infillings' although technically, this is not strictly correct. A few of the samples occur in other forms (Appendix B.6) e.g., the lamellar and some of the rock samples, but even the latter are mostly small in size and may originally have been formed as infillings.

4.3 TERRESTRIAL METASEDIMENTS AND IGNEOUS ROCKS

Despite the fact that all these rocks but one (sample 4732B) have undergone considerable mechanical abrasion, their lithology and disposition on the shelf corresponds well with that of the adjacent onland geology (Fig.1.2). Sample 4732B from 28 m depth off Cape Fria (Fig.4.1) is a very immature quartz mudstone possessing angularity, and probably represents the only specimen from this suite of rocks that was physically detached from the sea floor.

Terrestrial rocks such as metaquartzites, biotite-rich arkoses, biotite schists and vein quartz (Appendix B.4) were dredged from Palgrave Point and the Cape Cross-Swakopmund areas (Fig.4.1) and are typical of the eugeosynclinal Swakop Facies of the Damara System (Chapter 1). Pebbles of acidic lava occur widely on the inner shelf, and in the vicinity of Palgrave Point rhyolites are abundant. This may indicate that the Kaoko Lavas are actually more acidic than tholeiitic along the coast since only one sample of tholeiite was recovered far to the north off Rocky Point (Fig.4.1). Acid intrusive rocks too are much more common than their basic equivalents. Off Rocky Point the most frequently occurring intrusive rocks are granitic in composition; in the Swakopmund area,

LOCATION OF BEDROCK SAMPLES

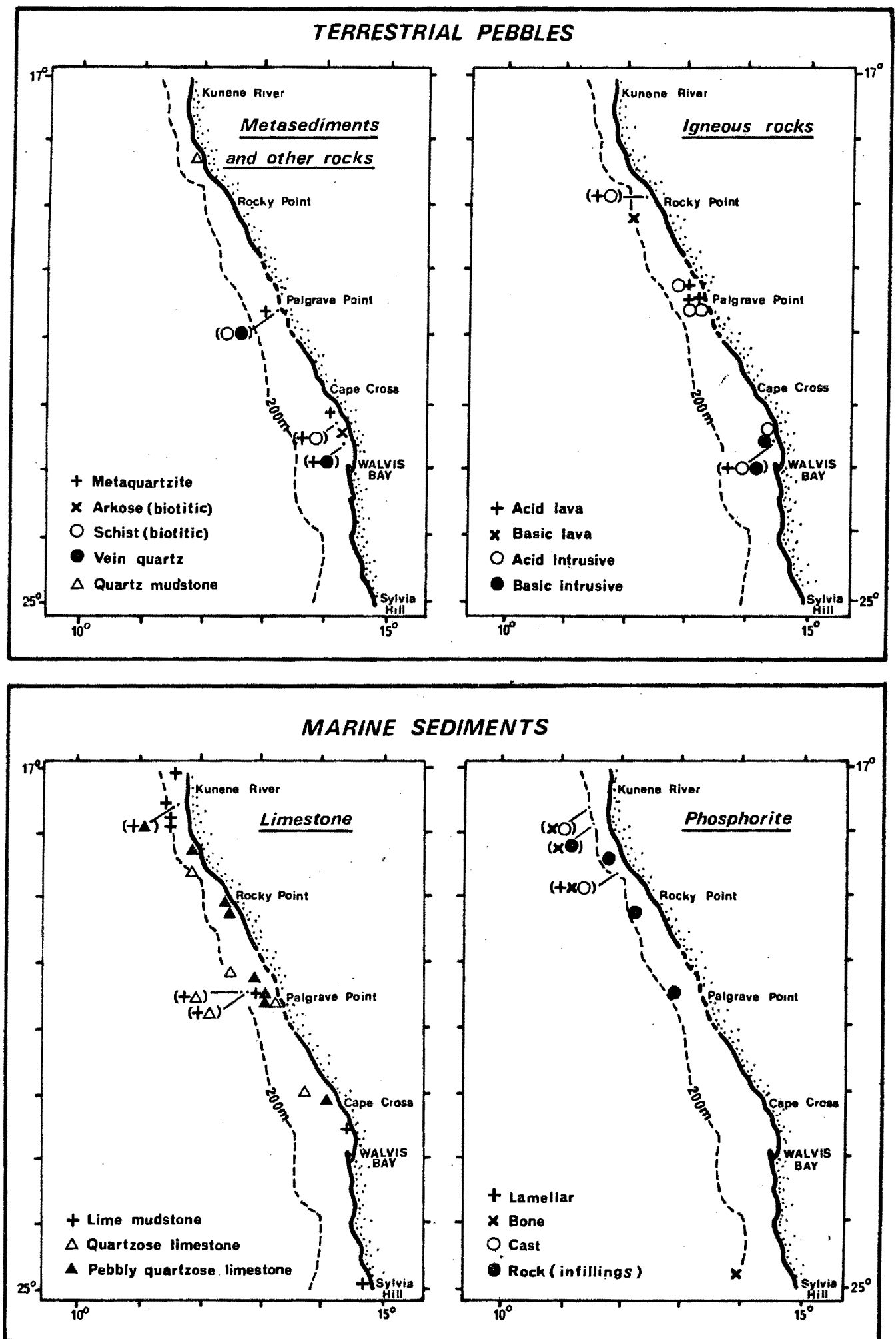


Figure 4.1

pegmatitic granites typical of the Salem Granite (Fig.1.2) are common; and only off Palgrave Point do a few dioritic rocks occur. Gabbroic pebbles were recovered from two locations, both in the vicinity of Swakopmund, and may have been derived from the acid-alkaline intrusive plugs that are thought to define the marginal fractures at 22,0°S and 22,5°S (Fig.3.1).

4.4 LIME MUDSTONES, QUARTZOSE LIMESTONES, AND PEBBLY QUARTZOSE LIMESTONES

4.4.1 Location

Lime mudstones, the best represented facies in the study area, have a wide-spread distribution, being particularly common off the Kunene River mouth, and the western part of the Palgrave Point area (Fig.4.1). At these two locations, the average depth of occurrence of lime mudstones is about 160 m, but farther south, they occur at much shallower depths viz., 25 m off Swakopmund and 60 m off Meob Bay.

Quartzose limestones (quartzose lime wackestones and packstones) are restricted in their occurrence to the Walvis Inner Shelf north of Swakopmund. The wackestones lie at about the same water depth as the mudstones, but the packstones are generally shallower. A single grainstone specimen (sample 4701C), consisting entirely of mollusc shells, that were well-cemented together and strongly bored, was recovered from 53 m off Palgrave Point.

The pebbly quartzose limestones (pebbly quartzose lime mudstones, wackestones and packstones) are commonly found on the inner shelf between Swakopmund and the Kunene River, and invariably occur in shallower water depths (average of 80 m) than the equivalent non-pebbly limestones. Glauconite when present, is found in significant quantities only in the mudstones and wackestones of this pebbly limestone facies, which lie, on average, at 100 m depth.

4.4.2 Petrography

Classification and detailed petrographic descriptions of these rocks are given in Appendices B.5 and B.6 respectively. The limestones are typically grey and range in value from yellowish grey to olive grey (5 Y 7/2 - 3/2). Rounded specimens, which are usually poorly cemented and friable, exhibit less chroma and range from medium grey (N5) to very light grey (N8).

The rocks in this facies sometimes contain trace amounts of planktonic, and less frequently, benthic foraminifera. Apart from sample 4701C (the mollusc lime grainstone), a few of the pebbly specimens also contain small mollusc shells. Most of these carbonate grains have been severely altered to microspar.

The most commonly occurring allogenic component is quartz. In the lime mudstones, it is angular and very fine sand-size; in the quartzose limestones,

fine angular quartz occurs with coarser and better rounded grains; and in the pebbly quartz limestones, the gravel-size components are generally subrounded to rounded. The lime mudstones contain 0-5% quartz and average about 2%; the wackestones contain 10-40% quartz, averaging about 20%; and the packstones contain 35-75% quartz, averaging about 50%. Other allogenic components tend to increase proportionately with the abundance of quartz, the most common of these being: feldspar, chert, biotite, and occasionally, trace amounts of magnetite and ferromagnesian minerals. In only one sample, from Palgrave Point (4702A), is feldspar a major component viz., 20%. The pebbles of the pebbly quartzose limestones are invariably quartz, and only rarely is metaquartzite and granite present.

Authigenic grains are common constituents of the granular fabric, but are normally present in only trace quantities. Phosphorite is present as fine to medium sand-size pellets and fragments and never exceeds 3% of the rock composition. Glauconite is most abundant in the pebbly quartzose limestones, and in two samples (4714A and 4737B) from the Palgrave Point and the Kunene River areas respectively, it attains concentrations of 10%. Whereas glauconite always exists as discrete grains, collophane is occasionally found replacing the outer edges of limestone samples. Of importance concerning the rocks of this facies is the presence in many samples of phosphorite infillings. The abundance of glauconite, as well as pelletal and fragmental phosphorite particles in these infillings, has resulted in many limestones with abnormally high P_2O_5 and K_2O values (Appendix B.6).

Pyrite, as a minor component of the granular fabric, is most abundant in the lime mudstones (trace to 2%) followed by the quartz lime wackestones (trace to 1%), and is not present at all in the packstones and the grainstone. The most common form of pyrite is silt-size grains which occur disseminated throughout the matrix, and more rarely, it is found as microfossil infillings (e.g., sample 4744A from the Kunene River area).

The intergranular fabric of these rocks consists of variable proportions of micrite and microspar. The lime mudstones and quartzose limestones contain more micrite than microspar, whereas the pebbly quartzose limestones are the reverse. In addition, two samples of the latter group, from the area around Palgrave Point (samples 4703A and 4706C), also contain significant amounts of pseudospar. The microspar is generally somewhat cloudy except where it surrounds allogenic grains as thin, clear envelopes of vertically oriented crystals. Microspar has also crystallized from lime mud at small nucleation centres within the matrix, and this has imparted a patchy appearance to some of the mudstones in thin-section. Occasionally, microspar is also present along minute shear planes as small lenses.

4.5 PHOSPHORITE CASTS, BONES, LAMINATIONS AND ROCKS

4.5.1 Location

This varied group of phosphorite samples occurs most commonly between Palgrave Point and the Kunene River (Fig.4.1), and lies in substantially deeper water than the glauconitic pebbly limestones from the same area viz., average of 170 m. All but one of them have been classified as rounded; nevertheless, their lithification is such that extensive transport from their places of origin would have resulted in their disintegration. The only truly angular specimen (sample 4727A) is a laminated phosphorite/wackestone, that in all probability represents the only sample that was physically broken from the sea floor.

An additional phosphorite rock fragment from south of the study area has been studied (sample 3232C), mainly because of its significance with relation to pelletal phosphorite in the unconsolidated sediment. It has been described petrographically by Rogers (1977), examined geochemically with an electron microprobe by the writer (see Chapter 8), and was recovered from a depth of 210 m at 25°22,0'S, 14°5,0'E (south west of Sylvia Hill).

4.5.2 Lithology

The mollusc casts, although slightly abraded, clearly indicate the general shape of the two valves and measure approximately 3 cms in width. The phosphatized bones are up to 15 cms in length, 3 cms thick, and vary from a semi-porous to a non-porous state. The laminated sample consists of several layers of micrite of approximately 1 mm thickness, the top member of which is collophane exhibiting well-preserved mud-cracks. Finally, the specimens grouped under the heading 'rocks' include two tiny fragments of phosphorite (samples 3710B and 4729) from the Rocky Point and Cape Fria areas respectively; a fairly large fragment of similar material welded to one of the phosphatized bones from north of Cape Fria (sample 4745B/); and an 8 cm spherical cobble exhibiting friability and weak porosity from the Palgrave Depressions (Fig.3.2) (sample 3761A).

4.5.3 Petrography

The classification and detailed petrographic description of the phosphorites is given in Appendices B.5 and B.6 respectively. They are more brownish in hue than the limestones, and particularly with the phosphatized bones, moderate browns (5 YR 4/4) predominate.

Biogenic particles are rare. In only 3 of the 13 samples included in this suite do trace quantities of echinoderm fragments and foraminifera occur. Sample 3232C, from south of the study area is exceptional in that besides foraminifera, it also contains fishbones and mollusc casts, all together totalling

2% of the rock volume (Rogers, pers.comm.).

Non-carbonate grains are present in amounts seldom exceeding 20% of the rocks. Quartz, followed by glauconite and then pelletal phosphorite are the most commonly occurring components, and feldspar, rock fragments and phosphorite fragments never constitute more than 1%. The size and angularity of the allogenic quartz grains corresponds to that of the equivalent lime mudstones, quartzose lime wackestones and quartzose lime packstones. The abundance of these different rock types in the two mineral facies vary markedly i.e., the number of mudstones: wackestones: packstones in the phosphorite facies is 5 : 8 : 1, and in the limestones it is 17 : 9 : 5.

Pyrite is a rarer component in the phosphorites than in the lime mudstones, and does not occur as silt-size disseminations. It is sometimes present as microfossil infillings e.g., foraminifera and echinoderm fragments (see Plate 8.11), and occasionally it occurs in the sutures of glauconite grains (see Plate 8.10). The most significant occurrence of pyrite is in a few limestone borings, or in cavities in mollusc casts. An example of the latter is provided by sample 4744C, where a small cavity has been infilled with fine-grained angular quartz, glauconite and pelletal phosphorite, all of which are set in a pyrite matrix.

The intergranular fabric consists of light brown isotropic collophane, and in the case of the phosphatized bones, weakly anisotropic diallage occurs as an essential structural component. Micrite is exceptionally rare and occurs in significant amounts in only one of the samples studied. This is the spherical cobble from the Palgrave Depressions (sample 4761A) where micrite constitutes 40% of the rock composition, and has clearly formed through collophane replacement of lime mud.

In summary, the granular fabric of the phosphorites and limestones reflect similar textures and compositions. Both contain pelletal phosphorite and glauconite, and an abundance of very fine-grained angular quartz. It is worth stressing that collophane replacement of lime mud has apparently played a very minor role in the total phosphorite occurrence. Apart from the spherical cobble mentioned above, replacement has been confined to a few of the limestone-boring walls (see Plate 8.8), and to the very outer edges of some of the limestone rocks. A pyrite matrix occasionally present in borings and other cavities is probably due to sulphate-reducing bacteria acting on organic matter in the strongly reducing confined space of the infillings.

4.6 AGE

Of 42 limestone and phosphorite samples submitted to W.G. Siesser of the Marine Geoscience Group, U.C.T. for age dating, none was found to contain any

recognizable nannofossils, and even the few planktonic and benthic foraminifera present were generally neomorphosed to such an extent that positive identification of species was not practicable. It is concluded that in contrast to limestone and phosphorite deposits south of the Orange River (Siesser, 1971; Rogers, 1977), bedrock within the study area has been extensively altered through diagenesis. Tentative ages are therefore suggested based on the petrographic relationships described earlier, and by correlating them with similar deposits that have been firmly dated farther to the south.

Concerning the limestones, Siesser (1971, 1972) has described a suite of quartzose lime wackestones from the Cape St. Blaize area of the Agulhas Bank that in most respects are similar to the limestones from the study area. Rogers (1977) has correlated them on petrographic evidence with similar material from the Orange Shelf, and Siesser (1977c) has recently established a firm Paleocene-Eocene date for them. Because the quartzose limestones in the study area frequently serve as hosts for phosphorite in animal borings, they are of necessity older than this phosphorite material; and since they contain pelletal phosphorite as part of their granular fabric, they must be younger than, or contemporary with this phosphorite material. For these reasons and others set out in the next section, the quartzose limestones from the study area are not correlated with those on Agulhas Bank, and are considered to have been formed in well-oxygenated open-shelf environments penecontemporaneously with the pelletal phosphorite.

At least three periods of phosphatization are apparent from petrographic evidence. The first period gave rise to the pelletal and fragmental phosphorite grains that occur scattered throughout the matrix of most limestone and phosphorite rocks, and also, to the pelletal and glauconitized pelletal phosphorite particles associated with the unconsolidated sediment. A common age is assigned to these pelletal grains based on the similarity of their morphologies and petrographic characters (see Chapters 5 and 8). The second period of phosphatization produced the collophane matrix of the phosphorite rocks, the latter occurring most commonly as infillings in the limestone borings and in the haversian canals of phosphatized vertebrate bones. The third period of phosphatization is that taking place in the diatomaceous muds at the present time. Here, phosphatic concretions of varying shape and size are currently forming through authigenic growth and diagenetic enrichment (see Chapter 8).

Several indirect lines of evidence point to a Middle to Late Miocene age for the first major period of phosphatization. Tankard (1974) has described a ?Middle Miocene phosphatic sandstone north of Cape Town called the Saldanha Formation, which gave rise during a Pliocene transgression to the pelletal phosphorite-containing beds of the Varswater Formation. Rogers (1977) has

dredged a rock specimen from the Orange Shelf (sample 2984) that shows an erosional unconformity between conglomeratic phosphorite and Early to Middle Miocene nummulitic limestone, the latter being older as indicated by truncated Nummulites tests. Siesser (in press a) has presented evidence from DSDP Site 362/362A on the Walvis Ridge Terrace (Fig.3.2) that a modest but sharp increase in the productivity of overlying waters occurred in Late Miocene times. Finally, stiff muds of Miocene age (Fig.3.1) lie immediately seaward of the most extensive deposits of unconsolidated pelletal phosphorite and glauconite on the mid shelf (see Chapter 5). It is therefore postulated that these authigenic minerals accumulated as lag deposits, and were concentrated during repeated sea-level regressions and transgressions in post-Miocene times.

The second period of phosphatization was in many respects similar to the first, but resulted in light brown collophane being deposited (less organic matter) which did not undergo fragmentation and pelletization. A Pliocene age is indicated for this episode, corresponding with the age of most phosphorite rocks that have been firmly dated south of the study area (Siesser, in press a). Further evidence on the productivity of waters at DSDP core site 362/362A (Siesser (op.cit.) indicates that a dramatic increase occurred in latest Miocene-Early Pliocene times accompanied by spasmodic increases in the abundance of diatom frustules. Summerhayes et al. (1973) and Rogers (1977) have suggested that pelletal phosphorite formed during the first period of phosphatization was eroded (reworked) from the phosphorite rocks (based on sample 3232C) to produce the unconsolidated sediments on the shelf in Late Pliocene - Early Pleistocene times. This seems improbable however, since both the pellets and matrix are composed of collophane, and would therefore have been equally susceptible to the effects of erosion. The alternative presented above, is that the sedimentary pelletal phosphorites represent lag deposits that were concentrated on the shelf during post-Miocene sea-level fluctuations.

The third phase of phosphatization is not discussed here, as various aspects of it are examined in detail in subsequent Chapters.

In summary then, the ages postulated for limestone and phosphorite from the study area, based on petrographic and morphological evidence and also by correlation with firmly dated equivalent lithofacies south of the study area, are as follows:

Phosphorite 'infillings'	- Pliocene
Limestones, pelletal and fragmental phosphorites	- Middle to Late Miocene
Glauconite	- ?Early Tertiary to Holocene

4.7 PROVENANCE AND DEPOSITIONAL ENVIRONMENTS

The micrite and collophane matrices of the limestones and phosphorites, and the occasional presence of glauconite and phosphorite particles in the granular fabric of these rocks, all indicate that the two mineral facies were formed in the marine environment. The ubiquitous presence of terrigenous quartz however, indicates that considerable sediment was derived from the hinterland, and its fine angular state suggests that it probably was aeolian (the mean sediment size of the present-day dunes is fine sand, see Table 5.2). A further indication that the terrigenous material originated from the arid interior, is the occurrence of sparsely concentrated, fresh, angular, feldspar.

The clay-size intergranular fabric of the limestones and phosphorites implies quiet, low-energy depositional environments where winnowing from wave and current action would have been minimal (Folk, 1968). Consequently, the intermixed sand-size terrigenous and authigenic grains which 'float' in the matrices of the rocks are anomalous, but textural inversions such as these have been noted from south of the study area as well. For example, the inversions exhibited by quartzose limestones on the Orange Shelf and Agulhas Bank have been attributed by Siesser (1972) and Rogers (1977) to bioturbation, and conglomeratic phosphorites on the Agulhas Bank have been explained in terms of mud flows and turbidity currents (Parker, 1971, 1975). Owing to the fact that the granular fabric of the two rock facies in the study area are essentially the same, bioturbation is negated because anoxic conditions created in some of the phosphorite infillings would have inhibited the presence of benthic organisms, and turbidity currents are ruled out because of the very gentle gradient of the continental shelf (Fig.3.4). Instead, a simple influx of wind-born terrigenous detritus into the depositional environments is therefore postulated as was implied above. Supporting this contention is the relationship between the depth of occurrence of the various limestones, and the abundance and coarseness of their associated terrigenous fractions i.e., the mudstones and wackestones are located in the deepest water followed by the packstones, and finally, the pebbly limestones are closest to shore. Concerning the latter, the pebble-size grains may have been deposited as storm beaches during periods of lower sea-level, and with the rise of sea-level the pebbles would have been submerged by lime mud that filtered downwards and eventually filled the interstices between them.

Siesser (1971, 1972) and Rogers (1977) both believe that textural and compositional indications point to a lagoonal environment for the formation of the quartzose limestones on the Agulhas Bank and the Orange Shelf. If these conclusions are correct, then a necessary corollary would be that these lagoons were much less restricted than the highly reducing environments that gave rise

to the pelletal and fragmental phosphorite in the study area. This is indicated by an exceptionally high C_{org} and S content in the pelletal grains from the unconsolidated sediment (see Table 5.10). To sustain such high levels of organic matter in the phosphatic mud, the environment must have been sufficiently restricted to inhibit the influx of well-oxygenated water, yet open enough to allow nutrients and planktonic flora and fauna to enter through estuarine circulation (Brongersma-Saunders, 1965; Brongersma-Saunders and Groen, 1966). The silt-size pyrite commonly found scattered through the lime mudstones probably formed by sulphate-reducing bacteria acting on organic matter in micro-environments.

The phosphorite pellets, approximately 20% of which exhibit an oolitic internal structure (see Plate 8.1), and roughly 5% of which contain an extraneous nucleus of quartz, glauconite, fishbone, etc. (see Plate 8.11), were most likely formed in the inter-tidal zone of semi-restricted lagoons. The fragmental phosphorite particles are envisaged as having been formed through disruption of a collophane mud layer by tidal currents near the mouths of the lagoons. Some evidence for this is obtained from the relatively greater abundance of phosphorite fragments in the more deeply disposed lime mudstones and quartzose lime wackestones, and a greater abundance of pellets in the shallower-disposed quartzose lime packstones (Appendix B.6). This of course implies that while collophane was forming in semi-restricted lagoons, micrite was forming concurrently in adjacent, but relatively more open environments. Criteria necessary for the precipitation of collophane (Kazakov, 1937) such as high dissolved inorganic phosphorous, high temperatures, and high pH (Tooms et al., 1969) would have been enhanced by the shallowness of the proposed lagoonal environment, and by the nutrient-rich character of water derived from estuarine circulation. Periodic breaching of lagoon barriers such as spit bars through storm-wave activity, would have allowed lime mud from the shelf to be washed into the semi-restricted environment thereby promoting its admixture with fragmental and pelletal phosphorite particles there. Most of the phosphorite however, remained in isolation as is evidenced by the extensive deposits of pelletal grains associated with unconsolidated sediment on the shelf today.

The Pliocene period of phosphatization resulted in phosphorite rock that commonly occurs as infillings in limestone borings, as mollusc casts, in the haversian canals of phosphatized vertebrate bones, and as small isolated fragments. The scarcity of organic matter and pyrite in these rocks, except in the confined space of some of the borings, indicates that the depositional environments were much less restricted and reducing than the Miocene lagoonal environments that produced the pelletal and fragmental phosphorite. The presence of fine-grained angular quartz, pelletal phosphorite and glauconite

in these rocks is interpreted as having been derived in similar fashion to the particles occurring in the limestones i.e., wind-born terrigenous detritus, washing of precipitated collophane mud over pre-existing lithified authigenic particles, and all being thoroughly admixed during periodic storm-wave activity. A modern analogy of this is the intermixing of medium to fine grained terrigenous sand, coarse to medium grained mica, and diatomaceous mud along the eastern edge of the diatomaceous mud belt (see Chapter 5). The average depth of these Pliocene phosphorite 'infillings' indicates that the locus of phosphate deposition at this time was in the vicinity of the present-day mid shelf, that is, seaward of the Miocene limestone facies, thus suggesting they were laid down during a period of sea-level regression.

Although chemical replacement of pre-existing calcareous sediment has been the principal mode of phosphatization on the Agulhas Bank and the Cape West Coast during the Pliocene (Parker, 1971; Birch, 1977; Siesser, in press a), this mechanism has played a very minor role in the genesis of phosphorite on the South West African shelf. Moreover, the diatomaceous mud belt, in which concretionary phosphorite is forming at the present time, is believed to be different from the environments that gave rise to the two Tertiary phosphorite deposits. These aspects are covered in some detail in Chapter 8, where the geochemistry and other properties of the authigenic minerals are used to evaluate their probable modes of origin.

Very little can be said about the glauconite that occurs in the limestones and phosphorites, mainly because its occurrence is limited to small sand-size grains. It has certainly occurred on the shelf since at least the Miocene, although Siesser (1971, 1972) has found it in Paleocene, Eocene and Cretaceous limestones from the Agulhas Bank. All the glauconite in the study area is well-ordered and chemically mature but these aspects are covered more fully in Chapters 5 and 8.

Chapter 5. TEXTURE AND COMPOSITION OF THE UNCONSOLIDATED SEDIMENT

5.1. INTRODUCTION

5.1.1 Aims

This chapter, composed of six sections, embodies the main effort of the thesis, which is to define the regional properties of unconsolidated sediment on the north-central continental margin of South West Africa.

The purpose of this section is threefold: to present a scheme of the analytical procedures; to introduce, in broad outline, the results of these analyses; and to describe the grouping of sediment samples into five different environments for individual study.

The next section is a discussion of the textural aspects of the sediment, and this is followed by three sections covering its chemical and mineralogical composition under the headings: Biogenic, Authigenic and Terrigenous.

The last section is a statistical evaluation (R-mode factor analysis) of the inter-relationships between the sediment properties and depth, and serves to define the main conclusions arrived at during the course of this sedimentological study.

5.1.2 Analytical Methods

Initial treatment of the samples was performed on board ship preparatory to detailed analysis later in the laboratory. This involved dialysis of two subsamples designated 'T' and 'C' (for texture and composition respectively), wet sieving the 'T' specimen through a 63 μ m screen, and storing the various subsamples in appropriately-sized plastic containers. Additional subsamples when required in the laboratory were obtained by taking top-to-bottom sections from the sediment storage tubs that otherwise were sealed and stored at room temperature.

A complete flowchart of the analytical procedures performed on the sediment is shown in Fig.5.1. It includes three main schemes, the first two of which are covered in this Chapter, and the last one in Chapters 7 and 8. The two schemes discussed in this Chapter involve firstly, the operations used for textural analysis of the sediment, and secondly, the operations undertaken for chemical and mineralogical study of the sediment. Detailed discussion of these techniques is given in Appendix A and reference to them is made in appropriate sections of this and following Chapters.

Precision tests on most of the techniques have already been established by other workers using a variety of different marine sediments. In this study, reproducibility tests are generally confined to four samples of the 'rarer' diatomaceous muds, a deposit that occupies a sizeable portion of the Walvis

FLOWCHART OF ANALYTICAL OPERATIONS PERFORMED IN ANALYSING THE UNCONSOLIDATED SURFICIAL SEDIMENT

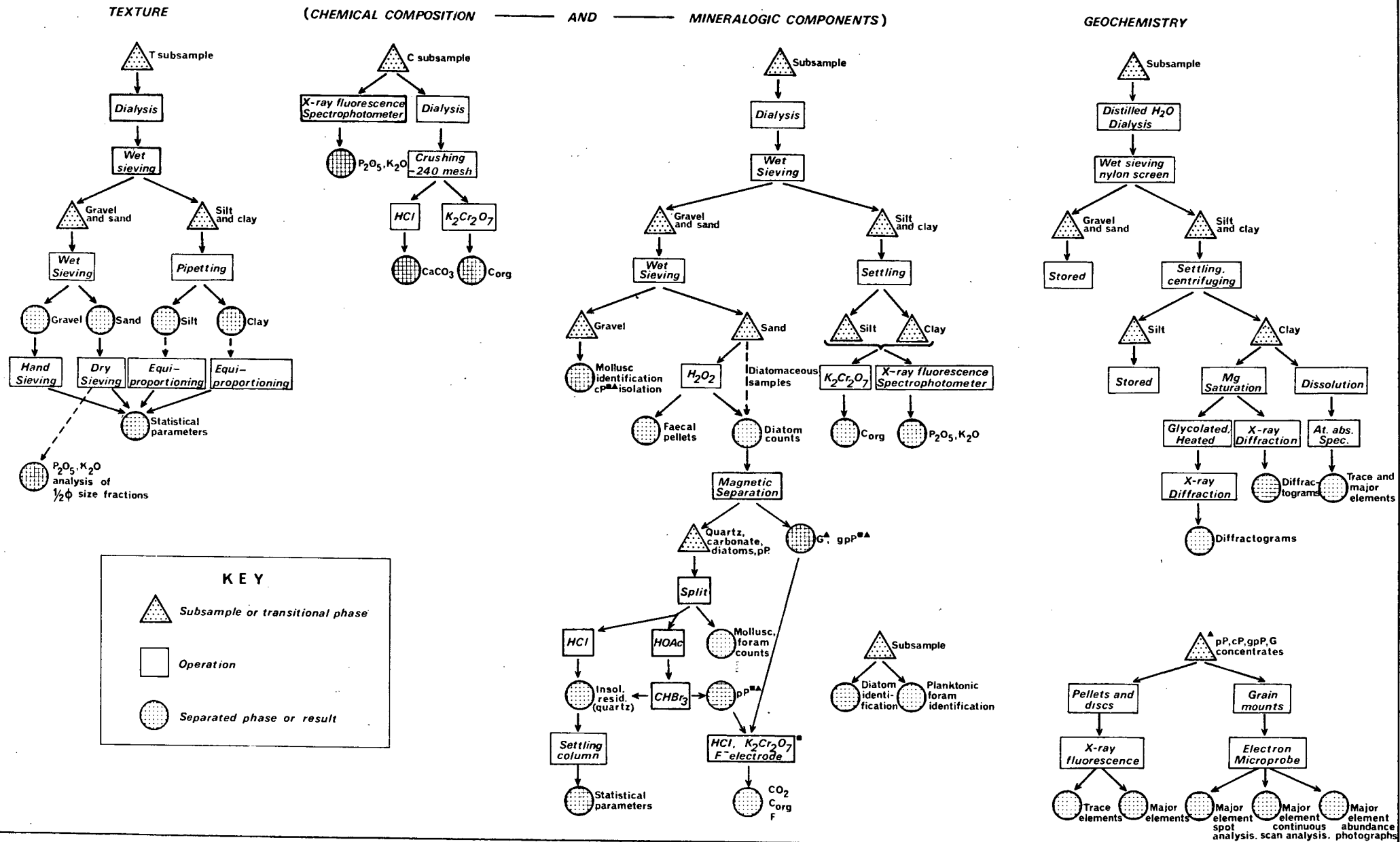


Figure 5.1

Inner Shelf. These four samples (3426, 3754, 3756 and 3950) have also been used in a geochemical study of the clay fraction of the sediments, and this aspect of them is discussed in detail in Chapter 7.

5.1.3 Outline of Results

All basic sedimentological results obtained in this study are listed in Appendix B.7. Several additional parameters were derived from these data, and although not reported here, are kept available on magnetic tape at the University of Cape Town Computer Centre. Included are: textural data (moment measures and percentage frequencies of the sediment size fractions); chemical data (weight percentages of C_{inorg} , and C_{org}); mineralogical data (carbonate-apatite and glauconite on carbonate-free bases), and some chemical data relating to studies made on selected numbers of samples.

(a) Texture

The unconsolidated sediment is classified texturally based on Folk's (1954) ternary diagram for gravel-sand-mud, and the regional distribution of these facies is shown in Fig.5.2.

Starting with the coarser sediments, elongate deposits of sandy gravel and gravelly sand occur along or just landward of the 200 m isobath, and a few small patches of gravelly sediment exist close to shore. South of Palgrave Point, these gravelly deposits underlie the western flank of the Holocene diatomaceous mud belt.

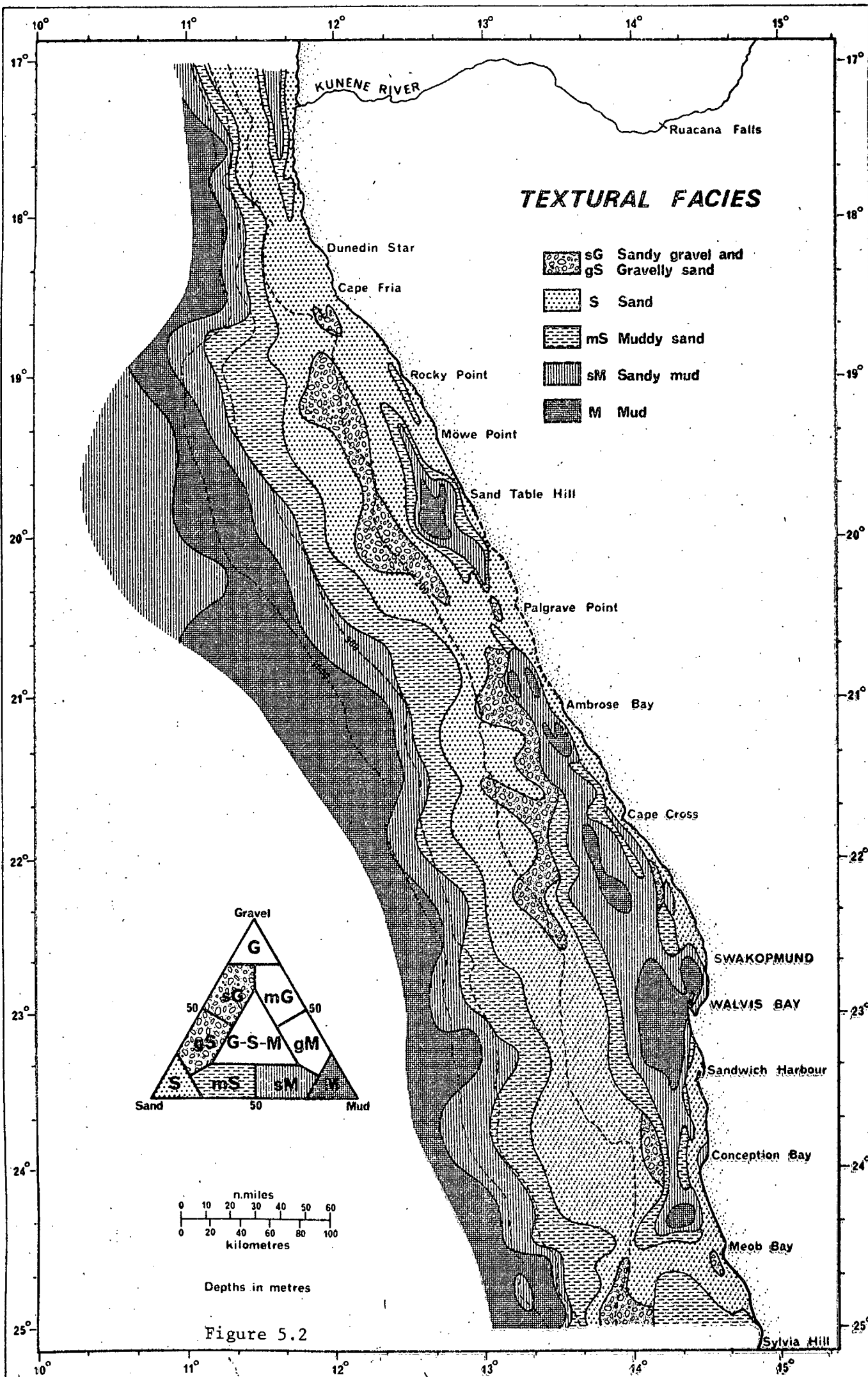
Sand-size sediment forms a continuous blanket over the mid shelf, and also occurs as a narrow strip adjacent to the shore. In the vicinity of Walvis Bay, the sand strip is locally replaced by diatomaceous mud, which in this area, reaches to within 10 m of the shore.

Of the finer sediment types, muddy sand occurs as two narrow, discontinuous strips along both flanks of the diatomaceous mud belt; and is also evident as a broad zone occupying most of the outer shelf. Sandy mud forms the main body of the diatomaceous mud belt, and also coincides roughly with the outer shelf break.

Mud occurs as a number of relatively small deposits within the central portion of the diatomaceous mud belt, and also constitutes the major textural type on the upper slope. West of Mbuwe Point, these upper-slope muds separate sandy mud on the Walvis Ridge Terrace, from sandy mud on the Walvis Ridge Abutment.

(b) Composition

Classification of the sediment into compositional facies is based on a biogenic-authigenic-terrigenous ternary diagram (Fig.5.3). The biogenic and authigenic sectors of the triangle have been further subdivided into diatomace-



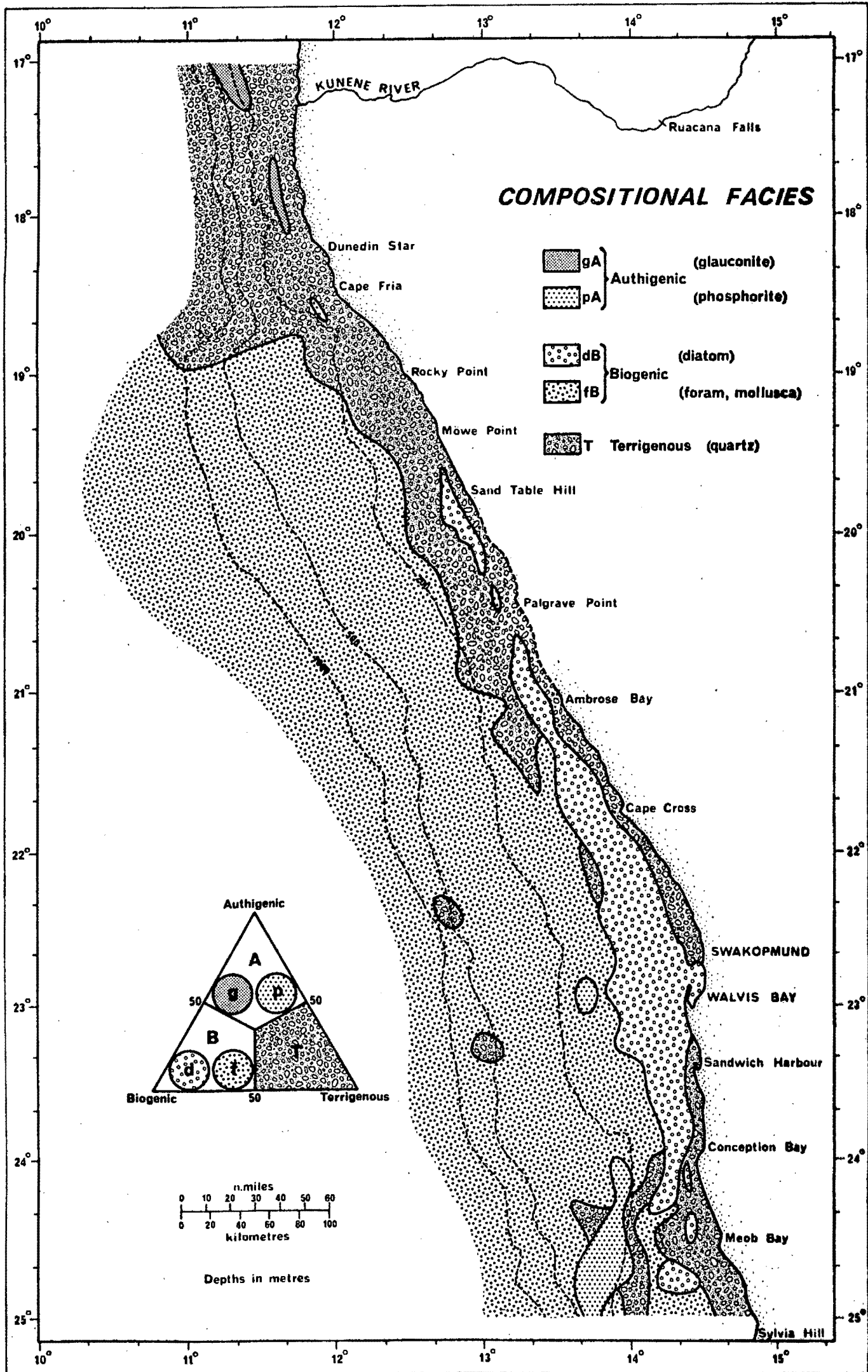


Figure 5.3

ous/calcareous and glauconitic/apatitic fractions respectively, in order to illustrate the individual contributions of these facies to the regional composition of the sediments.

Areally, it is evident that fully two thirds of the unconsolidated sediment within the study area is material of biogenic origin, and furthermore, that these sediments are almost exclusively confined to the Walvis Continental Margin. A large portion of the Walvis Inner Shelf is covered by an elongate deposit of diatomaceous mud, which is widest in the vicinity of Walvis Bay, and narrows to odd patches off Sand Table Hill and Meob Bay. The Walvis Outer Margin (outer shelf and upper slope) is mantled almost entirely by sediment of calcareous composition.

The southern part of the Walvis Mid Shelf, and at various locations on the Kunene Shelf, authigenic mineral deposits become important. In the former area, pelletal phosphorite (carbonate fluorapatite) is the dominant mineral, whereas on the Kunene Shelf, glauconite is more common.

Terrigenous sediment is characteristic of the Kunene Margin, but also covers most of the Walvis Inner Shelf northwards of Ambrose Bay. Between Ambrose Bay and Sylvia Hill, terrigenous sediment forms a continuous, narrow strip along the coast, except for a small break in the vicinity of Walvis Bay. It also occurs as a few isolated patches on the seaward side of the diatomaceous mud belt, and on the outer shelf-break between Cape Cross and Sandwich Harbour.

(c) Profiles

Four bathymetric profiles, which were chosen to transect the principal morphological features named on the bathymetry map (Fig.3.2), are shown in Fig.5.4 together with graphs of various sedimentological properties. These graphs illustrate the major sedimentological trends across the margin, and serve to introduce their detailed discussion later on. In isolation, the morphological features have exercised little influence on the gross textural and compositional properties of the unconsolidated sediment.

5.1.4 Lithofacies

The unconsolidated sediments can be grouped according to geographic location or composition into a number of individual deposits, each with a unique set of principal components. Five such groups are recognized within the study area, and the criteria used to classify the samples are discussed below:

Kunene Margin sediments - all samples north of latitude $18^{\circ}40'S$.

Walvis Margin sediments - all samples south of latitude $18^{\circ}40'S$.

The Kunene and Walvis Margins, apart from being morphologically distinct, are blanketed by unconsolidated sediment of radically different composition,

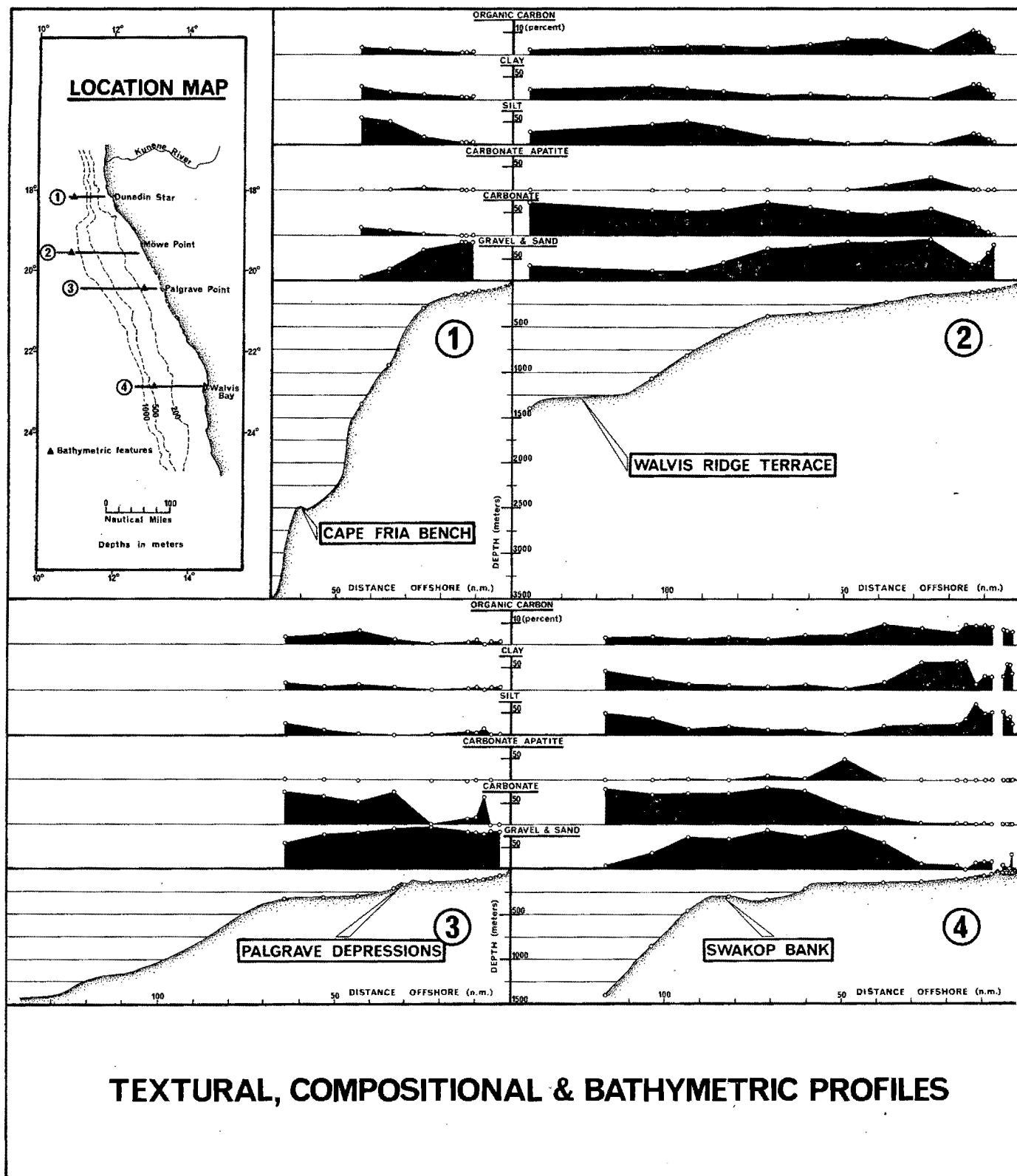


FIG. 5.4

the former being essentially terrigenous in origin, and the latter, biogenic. Latitude $18^{\circ}40'S$, where the abundance of $CaCO_3$ in the sediment changes rapidly from <25% in the north to >50% in the south (see Fig.5.15), serves as a natural boundary between the two regions, and coincides with the northern flank of the Walvis Ridge Abutment.

Diatomaceous sediments - all samples containing >5% opal.

Calcareous sediments - all samples containing >50% $CaCO_3$.

Authigenic and terrigenous sediments - balance.

The diatomaceous and calcareous sediments belong essentially to the Walvis Continental Margin. The concentrations chosen to classify these deposits are mutually exclusive for all the samples containing both components. Of the 521 samples that were analysed completely (Appendix B.7), 142 were classified as being diatomaceous and 193 were calcareous. Authigenic and terrigenous sediments occur on both the Kunene and Walvis Margins, and consequently, this group transgresses the division established at $18^{\circ}40'S$. With few exceptions, the 186 samples of this group represent relict sediments, whereas the >5% opal and >50% $CaCO_3$ groups are both Holocene. The authigenic sediments furthermore, are limited geographically to a number of relatively small, isolated deposits that do not lend themselves conveniently to characterization, and are therefore grouped together with the terrigenous sediments with which they are usually associated. In the lithofacies diagram of Fig.5.5, the authigenic and terrigenous components have been plotted as separate poles in the ternary plots of sediment composition, thereby illustrating their degree of association in each of the groups >5% opal, >50% $CaCO_3$ and Balance. The regional distribution of the sediment lithofacies is shown on a map alongside the ternary diagrams of sediment texture and composition (Fig.5.5), which represents in effect, a summary of Figs.5.2 and 5.3.

The average concentration of twelve principal-components in the sediment (Appendix B.7) have been determined for each of the 5 sedimentary groups discussed above, and are tabulated individually in sections of this Chapter dealing directly with them. The inter-relationship of the components in each of the sedimentary groups has been examined by means of R-mode factor analysis, and stemming from these results, a number of general conclusions on the sedimentation pattern as a whole, have been drawn.

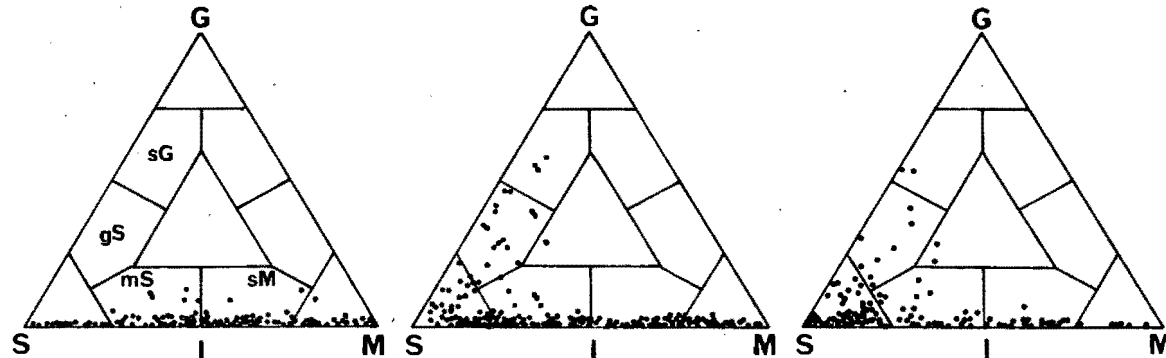
5.2 SIZE ANALYSIS

5.2.1 Introduction

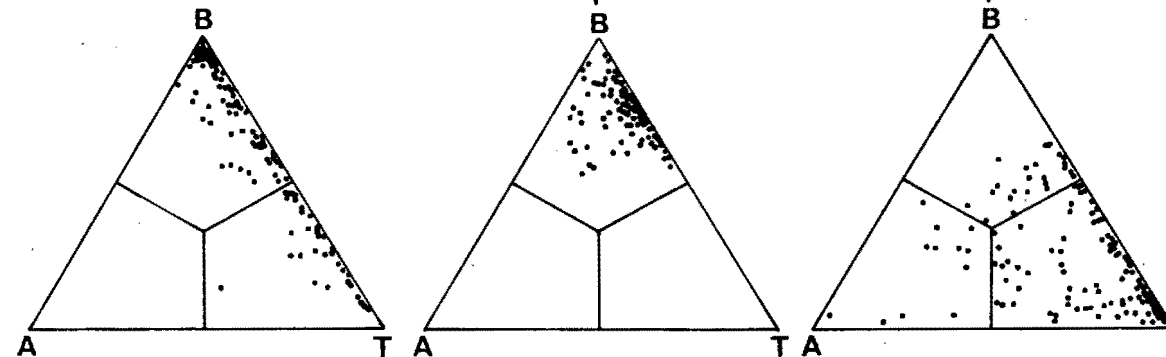
Unconsolidated sediment on the South West African continental margin is a complex mixture of biogenic, authigenic and terrigenous components of both

LITHOFACIES

TEXTURE



COMPOSITION



>5% OPAL

>50% CaCO_3

BALANCE

BIOGENIC

AUTHIGENIC AND
TERRIGENOUS

G - Gravel
S - Sand
M - Mud

B - Biogenic
A - Authigenic
T - Terrigenous

DISTRIBUTION OF SEDIMENT TYPES

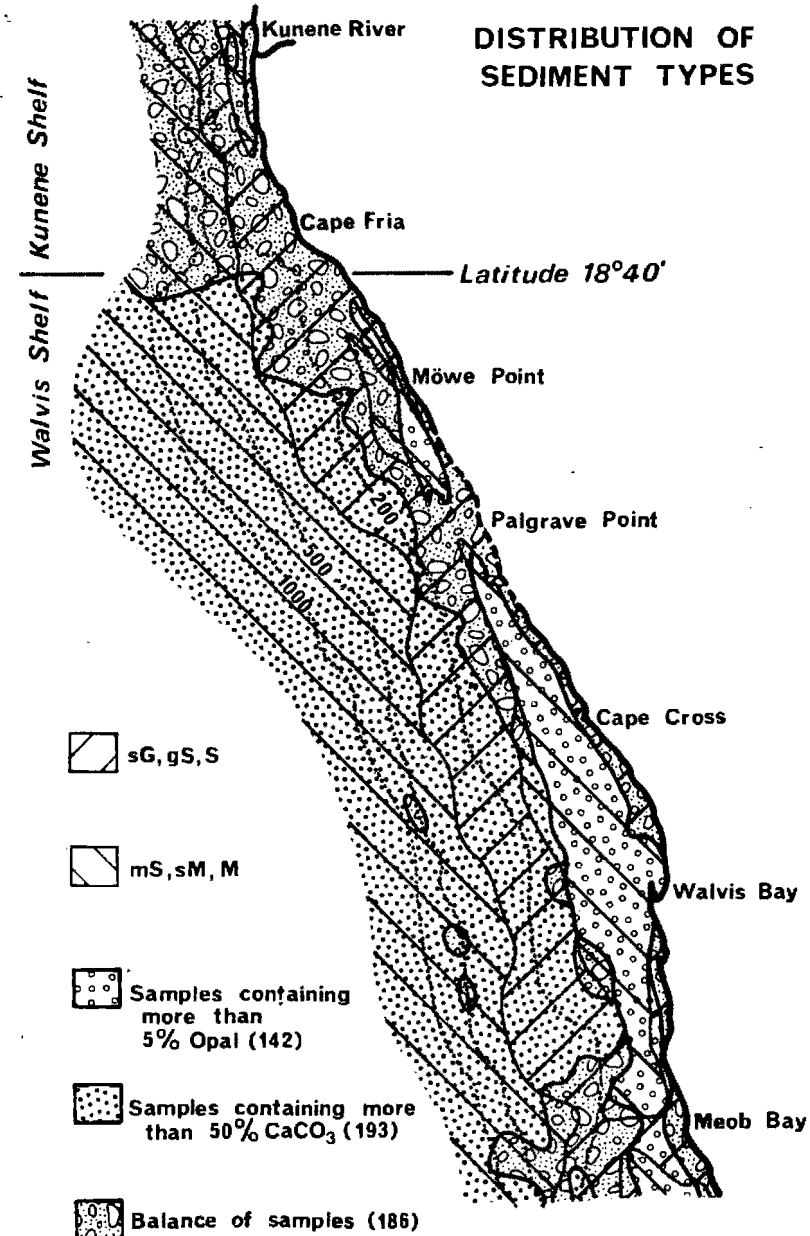


Figure 5.5

modern and relict origin. Some of the biogenic components, like diatom frustules, are unstable when subjected to prolonged mechanical abrasion, and others such as modern faecal pellets, are even susceptible to disintegration on passage down a settling tube. Therefore, despite the fundamental importance of texture in evaluating sedimentary processes, the predominance of biogenic components in the Walvis Margin sediments rendered them unsuitable for rigorous size analysis. In view of this problem, it was decided to restrict size studies to two basic investigations. The first of these was a physical separation of the sediment into gravel, sand, silt and clay fractions, and the second involved mechanical dry-sieving of the $>63\mu\text{m}$ fraction, with interpolation of the $<63\mu\text{m}$ fraction at $\frac{1}{2}\phi$ intervals. Both of these procedures are described in Appendix A.5.

Since sand-size faecal pellets composed of aggregated mud particles represent a modification of the natural sediment influx, the rôle played by faecal pellets in determining the textural character of the unconsolidated sediment is included in this Section as well. The relationship between faecal pellets and organic matter however, is reserved to the following Section dealing with the biogenic sediments. The technique used for removing faecal pellets from the sediment is described in Appendix A.6, and the results of both sediment size fractionation and faecal pellet studies are given in Appendix B.7.

5.2.2 Regional distribution of the size fractions

The average concentration of the four principal size fractions of the sediment, gravel, sand, silt and clay, are given, together with other statistical data, in Table 5.1. The regional distribution of these size fractions is shown in Figs. 5.6, 5.7, 5.8 and 5.9.

Table 5.1 Average abundance of various sediment size fractions in the unconsolidated sediment (weight percent)

	Entire margin	Area		Biogenic sediments		Terrigenous and authigenic sediments
		Kunene margin	Walvis margin	Diatomaceous	Calcareous	
		← 18°40'S →		>5% opal	>50% CaCO ₃	Balance
No. of Samples	521	64	457	142	193	186
<u>Gravel</u>						
Mean (%)	3,4	1,4	3,7	0,9	4,5	4,1
Std. Dev. (%)	8,5	4,0	8,8	2,1	10,4	8,7
Range (%)	0-57,0	0-25,6	0-57,0	0-11,7	0-57,0	0-54,6
<u>Sand</u>						
Mean (%)	55,3	61,7	54,1	42,9	51,7	67,9
Std. Dev. (%)	26,1	26,1	26,2	22,6	25,3	24,3
Range (%)	0,3-100,0	10,1-98,0	0,3-100,0	0,3-94,9	3,4-95,1	3,6-100,0
<u>Silt</u>						
Mean (%)	22,6	23,4	22,6	26,2	26,2	16,4
Std. Dev. (%)	17,4	18,6	17,2	14,2	18,1	17,0
Range (%)	0-78,3	0,5-60,6	0-78,3	0-78,3	0-66,2	0-62,7
<u>Clay</u>						
Mean (%)	18,7	12,9	19,6	29,9	17,7	11,4
Std. Dev. (%)	15,4	10,2	15,8	18,2	12,1	10,5
Range (%)	0-77,8	1,3-59,3	0-77,8	1,8-77,8	0,3-52,8	0-59,3

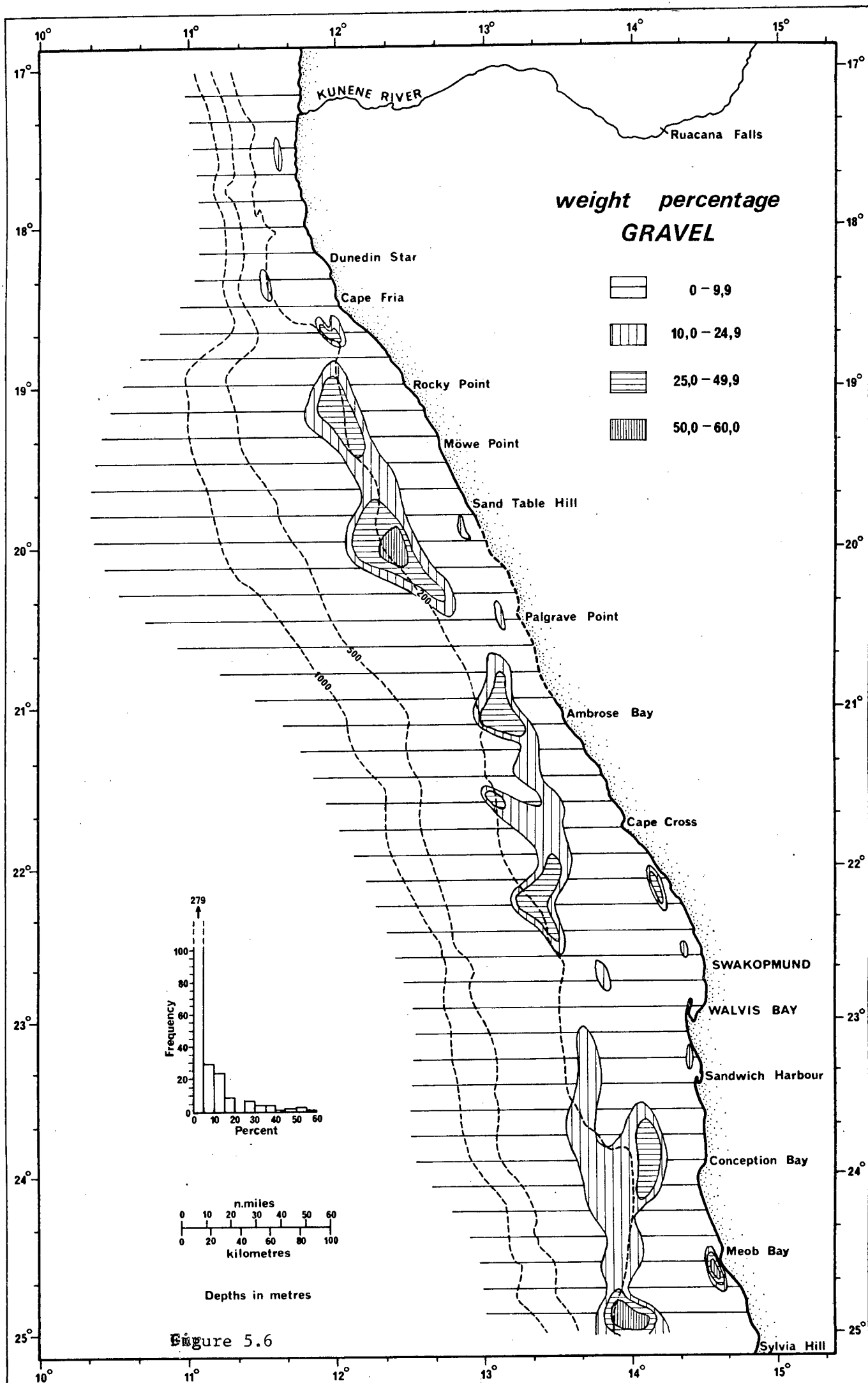
Note: In this and subsequent tables of average sediment properties, the standard deviation occasionally exceeds the mean concentration indicating highly skewed distributions.

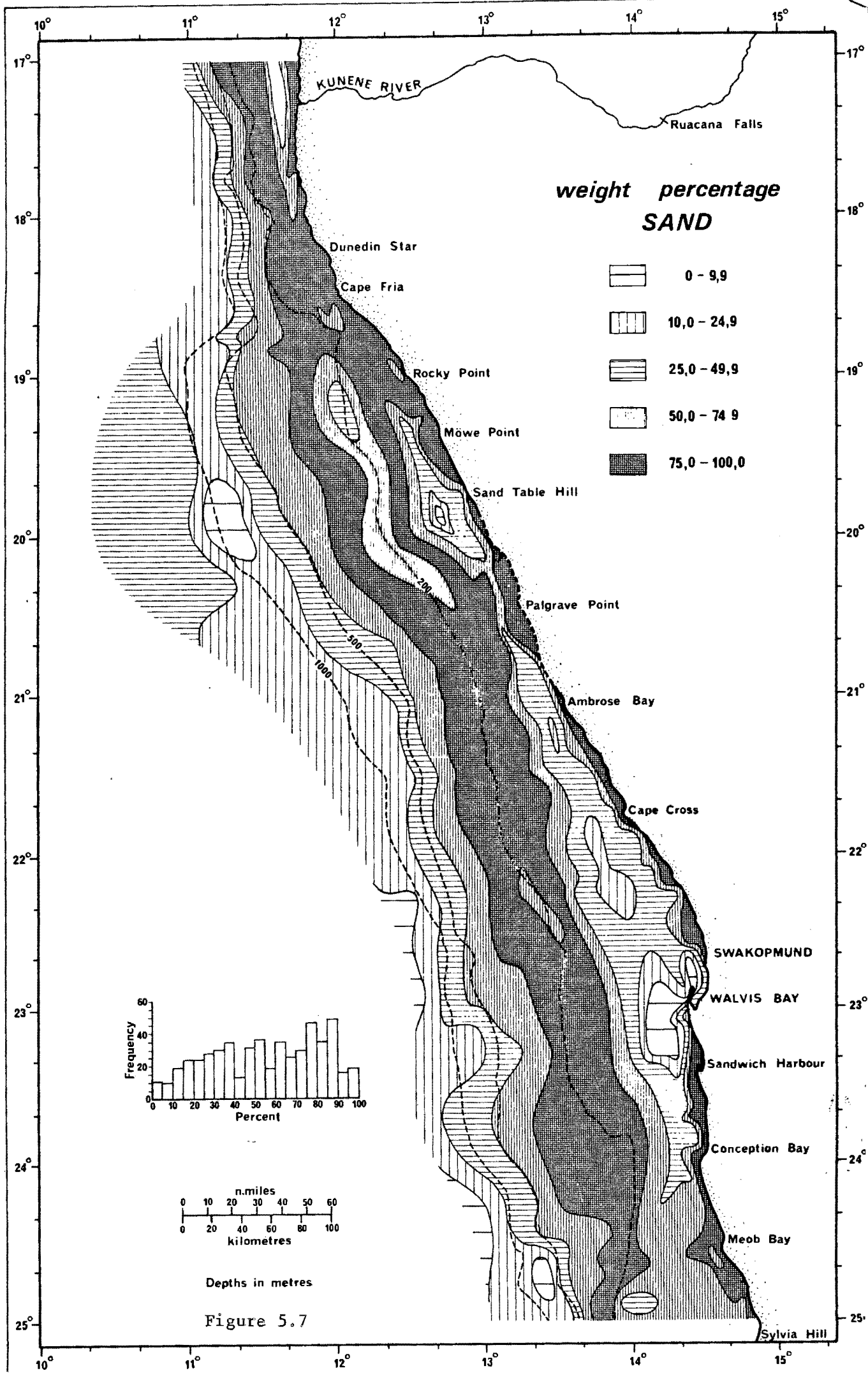
(a) Gravel

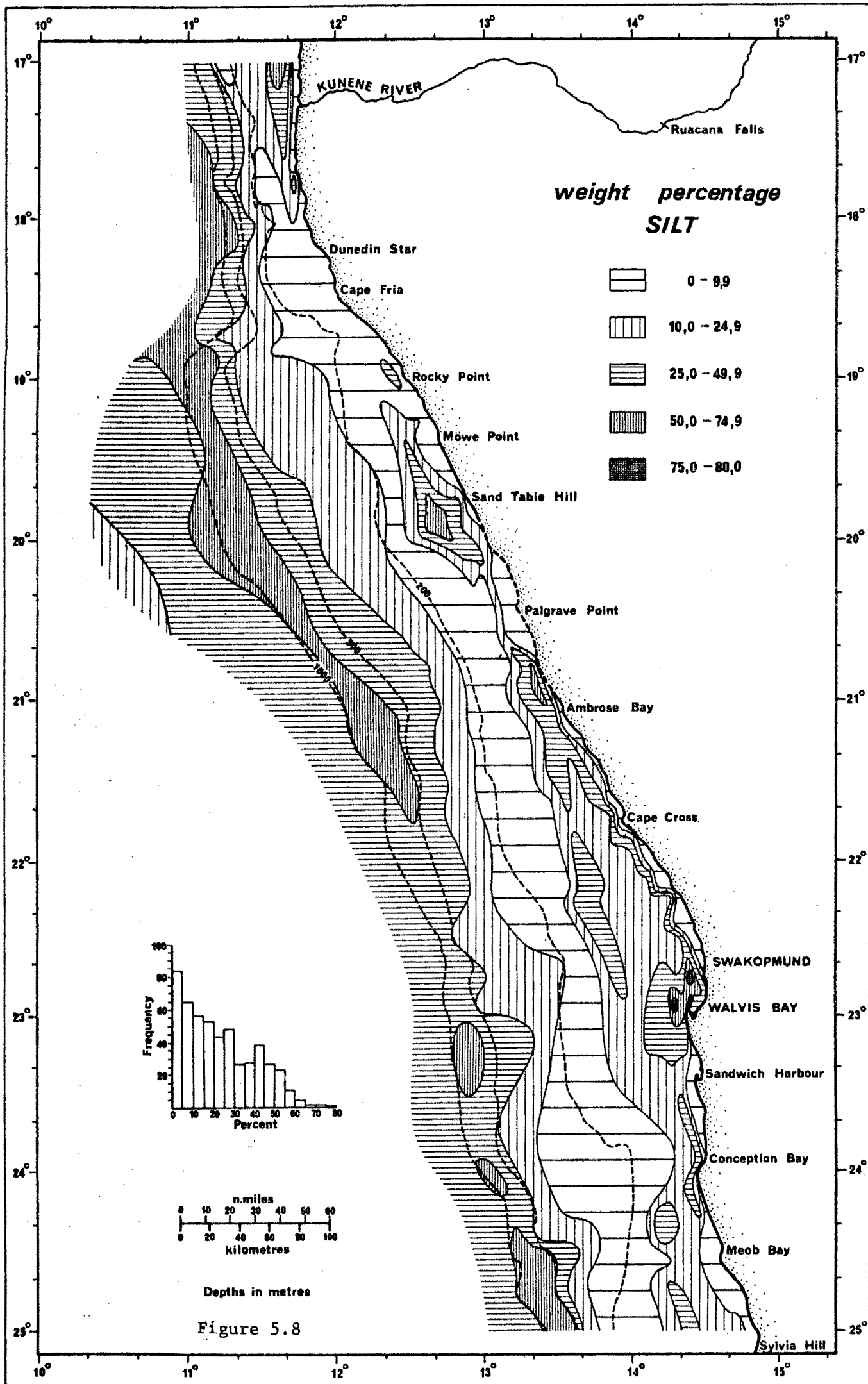
Gravel is a minor component of the unconsolidated sediment, the most extensive deposits occurring as discontinuous, elongate bodies along, or just landward of the 200 m isobath (Fig.5.6). Concentrations exceeding 50% of the sediment are confined to three small deposits, one on the mid shelf off Sand Table Hill, another on the mid shelf off Sylvia Hill, and the last in the near-shore zone off Meob Bay. The first two of these are biogenic in origin consisting entirely of mollusc shells, and the latter, in 18 m of water, is terrigenous. Although the shell beds on the mid shelf have not been dated, most available evidence suggests that they are relict, and probably date from the last Pleistocene sea level lowering (see Section 5.3).

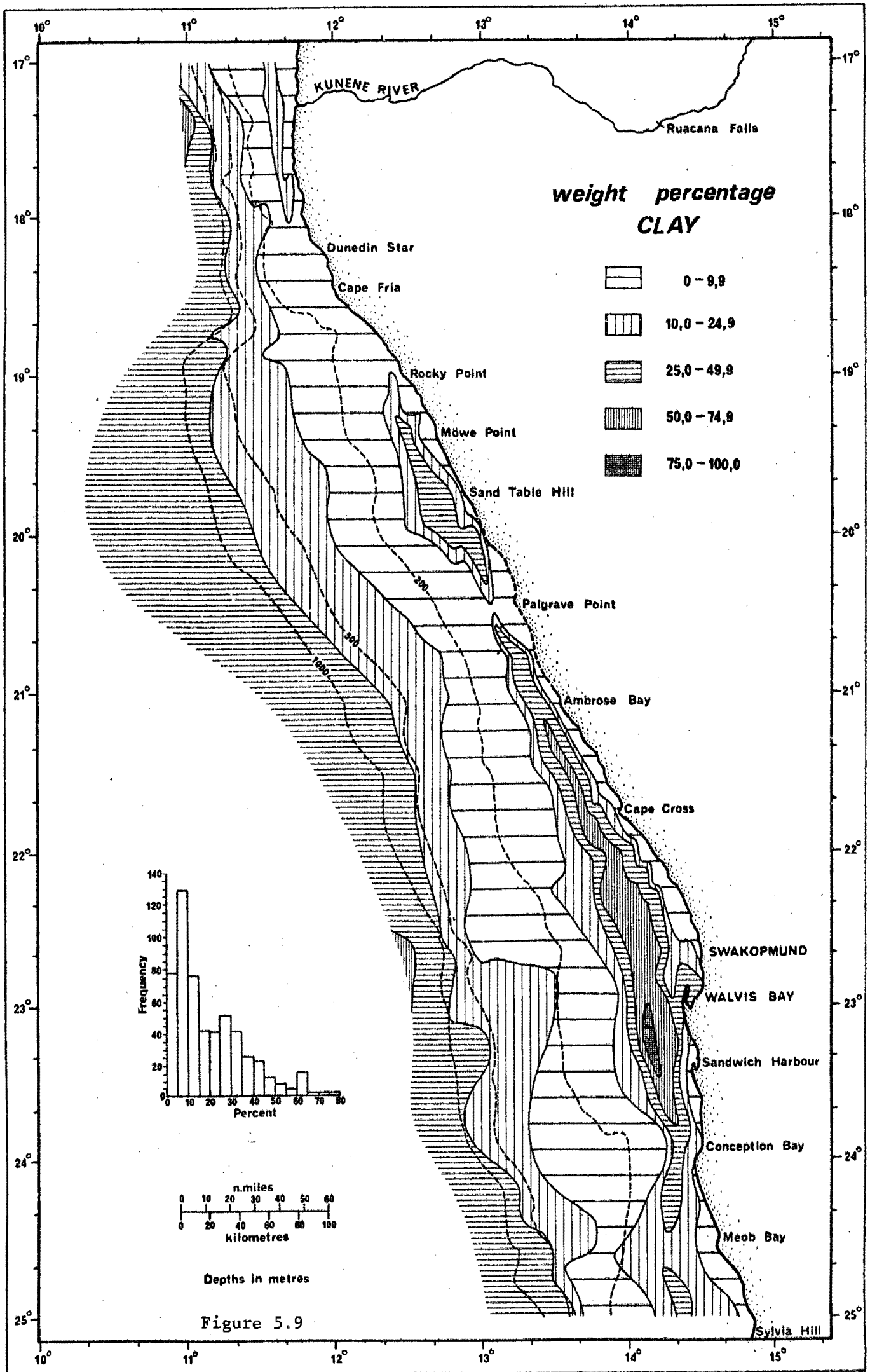
(b) Sand

By far the most widespread textural component of the unconsolidated sediment, sand concentrations exceeding 75% of the total occur in the nearshore zone as a narrow coastal strip, and also occurs on most of the Kunene Shelf and Walvis Mid Shelf areas (Fig.5.7). The coastal deposit lies between









the beach foreshore and the eastern edge of the Kunene and diatomaceous mud belts, and the mid shelf deposit, averaging 40 n.miles in width, straddles both sides of the 200 m isobath. In only one area does sandy sediment form a continuous cover over the entire continental shelf; and this is the region between Dunedin Star and Cape Fria, immediately north of the Kunene Margin-Walvis Margin junction at $18^{\circ}40'S$.

Low sand concentrations of <25% are encountered within the central portion of the diatomaceous mud belt, and along the upper slope. In the vicinity of the Walvis Ridge Terrace (Fig.3.2), these sand-poor upper-slope (muddy) sediments separate sandy material on the outer shelf from sandy material on the Walvis Ridge.

The presence of sand on the mid shelf can be ascribed to a number of different factors. On the seaward side of the 200 m isobath, faecal pellets produced by modern benthic organisms are common, whereas landward of the 200 m isobath, benthic foraminifera and relict terrigenous material are the dominant sedimentary components. Stormwave-induced bottom currents and the Ekman friction layer have also been effective in preventing fine sediment from settling on the landward side of the inner shelf break (Chapter 2).

(c) Silt

The regional distribution of silt, the next most abundant textural component, reflects strong negative correlation with that of sand (Fig.5.8), this being in large measure due to constant summation of the four sediment size fractions to a hundred percent.

The diatomaceous mud belt is fairly well delineated by the 10% silt isopleth, and silt values exceeding 25% are normal for the flanks of the deposit. The highest concentrations of silt occurring within the study area (maximum of 78.3%) lie along the eastern edge of the mud belt adjacent to Walvis Bay, and contrasting strongly with the central portion of the mud belt which contains <25% silt. The Kunene mud belt is also well outlined by the 10% silt isopleth, but only north of the river mouth does the concentration of silt exceed 50%.

Moving westwards from the mid shelf, the concentration of silt increases gradually to a maximum on the upper slope, and then decreases again at greater depths. A bivariate plot of silt vs. depth (Fig.5.10(a)) clearly shows this inverse relationship for the slope sediments, and the concentration of points at shallow depths on the plot reflect the Kunene and diatomaceous mud belts. The sand-poor sediment described earlier on the slope above the Walvis Ridge Terrace, is occupied here by this upper-slope silt maximum, and values >50% are attained.

BIVARIATE PLOTS OF SOME SEDIMENTOLOGICAL PARAMETERS

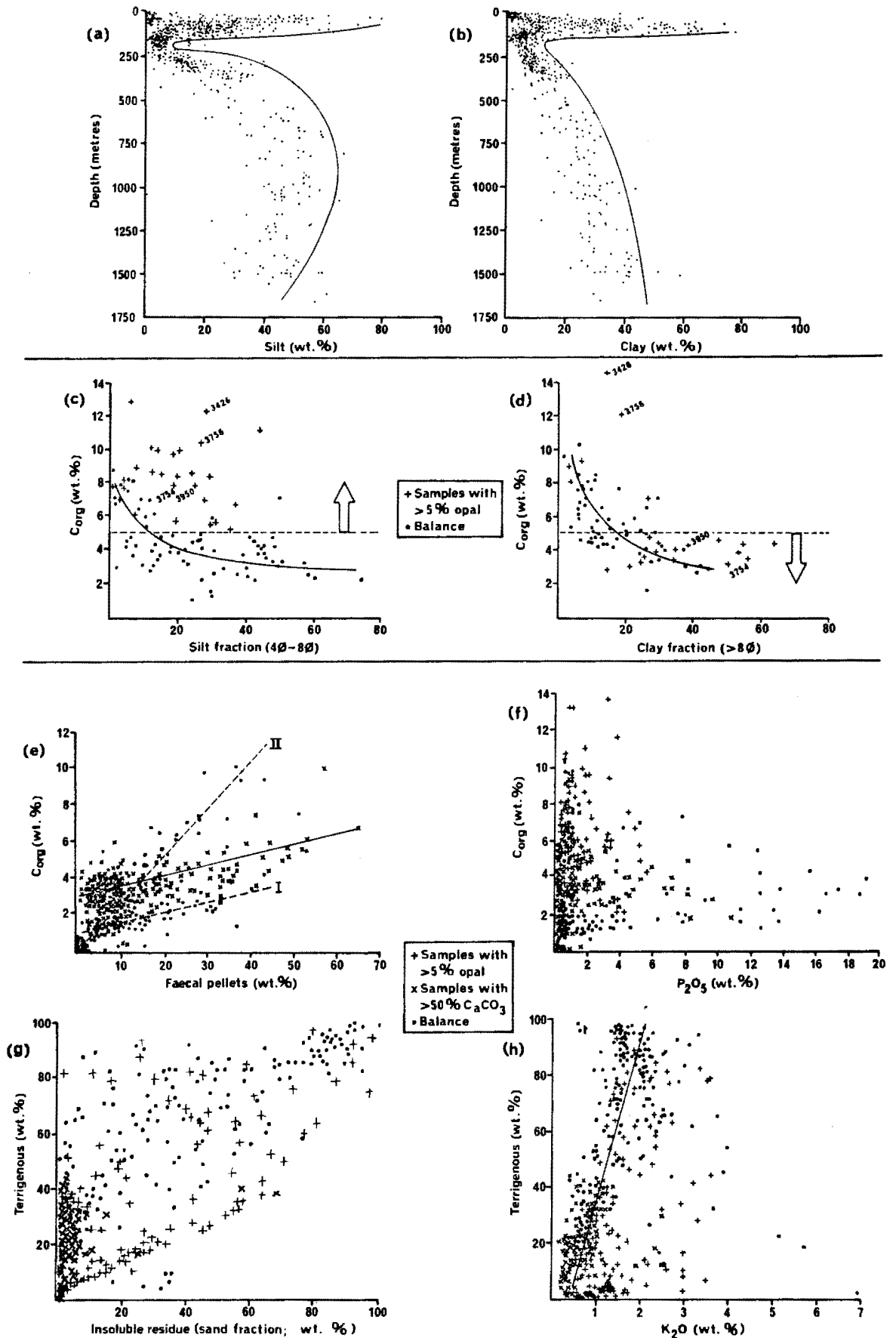


Figure 5.10

(d) Clay

The clay fraction is similarly distributed to that of silt, but generally reflects a simpler overall pattern (Fig.5.9).

The highest concentrations of clay (maximum of 77,8%) are found in the central portion of the diatomaceous mud belt, slightly south of the silt maximum between Walvis Bay and Sandwich Harbour. The Kunene mud belt by contrast, is overwhelmingly silty in texture, and the clay content never exceeds 25% of the total sediment texture.

The clay values, unlike those of silt, increase progressively from the mid shelf, with depth, and maxima of >50% clay are found off the Kunene River mouth and off Walvis Bay at a depth of 1 500 m. This is again evident on a bivariate plot of clay vs. depth (Fig.5.10(b)), and the concentration of points at shallow depths on the plot is due to the clay-rich central portion of the diatomaceous mud belt.

5.2.3 Statistical Parameters

This Part covers the results obtained from sediment size analysis by dry-sieving (>63 μ m fraction), and the methods employed for this, and interpolation of the mud fraction into $\frac{1}{2}\phi$ units, are described in Appendix A.5.

The regional distribution of the principal sediment size fractions, as outlined above, are generally well described by the four statistical parameters. For example, the diatomaceous and Kunene mud belts and the upper slope sediments all have similar parameters, and can be summarised from the classifications shown in Figs.5.11 and 5.12 as: Medium silt to coarse clay, very poorly sorted, coarse and very strongly coarse skewed, platykurtic to very platykurtic (verbal classification system of Folk, 1968). The sandy mid shelf and near-shore sediments, on the other hand, are: Coarse sand to coarse silt, poorly to very poorly sorted, strongly fine to fine skewed, leptokurtic to very leptokurtic.

Apart from a few local deviations, the four statistical parameters generally show systematic regional trends with a considerable degree of congruency. This similarity is particularly apparent between the diagrams of mean and kurtosis, but those of sorting and skewness show a number of subtle differences. For example, the diatomaceous muds are less well sorted than the upper slope muds, and on the Walvis Ridge Terrace, the muds are more nearly symmetrically skewed than the diatomaceous muds. The worst sorted sediments from the diatomaceous mud belt coincide geographically with the regions of highest organic matter (see Fig.5.19). This unexpected result probably reflects the odd inclusion of mollusc shells near the western edge of the mud belt where the concentration of organic matter is a maximum (discussed in next Section).

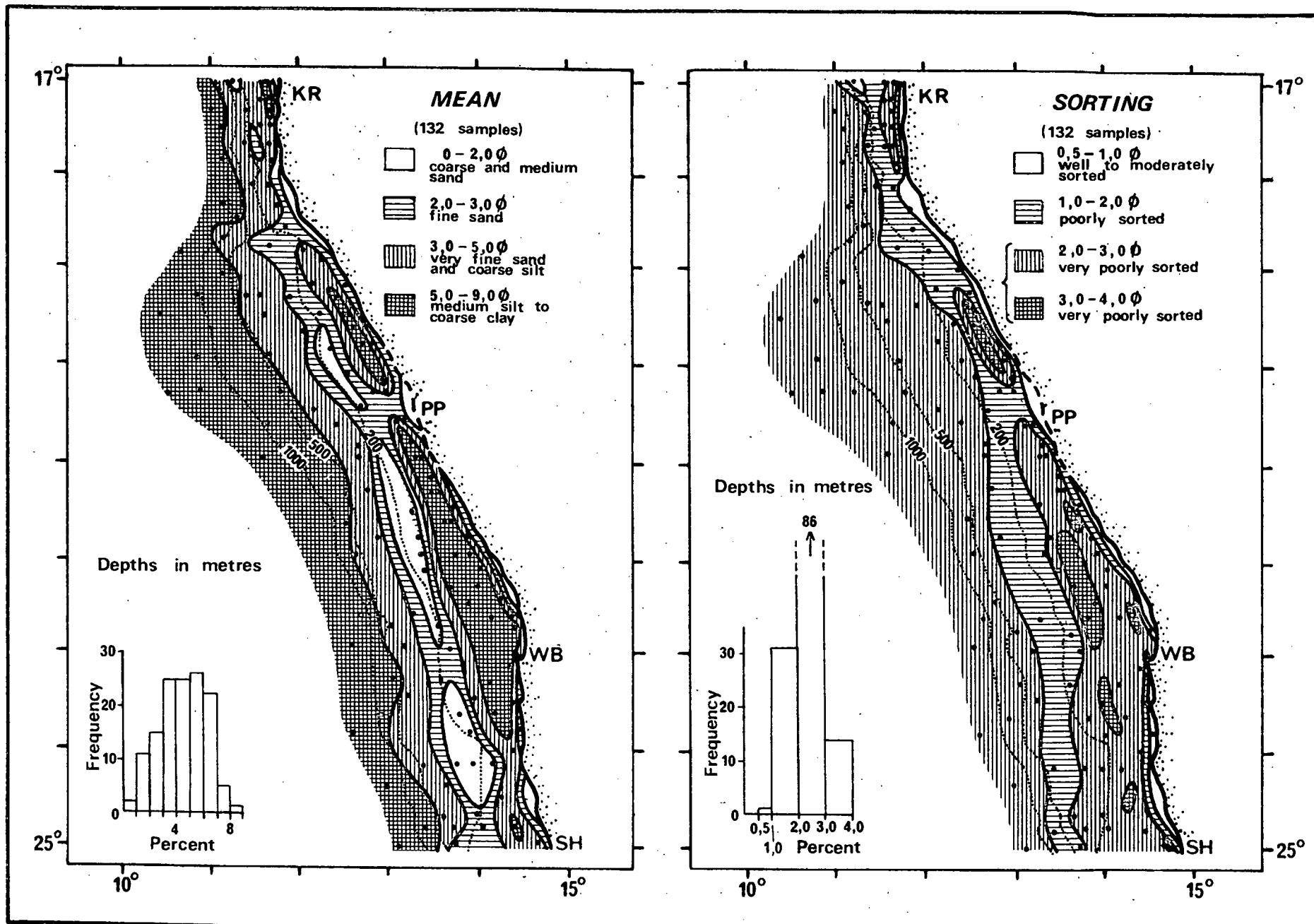


Figure 5.11

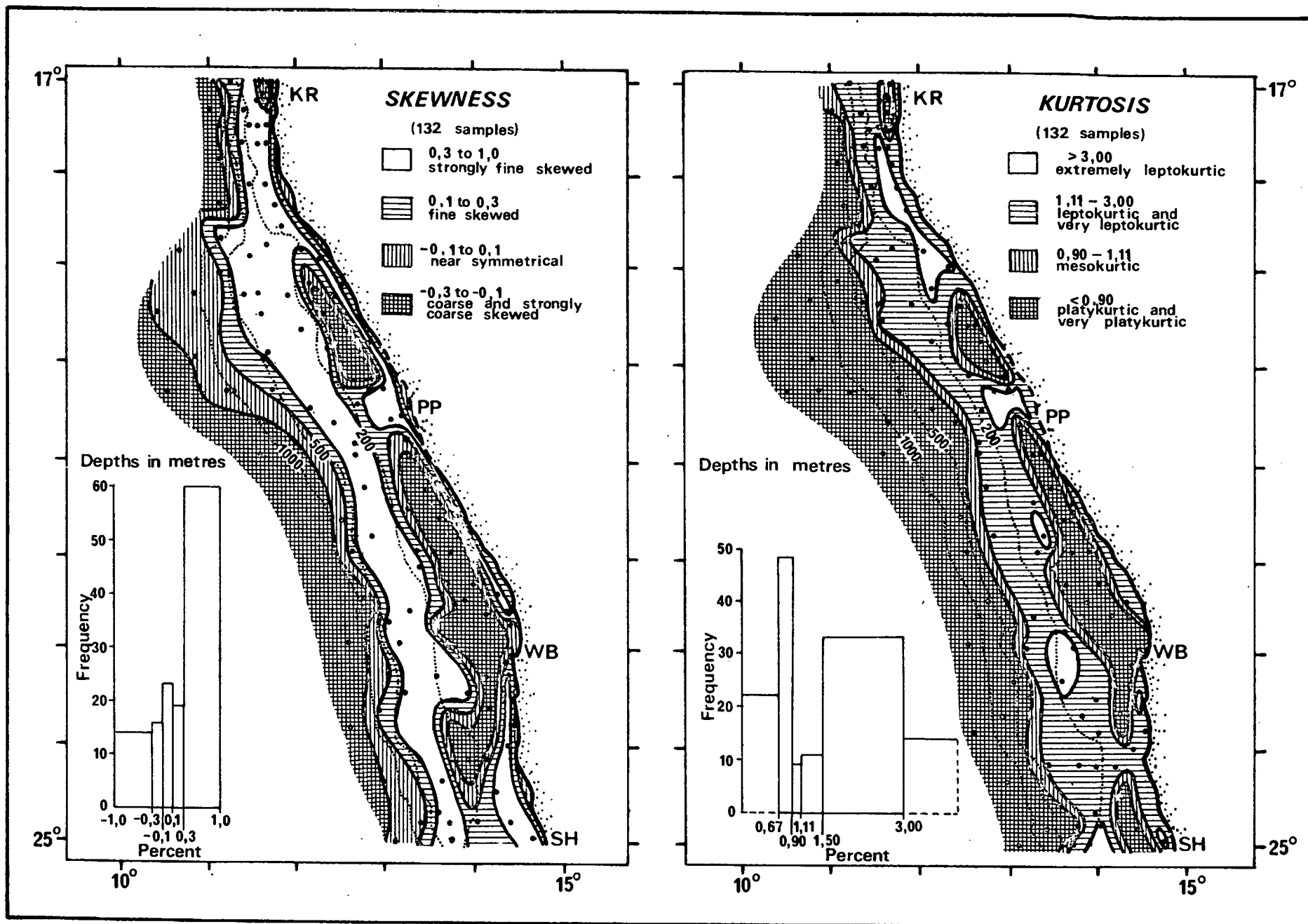


Figure 5.12

Another difference shown by sorting and skewness relative to the mean and kurtosis diagrams, are slight seaward shifts of the poorly sorted and strongly fine skewed regions of the mid shelf sand belt southwards from Walvis Bay. The reason for this may be due to the co-existence of gravel-size mollusc shells, sand-size pelletal phosphorite, and muddy diatomaceous sediment on the mid shelf in this general vicinity.

A number of samples from the beach foreshore, as well as from dune crests in the hinterland, were dry-sieved in an identical manner to the samples from the continental margin (Appendix A.5). Since the composition of these sediments is virtually entirely due to quartz, their discussion is reserved to the section dealing with terrigenous sediments (Section 5.5), and only the results are listed here for completeness.

Table 5.2 Statistical parameters of quartzose sediment from the beach foreshore and the hinterland dunes

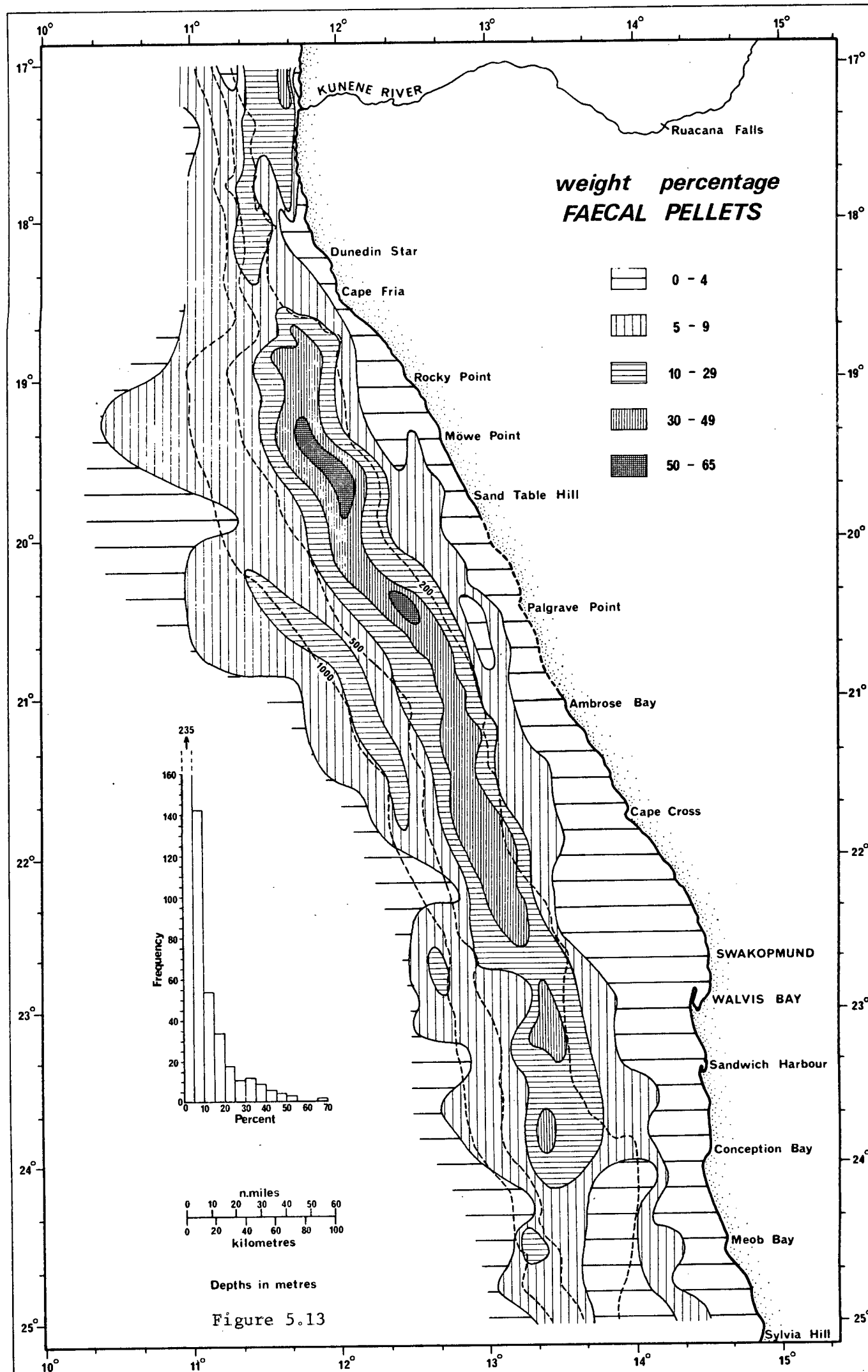
Sample Number	Location	Mean	Sorting	Skewness	Kurtosis
<u>Beach foreshore</u>					
BS - 63	Dunedin Star	1,69	,82	,30	1,16
BS - 58	Pelican Point	1,46	,45	,14	1,05
BS - 56	Walvis Bay	1,61	,55	,05	,96
JMB - 18	Meob Bay	1,98	,37	,19	,85
Averages		1,69	,55	,17	1,01
<u>Dune crests</u>					
JMB - 27	Palgrave Point	2,50	,42	0	,98
GOBABEB-3	Sandwich Harbour	2,49	,44	-,01	1,01
JMB - 20	Meob Bay	2,70	,40	-,03	1,24
JMB - 2	Sylvia Hill	2,03	,47	,42	1,05
Averages		2,43	,43	,10	1,07

5.2.4 Faecal Pellets

The diatomaceous muds are unable to support a community of benthic in-fauna due to its anoxic character, and the resulting lack of sand-size faecal pellets decided against their inclusion in the present study. The technique used for determining faecal pellet concentrations in the remaining sediment focusses attention on the organic matter which binds the mud particles together as sand-size ellipsoidal pellets. The method is described in Appendix A.6. and the results are shown in Appendix B.7.

(a) Regional Distribution

The regional distribution of faecal pellets in the unconsolidated sediment is shown in Fig.5.13, and the average concentrations in five different



environments. are listed in Table 5.3 below.

Table 5.3 Average concentration of faecal pellets in the unconsolidated sediment (weight percent)

	Entire* margin	Area		Biogenic sediments		Terrigenous and authigenic sediments
		Kunene margin	Walvis* margin	Diatom- aceous	Calcareous	
		← 18°40'S →		>5% opal	>50% CaCO ₃	Balance
No of Samples	379	64	315	-	193	186
Mean(%)	12,5	10,0	12,9	-	14,7	10,9
Std. Dev(%)	10,2	6,7	10,6	-	12,5	10,1
Range(%)	0-65	0-36	0-65	-	0-65	0-52

* Excluding samples from the diatomaceous mud belt.

In general, sediments from the Kunene Margin contain a slightly lower abundance of faecal pellets than sediments from the Walvis Margin, viz. 10,0% vs. 12,9% respectively (Table 5.3). The highest values recorded for the Kunene Margin (36%) come from the northern part of the Kunene mud belt at a water depth of 58 m. South of the Kunene River mouth, a branch of relatively faecal-pellet-rich sediment extends southwards across the shelf to a water depth of about 900 m, and eventually disappears in the vicinity of Cape Fria.

On the Walvis Margin, faecal pellets are concentrated along two sub-parallel belts, one lying just seaward of the 200 m isobath on the mid shelf, and the other coinciding roughly with the 1 000 m isobath on the upper slope. The mid-shelf belt reflects the highest concentration in the study area, and at 300 m depth off Mowe Point, a maximum of 65% is obtained. The upper-slope belt, with a maximum of 13% off Palgrave Point, is not as continuous or as rich as the mid-shelf belt, and essentially disappears south of Cape Cross where values of about 4% become norm. The mid-shelf belt also dies out in the southern part of the study area, but much farther to the south off Conception Bay. Here, gravel-size mollusc shells and sand-size pelletal phosphorite constitute the bulk of the sediment composition.

(b) Origin

The production of faecal pellets by planktonic fauna may be very high, for example, Marshall and Orr (1955) report that the copepod Calanus sp., which thrives in the nearshore waters off Sylvia Hill (de Dekker, pers.comm.), produces faecal pellets every 5 to 7 minutes when placed in a rich diatom culture. Their small size however (averaging coarse silt (Smayda, 1971)) makes their physical separation from diatom frustules almost impossible.

Seaward of the diatomaceous mud belt, sand-size faecal pellets, which

are relatively easy to separate, occur in abundance, and constitute on average 12,5% by weight of the unconsolidated sediment for the entire continental margin (Table 5.3). Polychaete worms, in particular, are responsible for their production (Christie, pers.comm.) and although no worm identifications were made, many of the samples contained dense masses of their chitinous tubes. According to Christie (pers.comm.), the following species are common to the west coast of southern Africa: Diopatra monroi, Hyolinoecia tubicola, Nephtys cf. macroura, Diplocirrus capenses.

Some polychaete species are found in water depths as much as 800 m in the vicinity of Lamberts Bay on the Cape West Coast, thus indicating that they are able to thrive under considerable water pressure (Christie, pers.comm.). Within the study area, a limiting depth is indicated at around 1 200 m by a marked drop in the concentration of faecal pellets to about 4%. This limitation may be due to water pressure, or lack of food, or both.

(c) Physical aspects

On the Walvis Mid Shelf faecal pellets are generally dark brown in colour, fine sand-size (0,250 - 0,125 mm), and fairly resistant to mechanical disaggregation. The Walvis Upper Slope and Kunene Shelf pellets are a lighter brown colour, mostly of medium sand-size (0,50 - 0,25 mm), and are somewhat more friable. Whereas comminuted foraminiferal fragments occur in all the faecal pellets, those from the Kunene Shelf contain silt-sized quartz as well.

(d) Influence on sediment texture

Scavenging benthic fauna, particularly polychaete worms, considerably modify the texture of freshly deposited sediment by ingesting the silt and clay size material and excreting sand-size pellets. Fig.5.14 has therefore been compiled to assess the 'true' mud content of the sediment by summing the 'old' mud values and faecal pellet concentrations in the samples. Note that since faecal pellets were not determined in samples containing more than 5% opal, the mud values plotted for the diatomaceous mud belt are simply the 'old' values.

The most significant adjustments to sediment texture occur on the Walvis Mid Shelf where the faecal pellet content is a maximum. For example, where sand values of >75% (i.e., mud <25%) were reported earlier on the seaward side of the 200 m isobath (Fig.5.7), mud concentrations are in reality found to be >50% (Fig.5.14). In particular, sample 3721 (off Mbe Point) was reported to contain 87% sand (Appendix B.7) but in reality, the concentration of mud is 77%, and that of sand only 10%. The pelletization of muddy sediment by benthic organisms therefore accounts for the lack of mud in the deeper parts of

the Walvis Mid Shelf, and an appeal to strong currents to explain this situation is therefore unnecessary.

After adjusting the mud content of the samples, two areas still show impoverishment in this fine sediment, and are of interest from a hydrological point of view. The one area is a southward pointing 'tongue' of mud-poor sediment on the northern part of the Walvis Ridge Abutment due west of Rocky Point (Fig.5.14). A similar tongue of low concentration occurs in the distribution of the planktonic foraminifer Orbulina universa at this location (see next Section), and immediately below it, a tongue of Radiolaria-rich sediment has been found to coincide with the belt of silty sediment on the upper slope. These phenomena are interpreted as being due to accelerated current velocities over the spur-like prominence of the Walvis Ridge Abutment between 400 - 500 m depth (Chapter 3), and relatively quiescent water in its lee at around 1 000 m depth. It would appear that the sand-size opaline silica tests of Radiolaria are less dense than the calcareous Orbulina tests, and exhibit similar settling properties to that of silt.

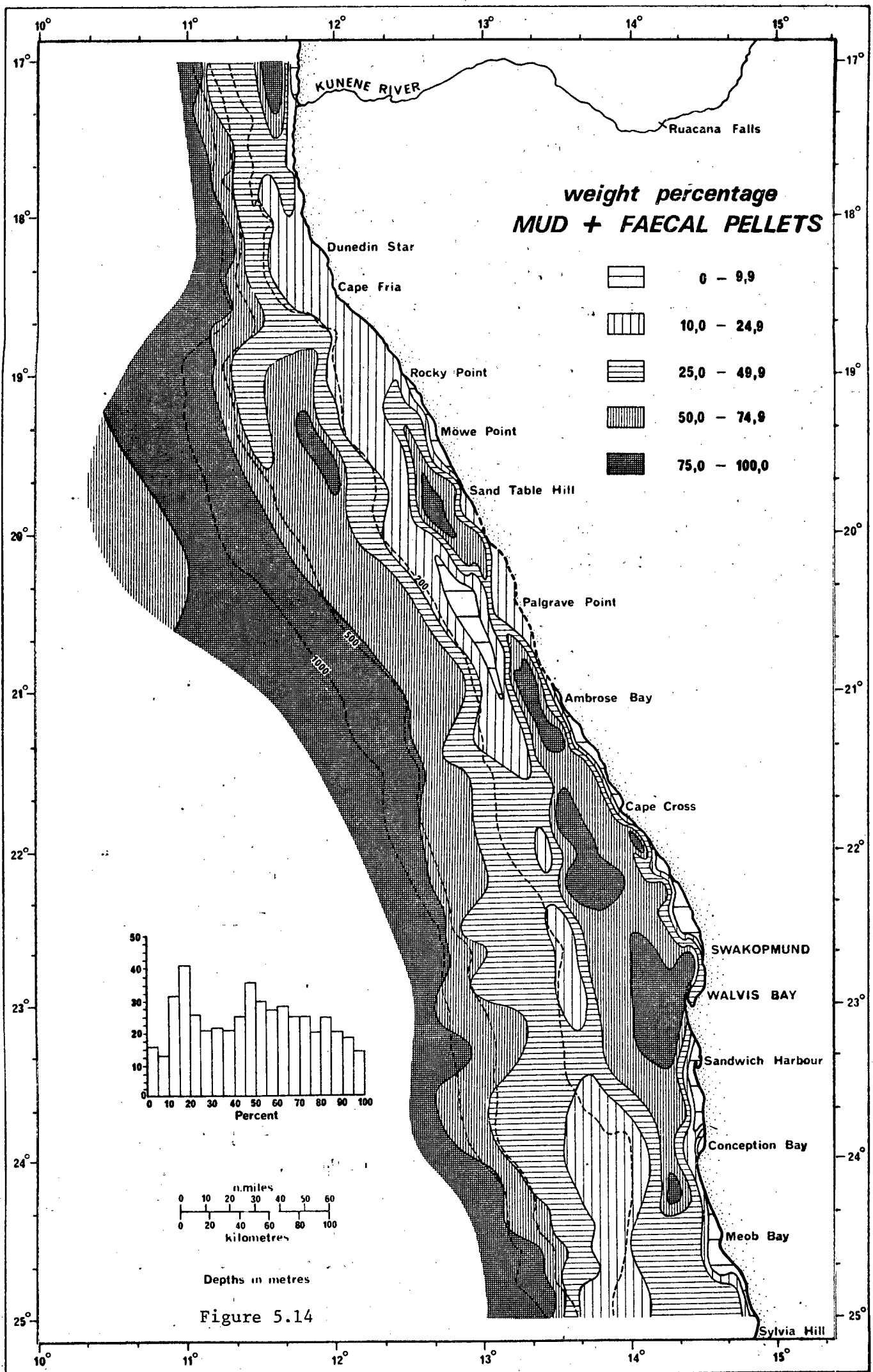
The other area of low mud content is the mid shelf landward of the 200 m isobath. Most relict sediments of the Walvis Shelf, such as terrigenous quartz and pelletal phosphorite, are exposed in this region, thereby indicating a very low rate of sediment supply. The reasons for this are attributed to storm-wave-induced bottom currents and the effects of the Ekman friction layer (Chapter 2). Theoretically, the velocity of the Ekman friction layer should increase at higher latitudes, and the greater areal extent of mud-poor sediment south of Sandwich Harbour (Fig.5.14) may therefore be a reflection of this. The extremely low mud content of sediment in the vicinity of Palgrave Point (<10%) is probably a response brought about by turbulence created over the Palgrave Depressions and on the Palgrave Shoal (Chapter 3).

The reason why faecal pellets are concentrated along discrete linear belts is also regarded as being due to oceanographic phenomena relating to the supply of food. This aspect is therefore discussed in the next Section dealing with organic matter.

5.3 BIOGENIC COMPONENTS

5.3.1 Introduction

This section covers the distribution and nature of various biogenic components in the unconsolidated sediment. Most attention is directed at the Walvis Margin, where sediments rich in organic detritus have accumulated as a result of upwelling within the Benguela Current. The Kunene Margin sediments are, by contrast, impoverished in biogenic components, this being due to the relative sterility of Angola Current waters (Chapter 2).



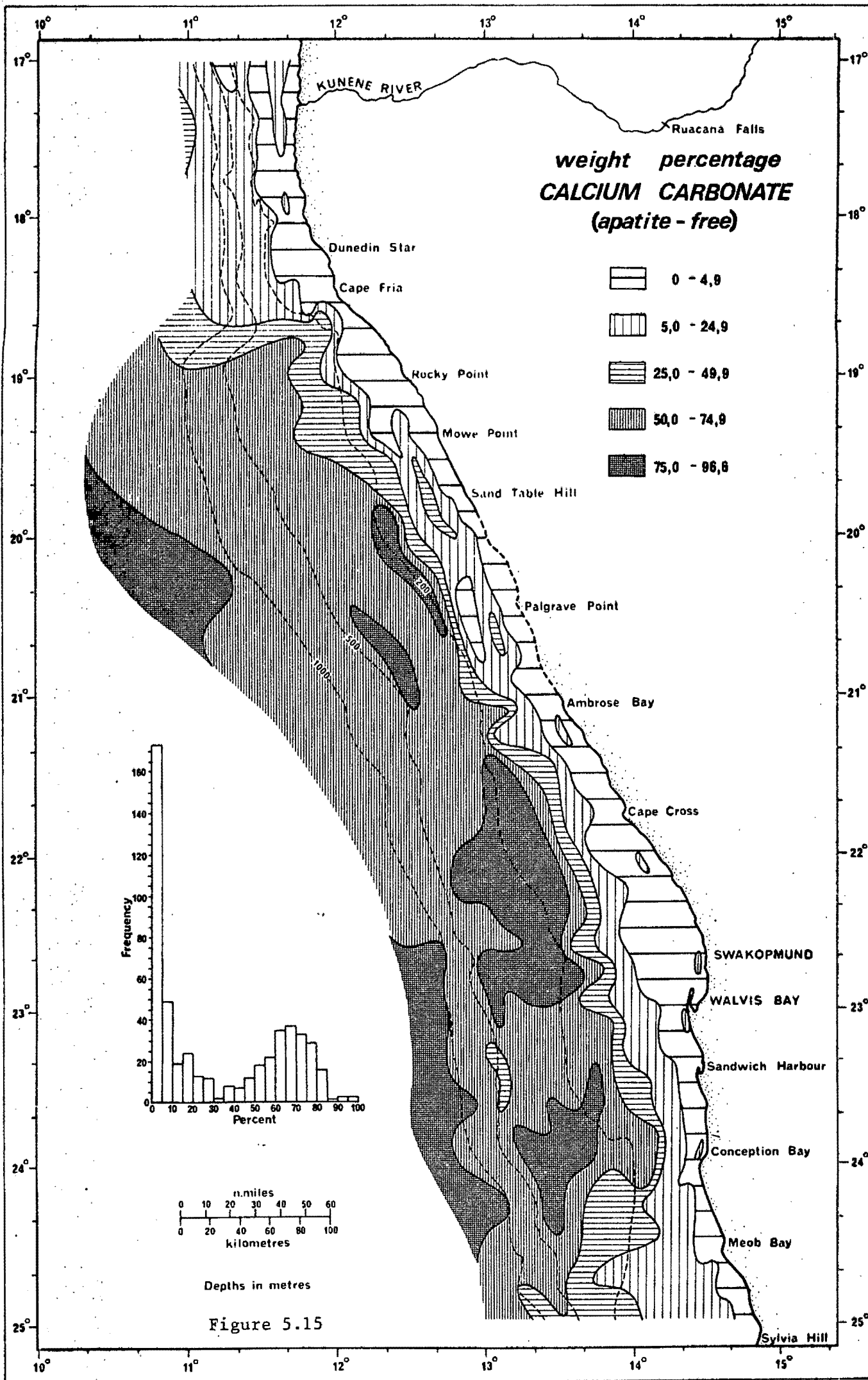


Table 5.4 Average concentration of CaCO_3 in the unconsolidated sediment (weight percent)

	Entire margin	Area		Biogenic sediments		Terrigenous and authigenic sediments
		Kunene margin	Walvis margin	Diatomaceous	Calcareous	
		← 18° 40' S →		>5% opal	>50% CaCO_3	
No. of samples	521	64	457	142	193	186
Mean (%)	32,2	8,4	35,5	5,9	68,1	15,0
St. Dev. (%)	30,4	7,5	30,9	7,1	9,3	17,2
Range (%)	0-96,6	0,4-35,7	0-96,6	0-48,7	50,1-96,6	0,3-49,1

Sediments mantling the Kunene Margin have a CaCO_3 content averaging only 8,4%, which reflects the nutrient-poor quality of the Angola Current waters. Although the CaCO_3 concentration nowhere exceeds 25% of the sediment (except for a single upper slope sample (3655) at 1 500 m depth off the Kunene River), a slow but steady increase is apparent westwards from the 200 m isobath. Slightly increased concentrations also occur in the Kunene mud belt, where values of 5 - 13% compare with the ambient sediment concentrations of 1 - 4%.

The overall distribution pattern of CaCO_3 on the Walvis Margin, which averages 35,5%, consists of a rapid westward increase from <5% to >50% along the seaward edge of the diatomaceous mud belt, and irregular discrete patches reaching >75% on the mid shelf and outer margin. The nearshore terrigenous sands, and the eastern half of the diatomaceous mud belt, are virtually devoid of CaCO_3 , except for a few small mollusc occurrences close to shore. The western half of the mud belt however, contains low but significant quantities of CaCO_3 , with approximately 5% being recorded from around the middle of the belt due to the influx of planktonic foraminifera. Farther west, foraminiferal abundance increases and occasional mollusc shells begin to appear, which raises the CaCO_3 content of the muds to ~25%. Along the western edge of the mud belt (Trace to 5% opal), at least between Ambrose Bay and Conception Bay, benthic foraminifera become dominant, and together with extensive beds of relict mollusc shells, the CaCO_3 content increases to ~50%. Patches of sediment containing >75% CaCO_3 west of the mud belt are due to a combination of benthic and planktonic foraminifera on the continental shelf, and to planktonic foraminifera alone on the upper slope.

The calcareous skeletal-grain assemblage on the South West African continental margin is typical of temperate-water biogenic deposits, for which Lees (1972, 1973, 1975) has coined the term 'foramol' to indicate dominance by foraminifera and Mollusca.

(b) Origin

(i) Mollusca

The majority of mollusc shells are concentrated shoreward of the 200 m isobath on the Walvis Inner Shelf (Fig.5.16(a)). Because of their rather limited geographic distribution, they do not constitute an important component of the shelf sediments although at a few locations, particularly along the western edge of the diatomaceous mud belt south of Conception Bay, they provide the bulk of CaCO_3 to the sediments. A great number of different species occur, 52 having been identified in all (Appendix A.8), but only the most common of these are listed in Appendix B.8.

Identifications were made by Dr. A.J. Tankard of the S.A. Museum, Cape Town, and by Mr. T.N. Kilburn of the Natal Museum, Pietermaritzburg, both of whom regard the shell deposits as modern. Their opinions are based on the general appearance of the shells and on the physical condition of specific parts of some of the rarer species e.g., the ligament of Venus chevreuxi, and the glossy aperture of Sveltia lyrata (Kilburn, 1975, pers.comm.). However, since no radiocarbon dates were made on the shells, they are considered to be relict (probably from the Würm II pleniglacial) for the following reasons: not a single living specimen was encountered from the many hundreds of shells recovered; all of them were filled with ambient sediment; on the mid shelf south of Conception Bay, they typically occur associated with relict pelletal phosphorite; and south of Palgrave Point they underly modern diatomaceous mud. The occurrence of occasional mollusc shells within the diatomaceous mud is explained by Tankard (pers.comm.) as being due to their siphons which he believes they are capable of extending to the surface. The anoxic condition of bottom waters militates against this hypothesis however, and an alternative suggestion is that they are carried upwards from the sub-bottom by H_2S eruptions within the deposit.

Lucinoma capensis is a fragile mollusc species that in many samples occurs with a high articulation ratio indicating preference for a moderately low-energy muddy environment. Apart from a high concentration of these shells off Palgrave Point, their distribution differs little from that of the thick-walled robust species Dosinia lupinus (Figs.5.17(a) and (b)), which suggests that the two distinct species were mixed, possibly during the Flandrian transgression. The next two most commonly occurring species, Tellina gilchristi and the gastropod Nassarius analogicus, are present in similar concentrations (>25%) and are confined to precisely the same areas as Lucinoma and Dosinia (Fig.5.17(c) and (d)). None of these common species is endemic to the South West African shelf; they have generally been recovered from waters ranging in depth from about 50 - 400 m, and occur in sediments of Neogene to

Recent age (Kensley, 1973).

(ii) Foraminifera

Recently, Basov and Belyayeva (1974) and Basov (1976) have published results of quantitative work on the distribution and abundance of foraminifera within the study area. In most respects the results of the present study are in agreement with their findings.

The regional distribution of mollusc/foraminifera ratios shown in Fig.5.16(a) may be misleading if the significance of the ratios is not properly understood. The unshaded area in the diagram adjacent to the coast is due to the absence of both Mollusca and foraminifera, whereas the unshaded area on the outer margin is a result of the complete absence of Mollusca and the great abundance of foraminifera. Fig.5.16(d), which illustrates the planktonic/benthic foraminifera ratios gives better insight of the regional distributions of these different foraminifera and at the same time, serves to contrast their relative abundances in the unconsolidated sediment.

On the Walvis Shelf, benthic foraminifera are dominant along a narrow irregular strip adjacent to the diatomaceous mud belt. Farther to the west, planktonic species increase in importance and reach very high concentrations on the upper slope (Fig.5.16(b)). On the Kunene Margin, benthic species predominate over the entire continental shelf with planktonic species becoming more abundant on the upper slope.

An extensive region of CaCO_3 -rich sediment ($>75\% \text{ CaCO}_3$) on the mid shelf off Swakopmund (Fig.5.15) is due mainly to the accumulation of planktonic foraminifera tests as indicated in Fig.5.16(b). This rich deposit may have accumulated from dense planktonic foraminifera populations that graze directly on diatomaceous flora being carried westward by the Benguela Current (Chapter 2).

(A) Benthic

Seven of the most prolific benthic foraminifera (Appendix B.9) have been counted as volume percentages (Appendix A.8), and the regional distribution of four of them is shown in Figs.5.18(a) to (d).

In general, Ammonia beccarii and Uvigerina sp. have similar distributions and concentration levels on the Kunene and Walvis Shelves. In the latter area however, they differ slightly in their location; small isolated concentrations ($\sim 7\%$) of Ammonia beccarii favouring the landward side of the 200 m isobath, and Uvigerina sp., the seaward side. Both types occur maximally (18% and 14% respectively) on the Kunene Shelf seaward of the 200 m isobath. The most abundantly occurring benthic foraminifera in the study area are Brizalina spathulatus and Bolivina sp. which reach concentrations in excess of 70% of the total foraminiferal assemblage in certain areas. Brizalina spathulatus

occurs across the full width of the Kunene and Walvis Mid and Outer Shelves, but Bolivina sp. is confined to the Kunene Upper Slope, and to a narrow discontinuous strip flanking the western edge of the diatomaceous mud belt. An area where both populations have accumulated just north of Walvis Bay deserves special mention because of its association with very high organic matter and trace metal contents (see Chapter 7). This apparent paradox can be accounted for by invoking the passage of weakly oxygenated water over the area, sufficient to sustain the benthic fauna and yet low enough to keep oxidation of the organic matter to a minimum. The depth of water and the rate of diatom settling are the principal factors that govern the supply of this organic food source to the benthic organisms (discussed below). Brizalina spathulatus reaches a maximum concentration of 75% on the Kunene Shelf just seaward of the 200 m isobath, and this rich belt deepens southwards to over 1 000 m off Cape Fria. Bolivina sp. also occur in this area with concentrations of ~20%, and are closely associated with trace quantities of diatoms.

(B) Planktonic

Although the sedimentary foraminiferal assemblage consists overwhelmingly of planktonics, only one species has been counted systematically viz., Orbulina universa (Appendix A.8) because of its ease of recognition and high concentration levels (Appendix B.9). Three additional widely spaced samples from the upper slope were examined by Dr. W.G. Siesser in order to establish the order of abundance of the most commonly occurring species (Appendix B.10).

Orbulina universa is restricted to the Walvis Margin. Two moderately concentrated areas exist on the Walvis Inner Shelf, but by far the greatest concentrations occur on the Walvis Upper slope (Fig.5.16(d)). The more northerly of the two inner shelf deposits averages about 10% by volume of the calcareous sediment fraction while the smaller southerly deposit off Cape Cross averages only about 5%. The highest concentrations, reaching 36%, are found just south of the Walvis Ridge Terrace on the upper slope. As described in the Section dealing with faecal pellets (Section 5.2), a southward pointing 'tongue' of sediment on the Walvis Ridge Abutment which contains no Orbulina at all and very low mud values, is attributed to the existence of a jet of the Angola Current over the 'spur-like' feature between 400 and 500 m depth.

The three upper slope samples that were selected for planktonic foraminifera abundance studies came from the Walvis Ridge Terrace, off Cape Cross, and off Sylvia Hill. In all of them the transitional species Globorotalia inflata was dominant. This was followed by a number of subantarctic species of which the southern most sample off Sylvia Hill showed the greatest species diversity.

MOLLUSCA-FORAMINIFERA RATIOS, RADIOLARIA AND ORBULINA

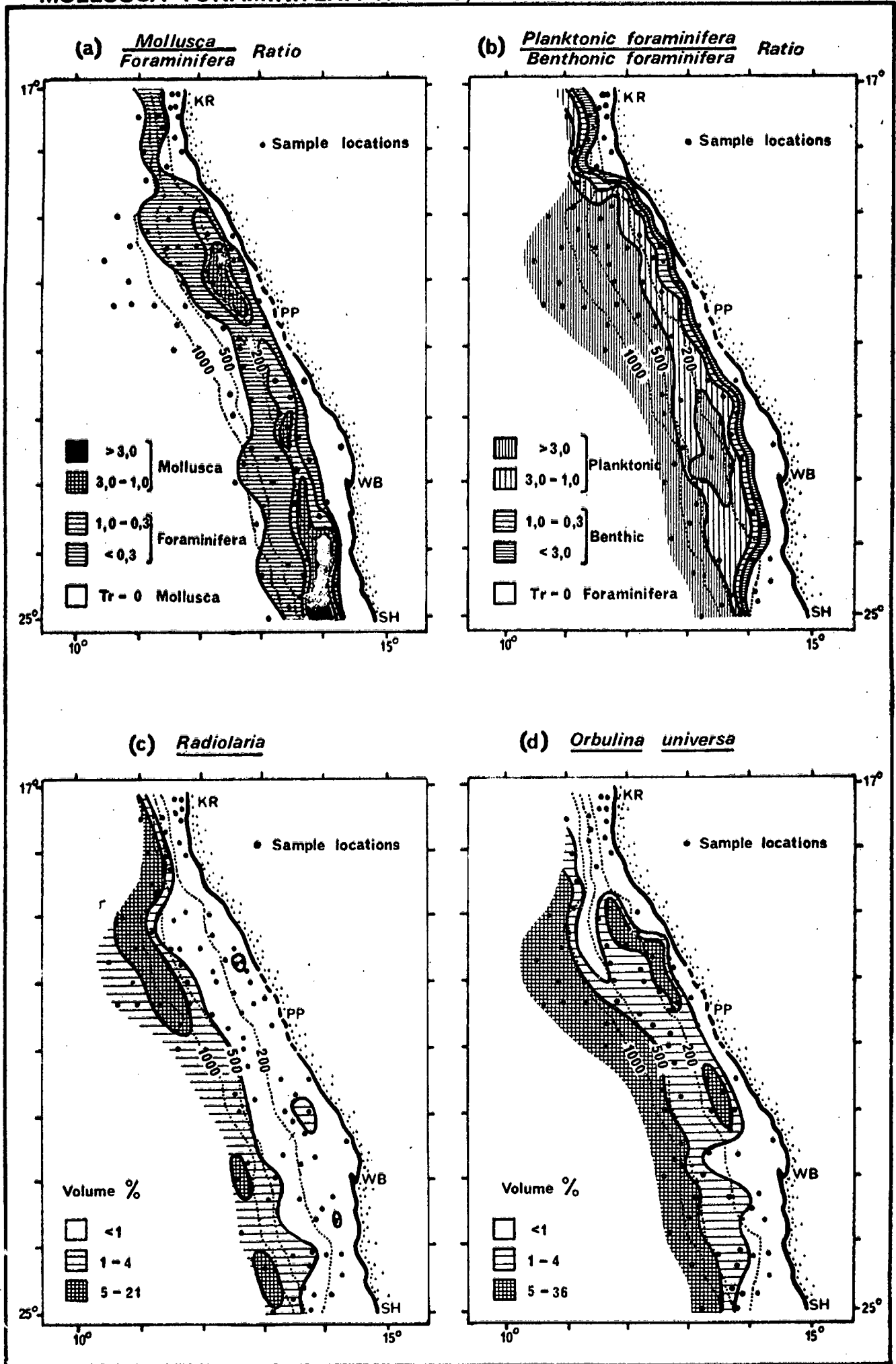
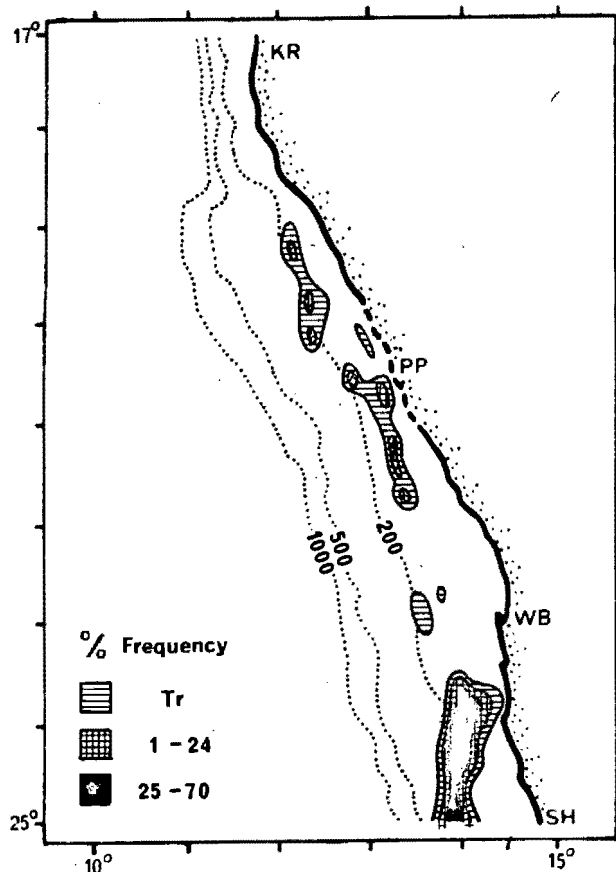


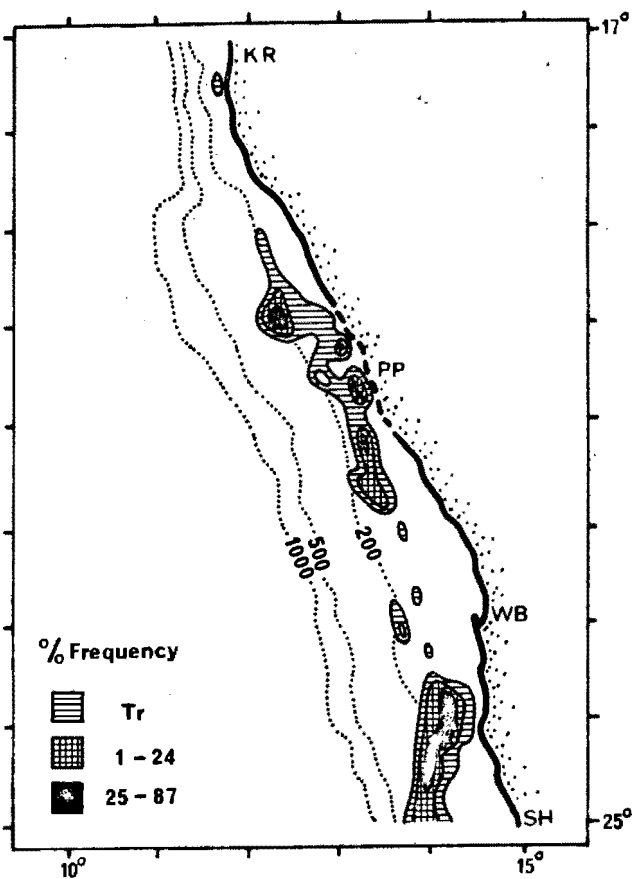
Figure 5.16

MOLLUSCA

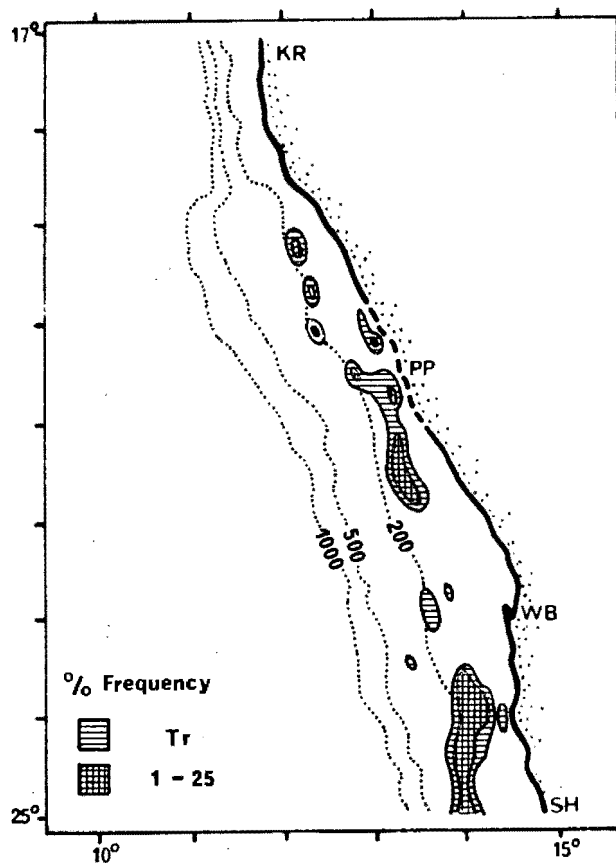
(a) *Dosinia lupinus*



(b) *Lucinoma capensis*



(c) *Tellina gilchristi*



(d) *Nassarius analogicus*

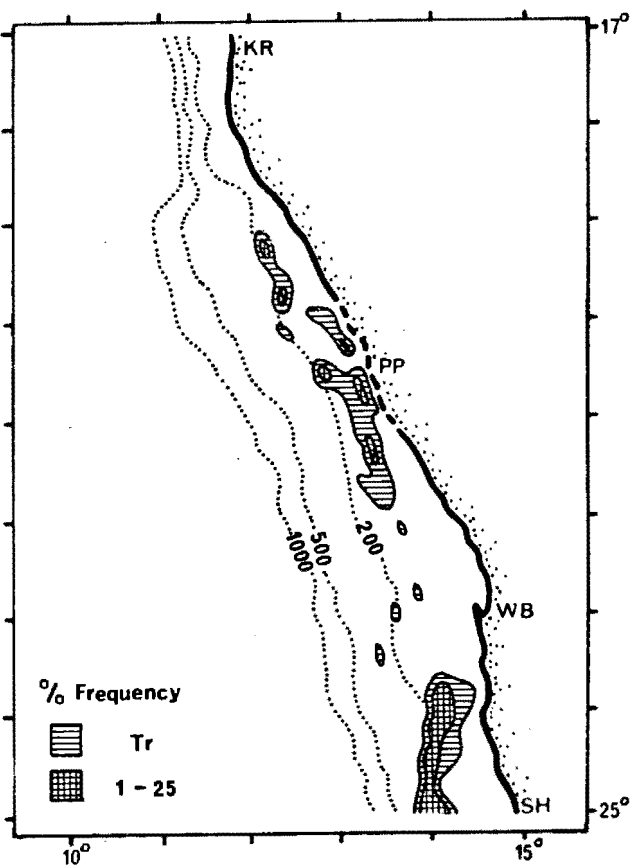
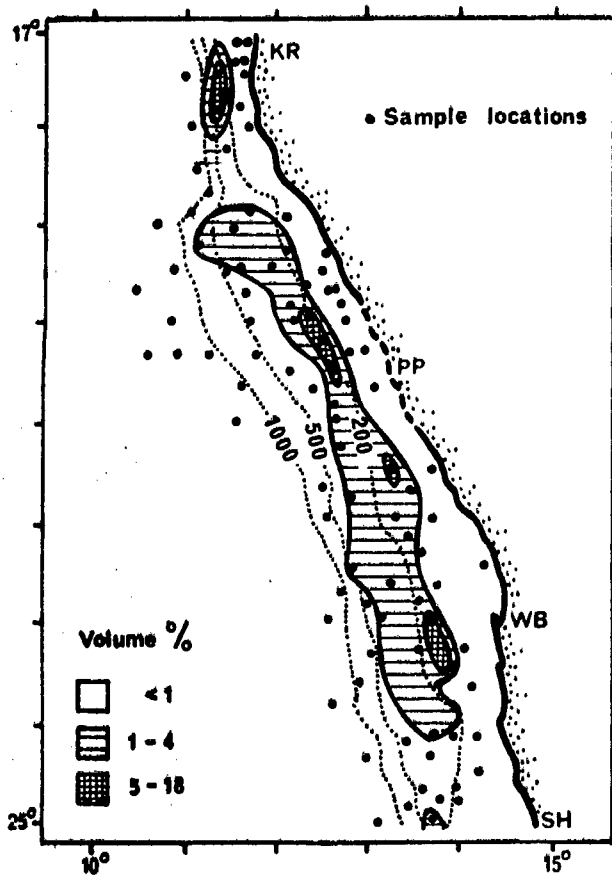


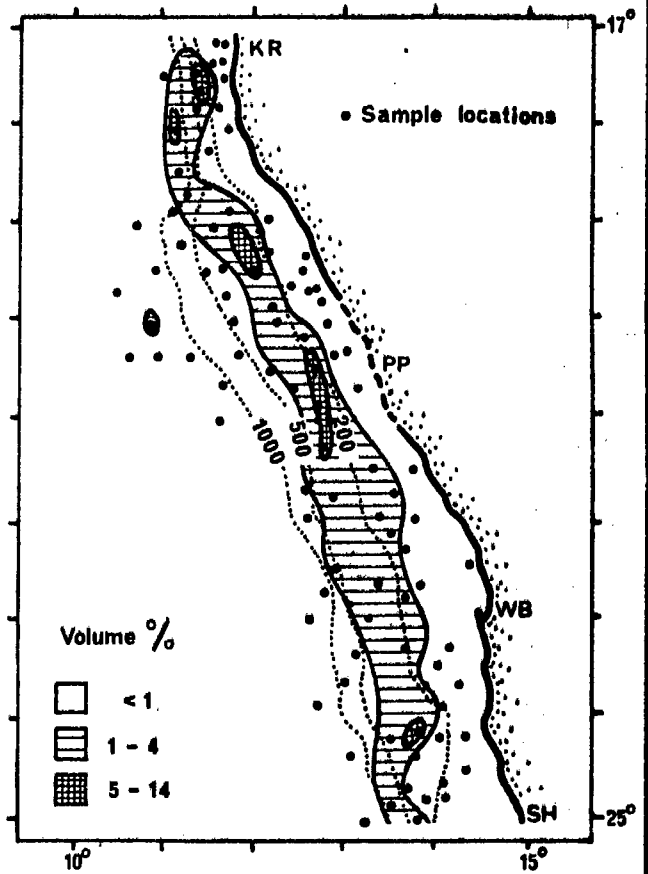
Figure 5.17

BENTHIC FORAMINIFERA

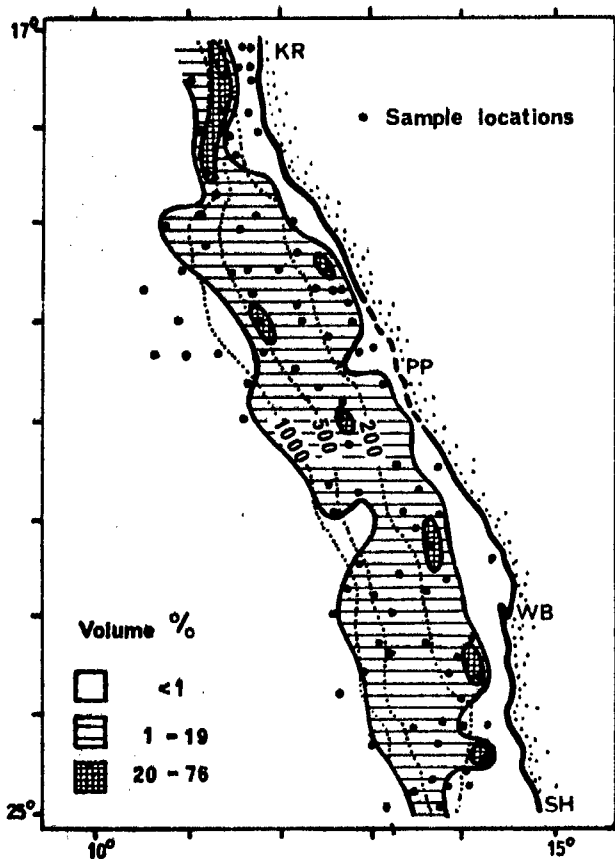
(a) *Ammonia beccarii*



(b) *Uvigerina* sp.



(c) *Brizalina spathulatus*



(d) *Bolivina* sp.

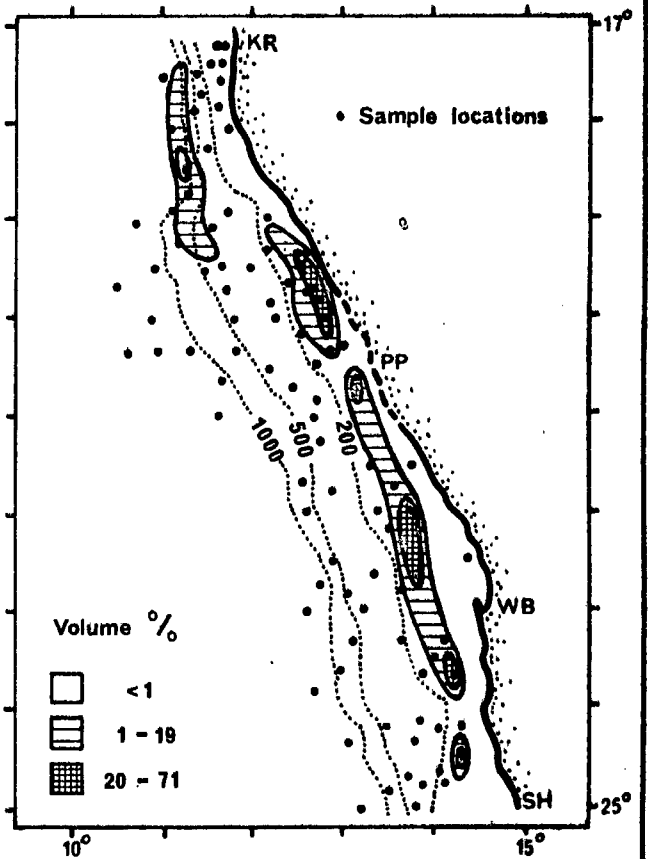


Figure 5.18

Subtropical species were next in abundance, but only in the northern sample, from the Walvis Ridge Terrace, were a few specimens of the tropical species Globigerinoides sacculifer present.

5.3.3 Organic matter

(a) Regional distribution

Compared with the world average organic matter content of continental shelf sediments (0,5%, Emery, 1960), the exceptionally high average value recorded for the study area (6,7%) attests to the high productivity of shelf waters along the South West African coast (Table 5.5).

Sediment from the Kunene Margin, in keeping with the low CaCO_3 and opal content, is less than half as rich in organic matter than the Walvis Margin sediments viz., 3,2% and 7,2% respectively (Table 5.5). The silty sediment of the Kunene mud belt contains marginally higher organic matter concentrations than the ambient shelf sediment with a maximum of 5,1%, and may be a reflection of diatom productivity resulting from nutrient introduction by the Kunene River (Fig.5.19). This aspect is discussed further in Chapter 7 dealing with the geochemistry of the sediments. The highest organic matter values on the Kunene Margin lie along the southern part of the upper slope at about 1 500 m depth. In this area, the organic matter content is 8,3% and coincides with fairly rich concentrations of planktonic foraminifera, and the benthic foraminifera Brizalina spathulatus and Bolivina sp. (Fig.5.18).

The Walvis Margin sediments contain three sub-parallel belts with abnormally rich concentrations of organic matter (>7%) (Fig.5.19). An inner shelf belt, between Rocky Point and Sylvia Hill, is one of the most organic-rich deposits known to exist for open-shelf sediments (maximum organic matter, 24,6%), and has accumulated almost entirely from planktonic flora, particularly diatoms. General anoxic conditions at the surface of the diatomaceous mud belt have inhibited its occupation by benthic organisms (other than bacteria), and hence the potentially rich source of food (organic matter) remains un-pelletized. The other two organic-rich belts have accumulated as a result of several factors of which diatomaceous and planktonic foraminiferal remains are the primary sources, and correspond closely with the distribution of faecal pellets (see below). One of these belts lies just seaward of the 200 m isobath on the mid shelf and contains a maximum of 12,5% organic matter; the other belt, with a maximum of 8,8%, coincides roughly with the 1 000 m isobath on the upper slope. Both of them decrease to less than 7% in the vicinity of the Swakop Bank (Fig.3.2), which may be an indication that local turbulent conditions around this topographic prominence effectively inhibits the settling of organic matter to the sea floor. Furthermore, the relatively rich mid-shelf belt disappears south of Sandwich Harbour where the concentration of relict

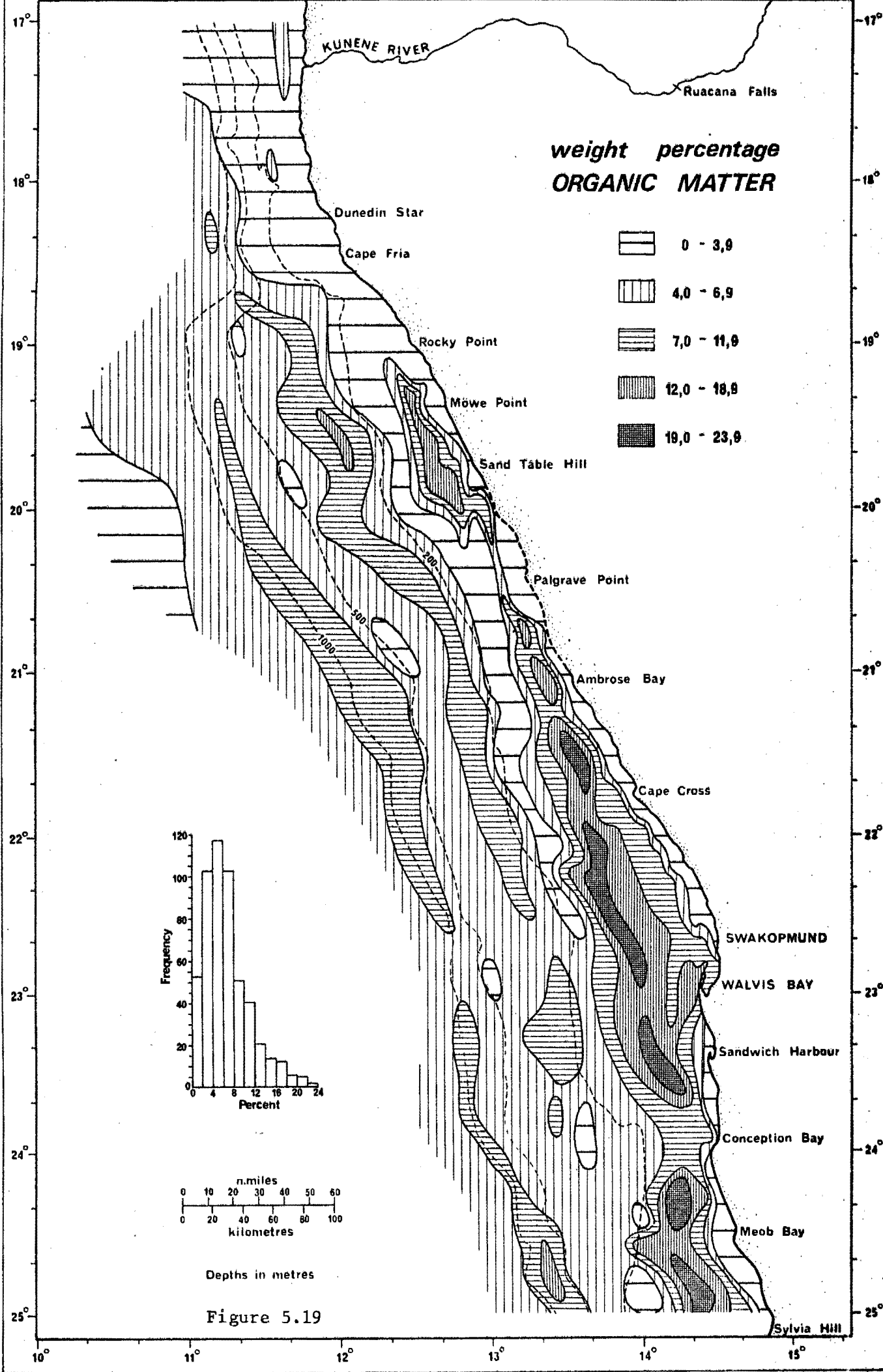


Figure 5.19

pelletal phosphorite and mollusc shell beds are the maximum, thus reflecting the slow rate of sedimentation in this area (Section 5.2).

The average concentration of organic matter in the unconsolidated sediment from different geographic areas, as well as from different sediment lithofacies, is summarised in Table 5.5. The method used for determining organic matter is described in Appendix A.9, and the results are shown in Appendix B.7.

Table 5.5 Average concentration of organic matter in the unconsolidated sediment (weight percent)

	Entire margin	Area		Biogenic sediments		Terrigenous and authigenic sediments
		Kunene margin	Walvis margin	Diatomaceous	Calcareous	
		← 18°40'S →		>5% opal	>50% CaCO ₃	
No. of samples	521	64	457	142	193	186
Mean (%)	6,7	3,2	7,2	9,8	6,5	4,3
Std. Dev. (%)	4,3	1,3	5,4	5,1	2,4	3,8
Range (%)	0,1-24,6	1,3-8,3	0,1-24,6	0,2-24,6	0,2-14,5	0,1-18,5

(b) Origin

The rich concentration of organic matter on the Walvis Continental Margin is primarily the result of upwelling within the Benguela Current System (Chapter 2). Nutrient-rich water drawn to the surface from depths of 200 - 350 m. leads to the production of intense phytoplankton blooms close to shore, and after death, a large proportion of the latter accumulate as sediment on the inner shelf. Some of the planktonic organic matter is transported westward by the Benguela Current and by storm-wave-induced bottom currents, thus providing a copious food source for benthic organisms on the mid and outer shelves. Large populations of planktonic foraminifera also feed on this phytoplankton but as described earlier, they accumulate mainly on the outer shelf and upper slope. The source of the organic matter is now briefly considered.

(i) Association with opal

Because of the very low discharge rate of rivers in the area (Chapter 1), organic matter deposited within the diatomaceous mud belt is derived almost entirely from planktonic sources, and this is demonstrated by the close association of the 5% opal and 7% organic matter isopleths (Fig.5.21). Careful examination of these boundaries reveals that the organic matter is actually displaced slightly seaward of the main body of the diatomaceous mud belt, the reason for this being due to differences in opal input along the two flanks of the deposit. Along the landward edge, diatom frustules have a relatively short water column to settle through, averaging 31 m from the sea surface to the sea floor (see Table 5.8). Using Calvert's (1966) average settling rate of 1 000 m/year for 10 - 20 mm diameter frustules, a figure of 11 days is

obtained for these frustules to reach the sea floor (assuming zero up- or downwelling of the water mass). Diatom frustules settling to the western edge have to settle through an average water column height of 130 m (Table 5.8), thus giving them a transit time of 47 days. During their passage to the sea floor, the less robust frustules slowly dissolve, whereas the organic matter is to some extent protected from oxidation by the silica cell walls. The relatively low organic matter concentrations along the eastern edge of the diatomaceous mud belt are therefore due to opal dilution (robust as well as delicate frustules being deposited), and the relatively high organic matter concentrations along the western edge are due to opal dissolution (only robust species being deposited). Calculation of organic matter on an opal-free basis would eliminate these differences, and the organic matter isopleths would then show improved coincidence with the boundaries of the diatomaceous mud belt.

Another factor promoting organic matter accumulation along the western edge of the diatomaceous mud belt is the favourable sedimentation rate. A slower rate would expose the organic matter to longer periods of oxidation at the sediment-water interface, and a faster rate would result in less opal dissolution. Finally, the oxygen-deficient character of Angola Current waters also helps in preserving organic matter, particularly in the area northward from Walvis Bay (Chapter 2). The greatest concentrations of organic matter in the study area (>19%) occur as narrow, discontinuous deposits along the western flank of the diatomaceous mud belt, and in these regions, the opal content of the sediment is only between 5 and 50%.

An approximate volumetric figure for the rate of accumulation of organic matter has been determined. This was done using the average linear dimensions of the diatomaceous mud belt (see Table 5.8), and also the average concentration of organic matter at the surface of the deposit (Table 5.5). The total amount of organic matter then comes to $(1,25 \times 10^{11}) \times 9,8/100 = 1,22 \times 10^{10} \text{ m}^3$, and assuming a constant supply over the past 5 000 years, a sedimentation rate of $2,4 \times 10^6 \text{ m}^3/\text{year}$ is obtained.

(ii) Association with faecal pellets and foraminifera

Benthic organisms contribute to the total organic content of the sediments, but are dependant on the supply of primary organic matter (from planktonic sources) for their existence. This is strikingly illustrated by the close similarity between organic matter and faecal pellet distributions (Figs. 5.19 and 5.13 respectively) on the Walvis Mid Shelf and Upper Slope, even to the extent of coinciding maxima on the mid shelf off Mowe Point. The reason for this strong positive correlation may be found in the movement of water masses immediately above the sea floor. In Chapter 2 it was seen that storm-wave-induced bottom currents, and the Ekman friction layer, both tend to

sweep muddy sediment away from the landward side of the inner shelf break, and the effects of upwelling along the outer shelf break were briefly described. It is precisely these two areas, the inner and outer shelf breaks, where the concentration of organic matter and faecal pellets is lowest. The coincident belts of high concentration on the seaward side of the 200 m isobath, and along the 1 000 m isobath, are therefore attributed to slackened bottom-current velocities in these areas. This would allow organic matter of diatomaceous origin to settle and be consumed by polychaete worms in the former area, and planktonic foraminiferal organic matter to settle and be consumed by polychaete worms in the latter. Indirect evidence for this is obtained from the relatively greater abundance of comminuted foraminiferal fragments in the upper slope pellets than in the pellets from the mid shelf.

The regional distribution of CaCO_3 (Fig.5.15) shows little similarity with the linear trends of organic matter and faecal pellets. This is most likely due to the CaCO_3 being supplied from several different sources, some of them being relict e.g., the mollusc shells, which do not contribute to the organic matter content of the sediments. Some of the benthic foraminifera, e.g., *Bolivina* sp., do occur along rough linear belts, but in general, their abundances are too low to significantly affect the distribution of organic matter on the outer margin.

The relationship between C_{org} and faecal pellets in the sediment, is shown by means of a bivariate plot in Fig.5.10(e). The two lithofacies considered here are the calcareous ($>50\% \text{CaCO}_3$) and the terrigenous/authigenic (Balance), since the diatomaceous sediments ($>5\% \text{opal}$) were excluded from the faecal pellet study. Regression lines through the densest distribution of points have been drawn visually to aid discussion - one for the calcareous sediments (solid line), and two for the latter (dashed lines). It is apparent that the calcareous sediment line, and line I of the terrigenous/authigenic sediment are parallel, thus indicating that the former contain, on average, 2% more C_{org} than the latter. These two lines represent sediment from the Walvis Outer Margin and the Kunene Margin respectively, whereas line II of the terrigenous/authigenic sediment represents both flanks of the diatomaceous mud belt. The eastern flank sediments are devoid of both organic matter and faecal pellets, whereas the western flank sediments are relatively rich in both components - hence the steep gradient of line II.

(c) Size distribution

Rogers (1972) and Summerhayes (1972a), in their studies of the Orange Shelf and Agulhas Bank sediments respectively, plotted the weight percentage of C_{org} against the weight percentages of silt and clay in the sediment, in order to establish the sediment size fraction most commonly associated with the

organic matter. This of course included the organic matter in sand-size faecal pellets and foraminifera and as a result, the scatter of points in their plots was very wide and difficult to interpret meaningfully.

In the present study, the sand fractions were isolated from all the sediment samples for a number of compositional and mineralogical studies (Fig. 5.1, column 3) and the remaining silt and clay fractions were divided into two groups, one for the analysis of P_2O_5 and K_2O , and the other for the analysis of C_{org} . The determination of C_{org} on the sediment size fractions themselves eliminated such contaminants as were mentioned above, and allowed plotting of regional distribution maps (Fig. 5.20) and easily interpretable bivariate plots (Fig. 5.10(c) and (d)).

From Fig. 5.20 it is apparent that most of the organic matter occurs on the continental shelves and that its abundance drops off rapidly in deeper water on the upper slope. The Kunene Shelf is dominated by clay-size organic matter in relatively low concentrations (4 - 7% C_{org}) thus reflecting the low productivity of waters introduced by the Angola Current. On the Walvis Shelf, the diatomaceous mud belt being close to the region of strong coastal upwelling and lying in relatively shallow water, contains mostly silt-size organic matter with C_{org} values >7% along its entire length. Farther seaward, clay-size organic matter (>7% C_{org}) again becomes dominant on the mid shelf and on the upper slope, both textural components decreasing to <4%, and <2% on the Walvis Ridge Terrace. This overall decrease in the size of pelagic organic matter with depth on the Walvis Margin probably reflects increased oxidation during its passage to the sea floor. However, the concentrations are still high enough to support dense populations of benthic foraminifera and polychaete worms on the outer part of the mid shelf, and polychaete worms alone on the upper slope.

The most organic-rich areas of the diatomaceous mud belt, as off Walvis Bay and Meob Bay, contain exceptionally high concentrations of silt and clay-size organic matter, and maximum concentrations of 12,6% and 14,4% C_{org} respectively are recorded (sample 3426, Fig. 5.10(c) and (d)). The combined C_{org} content of the mud fraction is therefore considerably higher (27,0%) than the maximum value found for the bulk sediment (13,7% - sample 3426, 24,6% organic matter divided by 1,8). This difference indicates that considerable dilution of organic matter by sand-size diatom frustules occurs, and was one of the deciding factors in restricting geochemical studies to the clay-size fraction of the sediments (see Chapter 7).

Bivariate plots of the weight percentage C_{org} in the silt and clay fractions are shown in Figs. 5.10(c) and (d) respectively. Evident from these plots is that the silt fractions of diatomaceous samples all contain

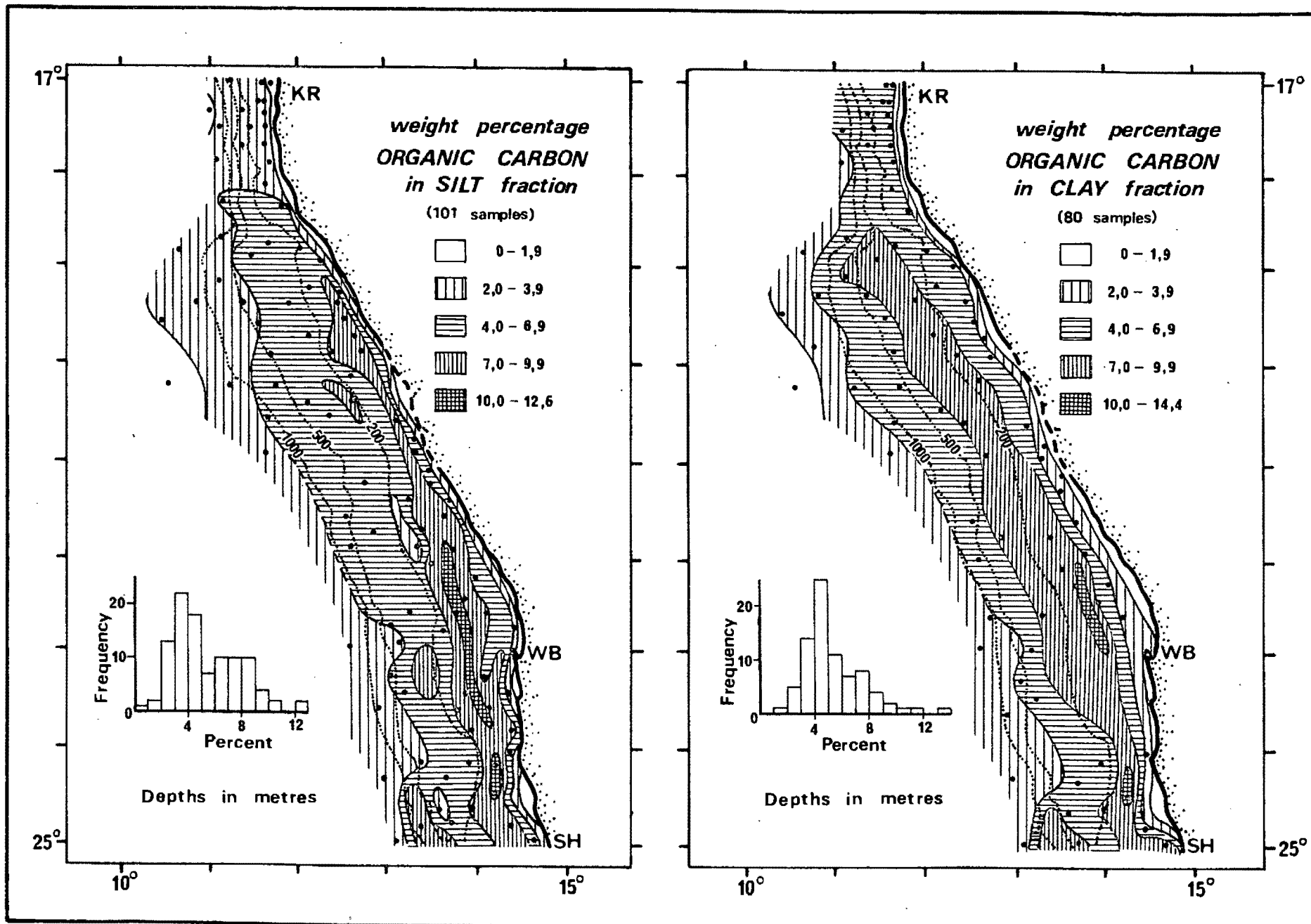


Figure 5.20

>5% C_{org}, whereas the clay fractions, with the exception of a few samples from the very carbon-rich areas mentioned above, all contain <5% C_{org}. This indicates the predominantly silty state of organic matter in the diatomaceous mud belt, a feature which is probably inherited from the average cell size of diatoms reaching the sea floor there. For non-diatomaceous samples (<5% opal), the concentration of C_{org} is inversely related to the abundance of silt and clay in the samples, and this reflects the lower organic matter values on the outer margin, with corresponding increases in the abundances of terrigenous silt and clay.

(d) Composition and economic implications

Organic matter is altered, primarily through the activity of bacteria, as it settles through the water column and eventually comes to rest on the sea floor. Once it has settled, considerable changes take place at the sediment-water interface through bacterial decomposition, and after burial, diagenesis modifies it even further. These changes in the composition of organic matter in marine sediments from the west coast of Southern Africa, and particularly that from the diatomaceous muds off Walvis Bay, have recently been the focus of international attention, and the preliminary results of a number of investigations have begun to appear in the literature. Romankevich and Baturin (1974) have extracted and compared the proportions of a number of organic components from the terrigenous sediments off Angola with those from the diatomaceous and calcareous sediments off South West Africa. Boon, de Leeuw and Schenk (1975) have studied the fatty acids of lipid material (bitumens) from the diatomaceous muds, and found that sulphate-reducing bacteria at the sediment-water interface were responsible for rapid conversion of algal acids to bacterial acids. Morris and Calvert (in press) have found that the diagenetic changes affecting organic matter with depth involve a decrease in the amount of both amino acids (protein) and unbound/weakly bound lipids (free bitumens), and an increase in the amount of fulvic acid (humics). Finally, scientists from the Woods Hole Oceanographic Institution are presently engaged with several geochemical investigations on the diatomaceous organic matter, including studies on NH₃ and bacteria, and a flood of new information on the composition and diagenesis of organic matter from the South West African continental margin is expected to reach publication soon.

To draw attention to the different compositions of organic matter accumulating on the Kunene Shelf (terrigenous sediment), Walvis Outer Margin (calcareous sediment) and the Walvis Inner Shelf (diatomaceous sediment), the following table is summarised from the work of Romankevich and Baturin (1974):

Table 5.6 Composition of organic matter from different regions of the continental margin (after Romankevich and Baturin, 1974)

	Diatomaceous sediments	Calcareous sediments	Terrigenous sediments
Carbohydrates	7,9	7,6	11,9
Humic acids (humic and fulvic)	40,8	37,2	52,4
Free bitumens (extractable lipids)	14,8	8,0	2,9
Bound bitumens	3,0	2,3	2,7
Readily hydrolyzable substances	17,3	6,9	6,3
Insoluble organic substances (Kerogen)	24,2	45,6	35,8
C/ N ratio	9,4	9,6	10,9

In concluding their paper, Romankevich and Baturin (op.cit.) imply that because of the low state of diagenetic transformation of organic matter in the diatomaceous muds, as indicated by the abundance of humic acids relative to insoluble organic substances, the deposit would become a rich source of oil and gas if it were deeply buried to reach maturity. Both Morris and Calvert (in press) and Boon et al. (1975) have found that once organic matter is buried by a few centimetres of sediment, the number of bacteria decrease, and it undergoes very slow transformation. Calvert and Morris (in press) have found that the concentration of nickel in insoluble organic residues (kerogen) is enriched and, according to Emery (1960), this element commonly forms the nucleus of porphyrin pigments in petroleum. Further indirect evidence that the diatomaceous mud belt represents a potential petroleum source similar to the shelf sediments off Southern California (Emery, 1960), is suggested by the fairly high organic matter content of concretionary phosphorite (Table 5.10) which is presently forming in the mud deposit (Powell et al., 1975). The relict, unconsolidated pelletal phosphorites on the continental shelf contain even higher concentrations of organic matter (Table 5.10), and considerable sulphur (see Chapter 8), and Powell et al. (1975), in presenting a detailed account of the carbon-phosphorite association, conclude that: "Several of the world's major oil fields are believed to have phosphatic source rocks".

Accepting similarity with the Southern California situation, a very rough estimate of the potential petroleum resource indicated by the existing diatomaceous muds is made using production and deposition figures listed by Emery (1960, p. 294). Of 120 000 tons organic matter deposited off California every year, only 100 tons is likely to be exploitable as petroleum, which gives a return figure of 0,08%. The total organic matter reserve in the diatomaceous mud belt was determined earlier to be $1,22 \times 10^{10} \text{ m}^3$ which gives a petroleum potential of $6,1 \times 10^7$ barrels ($1 \text{ m}^3 = 264,172 \text{ U.S. gallons}$, $42 \text{ U.S. gallons} = 1 \text{ barrel oil}$). Assuming a constant supply over the past 5 000 years, means that the annual rate of the petroleum precursor accumulation is approximately

$1,2 \times 10^4$ barrels. These quantities are interesting but too small to be of economic value.

An aspect of largely academic interest is the significant positive correlation found between the concentration of organic matter and certain trace elements in the diatomaceous mud (Calvert and Price 1971b; Calvert and Morris, in press; Chapter 7 of this work). This association is partly explained by the estuarine model of Brongersma-Saunders (1965) in which she suggests that metals are concentrated, for example in the German Kupferschiefer Formation, through entrapment by plankton. Calvert and Morris (in press) have examined the problem further, and find that a deficiency exists between the metal content of organic matter and that of the total sediment. They have shown furthermore, that diagenetic reactions result in the transfer of metals from the pore fluids to the organic matter, thus explaining the initial deficiency in the latter.

The concentration of 14 major and trace elements in the clay fraction of the diatomaceous mud and other shelf sediments are examined in detail in Chapter 7.

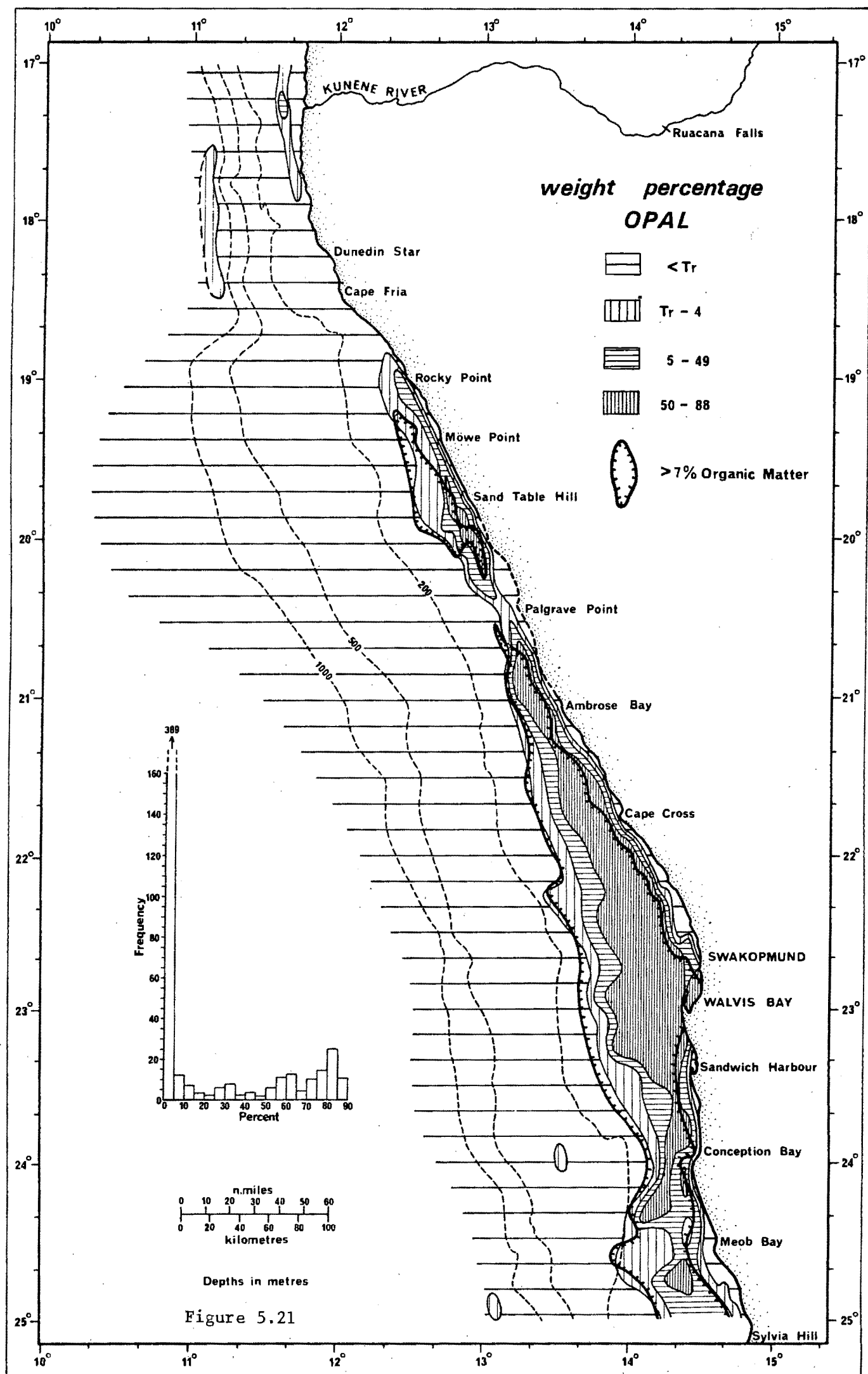
5.3.4 Opal

The method used for determining opal in the unconsolidated sediment is described in Appendix A.10, and the results are listed in Appendix B.7.

(a) Regional distribution and origin

(i) Diatoms

Between the nearshore zone and the mid shelf, a linear and remarkably uniform belt of Holocene diatomaceous mud extends into a broad embayment of the coastline between Rocky Point and Sylvia Hill (Fig.5.21). A straight line between these two locations defines fairly closely the western boundary of the mud belt, except at the southern end of the deposit where it breaks up into a number of discrete patches. At the northern end of the mud belt, the concentration of opal decreases from ~50% at Sand Table Hill to zero just north of Rocky Point, and approximately 45 n.miles south of Sand Table Hill, a 'break' occurs in the continuity of the mud belt, with opal values of <5%. This break has already been described in Chapter 3, and was seen to be due to wave-induced bottom currents preventing the accumulation of diatomaceous debris at the crest of the Palgrave Shoal (50 m depth). Immediately north of and behind the Palgrave Shoal (Fig.3.2), diatomaceous mud is again able to accumulate in deeper water, and this small body has, for descriptive purposes, been called the Sand Table Hill deposit. The main body of the diatomaceous mud belt, extending from Palgrave Point to Sylvia Hill, is referred to as the Walvis Bay deposit, and reaches its greatest width of almost 50 n.miles in the



vicinity of Walvis Bay. The highest opal concentrations in the mud belt are recorded from this area as well (>80%). Farther to the south between Conception Bay and Sylvia Hill, occasional patches of 50 - 60% opal lie within a broad seaward bulge of diatomaceous sediment that extends out to 200 m depth, and averages less than 5%.

As described in Chapter 2, this massive deposit of diatomaceous mud is stable on the Walvis Inner Shelf because of its great density, and also because the Ekman friction layer tends to sweep fine sediment landward from the inner shelf break. Its development there is a direct result of strong upwelling along the coast, particularly between Sylvia Hill and Lüderitz, and to northward transport of this nutrient-rich water by the Benguela Current into the coastal embayment at Walvis Bay. Massive phytoplankton blooms occur most prolifically in autumn when the prevailing southeasterly wind loses intensity and active upwelling of South Atlantic Central Water is replaced by stable thermoclines.

Apart from the large Walvis Bay deposit and the smaller Sand Table Hill deposit, a few minor occurrences of diatomaceous mud exist elsewhere on the continental margin. The richest of these lies northwards of the Kunene River mouth on the inner shelf where values of trace to 4% are average, and 8% is a maximum. The occurrence of these diatomaceous sediments beneath the essentially sterile waters of the Angola Current may perhaps reflect the introduction of nutrients from the perennial Kunene River. Slightly south of there on the Kunene Upper Slope, trace quantities of opal at 1 600 m depth indicate that either the diatoms are transported southwards from the Kunene River area by the Angola Current, or else they are deposited due to upwelling of nutrients along the shelf break (Chapter 2). The opal content is, however, definitely augmented by relatively high concentrations of Radiolaria in this region (see below). Finally, a few tiny patches of sediment containing trace to 4% opal occur on the Walvis Outer Margin, and this is due, as was seen earlier in the discussion of silt and clay size organic matter, to slack bottom current velocities in these areas thereby allowing diatomaceous debris to settle from the westward moving waters of the Benguela Current.

The average concentration of opal in the continental margin sediments as well as within different geographic and lithofacies regions are given in Table 5.7.

Table 5.7 Average concentration of opal in the unconsolidated sediment (weight percent)

	Entire margin	Area		Biogenic sediments		Terrigenous and authigenic sediments
		Kunene margin	Walvis margin	Diatomaceous	Calcareous	
		18°40'S		>5% opal	>50% CaCO ₃	Balance
No. of samples	521	64	457	142	193	186
Mean (%)	15,5	,5	17,6	54,3	,1	1,9
Std. Dev. (%)	28,2	1,6	29,5	26,6	,3	10,1
Range (%)	0-88,0	0-8,0	0-88,0	5,0-88,0	0-4,0	0-4,9

(ii) Radiolaria

Radiolaria are encountered together with planktonic foraminifera on the upper slope (Appendices A.8 and B.9). and their distribution is shown in Fig.5.16(c). Despite their relatively small size, 75µm - 400µm (Siesser, 1974), their opaline Si skeletons attain significant proportions on the Kunene Upper Slope and on the slope immediately above the Walvis Ridge Terrace. The four most commonly occurring radiolaria are a mixture of cold and warm water species viz., Spongotrochus glacialis (cold), Hexacontinium hostile (cold), Actinosphaera sp. (warm) and Actinomma sp. (Warm). Together they constitute about 4% by volume of the calcareous sediment on the Walvis Upper Slope, but on the Kunene Upper Slope, Actinosphaera sp. increase markedly and reach a maximum concentration of 21%.

A 'tongue' of Radiolaria-rich silty sediment on the slope immediately below the Walvis Ridge Abutment was described earlier in Sections dealing with the sediment texture and composition. It was shown there that the 'tongue' probably originated from quiescent water existing in the lee of the Abutment, thus contrasting with the foraminiferal sandy muds accumulating on the Abutment and on the Walvis Ridge Terrace.

(b) Diatom cell wall structure and stability

Diatom frustules are made up of a random network of tetrahedrally bound silicon atoms with approximately 10% nonstructural water (Calvert, 1966, 1974), and the wall microstructure consists of a sponge-like mass which gives the frustules an extremely high porosity (Lewin, 1961). This is reflected by the difference in specific gravity between biogenous opal (Hull et al., in Calvert, 1974) and dry diatomaceous sediment containing 84% opal (Table 5.8) viz., 2,00 - 2,07 vs. 0,18 respectively. The silicon utilized by diatoms, apart from being the basic structural unit for cell wall construction, also plays a fundamental role in the diatom cell metabolism (Calvert, op.cit.).

After death a protective organic coating on the silica cell walls is removed and diatom frustules, particularly the more fragile ones, undergo relatively rapid solution and consequent recycling (Lewin, 1961). Of the total silica ex-

tracted from the euphotic zone, perhaps only 1 - 10% reaches the sea floor (Calvert, 1968; Lisitzin, 1972), and with further dissolution after burial, 0,05 - 0,15% of the original amount is likely to be retained in the sediment (Hurd, 1973). This is well illustrated by the large discrepancy in the numbers of diatom species recovered from the water column (Hart and Currie, 1960), and those recovered from the unconsolidated sediment (Appendix B.11). Calvert (1966, 1974) has estimated the slow rate of settling of 10 - 20 μ m diameter frustules as being approximately 1 000 m/year, but considers that their transit times are probably greatly reduced by aggregation in faecal pellets (Calvert, 1974). Using these figures, an approximate settling time of 1 month is obtained for unpelletized diatom frustules of this size to settle to the average depth of the diatomaceous mud belt (83 metres).

(c) The diatomaceous mud belt

(i) Dimensions and physical properties

A number of physical parameters of the diatomaceous mud belt have been calculated as set out in Appendix A.11, and a summary of these data is presented in Table 5.8.

(ii) Age

Veeh et al. (1974) have determined the age of sediment from the bottom of 4 cores from the western half of the diatomaceous mud belt (depth range 119 - 132 m). ^{14}C measurements C_{org} , and CaCO_3 when sufficient material allowed, gave an average age of $\pm 2\,880$ years at an average depth of 88 cms (Veeh et al., 1974, Table 11). They found furthermore, that the ages indicated by CaCO_3 were invariably greater than those of C_{org} for the same core samples and for various reasons, considered the latter to be the more reliable. Morris and Calvert (in press) have recently obtained ^{14}C age measurements on C_{org} from another core that was collected at the same location as one of the earlier ones, and obtained a significantly younger age for sediment from a slightly shallower depth viz., ± 800 years at 57 cms depth (Morris op.cit., Fig.3). They consider this difference to be due to slumping or reworking of the diatomaceous sediment.

In view of the extremely gentle gradient of the sea floor (Fig.3.5), gravitational slumping is not likely to occur within the diatomaceous mud despite its highly hydrogenous state, but reworking of the sediment as a result of wave-induced bottom currents and/or rising H_2S gas bubbles is probably a very common phenomenon. Evidence pointing to sediment reworking is the contorted appearance of some colour-distinctive layers in cores, and the occasional presence of relict mollusc shells at the surface of the mud deposit (discussed earlier).

Table 5.8 Summary of physical parameters of the diatomaceous mud belt*

	Dimensions								Depth							Average opal concentra- tion (%)	Sediment density (g/cc)			
	Length(km)	Breadth(km)				Thickness (m)		Area ₂ (x10 ³ km ²)		Depth to sediment/water interface along the edges of the mud belt (>Tr Opal)(m)							>5% Opal	84,0% Opal Wet/Dry	54,4% Opal Wet/Dry	
		>Tr Opal		>5% Opal		>5% Opal	>50% Opal	>Tr Opal	>5% Opal	W edge			E edge							Overall mean
		Max.	Mean	Max.	Mean					Max.	Min.	Mean	Max.	Min.	Mean					
and Table Hill deposit	185	39	24	24	11	4,6	10,3	4,8	2,1	122	81	100	58	36	46					
alvis Bay deposit	555	83	56	76	41	5,2	6,6	29,2	22,3	222	93	141	48	1	29					
ntire mud belt	740	46		33		5,1	7,0	34,0	24,4	130			31			83	54,3	1,050,18 1,19/0,80		

See Appendix A.11 for derivation of this data

In the present study, the age of the diatomaceous mud belt is arbitrarily taken to be 5 000 years old, this being based on the many divergent opinions about the course of sea-level rise during the Flandrian transgression (Godwin, Suggate and Willis, 1958; Fairbridge, 1961; Shepard, 1960; Milliman and Emery, 1968; Guilcher, 1969). It is generally agreed that sea-level initially rose fairly rapidly, and that between 4 000 and 6 000 years B.P., it reached its approximate present-day position. With rising sea-level, the seaward half of the diatomaceous mud belt would have been deposited prior to the landward half, but this age difference is likely to be small due to the rapidity of the early Flandrian transgression. As discussed in Chapter 3, the probable depth of sea-level lowering during the Würm II pleniglacial was of the order of 110 m for this part of the continental shelf, and the average depth of the seaward edge of the mud belt has been found to be 130 m (Table 5.8). This would have placed the seaward edge approximately 20 m above wave base ($L_0/2$) using wave parameters of 'local' storm conditions existent today (Appendix A.2). In its present unconsolidated state, the diatomaceous mud belt would have been unable to survive the rigours of the Würm II surf zone, and the assumed age of 5 000 years is therefore likely to be fairly close to the truth for the central portions of the deposit.

(iii) Biogenic silica budget.

(A) Supply

The supply of biogenic silica to the Walvis Inner Shelf is almost entirely due to oceanic factors since the rivers draining the hinterland are all relatively small and intermittent in nature. The lack of long-term current measurements in the study area has necessitated that a number of basic assumptions be made regarding the inflow of nutrient-rich Benguela waters in order to calculate the silica budget for the region. First, the distinctly seasonal rate of flow of the Benguela Current (Chapter 2) is ignored, and an average annual velocity of 1 knot is considered to be a fair assumption (Bang, 1976; pers.comm.). Secondly, since standing crops of phytoplankton have been found to correspond closely with the concentration of opal in sediments from the Gulf of California (Calvert, 1966) and off Chile/Peru (Zhuze, 1971), a cross-section of the inner shelf through which northward-flowing Benguela water would move has been chosen to correspond with the average dimensions of the diatomaceous mud belt (Table 5.8). Furthermore, this hypothetical triangular cross-section is positioned at Sylvia Hill to separate the region of maximum upwelling in the south from the region of maximum productivity in the north. The height of the triangular section measures 130 metres (mean depth of the seaward edge of the diatomaceous mud belt - see Table 5.8), and the width is 46

kilometers (mean breadth of the mud belt), thus giving an area

$$= 130 \times 46 \times 1000/2 \text{ m}^2$$

$$= 2,99 \times 10^6 \text{ m}^2$$

The amount of water passing through the section every hour due to a 1 knot current is then

$$= 2,99 \times 10^6 \times 1852 \text{ m}^3 \quad (1 \text{ knot} = 1,852 \text{ km/hour})$$

$$= 5,54 \times 10^9 \text{ m}^3$$

And in one year, the volume of water

$$= 5,54 \times 10^9 \times 8760 \text{ m}^3$$

$$= 4,85 \times 10^{13} \text{ m}^3$$

$$= 4,85 \times 10^{13} \times 10^3 \text{ litres}$$

$$= 4,85 \times 10^{16} \text{ litres}$$

To establish the silica content of surface and bottom waters in the study area, the results of a nutrient survey conducted by Calvert and Price (1971b) along five sample lines were averaged to give 1 and 32 $\mu\text{g atoms Si/litre}$ respectively. These values were taken to represent the average concentration of silica in surface waters leaving the euphotic zone, and the average concentration of silica in South Atlantic Central Waters being upwelled into the euphotic zone respectively. That is, the top half of the water mass passing through the triangular section is regarded as being nutrient-poor water moving northwestwards away from the coast, and the bottom half of the water mass is envisaged as being nutrient-rich water moving northeastwards towards the coast.

The amount of silica lost from the hydrological environment due to the northwesterly moving water mass is therefore

$$= 4,85 \times 10^{16} \times 0,5 \times 1 \times 28 \times 10^{-6} \text{ g Si/year (At.wt. of Si} = 28)$$

$$= 6,79 \times 10^{11} \text{ g Si/year}$$

And the amount of silica gained by the hydrological environment due to the northeasterly moving water mass then

$$= 4,85 \times 10^{16} \times 0,5 \times 32 \times 28 \times 10^{-6} \text{ g Si/year}$$

$$= 2,17 \times 10^{13} \text{ g Si/year}$$

The net gain of silica in the hydrological environment due to supply from the ocean is therefore

$$= \underline{2,1 \times 10^{13} \text{ g Si/year}}$$

(B) Removal

Removal of silica from the hydrological environment through biogenic sedimentation is also calculated using the average dimensions of the diatomaceous mud belt (Table 5.8). On this basis, the total volume of the deposit containing more than 5% opal (assuming constant opal concentrations with depth) (Table 5.8).

$$= 1,25 \times 10^{11} \text{ m}^3$$

Since the age of the diatomaceous mud deposit has been taken to be 5 000 years old (see previous section), the yearly sedimentation rate on the inner shelf

$$= 2,49 \times 10^7 \text{ m}^3$$

The density of the mud containing about 54% opal (the average for all diatomaceous samples with more than 5% opal, see Table 5.8) is 0,8 g/cc, and the yearly sedimentation rate in mass is therefore

$$\begin{aligned} &= 2,49 \times 10^7 \times 0,8 \times 10^6 \text{ g/year} \\ &= 1,99 \times 10^{13} \text{ g/year} \end{aligned}$$

Of this, 54,3% is due to opal (Table 5.8), which

$$\begin{aligned} &= 1,99 \times 10^{13} \times 0,543 \text{ g SiO}_2/\text{year} \\ &= 1,08 \times 10^{13} \text{ g SiO}_2/\text{year} \end{aligned}$$

Disregarding approximately 10% water in opal (Calvert, 1966), the total amount of silica lost from the hydrological environment due to biogenic sedimentation is therefore

$$\begin{aligned} &= 1,08 \times 10^{13} \times 28/60 \text{ g Si/year} && (\text{At.wts. of Si and SiO}_2) \\ &= \underline{5,0 \times 10^{12} \text{ g Si/year}} \end{aligned}$$

From these rough calculations, it is apparent that the amount of silica being supplied to the hydrological environment from the ocean adequately accounts for the amount of opal being sedimented onto the Walvis Inner Shelf. The discrepancy between the rates of supply and removal of silica from the hydrological environment (by a factor of 4,2), reflects the many assumptions involved in making the calculations. No account was taken of the effect of the Angola Current northwards from Walvis Bay, but the influence from this source is likely to be small due to the low nutrient content of these waters.

(C) Comparison with the Gulf of California

Calculations on the silica budget for the semi-enclosed Gulf of California (Calvert, 1966), compare interestingly with those of the open shelf off Walvis Bay. The rate of silica supply from rivers (mainly the Colorado) and the ocean is 4,8 times greater in the Gulf than is the oceanic supply on the Walvis Inner Shelf, and furthermore, the rate of removal due to biogenic sedimentation is 3,0 times greater in the Gulf than it is off Walvis Bay. This is given expression by the larger area of diatomaceous sedimentation in the Gulf than on the Walvis Inner Shelf viz., in the Gulf, sediments with >10% opal extend over an area of $3 \times 10^4 \text{ km}^2$, whereas off Walvis Bay, sediments with >5% opal cover an area of only $2,4 \times 10^4 \text{ km}^2$. The degree of contamination of diatomaceous sediment in the Gulf, particularly from terrigenous material, is however much greater than that occurring at Walvis Bay viz., sediments containing >10% opal in the Gulf have an average of 25% opal, whereas sediments con-

taining >5% opal off Walvis Bay have an average of about 54% opal. Finally, the maximal rate of sedimentation off Walvis Bay, assuming constant supply where the diatomaceous mud measures 15 m thick, exceeds that for the Guaymas Basin in the Gulf of California viz., $15\,000/5\,000 = 3\text{ mm/year}$ vs. 2 mm/year respectively.

In summary then, the diatomaceous mud deposit off Walvis Bay is smaller but 'purer' than the Gulf of California deposit, and the rate of accumulation on the open shelf is relatively faster than that in the deep basin environment of the Gulf.

(iv) Composition

Despite the relative 'purity' of diatomaceous mud on the Walvis Inner Shelf, the flanks of the deposit receive considerable input from other sources. Terrigenous material is the sole diluent in the landward flank, whereas calcium carbonate and organic matter are the most common additions in the seaward flank. Fig.5.22 illustrates the regional variations in concentration of these four principal components between the three opal isopleths shown in Fig.5.21, viz., trace, 5% and 50%.

It is apparent from this diagram that the chief diluent in the diatomaceous mud is terrigenous material, which, for the trace and 5% graphs show strong negative correlation with the concentration of opal. The ratio between the average opal and average terrigenous concentrations between the three isopleths is $\text{Tr} : 5\% : 50\% = 0,8 : 1,3 : 5,5$, which accentuates the increasing importance of terrigenous contamination on the flanks of the mud belt (particularly the landward flank). In fact, for the area defined between the trace opal isopleths, opal dominates over terrigenous material only from Palgrave Point to Conception Bay, which is roughly half the length of the diatomaceous mud belt (Table 5.8). Other striking inter-relationships between these two components are indicated by a peak and a depression in the opal concentrations off Walvis Bay and Swakopmund respectively. The former is due to intense diatom productivity around Pelican Point, and the latter reflects periodic flash-flooding of the Swakop River (Chapter 1).

Organic matter and CaCO_3 are subordinate contaminants when compared with the average concentration of terrigenous material (Fig.5.22). In the area defined between the trace opal isopleths, it is apparent that CaCO_3 and organic matter occur in roughly the same proportions, whereas in the purer more central regions of the mud belt, as defined between the 5% and 50% isopleths, organic matter is invariably more concentrated than CaCO_3 . This reflects the intrinsic relationship between organic matter and the diatomaceous mud, whereas CaCO_3 represents an extraneous diluent.

VARIATIONS IN COMPOSITION AT THE SURFACE OF THE DIATOMACEOUS AND KUNENE MUD BELTS ALONG 46 SAMPLE LINES

- Terrigenous
 - × Opal
 - + Organic matter
 - CaCO_3
- } Biogenic

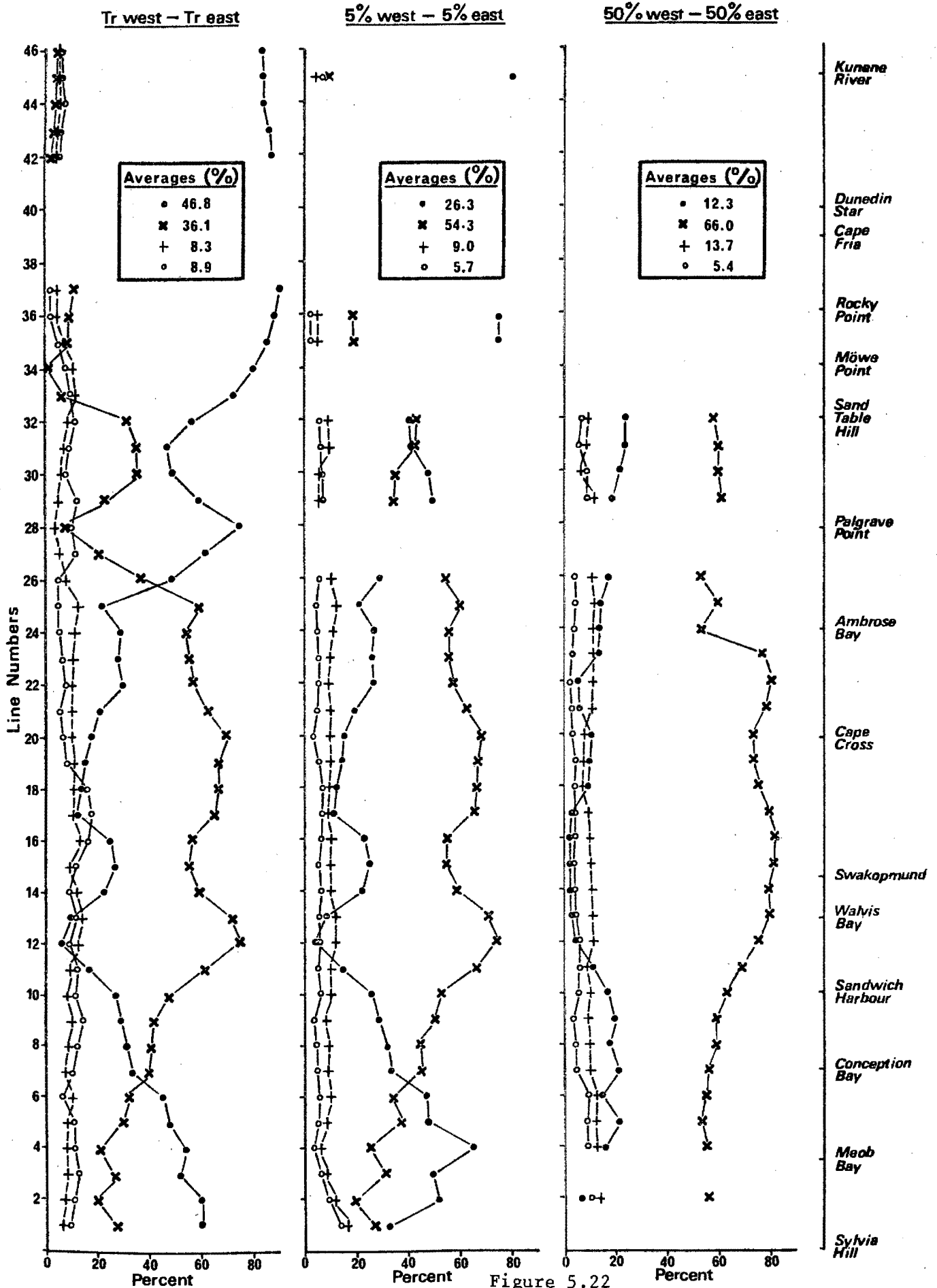


Figure 5.22

Although the graphs in Fig.5.22 are useful for depicting the average composition of the mud belt between various isopleths, differences in the concentration of the four components in the two flanks of the deposit are obscured by the smoothing process. The variations are therefore discussed more explicitly in the paragraphs below.

Terrigenous material is introduced into the diatomaceous muds in three main ways: wave action in the surf zone, discharge from rivers during occasional flash floods, and aeolian transport of very fine sediment by bergwinds. Of these three processes the first is probably the most important by virtue of its continuous operation, and the last is probably least significant although it alone accounts for the deposition of silt-size sediment on the outer shelf (see Section 5.5). The terrigenous material consists predominantly of quartz, minor amounts of feldspar, rock fragments, mica (mostly biotite), and trace amounts of almandine garnet, magnetite and ferro-magnesian minerals. The boundary between quartzose and diatomaceous sediment is generally of the order of 2 n.miles in width and quite often, this transition zone is marked by a strip of biotite-rich sediment sometimes containing up to 40% mica e.g., between Cape Cross and Swakopmund (see Section 5.5).

The east-central portion of the mud-belt is generally 'purer' than the west-central portion, and maximum opal values of over 80% are attained in the vicinity of Pelican Point. As will be seen later however, the highest diatom counts come from the western half of the deposit (Richert, in press). This discrepancy between the opal content and diatom counts is probably due to a similar situation to that reported from Chile/Peru. Here, Zhuze (1971) has found that regions containing robust diatom species corresponded fairly well and regions containing thin-walled species diverge substantially. The principal diluents of the east-central portion of the diatomaceous mud belt are therefore very fine quartz and mica, and it is noteworthy that the highest concentration of concretionary phosphorite nodules, fish scales and fish bones are also generally found in this region as well (see Chapter 8).

Moving now to the western half of the mud belt, the concentrations of organic matter and CaCO_3 are, as mentioned earlier, higher here than in the eastern half. This is reflected by several patches of diatomaceous sediment along the western flank of the mud belt with extremely high levels of organic matter (maximum concentration, 24.6%). The abundance of CaCO_3 tends to increase progressively from about 5% near the middle of the mud belt, to about 50% along its western edge. This is due to the influx of planktonic foraminifera in the central region together with mollusc shells and benthic foraminifera along the western edge. As a result of these differences, the concentration of certain trace elements and clay minerals in the western half greatly

exceeds that in the eastern half (see Chapter 7).

(d) Diatom assemblage

Two different batches of samples have been independently examined by workers familiar with diatom taxonomy. One of the batches, consisting of 11 samples, came from the continental margin south of Walvis Bay and was examined by Mr. I. Kruger of the Division of Sea Fisheries; the other batch, consisting of 85 samples, came from the diatomaceous mud belt and was studied by Dr. P. Richert of Kiel University.

From the first batch of samples (28 - 1310 m depth), 11 genera and 19 species were identified (Appendix B.11). Five of these species were dominant in the diatomaceous muds and, apart from one of them, Chaetoceros didymus, were also the only species found to occur on the outer margin viz., Actinocyclus ehrenbergii, Chaetoceros didymus, Coscinodiscus centralis, C. gigas var praetexta and Fragilaria karstenii.

They are subtropical neritic species with thick, robust cell walls (Kruger, pers.comm.), and are the only sedimentary representatives of the 95 species listed by Hart and Currie (1960, p.219) from the euphotic zone. Hart and Currie (op.cit.) note furthermore, that Chaetoceros sp. and Fragilaria karstenii are exceptionally common in the coastal waters around Sylvia Hill, and whereas four Chaetoceracea species were recorded from the sediments north of there, they were totally absent from the sediments farther to the south (Rogers, 1973).

The second batch of samples established that Chaetoceros spores account for 25% of the diatom assemblage in 75% of the samples. Other dominant species identified in the mud were: Actinocyclus ehrenbergii, Coscinodiscus perforatus, Thalassionema nitzschioides, Thalassiosira eccentrica, Raphoneis surirellioides. Since both batches of samples were collected in autumn, the differences between dominant species recorded in the two studies may be a reflection of the water masses existant north and south of Walvis Bay. From Walvis Bay to Sylvia Hill, the shelf water is essentially part of the Benguela Current System, whereas north of Walvis Bay, it is a complex mixture of Angola and Benguela waters (Chapter 2).

Diatom counts made on the second batch of samples indicate that the greatest number of specimens occur in the west-central part of the diatomaceous mud belt between 80 and 130 m depth (150×10^9 counts /g of sediment). The eastern half of the mud belt between 20 and 80 m depth, as well as the western edge between 130 and 140 m depth, contain fewer frustules viz., 50×10^9 counts /g of sediment. All together, the values far exceed the numbers recorded from the Gulf of California, where Zhuze (1971) obtained 154×10^6 counts /g and 203×10^6 counts /g for two different samples. The sedimentary diatom

assemblage there is similar to that off Walvis Bay, with Chaetoceros, Coscinodiscus and Thalassionema species, amongst others, being dominant (Calvert, 1966), and the main difference is therefore probably due to more terrigenous dilution in the Gulf than off Walvis Bay.

Although the diatom productivity of Walvis Bay waters does reflect periodicity in that the numbers are greatest in summer and autumn when the intensity of upwelling is least (du Plessis, 1967), regularly laminated diatomaceous sediments, as occur in certain regions of the Gulf of California (Calvert, op.cit.), have not been observed in the few cores collected from the Walvis Bay muds. Instead, highly contorted layers of variable shades of light and dark green, sometimes alternating with thick bands of uniformly-coloured, unstructured mud occur, and this has been attributed to rising H_2S gas-bubbles, and to wave-induced bottom currents (see Chapter 8).

5.4 AUTHIGENIC COMPONENTS

5.4.1 Introduction

This section describes the concentration and distribution of glauconite and three different phosphorite minerals in the unconsolidated shelf sediments. The areal extent of these authigenic deposits is insignificant compared to the distribution of biogenic and terrigenous sediments, but locally, they are sufficiently enriched to constitute potential economic resources.

Two of the phosphorite types are relict, and are generally found closely associated in two mineralized provinces on the mid shelf. These are pelletal phosphorite (pP) and glauconitized pelletal phosphorite (gpP), and the areas of mineralization are referred to as the Northern and Southern Mineral Provinces respectively. The former province transgresses the Kunene-Walvis boundary at $18^{\circ}40'S$, and also contains the richest concentrations of glauconite (G). The third phosphorite type is concretionary phosphorite (cP), which is exclusively found in the diatomaceous muds, and ranges in age from Mid Pleistocene to the present.

Because of the friable nature of many of the concretions, and also because they occur randomly distributed in the diatomaceous muds, their extraction and quantification was not possible. They are therefore shown together with pelletal phosphorite in the same diagram (Fig.5.23). The distinctive locales of the two minerals however, allows them to be easily distinguished in the diagram. Glauconite and glauconitized pelletal phosphorite are magnetically susceptible, and were thus separable from the non-magnetic sedimentary components. Determination of P_2O_5 and K_2O in the samples, and the methods used for extracting various authigenic phases from the sediment, are described in Appendices A.12 and A.13 respectively. The results are given in Appendix B.7.

In addition to discussing the regional distribution and concentration of the authigenic mineral deposits, a number of other aspects are covered in this Chapter. These include the P_2O_5 and K_2O contents of the sediment mud fractions (discussed in Appendix A.12); $\frac{1}{2}\phi$ sieve analysis of phosphorite and glauconite (discussed in Appendix A.14); X-ray diffraction analysis of the authigenic minerals (discussed in Appendix A.15); CO_2 , C_{org} and F determinations on the different phosphorites (discussed in Appendix A.16, and reported in Appendices B.12 and B.13); and finally, calculation of the mineral and P_2O_5/K_2O resources on the continental margin. In determining the mineral resources, only samples containing more than 5% by weight of the authigenic minerals have been taken into account, and since the average depth of penetration of the two sampling devices used to obtain the samples, a short gravity corer and a 0,1 m³ van Veen grab, is 10 cm, this depth was used in evaluating each of the mineral deposits.

The average concentration of the authigenic minerals on the Kunene and Walvis Shelves, as well as that associated with three different lithofacies, is shown in Table 5.9.

Table 5.9 Average concentration of the authigenic minerals in the unconsolidated sediment (weight percent)

	Entire margin	Area		Biogenic Sediments		Terrigenous and authigenic sediments
		Kunene margin	Walvis margin	Diatomaceous	Calcareous	
		← 18°40'S →		>5% opal	>50% $CaCO_3$	
No. of samples	521	64	457	142	193	186
<u>pP, cP</u>						
Mean(%)	3,9	3,5	3,9	4,0	1,9	5,7
Std. Dev. (%)	6,9	3,9	7,2	4,9	3,7	9,7
Range(%)	0-51,3	0-19,4	0-51,3	0,6-38,6	0-25,4	0-51,3
<u>gpP</u>						
Mean(%)	1,1*	2,2	1,0*	-	1,3	1,7
Std. Dev. (%)	3,5	6,4	2,8	-	3,0	4,9
Range(%)	0-34,6	0-34,6	0-20,8	-	0-20,8	0-34,6
<u>G</u>						
Mean(%)	1,7	11,3	,4	,2	,4	4,3
Std. Dev. (%)	7,6	18,8	1,5	,5	1,9	12,2
Range(%)	0-92,0	0-92,0	0-24,1	0-5,0	0-24,1	0-92,0

* Excluding diatomaceous muds (>5% opal).

5.4.2 Morphology of phosphorite and glauconite particles

In addition to the three different phosphorite minerals already mentioned, three different glauconite minerals occur in the unconsolidated sediments as well. However, the glauconites are all mineralogically similar and chemically

identical (see Chapter 8), and they are therefore discussed together under a single heading (cf. Birch, 1971). For brevity, the authigenic minerals are generally referred to by symbolic names pP, gpP, cP and G. Their chief physical properties are listed below:

Pelletal phosphorite (pP) - medium to fine sand-size (1,5 to 3,0 ϕ), spherical and very well rounded, black, resinous reddish lustre, indurated, non-magnetic.

Glaucinitized pelletal phosphorite (gpP) - medium to very fine sand-size (1,0 to 3,5 ϕ), unfragmented grains are spherical and well-rounded whereas fragments are angular, variable colour ranging from yellowish-greens to reddish-browns, earthy lustre, deeply open-sutured and consequently fragile to mechanical abbrasion, weakly to moderately magnetic.

Concretionary phosphorite (cP) - pebbles to fine sand-size (-6,0 to 3.0 ϕ), rounded to sub-rounded and spherical to irregular in form, colour range from pale yellow to dark brown, earthy lustre, generally friable but darker ones tend to be more lithified, non-magnetic.

Glaucinite (G) - very fine sand-size (3,5 to 4,0 ϕ), sub-angular, dark green to black, polished, unsutured, very strongly magnetic.

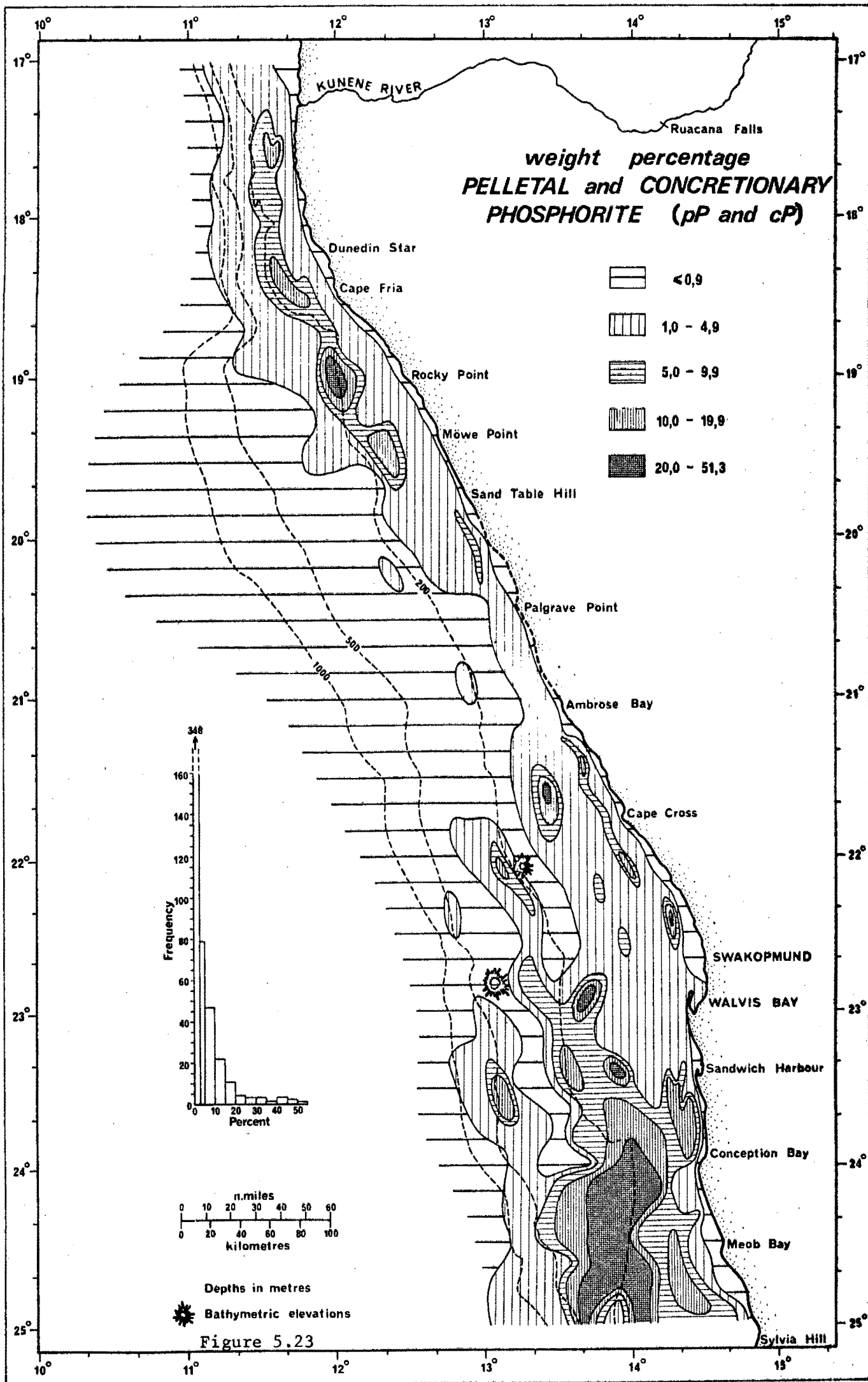
- fine to very fine sand-size (2,5 to 3,5 ϕ), sub-rounded and some as planktonic foraminiferal casts, dark green, polished, moderately sutured, strongly magnetic.

- medium to very fine sand-size (1,5 to 3,5 ϕ), sub-rounded but fragmented grains are angular, yellowish-green and mottled, dull, moderately sutured, moderately magnetic.

5.4.3 Regional distribution

(a) Pelletal phosphorite (pP)

The distribution of pP in the Northern Mineral Province reflects a much simpler pattern than its Southern counterpart because the only diluent of significance is terrigenous detritus. It consists of a 10 to 20 n.-mile-wide belt predominantly on the landward side of the 200 m isobath, and extends from the Kunene River to Sand Table Hill (Fig.5.23). Within this belt, as defined by sediment containing >5% pP, lie four discrete concentrations with values in excess of 10%. The richest of these, offshore from Rocky Point, contains a maximum concentration of 23,5% pP. The other three occurrences lie 20 n.miles south of the Kunene River mouth, and directly offshore from Cape Fria and Mowe Point. These four concentrations of pP, which are identical mineralogically and chemically, are separated one from the next by three valley-shaped features on the inner shelf (Chapter 3). In order to explain their present isolation, it is necessary that fluvial erosion during periods of lower sea-level and



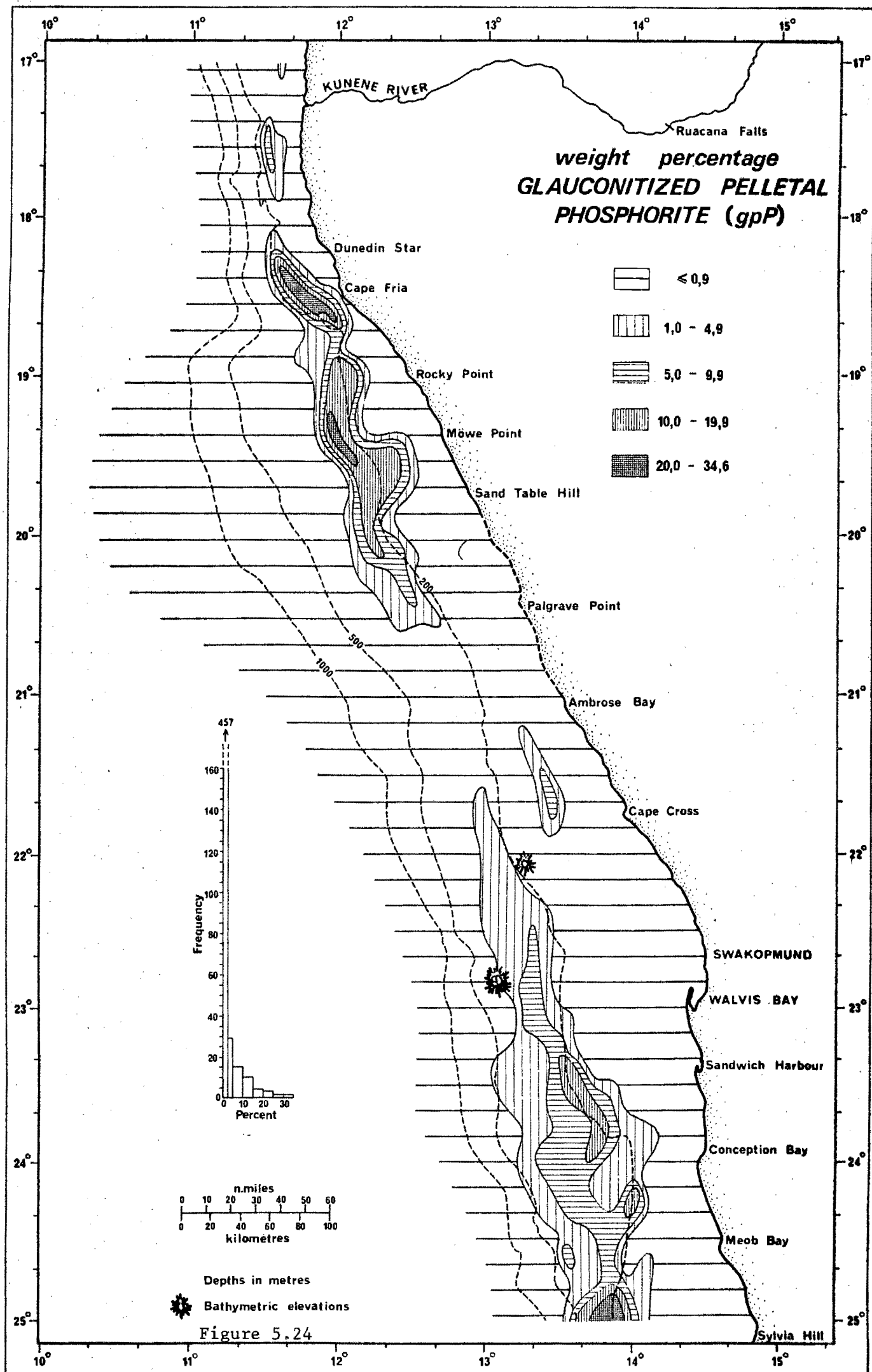
higher humidity must at least have played a part in the formation of the valleys.

The Southern Province of pelletal phosphorite, although much richer than the Northern Province, is thoroughly admixed with terrigenous and various biogenic components, and its distribution pattern is therefore much more complex. Northwards from Walvis Bay, several small patches of sediment occur with >5% pP, the richest of them lying on the inner shelf off Cape Cross with a maximum concentration of 26,0% pP. No clear relationship between the various patches is evident, some co-existing with terrigenous sediment along the western flank of the diatomaceous mud belt (see Section 5.5), and others occurring with calcareous sediment on the mid and outer shelves. The topographic prominences of the Cape Cross and Swakop Banks (Figs. 3.3 and 5.23) appear to have influenced the distribution of pP on this part of the continental shelf as the sediments, both north and south of the two features, contain <1% pP. Southwards from Walvis Bay, a mineralized belt containing >5% pP increases irregularly in width towards Sylvia Hill. Off Walvis Bay, the belt measures about 20 n.miles in width and lies predominantly on the landward side of the 200 m isobath, whereas off Sylvia Hill, it is over 60 n.miles in width and extends onto the upper slope to a depth of about 500 m. Within this belt are the highest concentrations of pP in the study area, these being located on the mid shelf south of Conception Bay. This elongate highly mineralized region containing >20% pP and a maximum of 51,3% pP lies roughly between the 100 and 300 m isobaths, and measures about 30 n.miles across. Off Sylvia Hill, it splits into two branches around a small highly concentrated deposit of gpP at 200 m depth (see below).

(b) Glauconitized pelletal phosphorite (gpP)

In broad outline the distribution of gpP (Fig. 5.24) closely follows that of pP but in contrast with the latter, gpP occurs more abundantly in the Northern Mineral Province than in the Southern. Of the four discrete concentrations of pP in the Northern Province however, only the northernmost two, off the Kunene River and Cape Fria, are associated with similar concentrations of gpP. The Cape Fria deposit also has the distinction of possessing the highest gpP concentrations in the study area viz., 34,6%. In place of separate gpP concentrations coinciding with the two pP deposits at Rocky Point and Møwe Point, a single irregular belt with >10% gpP and a maximum of 20,1% extends predominantly on the seaward side of the 200 m isobath as far south as Palgrave Point.

The Southern Mineral Province contains gpP in approximate correspondence with the main trend of the pP, and extends as a highly irregular belt of >5% gpP predominantly on the seaward side of the 200 m isobath. A few



patches of sediment with >10% gpP lie within this mineralized belt to the south of Sandwich Harbour. The richest of them, the one mentioned earlier off Sylvia Hill, has a concentration of 20,8% gpP and lies at a depth of 200 m. Whereas pP often occur along the seaward edge of the diatomaceous mud belt, gpP are generally lacking in this region. An exception is the small patch of sediment described earlier off Cape Cross, where a high concentration of pP occurs together with 8,4% gpP.

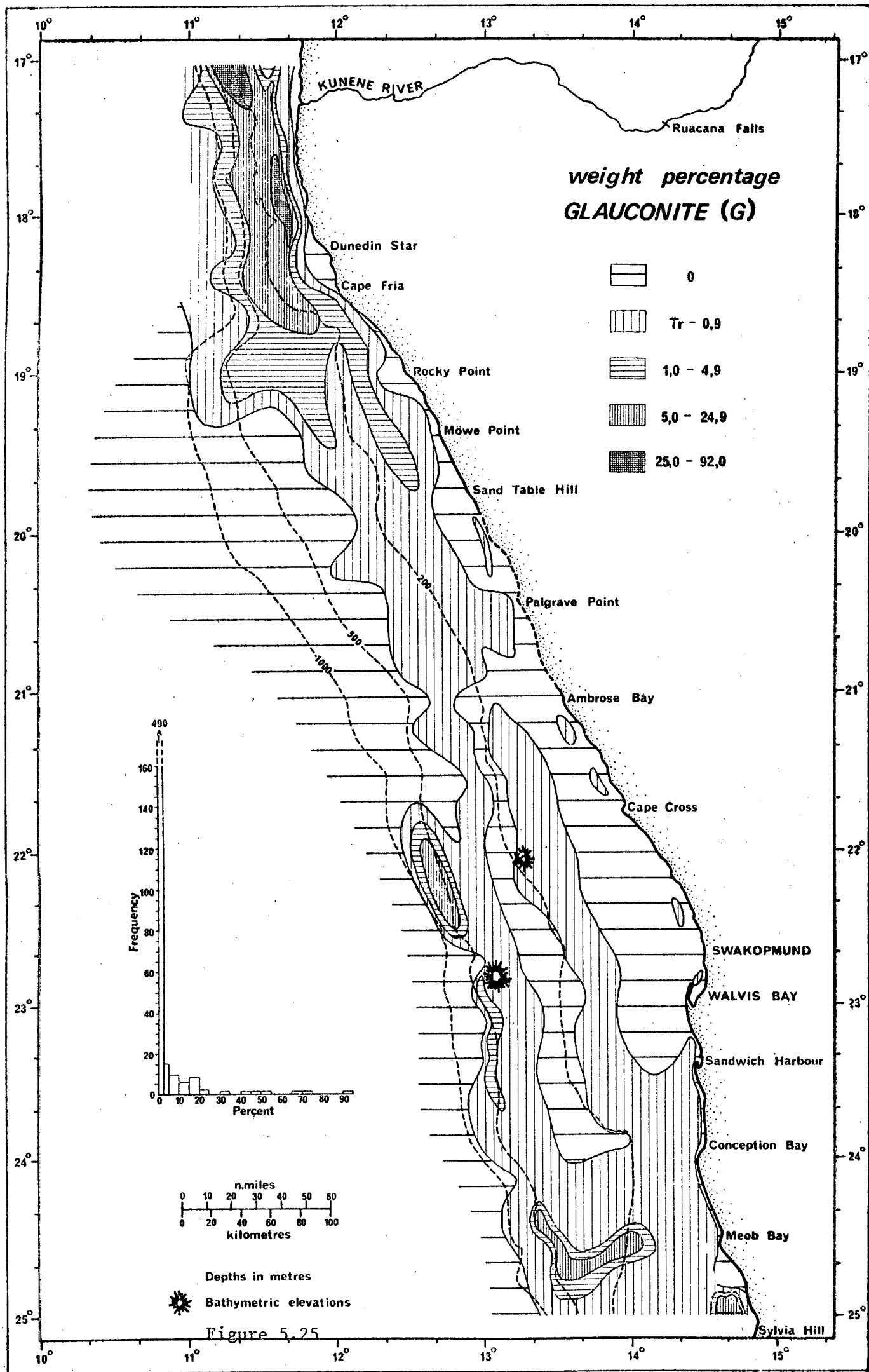
(c) Concretionary phosphorite (cP)

The distribution of cP, which is exclusively confined to the diatomaceous mud belt, is shown together with that of pP in Fig.5.23. The only region where P_2O_5 enrichment in the sediment may be due to contributions from both cP and pP is within a discontinuous strip of terrigenous sediment lying along the seaward edge of the diatomaceous mud belt (see Section 5.5).

The landward half of the diatomaceous mud belt contains a relatively higher proportion of cP than the seaward half, and maximum values are usually found between 6 and 10 n.miles from shore. Northwards from Walvis Bay, this area of concentration occurs as a narrow strip of >5% cP that extends irregularly as far north as Sand Table Hill. Within this strip, a few spot-concentrations of >10% cP occur, and 10 n.miles north of Swakopmund, the maximum value for the diatomaceous muds is found (38,6%). Southwards from Walvis Bay, cP are distributed in fairly broad patches with concentrations of >10%. In the area around Walvis Bay where the concentration of opal is greatest (Fig. 5.22), cP occur in very low abundance and average only 1 or 2%.

(d) Glauconite (G)

Glauconite occurs more abundantly in the Northern and Southern Mineral Provinces than elsewhere on the continental shelf, but is neither restricted there, nor associated with the deposits of pP and gpP there. The richest concentrations of G occur in the Northern Province where a maximum of 92,0% is found on the outer margin north of latitude $17^{\circ}S$ (Kunene River mouth)(Fig.5.25). Another highly concentrated region within this mineral province, with a maximum of 72,8% G, lies on the landward side of the 200 m isobath between the two northerly deposits of pP and gpP. Both of the glauconite concentrations lie within a broad belt of >5% G that extends roughly between the 100 and 500 m isobaths, and southwards as far as latitude $18^{\circ}40'S$. It is thus the only authigenic mineral that, at this concentration level, does not transgress the Kunene-Walvis boundary at $18^{\circ}40'S$. The glauconite type found in this province is the large yellowish-green variety, but on the landward side of the mineralized belt, it is often fractured along sutures into smaller, angular fragments.



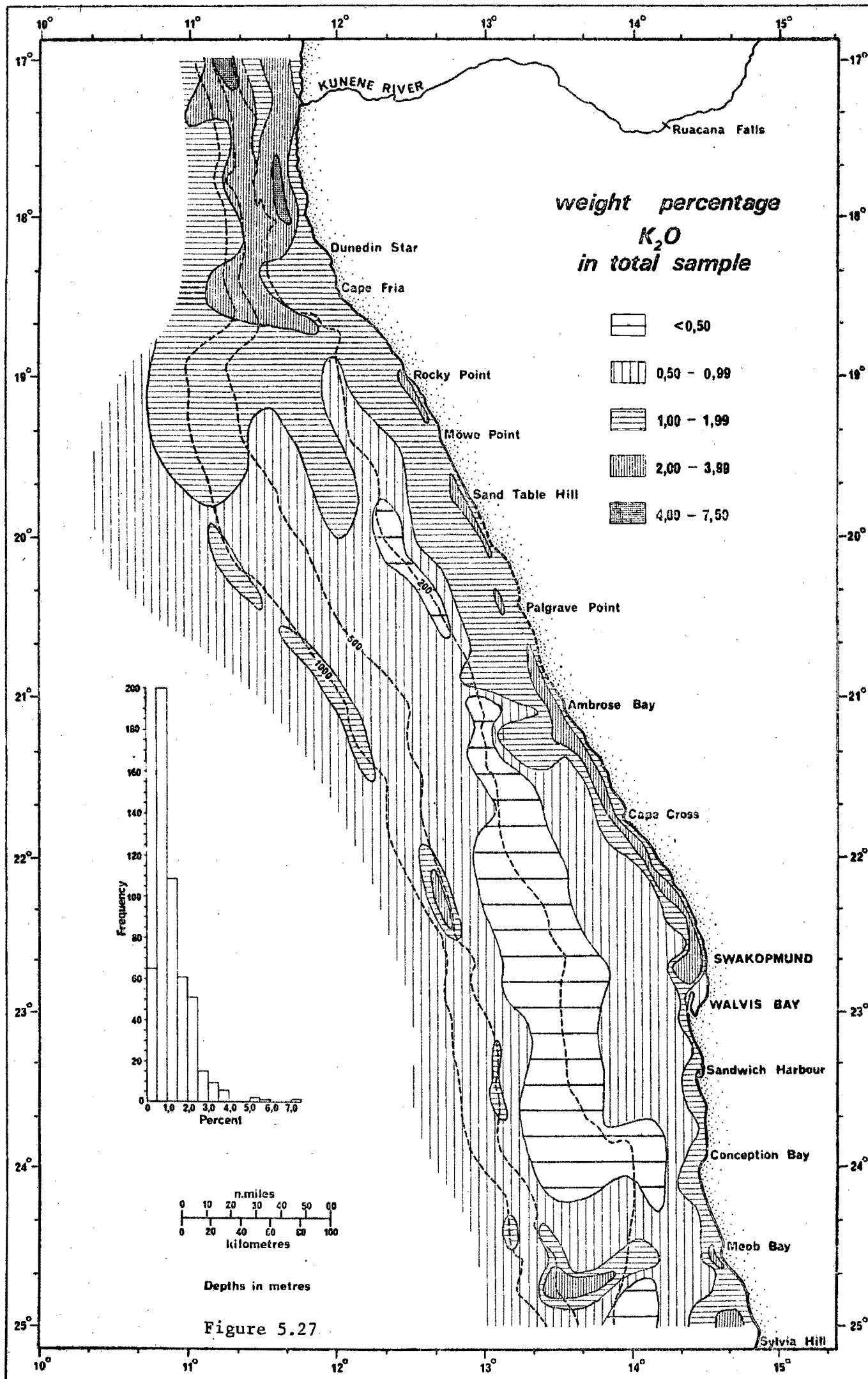
The Southern Mineral Province consists of a few isolated deposits of glauconite with relatively low concentrations. The richest of these, with 24,1% G, lies on the upper slope west of Cape Cross roughly between the 500 and 700 m isobaths. It is an elongate shaped deposit, and appears to be truncated at both ends by large embayments of the continental slope (see bathymetric map, Fig.3.2). Glauconite occurring there is the medium sand-size, dark green variety, some of which exhibit the internal morphology of planktonic foraminifera. South of the Swakop Bank (Fig.3.2), a narrow strip of sediment containing about 2,0% of this glauconite extends southwards along the shelf break and upper slope for 60 n.miles. Off Meob Bay, it widens and swings landward across the outer shelf and consists of a mixture of the yellowish-green and dark green glauconite varieties. It reaches a maximum concentration is 8,0%.

The third glauconite type, the very fine, subangular, black variety, is widely distributed on both the Kunene and Walvis Continental Margins, but nowhere is it sufficiently concentrated to form a distinctive deposit on its own. The distribution of this glauconite is defined roughly by the concentration range Tr - 0,9% in Fig. 5.25.

5.4.4 P_2O_5 - phosphorite and K_2O - glauconite relationships

The P_2O_5 content of the unconsolidated sediment is due entirely to individual contributions from the three phosphorite minerals pP, gpP and cP. Since the distribution of gpP is shown separately from that of pP + cP in Figs. 5.23 and 5.24, a comprehensive map showing the P_2O_5 content of the total sediment is presented in Fig. 5.26. In addition to this, the P_2O_5 content of the mud fraction (silt + clay) has been determined in a number of selected samples, and the regional distribution of these results is illustrated in Fig. 5.28. The vast bulk of the relict phosphorite is sand-size (see next Part), and consequently, the P_2O_5 content of the mud fractions is low (maximum 1,34%). The highest P_2O_5 values are generally found associated with cP in the diatomaceous muds, and probably reflect the presence of silt-sized clots of phosphatic material there (Veeh et al., 1974). Another region where relatively high P_2O_5 values occur in the mud fraction of the sediments (>0,5%) is the area of maximum pP/gpP concentration on the outer shelf south of Conception Bay. Fragmentation of deeply open-sutured gpP during periods of lower sea-level may have been the source for the elevated P_2O_5 values in this vicinity.

The concentration of K_2O in the sediment (Fig.5.27) reflects not only authigenic glauconite, but also terrigenous minerals such as muscovite, biotite and to a lesser extent, K-feldspar (see Section 5.5). Except for the Kunene Shelf and the nearshore zone of the Walvis Inner Shelf, these terrigenous minerals occur in low abundance and consequently, the distribution of K_2O



is fairly well represented by the distribution of glauconite in the sediment (Fig.5.25). The most potash-rich of the glauconite-free areas is a narrow strip adjacent to, and landward of, the cP concentrations in the diatomaceous mud. In this region, coarse and medium sand-size mica has been found to occur in great abundance (maximum 40%, see Section 5.5). A notable difference between the concentration of sand-size glauconite (Fig.5.25) and the concentration of K_2O in the sediment (Fig.5.27) occurs on the Walvis Outer Margin north of Cape Cross. Glauconite is completely lacking in this area but K_2O values between 1,00 and 2,00% are found to occur along the 1 000 m isobath. This may be due to K-adsorption by an abundance of montmorillonite in this region (see Chapter 7), and possibly reflects on the mode of formation of the glauconite foraminiferal casts on the upper slope west of Cape Cross. Some support for this contention is obtained from the K_2O concentration levels in the mud fraction ($<63\mu m$) of the sediments (Fig.5.28) which also indicate between 1,00 2,00% K_2O in this area. In general, it has been found from factor analysis of the clay mineralogy and clay geochemistry that K is strongly correlated with montmorillonite, and to a lesser extent with kaolinite (see Fig.7.12).

5.4.5 Size distribution of pP, gpP and G

Despite the higher density of apatite relative to calcite/aragonite and quartz (Berry and Mason, 1959), the size distribution of pP, as indicated from $\frac{1}{2}\phi$ sieve analyses (Appendix A.14), consistently reveals a fine-sand mode between 2,0 and 2,5 ϕ corresponding with the mode of the rest of the sediment (Fig.5.29). Non-equivalence between the hydraulic behaviour of apatite and the rest of the sediment indicates that relict pP has been thoroughly intermixed with modern calcareous and relict terrigenous sediments.

The gpP are less well sorted than the pP and reflect a fine sand mode coarser than that of the rest of the sediment (Fig.5.29). As implied earlier, the highest concentrations of gpP are generally displaced slightly seaward of the main pP deposits, and a possible explanation for this is that at lower sea-level times, the larger surface area of gpP particles compared to pP resulted in them being fractionated into deeper water by wave-induced bottom currents. The relative fineness of sediment associated with gpP therefore probably reflects the texture of sediment being deposited in these regions today.

The density of glauconite is similar to that of quartz (Berry and Mason, 1959) which is the principal diluent in deposits of this material. In areas of minimal modern sedimentation and benthic activity, glauconite would be expected to have a similar modal distribution to that of the rest of the sediment and this appears to be the case with the single sample that was size-analysed, both being fine-sand size (Fig.5.29).

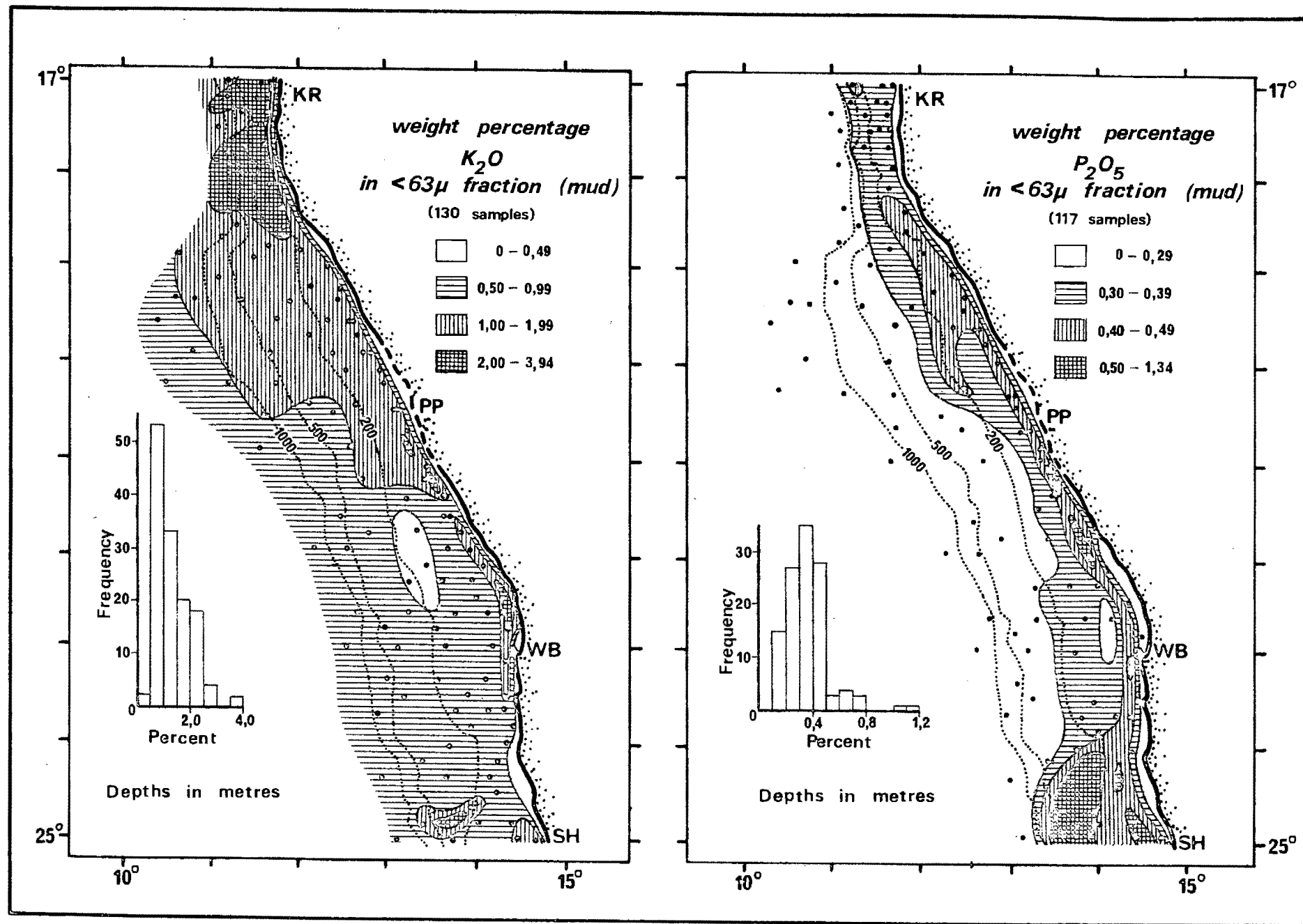
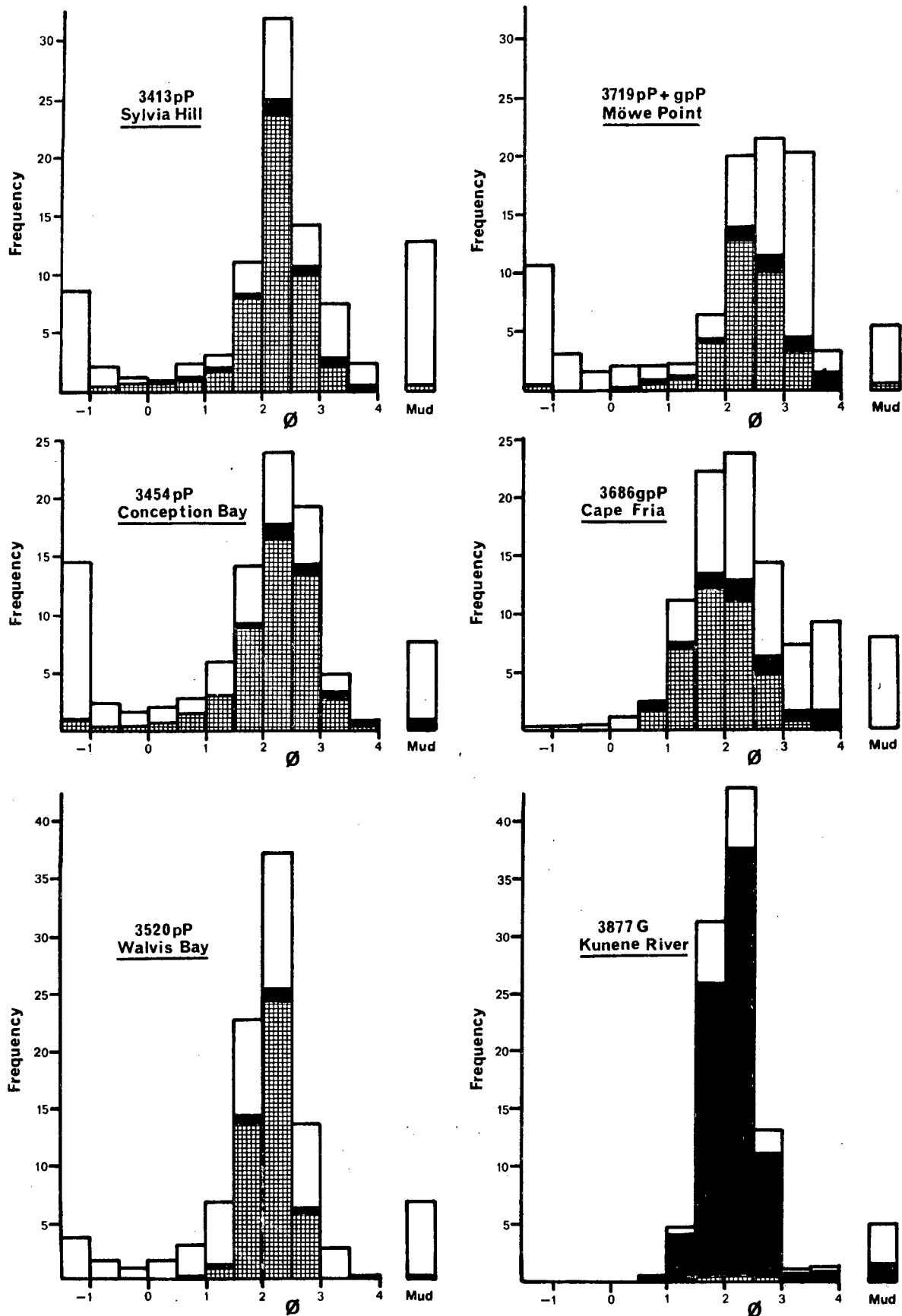


Figure 5.28

SIZE DISTRIBUTION OF PHOSPHORITE AND GLAUCONITE



 Non-authigenic components
 Glauconite
 Francolite

pP = pelletal phosphorite
 gpP = glauconitized pelletal phosphorite
 G = Glauconite

Figure 5.29

5.4.6 Relationship between P_2O_5 and C_{org} in the sediment

Senin (1970) has found that the highest concentrations of P_2O_5 in the sediment occur in the fine to medium sand-size fractions, and furthermore, that no correlation exists between the P_2O_5 and C_{org} contents of the sediment. His study was based on only 28 samples and he consequently attributed this disparity to a lack of data. A bivariate plot of the sediment P_2O_5 and C_{org} contents of over 500 samples is shown in Fig. 5.10 (f), which confirms the absence of any correlation even for the diatomaceous samples where cP and organic matter coexist. Moreover, from the regional distribution maps of organic matter and P_2O_5 (Figs. 5.19 and 5.26 respectively) it is clear that the two components have an antipathetic relationship to each other. The reason for this is that most of the P_2O_5 measured in the sediment is obtained from pP and gpP, which are Late Tertiary in age (Chapter 4), and are therefore unrelated to the distribution of recently deposited organic matter.

5.4.7 X-ray diffraction analysis

A number of hand-picked phosphorite and glauconite concentrates have been analysed by X-ray diffraction (Appendix A.15). The patterns shown by the three phosphorite minerals, pP, gpP and cP, all reflect well-defined diffraction lines at d-spacings listed by Rooney and Kerr (1967) for the mineral francolite (Fig. 5.30). The sharpest and best-defined peaks are exhibited by the cP traces, and the most subdued peaks characterize the gpP traces. In addition, some of the gpP traces show the presence of glauconitization e.g., sample 3914 gpP, whereas others reflect no glauconitization at all e.g., sample 3941 gpP. This aspect is examined fully in Chapter 8 in the discussion of the geochemistry of the authigenic minerals.

The X-ray diffractograms of dark green and yellowish-green glauconites both possess sharp, symmetrical, basal diffraction peaks of the $10\text{\AA}$ mica lattice (Carrol, 1970) e.g., sample 3677 G. Heat treatment at 550°C resulted in no perceptible change in the intensity of the peaks, and this together with geochemical evidence relating to the abundance of potassium, has led them all to be classified as well-ordered and chemically mature (Burst, 1958a,b). The colour of the yellowish-green grains from the Kunene Shelf does not correspond with the findings of Birch (1971, 1977) for well-ordered glauconites, and it may be that despite their maturity, they are relatively less well-ordered and consequently younger than the dark green glauconite grains from the upper slope off Swakopmund.

5.4.8 Chemical aspects of the phosphorites

Carbonate-fluorapatite (francolite) has been defined as an apatite mineral containing up to 6% CO_2 (Deer et al., 1962) and more than 1% F (McConn-

X-RAY DIFFRACTOGRAMS OF PHOSPHORITE AND GLAUCONITE

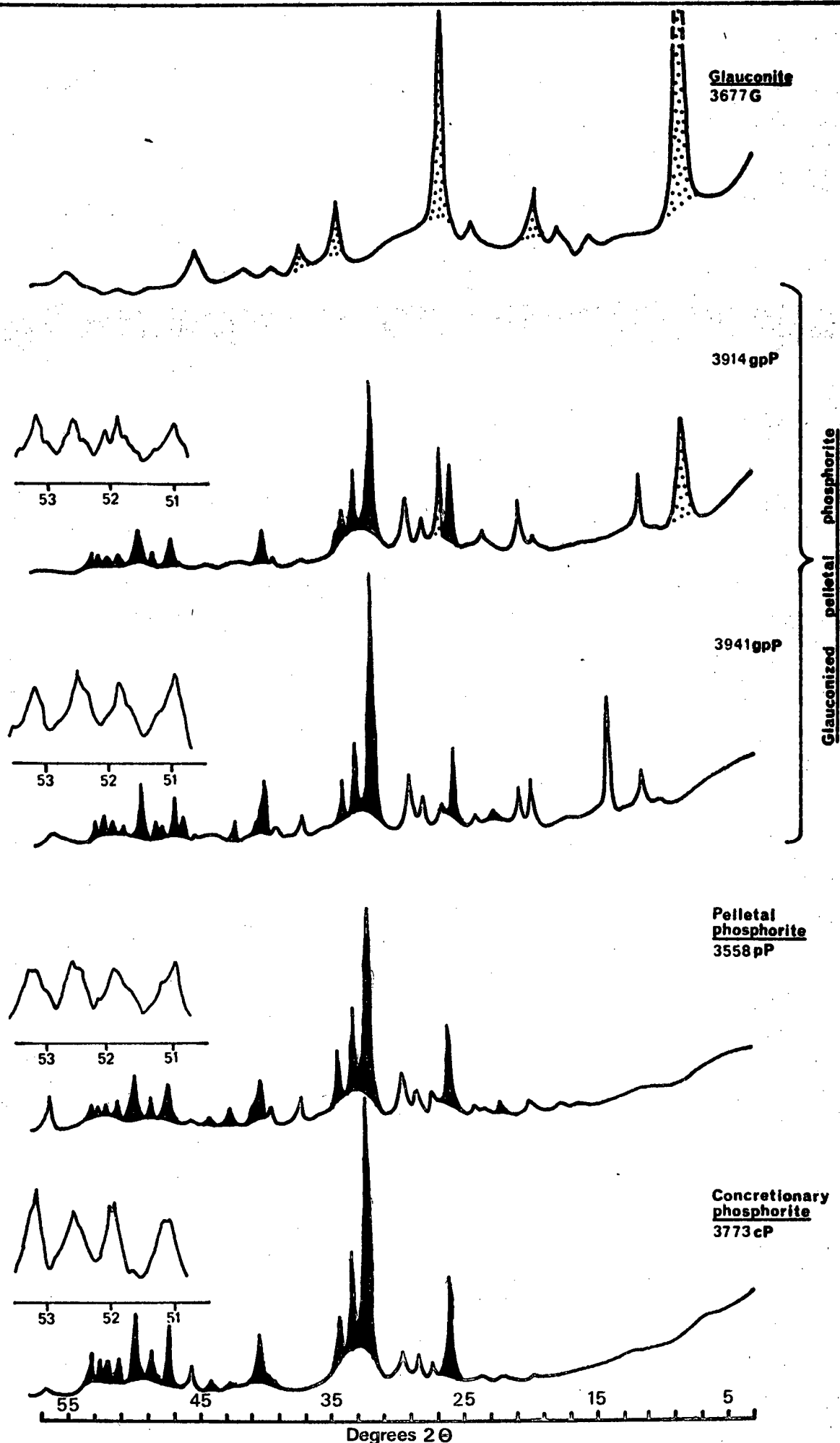


Figure 5.30

ell, 1952). Altschuler et al. (1958) have calculated that its composition approximates the formula: $\text{Ca}_{10}(\text{PO}_4, \text{CO}_3)_6\text{F}_{2-3}$, and Powell et al. (1975) have found that it sometimes contains appreciable C_{org} (up to 2%). In this Section, the concentration of CO_2 , C_{org} and F in the three different phosphorite minerals is discussed, and the methods used for determining them, and the results obtained are listed in Appendices A.16, and B.12 and B.13 respectively.

(a) CO_2

CO_2 is present in francolite as an integral part of the apatite structure (McConnell, 1952, 1960; Rooney and Kerr, 1967) and does not occur, as originally thought, as discrete calcite impurities (Neuman and Neuman, 1953). The carbonate radical CO_3^{2-} substitutes primarily for PO_4^{3-} , and with increasing carbonate substitution, the shape of the crystal changes from needle-like to more equiaxial (McClellan and Lehr, 1969). This has been well demonstrated by X-ray diffraction analysis of carbonate-fluorapatite where the (410) reflection shifts to a higher 2θ angle and the (004) reflection, to a lower 2θ angle (LeGeros, 1965; LeGeros et al., 1966). Typical X-ray diffractograms of pP, gpP and cP covering the range $50,5^\circ - 53,5^\circ 2\theta$ (Fig.5.30) indicate that cP not only possesses better crystallinity than pP or gpP, but also that it contains the highest proportion of CO_2 . The average CO_2 content of the three different phosphorite minerals, as well as their average concentrations of C_{org} and F, are summarised from Appendices B.12 and B.13 in Table 5.10.

Table 5.10 Average CO_2 , C_{org} and F concentrations in cP, pP and gpP (weight percent)

	cP	pP	gpP
CO_2	4,9	3,6	3,9
C_{org}	1,3	2,6	1,4
F	3,2	3,3	2,5

The pP and gpP contain about half as much CO_2 as the consolidated phosphorite rocks on the Agulhas Bank (5,5%) (Parker, 1971), but more than twice as much as the average value for the Phosphoria Formation, U.S.A. (1,8%) (Gulbrandsen, 1970). From a regional study of the Phosphoria Formation, Gulbrandsen (op.cit.) was led to the conclusion that CO_2 abundance is mainly a function of the water temperature at the time of formation of the apatite. This supposition was based on a correlation he found between the CO_2 content of apatites, and the depths and water temperatures inferred from east-west

facies changes in the rocks (easterly apatites contain 3,4% CO_2 , and those in the west, 1,2%). If this observation is applicable to phosphorite deposits in general, it would follow that the Miocene pP and gpP (Chapter 4) were deposited in much warmer water than the Permian Phosphoria deposits, but in relatively colder water than the Pliocene Agulhas Bank deposits (Siesser, 1977a). Moreover, the significantly higher CO_2 content of cP relative to pP and gpP would indicate a rise in the temperature of the Benguela Current since the Miocene which is contrary to field evidence (Shackleton and Kennett, 1975; Siesser, op.cit.). It would thus appear that while Gulbrandsen's (1970) contention is valid for inter-mineral comparisons within a single deposit, inter-deposit comparisons, particularly between those containing phosphorite of different origins, is not.

No regional trends in the distribution of pP and gpP are evident based on their CO_2 contents (as is the case with the Phosphoria Formation), thus indicating that these minerals were widely dispersed by wave-induced bottom currents and littoral currents at lower sea-level times, and as described earlier, have been intermixed with non-phosphatic sedimentary components by benthic organisms in modern times.

(b) C_{org}

The South West African phosphorite minerals, in contrast to their 'intermediate' levels of CO_2 enrichment, contain abnormally high concentrations of C_{org} (Table 5.10). The range of C_{org} in phosphorite from 18 different localities around the world is 0,11% to 1,98% (Powell et al., 1975), which is considerably below the range obtained for pP in the present study viz., 2,21 to 2,91% (Appendix B.13). The gpP however, despite being contemporary in age with the pP (Chapter 4), reflect a lower and much wider range of C_{org} values viz., 0,51 to 2,26%, and thus approximate more closely to the 'world' values of Powell et al. (1975). The reason for this difference is discussed in detail in the last Section of Chapter 8, which deals with the origin of the various authigenic minerals, and is therefore only briefly reviewed here.

Both pP and gpP are considered to have formed through direct inorganic precipitation from sea water in semi-enclosed, shallow-water lagoons. The gpP originated relatively nearer to shore than the pP in an environment being modified by the influx of river waters. As a result of the less reducing conditions in this environment, oxidation of some of the organic matter occurred whereas farther away from the river mouth, the organic matter remained unoxidized and became incorporated in the pP. The present seaward displacement of gpP mineral deposits relative to the pP deposits simply reflects their fractionation into deeper water by wave induced bottom-currents in lower sea-level times as was described earlier.

The C_{org} content of cP (1,3%) lies well within the 'world' range of Powell et al. (1975) and thereby suggests that the present-day diatomaceous muds are much less reducing than the Middle to Late Miocene lagoonal environments that gave rise to the pP and gpP (Chapter 4).

Romankevich and Baturin (1972) have examined a range of concretionary phosphorites of varying age in order to follow the diagenetic transformations undergone by C_{org} during lithification of the nodules. Their findings indicate that with increasing maturity, the P_2O_5 content tends to increase at the expense of organic matter and other contaminants in the concretions, and the order of retention of various organic phases is: carbohydrates < free lipids < organic nitrogen compounds (especially humics) < bound lipids. They attribute these changes to partial consumption of C_{org} by sulphate-reducing bacteria, and the CO_2 that is liberated is thought to combine with P_2O_5 in the diatomaceous mud to form carbonate-fluorapatite. In addition, Romankevich and Baturin (op.cit.) have found that opaline diatom frustules dissolve more rapidly than organic matter decomposes and consider this to be due to alkaline conditions arising at the surface of the frustules. Powell et al. (1975) have found that the high S values normally associated with phosphorite are partly due to its indigenous relationship with kerogen, and partly due to the intimate association in pyrite. They have also detected incipient graphite formation in old lithified phosphorites by X-ray diffraction analysis.

(c) F

As with CO_2 , F forms an intrinsic part of the francolite structure (Gulbrandsen, 1966) and apparently, is fixed in the mineral at an early stage of its formation (Altschuler, Clarke and Young, 1958; Price and Calvert, in press b). To compensate the charge imbalance introduced by CO_3^{2-} substitution of PO_4^{3-} , F^- , OH^- , or both, are incorporated into the lattice (Gulbrandsen, op.cit.; Altschuler, Cisney and Barlow, 1953; Ames, 1959).

From Table 5.10 it is evident that the F content of the two pelletal phosphorite minerals is higher than the reported values for phosphorite from other locations viz., Southern California 3,08% (average of 6 samples, Dietz et al., 1942); the Phosphoria Formation 3,10% (average of 60 samples, Gulbrandsen, 1966); Baja California 2,8% (average of 2 samples, D'Anglejan, 1967); the Soviet Union, 2,04% (average of 21 samples, Parker, 1971). However, there appears to be no relationship between the abundances of CO_2 and F in the South West African minerals which suggests that the charge imbalance is satisfied by a variable uptake of OH^- radicals. In the case of pP, the dearth of F associated with 'intermediate' CO_2 values indicates predominance of the mineral francolite, whereas with cP, the relatively higher CO_2 values

associated with roughly equivalent amounts of F indicate that at least some of the apatite is dalhite. The gpP have lower F and similar CO_2 concentrations to pP but because of the decreased abundance of P_2O_5 (see Chapter 8), some of the CO_2 probably occurs in minute crystallites of calcite in the grain sutures.

5.4.9 Phosphorite and glauconite resources

The presence of pelletal phosphorite (pP) on the southern part of the Walvis Shelf, glauconite (G) on the Kunene Shelf, and concretionary phosphorite (cP) within the diatomaceous mud belt, has been known about for almost a decade (Emelianov and Senin, 1969; Baturin, 1969; Senin, 1970). Glauconitized pelletal phosphorite (gpP) however, has not been previously reported. The sample density of these early investigations was sufficient to locate deposits of the first three authigenic minerals, but only now has the stage been reached when tentative estimates can be made on the resources. The physical dimensions, grade, and mineral and oxide reserves for the various mineralized provinces are summarized in Table 5.11, and following this is a brief discussion on the nature of the deposits relating to their economic potential.

On the seaward side of both the Northern and Southern Mineral Provinces exist extensive areas where Neogene and Quaternary stiff muds are exposed (Chapter 3) thus suggesting that the unconsolidated sediment cover in these areas is thin. The landward edge of the deposits however, particularly where they become intermixed with Pleistocene terrigenous and Recent biogenic sediment, is probably much thickened but as a consequence of dilution, are of lower grade. Regarding the diatomaceous mud belt, it has been shown that concretionary phosphorite occurs most commonly along its landward flank but the abundance and size of the concretions with depth is not known.

It should be emphasized that the Northern and Southern Mineral Provinces as defined within the boundaries of the study area are 'open' at both ends. The richest glauconite occurrence (92,0%) lies 10 n.miles north of the international boundary, but judging from maps published by Senin (1970), the areal dimensions of the Northern Province are much more extensive south of the Kunene River than north of it. The richest deposits of pelletal phosphorite lie outside of the study area just south of latitude 25°S (Rogers, 1973), but as in the case of glauconite, the major extent of the mineralized region, the Southern Mineral Province, lies within the study area.

Non-geological factors influencing the economic viability of unconsolidated sand-size mineral deposits such as these are the special considerations of marine engineers and metallurgists, and as such are only given brief mention

Table 5.11 Phosphorite, glauconite and oxide resources in areas with >5% mineralization

	Northern Mineral Province			Southern Mineral Province			Diatomaceous mud belt
	pP	gpP	G	pP	gpP	G	cP
No. of samples (>5% mineralization)	24	18	26	43	15	4	30
<u>Parameters of mineral deposits</u>							
1. Area (sq. km)	6,340	7,480	7,250	18,350	9,060	2,040	4,530
2. Volume (cub.m. x 10 ⁶)	634	748	725	1,835	906	204	453
3. Mass (metric tons x 10 ⁶)	1,858	2,192	1,921	5,377	2,655	541	969
4. Average concentration (%)	9,1	14,4	24,9	18,9	9,5	13,1	10,8
<u>Mineral resources</u>							
5. Metric tons (x 10 ⁸)	1,7	3,2	4,8	10,2	2,5	,7	1,0
6. Metric tons/sq.km (x 10 ⁴)	2,7	4,3	6,6	5,6	2,8	3,4	2,2
<u>Oxide resources</u>							
7. Metric tons (x 10 ⁶) $\begin{bmatrix} P_2O_5 \\ K_2O \end{bmatrix}$	47,7	80,8 1,9	38,6	286,0	63,1 1,5	5,6	32,6
<u>Total oxide resources</u>							
8. Metric tons (x 10 ⁶) $\begin{bmatrix} P_2O_5 \\ K_2O \end{bmatrix}$		128,5 40,5		349,1 7,1			32,6

*Notes: 1. Areas were measured with a polar planimeter using Figs. 5.23 and 5.24.

2. Volumes were calculated using a depth of 10 cm, which is the approximate depth to which a 0,1 m³ van Veen grab will penetrate the substrate.

3. The mass was calculated using average mineral densities given in Berry and Mason (1959): Apatite = 3,15, glauconite = 2,65, calcite = 2,71, quartz = 2,65, and wet diatomaceous mud containing 54,4% opal = 1,19 (Table 5.8). The pP and gpP is mostly associated with CaCO₃ and quartz, so the density of this phosphatic sediment was taken to be $\Sigma(3,15 + 2,71 + 2,65)/3 = 2,84$. The G is mostly associated with quartz, so the density of glauconitic sediment was taken to be $\Sigma(2,65 + 2,65)/2 = 2,65$. The cP is exclusively associated with diatomaceous mud, so the density of this phosphatic sediment was taken to be $\Sigma(3,15 + 1,9)/2 = 2,17$.

4. Average concentrations were determined from all samples with >5% mineralization.

5. Mineral resources in metric tons = mass x average concentration

6. Mineral resources in metric tons/sq.km. = tonnage/area

7. From chemical analysis of the authigenic minerals by XRF (see Chapter 8), average oxide abundances are pP = 28,04% P₂O₅, gpP = 25,25% P₂O₅, 0,60% K₂O, and cP = 32,62% P₂O₅

8. Total oxide resources are the summation for each area.

here. Recovery of pelletal grains from sea floor depths of less than 500 m and concretions from less than 100 m depth are well within the scope of modern technology, as equipment now exists for the recovery of manganese nodules by air-lift dredging from the deepest oceans (Summerhayes, 1972a). Physical properties of the authigenic minerals that may be utilized for initial beneficiation of the recovered ore include the coarseness of the particles relative to the largely non-authigenic mud fractions, the magnetic susceptibilities of gpP and G, the non-reactability of apatite to dilute acetic acid and glauconite to dilute hydrochloric acid, and the high density of apatite relative to all other mineral components. Extraction of the oxides P_2O_5 and K_2O could be accomplished by flotation methods as practised by the Phosphate Development Corporation (FOSKOR), or by other established chemical techniques.

The distance between the authigenic provinces and deep-water ports, as well as the availability of markets both local and foreign, are also factors to be considered. The only port capable of handling ore-carriers within the study area is Walvis Bay, which is approximately 120 n.miles north of Sylvia Hill and 300 n.miles south of the Kunene River. Alternative port facilities exist at Lüderitz, approximately 100 n.miles south of Sylvia Hill, and at Mocamedes in Angola, approximately 120 n.miles north of the Kunene River.

There is little doubt that these authigenic mineral deposits constitute an important natural resource to South West Africa, and since no onland occurrences of potash or phosphate are known within the territory, it may in the future become profitable to exploit them. Certainly, the availability of phosphate from unrefined phosphorite has been established as being comparable to that of superphosphate by FOSKOR in a series of pot-plant tests (Viljoen, pers.comm.). An additional factor of interest is the apparent association between phosphorite and petroleum as suggested by Emery (1960), and Powell, Cook and McKirdy (1975).

5.5 TERRIGENOUS COMPONENTS

5.5.1 Introduction

In this section, the concentration, regional distribution and size distribution of quartz and mica are described. Aside from these two widespread terrigenous components, the regional distribution of the entire terrigenous fraction of the unconsolidated sediments is also discussed, however, the weight percentage of this material was determined indirectly by means of deductive evaluation (Appendix A.17). A cursory thin-section study of a few terrigenous concentrates showed that despite the potential for significant feldspar addition from the arid hinterland, the abundance of this mineral is,

in general, very limited. Other minerals of terrigenous origin occasionally recognized in the thin-sections were almandine garnet, magnetite, and ferromagnesians, but these were even less common than feldspar. The term 'quartz' is therefore used synonymously with 'insoluble residue'.

The insoluble residues have been determined in the sand fractions of all the samples (Appendix A.18), and these results, together with the weight percentages of the terrigenous fractions, are listed in Appendix B.7. The difference between these two sedimentary parameters has provided an indication of the abundance and distribution of silt-size quartz on the continental margin. Size analysis of very small amounts of insoluble residue was accomplished with a settling tube (Appendix A.19), and the results of this study are shown in Appendix B.19. Finally, a number of coarse-grained quartz particles were examined by scanning electron microscope to see if their surface textures revealed any clues as to their provenance (Appendix A.20).

Mica, the next most abundant terrigenous mineral after quartz, is discussed qualitatively in terms of its onland occurrence in the Namib Desert. Methods used for extracting mica from the unconsolidated sediment are described in Appendix A.21, and the results, from a number of selected samples, are given in Appendix B.15.

The average concentration of terrigenous sediment in various geographic and lithofacies regions of the continental margin is shown in Table 5.12.

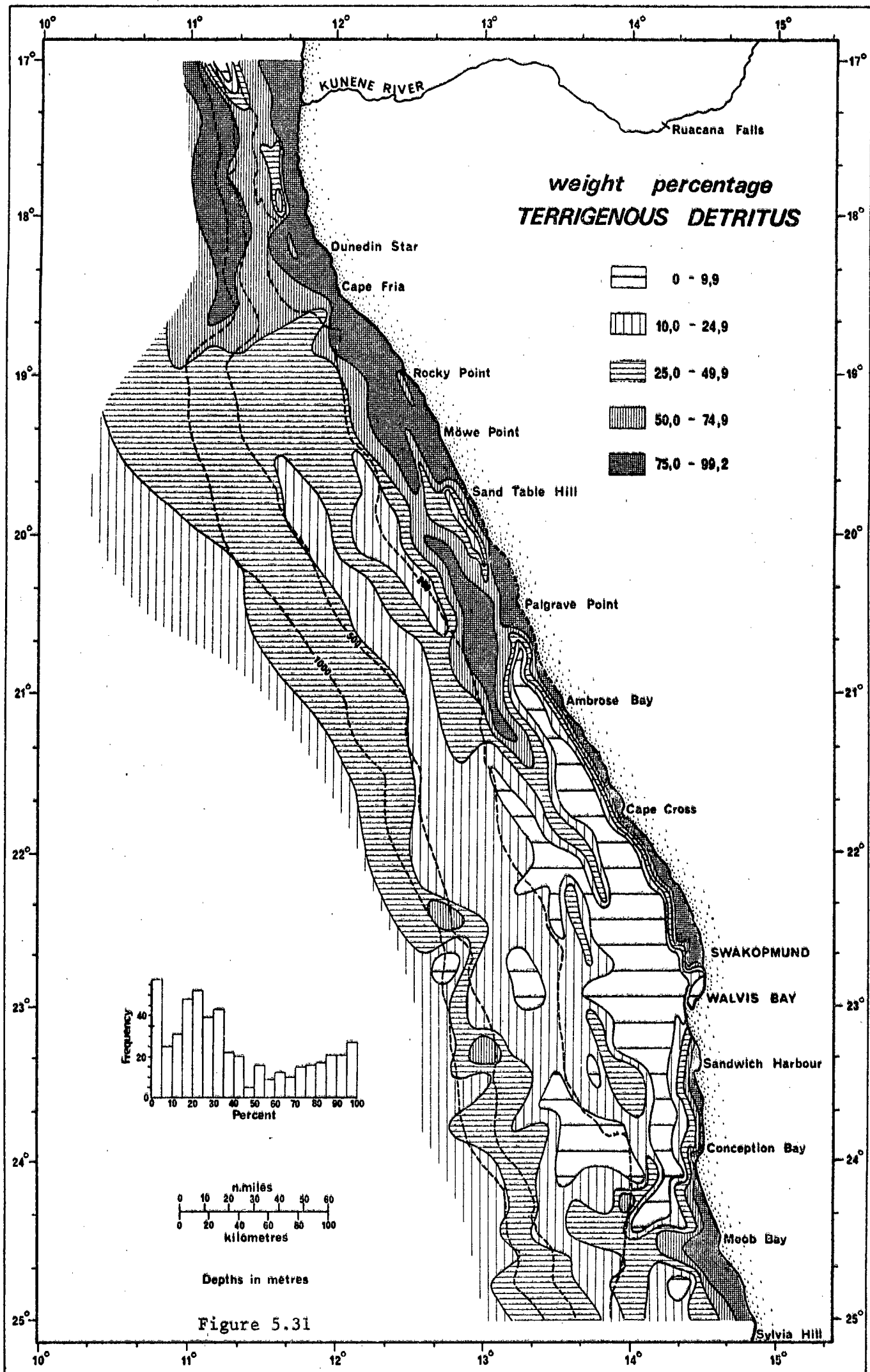
Table 5.12 Average concentration of terrigenous components in the unconsolidated sediment (weight percent)

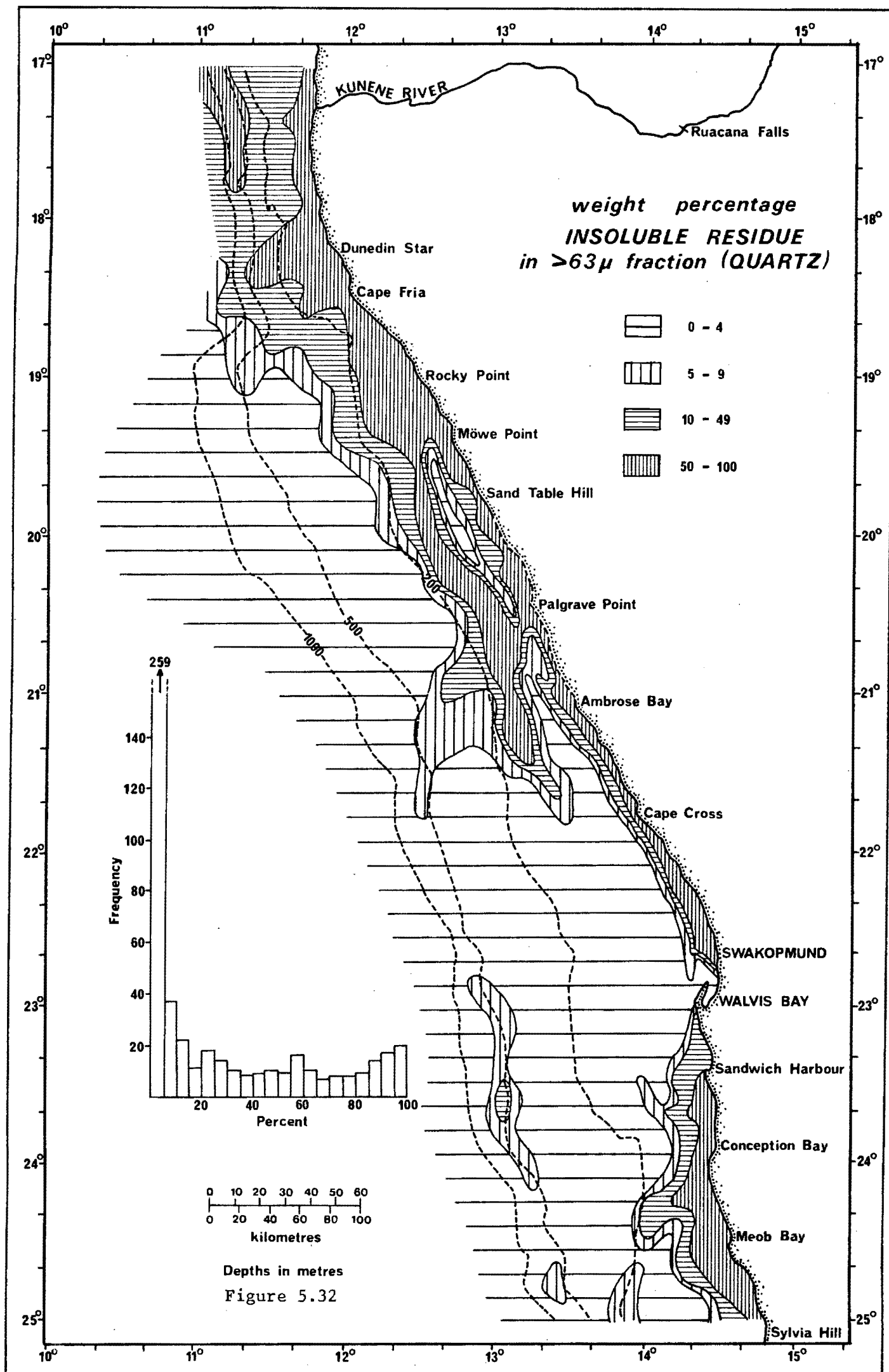
	Entire margin	Area		Biogenic sediments		Authigenic and terrigenous sediments Balance
		Kunene margin	Walvis margin	Diatomaceous	Calcareous	
		← 18° 40' S →		>5% opal	>50% CaCO ₃	
No. of samples	521	64	457	142	193	186
Mean (%)	39,4	71,3	34,9	26,3	22,2	67,2
Std. Dev. (%)	30,5	20,2	29,0	28,4	9,1	26,3
Range (%)	0-99,2	3,4-98,6	0-99,2	0-93,4	1,3-43,9	0-99,2

5.5.2 Regional distribution

(a) Terrigenous sediment

The richest deposit of terrigenous sediment is a narrow strip in the nearshore zone adjacent to the coast (Fig. 5.31). In this region, the concentration of terrigenous material always exceeds 75% of the sediment and in places, it reaches over 95%. Southwards from Sand Table Hill, the terrigenous strip lies wedged between the diatomaceous mud belt and the foreshore,





and usually measures between 2 and 5 n.miles in width. Northwards from there, the strip occupies most of the inner shelf and widths of 10 to 40 n.miles are most common. Apart from a small gap in the vicinity of Walvis Bay, the terrigenous strip extends continuously from the Kunene River to Sylvia Hill.

The next most concentrated area of terrigenous sediment (>75%) is an elongate deposit on the inner shelf off Palgrave Point. To the north it links up with the wider part of the nearshore terrigenous strip at Sand Table Hill, and to the south, southwards from Cape Cross, it breaks up into a series of discrete patches of low concentration. Between the nearshore terrigenous strip and the inner shelf deposit just described, the areal dimensions of the diatomaceous mud belt are fairly well delineated.

Finally, a belt of terrigenous sediment (25-50%) exists on the Walvis Upper Slope that, south of Swakopmund, is narrow and highly irregular, and to the north is broad and continuous. An equivalent but much richer deposit occurs on the Kunene Upper Slope (75-100%), and is separated from the nearshore terrigenous strip by a mid shelf zone of authigenic minerals and benthic foraminifera.

(b) Insoluble residue (quartz)

The concentration and distribution of sand-size quartz in the unconsolidated sediment is shown in Fig.5.32. In general terms the distribution differs little from that of total quartz (Fig.5.31) thus indicating that most terrigenous sediment on the continental margin is sand-size. The most significant differences between Figs.5.31 and 5.32 are on the Kunene and Walvis Outer Margins, and this is due to the presence there of silt-size quartz.

A bivariate plot of the concentrations of terrigenous material vs. insoluble residue (sand-size quartz) in the samples is shown in Fig.5.10(g). Calcareous sediments evidently contain very little terrigenous sediment and most of it is silt-size quartz (terrigenous material > insoluble residue). The diatomaceous mud and the balance of the sediment also contain some silt-size quartz but, particularly with the diatomaceous muds, sand-size quartz appears to predominate (terrigenous material $\approx$ insoluble residue).

The weight percentages of a number of individual size fractions of the insoluble residue have been plotted on regional distribution maps (Figs.5.33 and 5.34). From Fig.5.33, very coarse and coarse quartz sand (~ 1.0 to 1.0ϕ) coexist at two principle locations on the Walvis Inner Shelf, viz., at Palgrave Point, and at Meob Bay. At both of these locations, the quartz is associated with pebbles and cobbles deposited at the site of relict storm beaches (Fig.3.6). Furthermore, the underlying bedrock in these areas commonly consists of pebbly quartzose limestones (Fig.4.1). Medium-grained

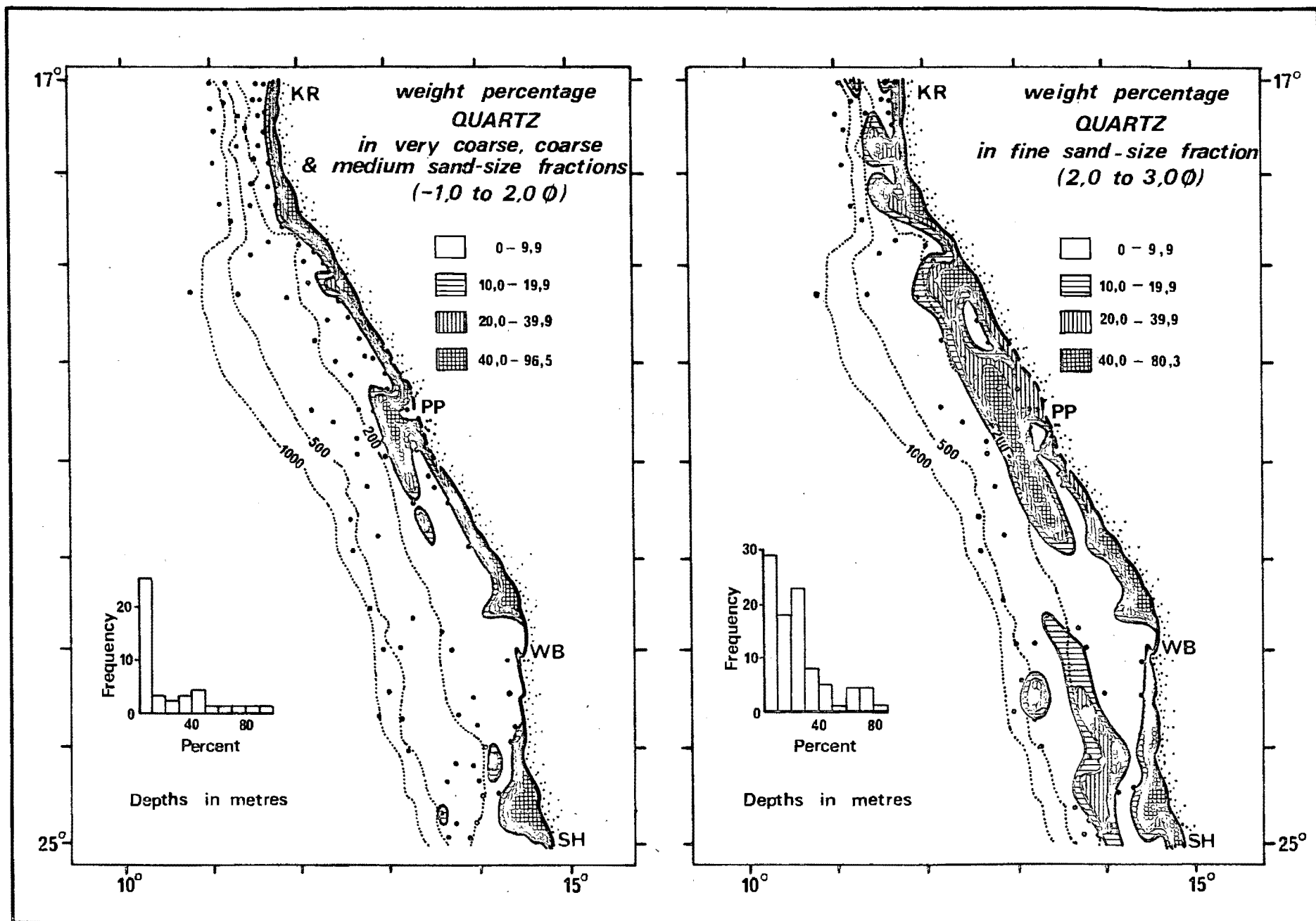


Figure 5.33

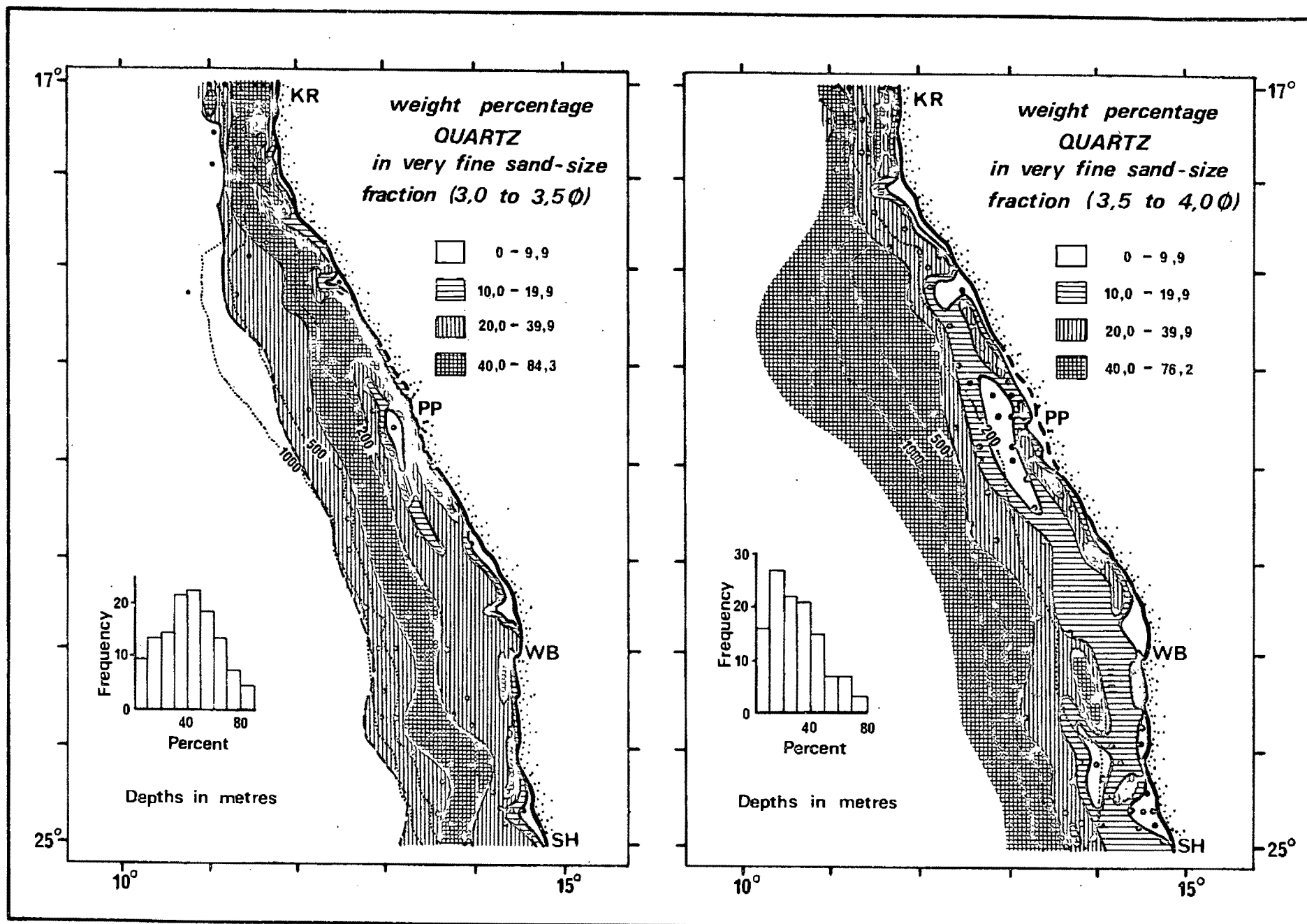


Figure 5.34

quartz sand (1,0 to 2,0 ϕ), which is the dominant mode in the highly concentrated strip of terrigenous sediment in the nearshore zone, is also the mean size of sediment on the beach foreshore (Table 5.3). Fine-grained quartz sand (2,0 to 3,0 ϕ), the mean size of terrigenous sediment composing the dunes of the Namib Sand Sea (Table 5.3), occupies the major portion of the Kunene Inner Shelf and parts of the Walvis Inner Shelf. Close similarity between the dispositions of these fine-sand areas (Fig. 5.33) and the total insoluble residue (Fig. 5.32) indicates that this size fraction is the dominant terrigenous mode on the inner shelves.

Of the very fine-grained quartz sand fraction, 3,0 to 3,5 ϕ quartz is the most common terrigenous component on the Walvis and Kunene mid and outer shelves, and occurs there in relatively low concentration (cf. Figs. 5.31 and 5.34). 3,5 to 4,0 ϕ quartz is typical of the shelf break and upper slope of the two continental margins. The distribution of both these very fine-grained sand fractions shows no relationship to the distribution of the modern biogenic sediments, and their occurrence appears to be a simple function of their distance from shore.

(c) Mica

(i) Onshore

The abundance of mica in the Namib Desert is very high but difficult to estimate quantitatively on a regional basis because of its tendency to concentrate in the lee of dunes, and its virtual absence (as stable grains) on the windward faces of the dunes. The hexagonal crystallographic form of these mica flakes is generally destroyed during transport, and well-rounded outlines become worn as they 'wheel' along at a very rapid rate. The proportion of muscovite to biotite in accumulations on the leeward side of dunes is about 50:50 based on flake counts, but due to the relatively larger size of the muscovite flakes the ratio increases to about 80:20 based on volume percentages. Individual muscovite flakes measuring 10 mm across occur, but the average size is about 3-4 mm (gravel-sized). Maximum biotite flake diameters are of the order of 2 mm (very coarse sand-sized), and the average size is about 0,5-1,0 mm (coarse sand-sized).

(ii) Offshore

Mica is a widespread terrigenous component in the unconsolidated sediments but its concentration and the coarseness of the flakes decreases rapidly with distance from shore. Maximum concentrations occur along a narrow strip, usually within 5 n.miles from shore, and at approximately 40 m depth. The strip is best developed along the interface between diatomaceous muds and the nearshore terrigenous sands, and for the stretch between Sand Table Hill

and Swakopmund, mica constitutes, on average, 19% of the unconsolidated sediment and a maximum of 40% (Appendix B.15). Methods used for separating mica from the sediment are described in Appendix A.21.

The proportion of muscovite to biotite in these offshore sediments differs radically from that of the onshore mica concentrates. A muscovite:biotite ratio of approximately 20:80 was obtained for volume percentages indicating that large muscovite flakes are much less stable in the nearshore marine environment than the small biotite flakes. Furthermore, the overall size of the mica population is also considerably reduced compared with the onshore concentrates, the mode of their distributions, regardless of location, always falling in the very fine sand fraction (0,13-0,06 mm). Drysieving of the unconsolidated sediment, as described in Section 5.2, allowed detection of the coarsest mica flakes present in each of the samples, and these results are shown in Fig. 5.36. It is clear that a definite size gradation exists, from coarse to medium-grained flakes (1,00-0,25 mm) within about 5 n.miles from shore, to very fine flakes (0,06-0,13 mm) on the mid shelf. Most upper-slope samples contain only trace quantities of very fine-grained mica, but north of Cape Cross, K_2O values of between 1,0 and 2,0% have been found to occur (Fig. 5.27). These high K_2O values cannot be due to mica and are therefore attributed to K^+ adsorption by montmorillonite which is fairly abundant in this region (Section 5.4). Factor analysis of the clay mineralogy and clay geochemistry has revealed that montmorillonite and K are very strongly correlated (see Fig. 7.12).

5.5.3 Size distribution of the insoluble residue (quartz)

Variations in the size distribution of quartz in the unconsolidated sediment are shown in Fig. 5.35. Samples along four transects of the continental shelf were chosen for presentation, and this was accomplished by plotting their size frequencies in the form of histograms at 0,1 ϕ size intervals.

The Kunene-River line illustrates the dominance of very fine-grained quartz over most of this part of the continental shelf. The Palgrave Point line shows the presence of coarse- and medium-grained quartz roughly 10 n.miles from shore (at about 110 m depth), with strongly negatively-skewed, fine-grained quartz distributions on either side of it; at the shelf break, 55 n.miles from shore, very fine-grained quartz with a bimodal distribution indicates overlap of two different size populations. The Walvis Bay line, because of diatomaceous mud on the inner shelf, possesses no fine sand equivalent of the Namib Desert dunes, and instead, a simple gradation of the very fine sand fractions from (3,0 to 3,5 ϕ) to (3,5 to 4,0 ϕ) occurs towards the shelf break. The Sylvia Hill line shows coarse quartz 8 n.miles from shore (at 43 m depth) beyond which the size decreases to fine sand on the mid shelf,

SIZE FREQUENCY DISTRIBUTION OF INSOLUBLE RESIDUES (QUARTZ) ALONG FOUR PROFILES

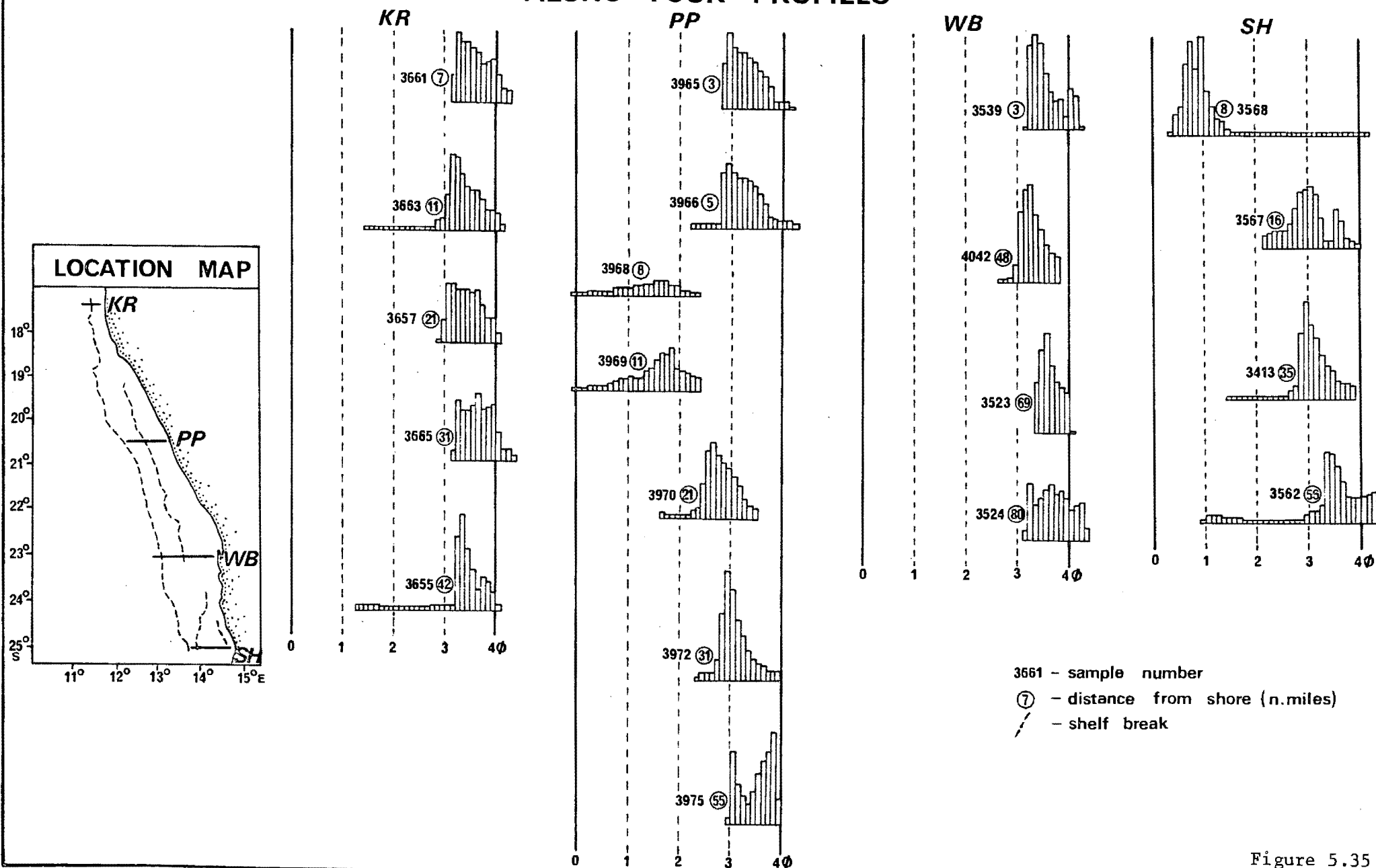


Figure 5.35

and very fine sand on the outer shelf break.

The presence of silt-size quartz in some of the distributions probably reflects disaggregation of weakly-cemented composite grains during the many analytical operations performed on the sand fractions of the sediment prior to concentration of the insoluble residues.

5.5.4 Surface textures of coarse-grained quartz particles

Aeolian- and littoral-transport processes impart different characters to the surface texture of quartz particles (Margolis, 1968; Krinsley and Doornkamp, 1973), and based on these findings, it was decided to examine the surfaces of a few coarse-grained quartz particles for possible clues as to their provenance. For this purpose, quartz particles from the Namib dunes, the beach foreshore, and the inner shelf were isolated and photographed by scanning electron microscope (Appendix A.20). Particles of this coarseness are unlikely to have been transported for any great distance by bergwinds (Chapter 1), but under suitable storm-wave conditions, locally generated waves would theoretically be capable of placing them in suspension in water shallower than 15 m ($U_m=101,2$ cm/sec) and distant storm-waves would then be able to move them as bedload to 150 m depth ($U_m=6,4$ cm/sec) (Appendix B.2). However, with the diatomaceous mud belt shielding the Walvis Mid Shelf from terrigenous sediment in the nearshore zone, it is almost certain that these grains, as well as the rest of the terrigenous material on the seaward flank of the diatomaceous mud belt, is relict.

The quartz grains from the Namib Sand Sea are typically subrounded with dish-shaped concavities (Plate 5.1(a)), both features being considered by Krinsley and Doornkamp (1973) to be aeolian-derived, and inherited from violent saltation. An example of a dish-shaped concavity with a freshly fractured surface is shown in Plate 5.1(b). On a smaller scale, the frosted surfaces shown in Plate 5.1(c) are also considered to be aeolian features formed from alkaline dew dissolving the surface silica of the grains at night, and redepositing it as amorphous silica when the dew evaporates in the morning (Keunen and Perdok, 1962).

Grains from the beach foreshore adjacent to the Namib Sand Sea tend to be well-rounded with dish-shaped concavities as well (Plate 5.1(d), thus suggesting some aeolian influence. A distinctive feature of these grains are scaphoid grooves (Rogers, 1975) which are large (80-300 μ m long) boat-shaped concavities, pointed at both ends (Plate 5.1(e), and believed to result from impact in a high-energy subaqueous environment. Other features evident at high magnifications (5000 X) are smooth abrasion surfaces and numerous V-shaped pits. Some of these pits are randomly orientated and due to percussion in the vigorous surf zone (Krinsley and Doornkamp, 1973); whereas others are oriented and flat-bottomed, and thought to be the result of sea-water etching produced from alter-

nate wetting and drying in the intertidal zone (Margolis, 1968; Rogers and Tankard, 1974) (see Plate 5.1(f)).

Both aeolian and littoral features are found on the surfaces of quartz grains from the continental shelf. Two grains are illustrated in Plate 5, one from Sylvia Hill (43 m depth) and the other from Palgrave Point (81 m depth). Both of them exhibit subrounded forms with concave facets (Plates 5.1(g) and 5.1(j)), and their surface textures are extremely rough (Plates 5.1(h) and 5.1(k)). The Palgrave Point grain also has well-preserved upturned plates (Plate 5.1(h)), a feature which is related to aeolian environments by Blatt et al., (1972). The Sylvia-Hill grain possesses a smoother surface (Plate 5.1(h)) with superimposed V-shaped pits, thus suggesting a longer residence time in the littoral zone. Although no scaphoid grooves were found on the surfaces of continental-shelf grains, parallel fracture cleavages on the grain from Palgrave Point (Plate 5.1(i)) are considered by Rogers (1975) to be features inherited from the primary host rock. The grain from Sylvia Hill shows exfoliated surface silica at the site of an impact (Plate 5.1(l)).

Despite the tenuous reliability of surface textures and grain morphology in interpreting the provenance of quartz particles, the features recognized on the continental shelf grains do suggest that an initial aeolian imprint was subsequently modified, to a greater or lesser extent, by littoral marine processes.

5.5.5 Origin

(a) Quartz

In Chapter 3. evidence was presented to suggest that during the Würm II pleniglacial there was a northward shift in the climatic belts, and sea-level dropped to approximately -110 m. Furthermore, it was shown that the inner shelf break could be explained in terms of the Namib Sand Sea coastal dunes migrating onto the inner shelf during this period of intensified aridity. Other indications of this event having occurred are obtained from the following indirect lines of evidence:

- The average mean size of quartz composing the Namib Desert dunes (Table 5.2) is the same as the quartz on most of the inner shelf viz., fine sand-size (2,0 to 3,0 ϕ).
- Discrete patches of this fine-grained quartz sand occur along the western edge of the diatomaceous mud belt thus suggesting the presence of terrigenous sediment beneath the modern biogenic mud.
- A highly irregular sub-bottom is evident beneath parts of the acoustically transparent diatomaceous mud, and may be due, at least in part, to terrigenous sediment existing as relict dunes and cheniers (see Fig. 3.6).
- The surface textures of coarse-grained quartz particles from the inner

shelf indicate that several aeolian features have been overprinted by features developed in the littoral environment.

The very coarse and coarse-grained quartz sizes are therefore believed to have been derived from sub-aerial erosion of underlying pebbly quartzose limestones during the Würm II sea level regression, and are concentrated in close proximity to gravelly storm-beaches that formed at that time. Medium-grained quartz sand was probably derived from this same source material, as well as from disintegration of exposed bedrock in the hinterland. It is concentrated in favour of other grain-sizes in the nearshore zone today, because of its hydraulic stability in the wave-energy flux between the breaker zone and the beach. Fine-grained quartz was derived largely from the Namib Sand Sea during the Würm II regression when mobile coastal dunes moved onto the inner shelf, and it probably underlies most of the Holocene diatomaceous mud belt. Very fine quartz sand, as well as silt-size quartz, are believed to reflect a modern aeolian origin since the concentration of these components is apparently controlled by their distance from shore.

Ultimately, all of this quartz was derived from two main sources: exfoliation and granular disintegration of quartzose bedrock exposed in the hinterland, and from terrigenous detritus transported from the Orange River mouth by strongly northward flowing littoral currents. Whereas the Orange River detritus forms the principle source of nourishment for the coastal dunes of the Namib Sand Sea (Rogers, 1977), terrigenous contributions from rivers draining the study area are small. Exceptional flooding of these rivers occurs, on average, only once every 50 years (Chapter 1).

(b) Mica

Micaceous rock formations in the hinterland are very common (Chapter 1) and mechanical disintegration of this material provides a copious source for the abundance of mica in the Namib Desert dunes. Unlike Orange River-derived medium- and fine-grained quartz sand, which oscillates in its passage northwards between aeolian and littoral transport modes (Rogers, 1975b), sand-size mica is hydraulically equivalent to smaller particles of quartz (Doyle et al., 1968) and is deposited seaward of the surf zone. Bergwind conditions (Chapter 1) carry much of the mica onto the shelf as indicated by the size gradation of flakes with distance from shore (Fig. 5.36), but some of it first passes through the surf zone where comminution to very fine-grained sizes occurs. Subsequently, this fine mica is transported to greater depths by wave-induced bottom currents. Evidence for the very fine state of comminuted muscovite is obtained from the overwhelming abundance of illite in the clay fractions of the sediments

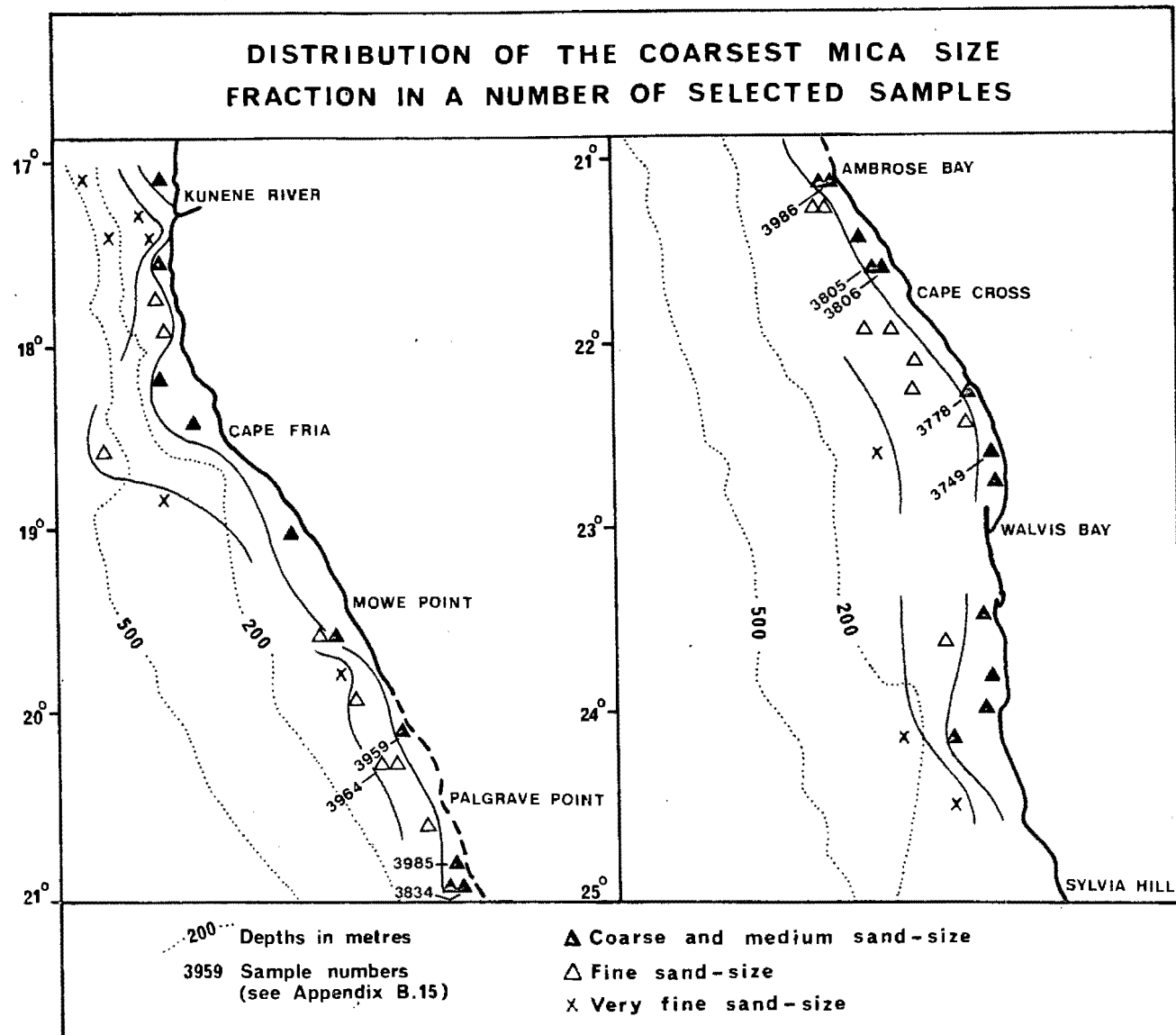


Figure 5.36

from the entire continental shelf (see Chapter 7). The marked decrease in abundance of muscovite relative to biotite in the nearshore zone reflects a greater susceptibility for muscovite to disintegrate in the surf zone.

5.6 SEDIMENTOLOGICAL ASSOCIATIONS

5.6.1 Introduction

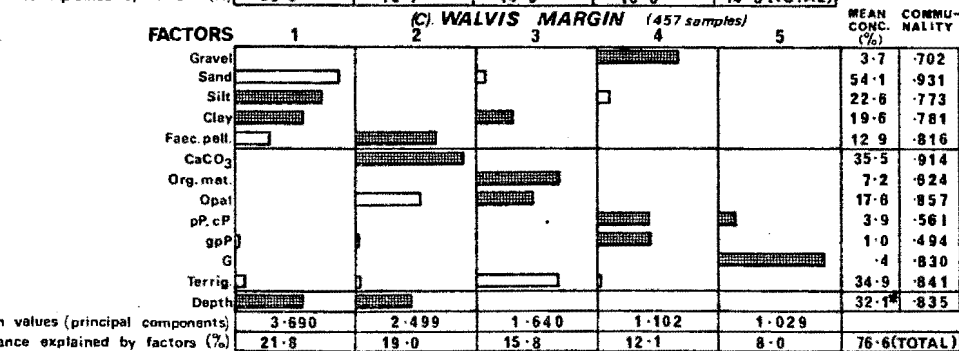
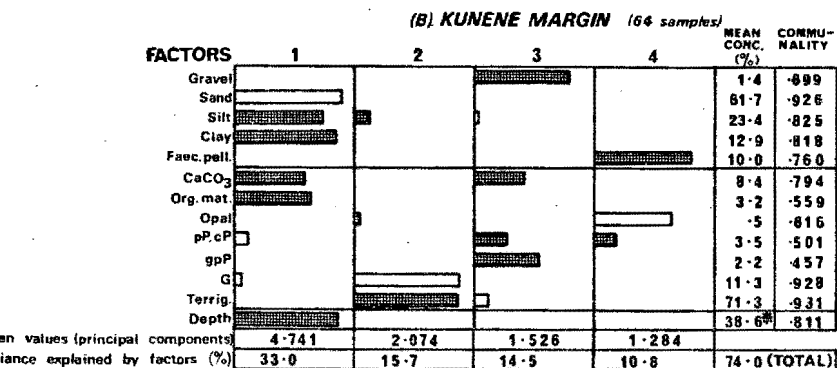
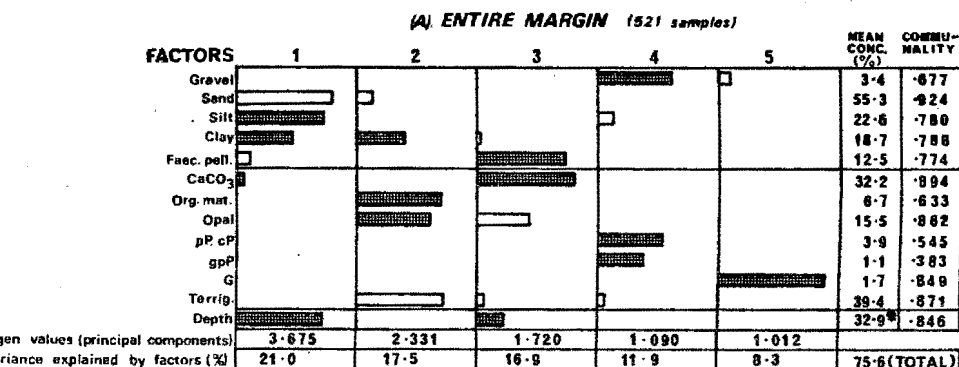
In this concluding Section of Chapter 5, an attempt is made to define associations among the principle compositional and textural parameters of the unconsolidated sediment, and to relate them in terms of depth of occurrence on the continental margin. To this end, the statistical technique of R-mode factor analysis (principal components procedure) has been employed, and background information relating to the procedure is given in Appendix A.22. The main findings of this sedimentological study are synthesized in the final Chapter of the thesis, Chapter 9.

5.6.2 R-mode factor analysis

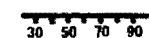
The philosophy behind grouping the continental margin sediments into different geographic and lithofacies types was discussed in Section 5.1 of this Chapter. The grouping procedure was based on the concentration of two widespread biogenic components in the sediment viz., CaCO_3 and opal, and conveniently afforded recognition of five individual groups within the boundaries of the study area. Only one of these groups is exclusively confined to the study area viz., the diatomaceous group (>5% opal), whereas the other four are all open-ended at either latitudes 17°S or 25°S . Based on the definitions of the sample groupings, it is important to realise that considerable overlapping of some of their areal dimensions exists. For example, the Kunene and Walvis Margin groupings form part of the Entire Margin grouping; the >5% opal and >50% CaCO_3 groupings form part of the Walvis Margin grouping; and the Balance grouping (authigenic and terrigenous sediments) includes most of the Kunene Margin grouping and a small part of the Walvis Margin grouping (Fig. 5.3).

Factor matrices of each of these groupings are shown graphically in Fig. 5.37. A separate evaluation of the variable inter-relationships indicated by each of the factors in these matrices would incur considerable repetition, and for this reason, it was decided to limit discussion to the smallest of them viz., the >5% opal group, the >50% CaCO_3 group and the Balance group. This in no way detracts from the generalised relationships indicated by the larger groupings viz., the Entire Margin grouping, the Kunene Margin grouping and the Walvis Margin grouping, but simply serves to focus on some of the more subtle variable associations that otherwise might have been obscured.

DIAGRAMMATIC REPRESENTATION OF ROTATED FACTOR MATRIX (VARIMAX PROCEDURE) FOR SEDIMENTOLOGICAL DATA AND DEPTH



FACTOR LOADINGS



■ +ve loading
□ -ve loading

(only factor loadings >0.25 are illustrated)

* Mean depth is the average for all samples in each of the designated areas

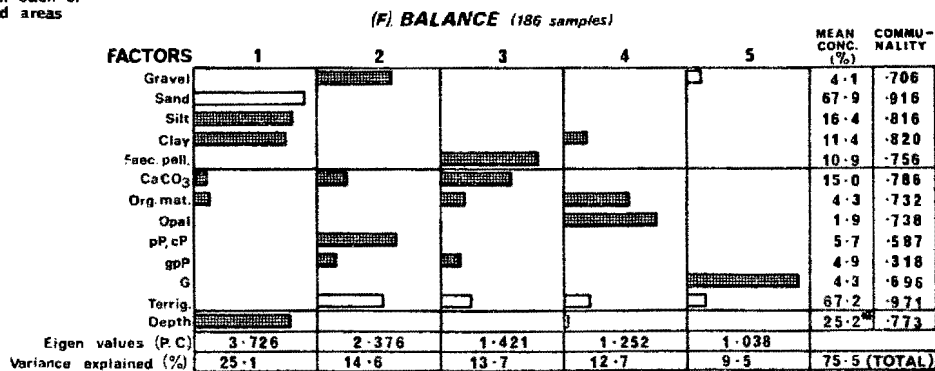
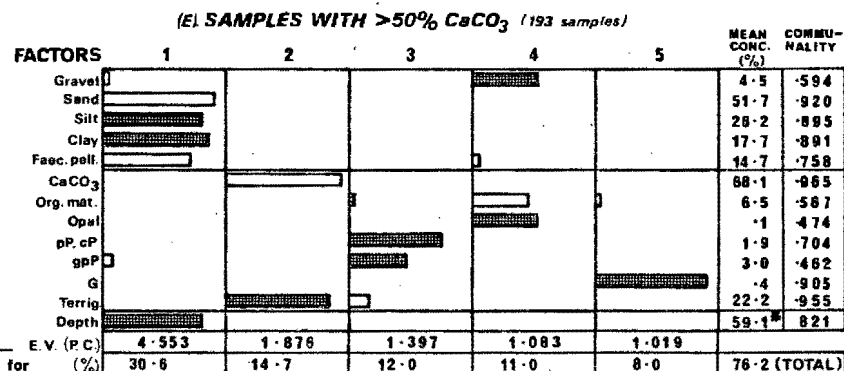
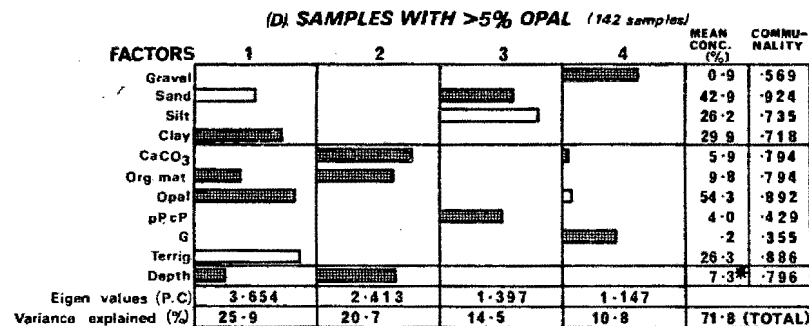


Figure 5.37

Many of the variable associations portrayed in the factor matrices will already have become apparent from the regional distribution maps presented earlier, however, associations between component variables of low concentration have not been so easily discerned, and in many cases, were simply overlooked. The main assets of this statistical analysis is therefore that all variable associations of significance are recognized (programme aborts when the total variance explained by the factors exceeds 70%), and secondly, that a quantitative significance value is assigned to the variable associations in each of the factors (percentage variance explained). The technique has been widely used, especially for investigating geochemical data e.g., Summerhayes (1972b), Reinson (1975).

5.6.3 Results

(a) >5% opal matrix (diatomaceous samples)

Factor 1 accounts for much of the total variance of the matrix (25,9%), and contrasts two inversely related variable associations. One of these associations consists of strong positive loadings on clay and opal and slightly weaker positive loadings on organic matter and depth, and is interpreted as indicating the fine textural state of diatomaceous debris in the central portion of the mud belt. The antipathetic association, consisting of strong negative loadings on the variables sand and terrigenous, indicates quartz contamination along the shallow landward flank of the diatomaceous mud belt. The inverse relationship between this sand-size quartz and the positively loaded variables described above emphasizes the high degree of 'purity' of the main body of the mud belt, and the essential confinement of terrigenous contamination to the nearshore zone.

No textural affiliations are indicated by Factor 2, and the matrix variance explained by it (20,7%) is due entirely to the association of three positively loaded variables: CaCO_3 , organic matter and depth. The greater abundance of organic matter at the seaward (deeper) edge of the mud belt is due to an increased state of dissolution of opaline diatom frustules. The greater abundance of CaCO_3 there reflects the planktonic foram populations existing seaward of the coastal zone of upwelling and the diatom populations.

Factor 3 is characterized by strong positive loadings on sand and cP, and a strong negative loading on silt. The landward edge of the diatomaceous mud belt is predominantly sandy in texture, this being due to undissolved diatom frustules, and to a lesser extent, to terrigenous quartz. Association of this sandy biogenic sediment with the cP may perhaps be due to the fractionation of silt-size diatom frustules to deeper water by storm-wave-induced bottom currents.

The remaining factor, Factor 4, accounting for only 10,8% of the total matrix variance, defines the association of two strongly correlated variables, viz., gravel and G. It is thought to reflect the extreme seaward edge of the diatomaceous mud belt northwards from Sandwich Harbour, where trace amounts of very fine sand-size dark green G co-exist with patches of relict mollusc shells. A very weak correlation of these two variables with CaCO_3 , and a weak antipathetic relationship between them and opal, lends some support for this contention.

(b) $>50\%$ CaCO_3 matrix (calcareous samples)

Two inversely related variable associations are indicated in Factor 1 which accounts for the major portion of the total matrix variance (30,6%). One of these associations, with strong positive loadings on silt, clay and depth signifies, as may be expected, an increasing state of fineness of the Walvis Outer Margin sediments with distance from shore. Being calcareous ($>50\%$ CaCO_3), this fine sediment probably reflects the deposition of lime mud on the upper slope. Conversely, strong negative loadings on sand and faecal pellets indicate that these two variables are depth-limited, both attaining maximum concentrations on the mid shelf. A very weak negative loading is indicated for the gravel variable which implies an occasional overlap between the gravelly mollusc patches on the inner shelf, and the faecal pellet sands on the outer shelf. Another weak negative loading occurs on the gpP variable which reflects the seaward displacement of gpP relative to pP, thus bringing it relatively closer to the faecal pellet deposits on the outer shelf.

Factor 2 has no textural or depth connotations, and simply contrasts two strong, and inversely related compositional variables CaCO_3 and terrigenous. The CaCO_3 content of the unconsolidated sediment is largely determined by modern foraminiferal remains, whereas the terrigenous material is predominantly relict quartz sand. This implies that terrigenous material only occurs where the modern carbonate sedimentation rate is low, and probably reflects a hydrological control such as the Ekman friction layer on the inner shelf.

No textural or depth relationships occur in Factor 3 either, and the most significant association is that between pP and gpP. This association is easy to understand in view of the common origin of the particles, and their similar physical properties; the greater density of apatite relative to quartz and CaCO_3 having resulted in the accumulation of pP and gpP as lag deposits on the continental shelf. A very weak positive loading on organic matter is interpreted as reflecting a slight overlap between gpP and faecal pellets on the outer margin, and a very weak negative loading on the terrigenous variable probably indicates that the pP and gpP occur separately from quartz on the inner shelf.

Strong positive loadings on gravel and opal occur in Factor 4, and this is taken to indicate the boundary region between diatomaceous and calcareous sediments on the inner shelf. In this region, relict mollusc shells are in the process of being buried by highly altered diatom frustules e.g., off Palgrave Point and Sylvia Hill (Fig. 5.17). The gravel-G association (Factor 4 of the >5% opal matrix), and the terrigenous variable (Factor 2 of this matrix), do not show similar relationships with opal because mollusc shells occur within the seaward flank of the diatomaceous mud belt, whereas G and terrigenous do not. Similarly, an inverse relationship between the gravel-opal association and organic matter, and a very weak negative loading on faecal pellets is interpreted as reflecting low polychaete worm population densities in the organic matter-rich seaward edge of the mud belt, but none within the flank of the deposit where relict mollusc shells occur.

Factor 5 satisfies only 8.0% of the total matrix variance, and is described almost exclusively by a strong positive loading on the variable glauconite. Low concentrations of glauconite occur along parts of the outer shelf break and the upper slope, and a very weak negative loading on the organic matter variable indicates that most organic matter is oxidized before it reaches these sea-floor depths.

(c) Balance Matrix

Factor 1 is in many respects similar to Factor 1 of the >50% CaCO_3 matrix, and refers to an increasing state of fineness of the Kunene Margin sediments with depth. A weak correlation between CaCO_3 and organic matter signifies that the latter is derived mainly from foraminiferal sources, and that the concentration of both components increases with distance from shore. In contrast to the sand-faecal pellet association indicated by Factor 1 of the >50% CaCO_3 matrix, the sand variable is portrayed in isolation here because of the multi-component nature of sand-size sediment on the Kunene Mid Shelf.

Positive loadings on gravel, CaCO_3 , pP and gpP in Factor 2 indicate an association between gravel-size shell deposits, and sand-size phosphorite deposits. This association refers specifically to the Northern Mineral Province where the concentration of Mollusca is low. No equivalent variable association was indicated by the >50% CaCO_3 matrix because Mollusca deposits occur in the vicinity of Palgrave Point to the practical exclusion of phosphorite. In the Southern Mineral Province however, high concentrations of Mollusca and phosphorite are intimately associated, and were probably mixed during the Flandrian transgression. A negative loading on the terrigenous variable gives indirect support for this contention, in that the hydrodynamic properties of sand-size quartz would have resulted in their fractionation from sand-size phosphorite and gravel-size Mollusca during the transgression.

In Factor 3, strong positive loadings on faecal pellets and CaCO_3 , and somewhat weaker loadings on organic matter and gpP, is in some respects similar to the negatively loaded variables of Factor 1 in the >50% CaCO_3 matrix. The association between faecal pellets, CaCO_3 , and organic matter in this matrix implies a dependance by polychaete worms on foraminiferal food sources on the Kunene Shelf, whereas on the Walvis Shelf, diatomaceous debris is the principle food source. The weak association between faecal pellets and gpP in both matrices however, reflects the same seaward displacement of gpP relative to pP. The negative loading on the terrigenous variable is interpreted as indicating that polychaete worms tend to avoid habitation of regions dominated by quartz sand because of the low influx of biogenic detritus there.

Factor 4 describes an association of positively loaded variables characteristic of the northern part of the Kunene mud belt, viz., clay, organic matter and opal. Weak negative loadings on the terrigenous and depth variables suggest a similar situation to that occurring in the diatomaceous mud belt, i.e., terrigenous contamination being restricted to the landward flank of the two deposits.

Factor 5, as with Factor 5 of the >50% CaCO_3 matrix, is almost exclusively defined by the variable G, thus indicating that it is totally unrelated to other textural and compositional parameters of the sediment. A weak inverse relationship between G and the gravel and terrigenous variables signifies that G is largely confined to the outer margin.

5.6.4 Discussion

The north-central part of the South West African continental margin as defined by the boundaries of the study area, is blanketed by a complex mixture of unconsolidated relict and modern surficial sediments. This material is composed of eight principal sedimentary components, of which three are biogenic in origin (CaCO_3 , organic matter and opal), four authigenic (cP, pP, gpP and G), and one terrigenous (quartz). The CaCO_3 and quartz components are in part modern and in part relict, the pP, gpP and G are wholly of relict origin, and the remaining biogenic and authigenic components are all modern. Several Pleistocene sea-level regressions (Guilcher, 1971) have caused wide-spread dispersal of some of the relict components, and superposition of Holocene sediment with reworking in places by benthic infauna has resulted in complex component associations. In places these associations indicate a genetic relationship among the components, whereas in others, the associations simply reflect a change in the hydrological environment with concomittant changes in the pattern of sedimentation

Factor analysis has served to highlight significant associations among

the various textural and compositional parameters of the unconsolidated sediment, and has drawn attention to some of the less significant ones that were not previously recognized in the regional distribution maps. Interpretation of the associations was simplified by having separate factor matrices for each of the three sediment lithofacies groups (matrices D, E and F, Fig. 5.37), and the more significant of these associations are recognizable in the matrices of the regional sediment groupings (matrices A, B and C, Fig. 5.37).

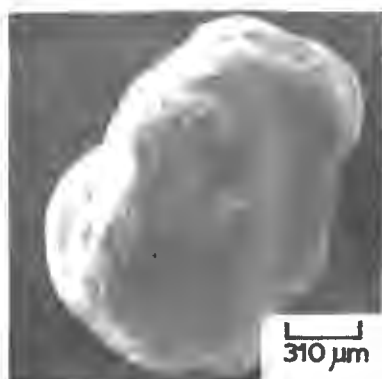
In summary, the factor analysis results have indicated the following:

- The diatomaceous mud belt (samples with >5% opal) is 'purest' in the central regions, where it consists predominantly of clay-size, opaline diatom frustules. The shallow, landward flank of the deposit is contaminated by sand-size quartz, and the highest concentrations of cP occur there as well. The deep, seaward flank of the deposit is contaminated by foraminifera and contains the richest concentrations of organic matter. The seaward edge of the deposit in places overlies relict mollusc shells with trace amounts of G.
- Calcareous sediments (samples with >50% CaCO_3) on the Walvis Outer Margin, become increasingly fine-grained with depth, and sand-size components, such as faecal pellets, are confined essentially to the mid shelf. Quartz sand occurs separately from sand-size pP and gpP, and generally reflects regions of low modern carbonate sedimentation on the inner shelf. Gravel-size mollusc shells occur within the seaward flank of the diatomaceous mud belt, but quartz, faecal pellets and glauconite are restricted to its seaward edge.
- The terrigenous and authigenic sediments (remaining samples), represented mainly on the Kunene Margin, also become increasingly fine-grained with distance from shore, and contain a greater abundance of foraminifera and organic matter on the upper slope. The pP and gpP of both the Northern and Southern Mineral Provinces are associated with mollusc shells. Polychaete worms on the Kunene Margin depend on foraminiferal debris for their food as opposed to diatomaceous debris on the Walvis Margin. The Kunene mud belt is similar to the diatomaceous mud belt compositionally, and is contaminated by quartz sand only on its landward flank. Relict G is largely confined to the outer margin and occurs independently of all other sedimentological parameters.

Plate 5.1

SEM photographs of coarse-grained quartz particles from
aeolian, littoral and deep-water environments

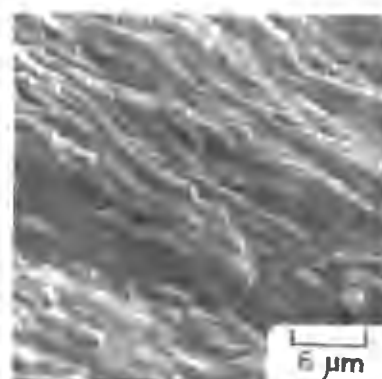
- a,b and c. Sediment from a dune crest near Conception Bay (sample JMB-15).
- a. (60x) Subrounded grain showing 'dish-shaped' concavities.
- b. (200x) A dish-shaped concavity with a freshly fractured surface.
- c. (3400x) Frosted surface from deposition of amorphous silica.
- d,e and f. Sediment from the beach foreshore at Pelican Point (sample BS-58)
- d. (120x) Subrounded grain with dish-shaped concavities.
- e. (1000x) 'Scaphoid grooves' formed in high-energy subaqueous environments.
- f. (5000x) Randomly orientated impact V's, and others with orientation
from sea water etching.
- g,h and i. Sediment from the inner shelf off Palgrave Point (sample 3837,
depth 81 m).
- g. (60x) Subrounded grain with dish-shaped concavities.
- h. (3000x) Upturned plates - an aeolian feature.
- i. (3000x) Parallel fracture cleavages inherited from primary host rock.
- j,k and l. Sediment from the inner shelf off Sylvia Hill (sample 3568, depth
43 m).
- j. (70x) Subrounded grain with dish-shaped concavities.
- k. (1000x) Smooth surface with superimposed random V's.
- l. (2000x) Exfoliated surface layer of quartz probably from impact.



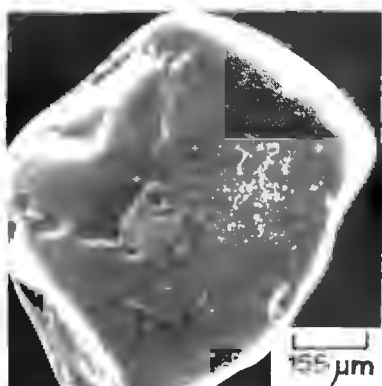
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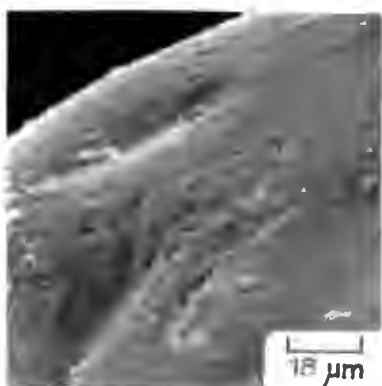
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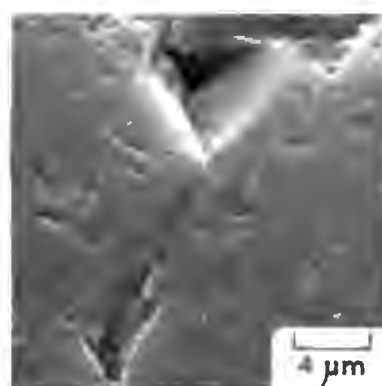
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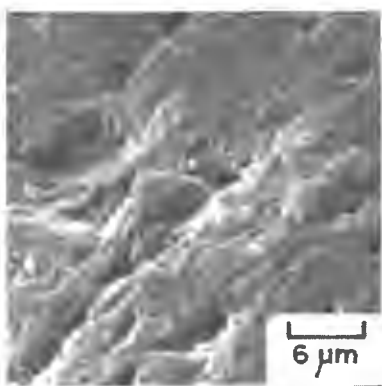
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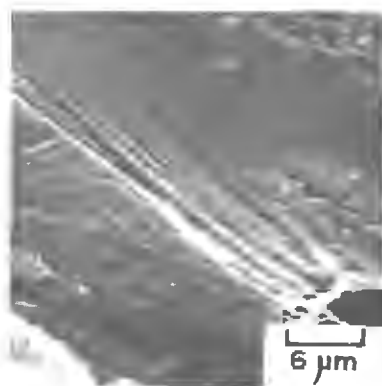
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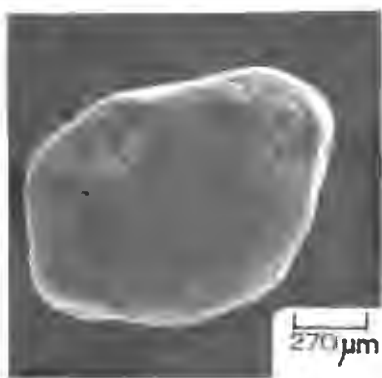
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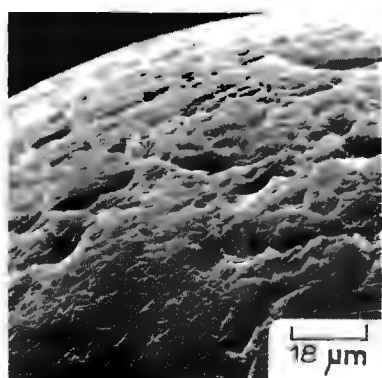
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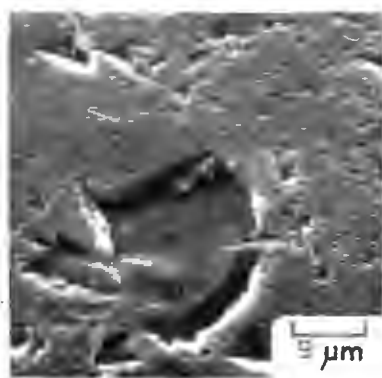
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l

Chapter 6. SARDINOPS CORES

6.1 INTRODUCTION

This chapter is intended to give a brief account of some of the chemical variations that occur in depth in the unconsolidated sediments of the Walvis Continental Shelf. Eleven long gravity cores were collected from the study area during the course of routine sediment sampling (Table 1.1), but in view of the principal objectives of the study (Chapter 1) it was decided not to embark on a major in-depth investigation of the shelf sediments. The cores therefore remain capped and sealed in the U.C.T. Sediment Storage Room. The Sardinops cores were inherited by the writer in a sub-sectioned and partially analysed state from Dr. C.P. Summerhayes (Appendix A.23), and were thus available for inclusion in some of the routine analyses being carried out on the unconsolidated surficial sediments.

The cores were collected by the Division of Sea Fisheries in 1963 from the R.V. SARDINOPS. In all, 27 cores numbering 24 to 50 were recovered, and the area of collection was the Walvis Shelf between Ambrose Bay (21°S) and Conception Bay (24°S). The shallowest core was recovered from a depth of 75 m (core No.29) and the deepest one from 357 m (core No.47).

All the cores have been classified into two sets, an 'online set' and a 'grouped set', and this was based on a consideration of their geographic locations. The online set, consisting of 18 cores, lies along six latitude lines spaced roughly 30 n.miles apart, and the grouped set, consisting of nine cores, lies clustered around the two shoreward core-stations of Line 4 (core Nos.33 and 34) (Fig. 6.1).

Most of the 193 sub-sections which were available for study, consisted of between 2 to 5 grams of material, and were analysed for four chemical components viz., CaCO_3 , C_{org} , P_2O_5 and K_2O . The results of these analyses are listed in Appendix B.16. The online core results are also shown graphically in Fig. 6.1, and the grouped core results have been summarized in Table 6.1. The geographic location of the cores is shown in Fig. 6.1 where their regional setting in relation to the unconsolidated surficial sediment is shown by means of concentration isopleths of the four chemical components.

6.2 RESULTS AND DISCUSSION6.2.1 Grouped cores

With the exception of a few CaCO_3 values, this set of cores tends to be fairly consistent internally and are therefore conveniently summarized (Table 6.1).

Table 6.1. Average concentrations of 4 chemical components in the 'grouped' Sardinops cores

Core			Average concentration (weight percent)			
Core No.	Depth (m)	Length (cm)	CaCO ₃	C _{org}	P ₂ O ₅	K ₂ O
Online core No.33	93	63	2,6(12)	5,1(13)	,5(13)	,6(12)
24	80	20	1,4 (4)	8,1 (4)	,8 (4)	1,1 (4)
25	104	33	3,4 (6)	5,1 (7)	,4 (6)	,6 (6)
28	106	91	3,3(17)	5,7(18)	,4(18)	,6(17)
29	75	65	1,2(13)	4,1(12)	,5(13)	,6(12)
30	95	37	2,0 (6)	6,3 (6)	,5 (6)	,8 (3)
32	95	53	1,4 (9)	5,5(11)	2,6(11)	,7(10)
Mean			2,2	5,7	,8	,7
Online core No.34	135	33	34,4 (7)	13,6 (7)	,7 (7)	,8 (5)
26	129	39	6,5 (8)	8,5 (8)	,7 (8)	,6 (8)
27	130	40	14,2 (7)	11,3(11)	,7 (8)	,6 (7)
31	121	43	4,0 (9)	8,0 (9)	,5 (9)	,6 (6)
Mean			14,8	10,4	,7	,7

(n) = number of subsections analysed.

(a) Core group associated with online core No.33.

These cores, because they are located along the eastern flank of the diatomaceous mud belt, contain low concentrations of all four chemical components due to the heavy dilution from opal. The richest of these, C_{org}, varies erratically over a small range down the length of the cores, and shows no correlation with changes in the concentration of the other components. These C_{org} variations are probably a response to fluctuations in the oxygen content of the water column, and to the degree of dissolution undergone by diatom frustules during diagenesis in the substrate. The low average C_{org} content of core No.29 is due to its location within a 'tongue' of organic matter-poor sediment that extends southwards from Swakopmund, and seaward of Pelican Point. The complexity of Fig. 6.1 prevented illustration of this tongue, but from Fig. 5.19, its configuration suggests that it may be related to an inshore counter current in this area (Chapter 2).

The average concentration of CaCO₃ in the cores exhibits the same regional trend of westward increasing values that was so apparent in the unconsolidated surficial sediments (Chapter 5) e.g., core No.24 at 80 m depth has 1,4% CaCO₃, and core No.25 at 104 m depth has 3,4% CaCO₃ (Table 6.1). Another interesting aspect of the cores is that their CaCO₃ contents exhibit no decrease

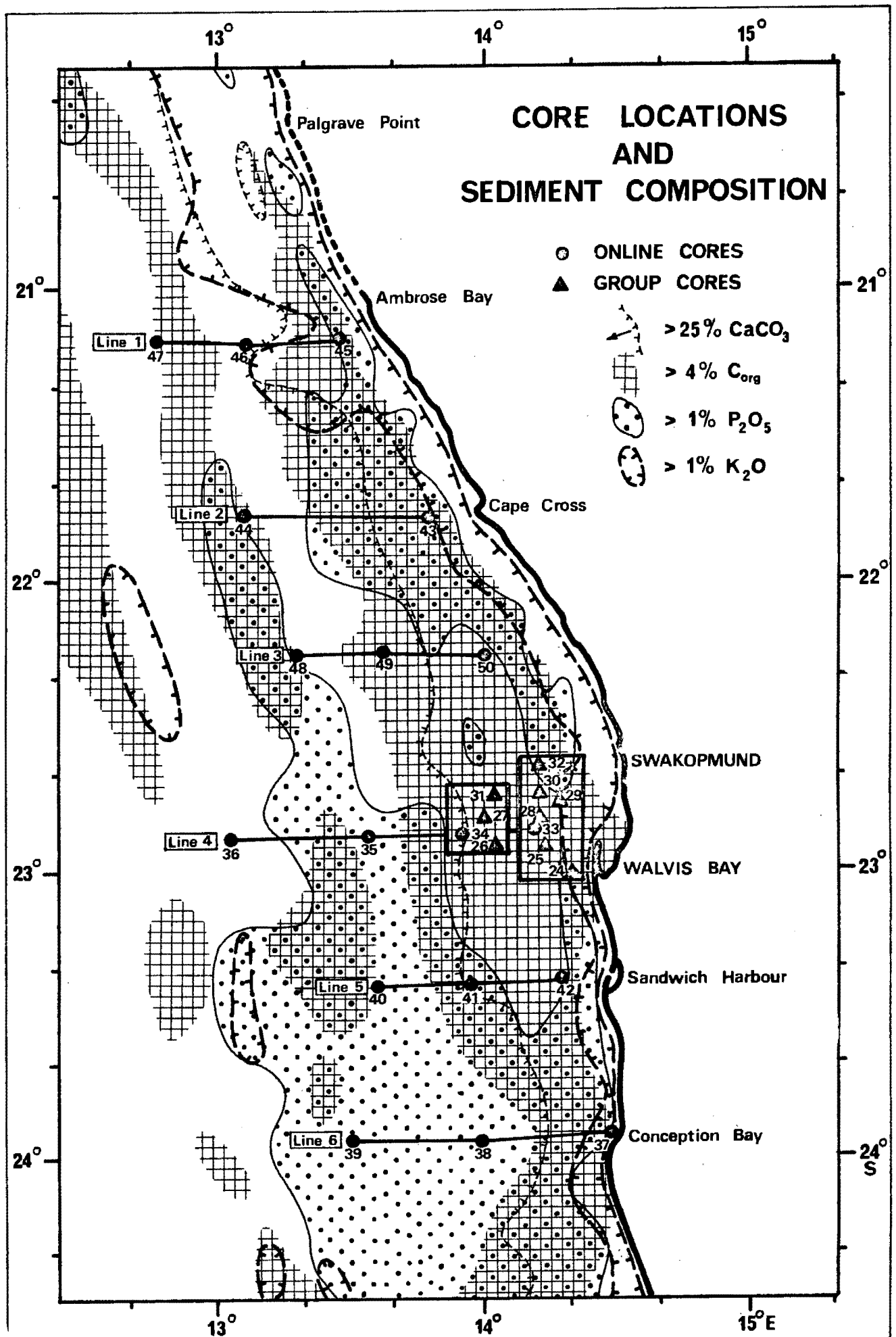


Figure 6.1

in concentration with depth, and in some of the deeper core sub-sections, an actual increase is apparent e.g., core No.25 increases from 2,5% at 5-10 cms depth, to 6,5% at 10-15 cms depth; and core No.28 increases rapidly from 1,6% at 65-70 cm depth, to 9,9% at 85-91 cm depth (Appendix B.16). This is rather surprising in view of the high H_2S content of the muds (Chapter 2), and the finding of Mason (1966) that $CaCO_3$ tends to dissolve at a pH below 7,8. Romankevich and Baturin (1972) have found that the pH rises progressively with depth in the mud, and reaches 7,8 at about 200 cm below the surface. Planktonic foraminifera tests, the only source of $CaCO_3$ on the eastern flank of the mud belt, must therefore be undergoing slow, continuous dissolution in the top 2 metres of the deposit. This factor, together with the limited influx of foraminifera here, satisfactorily accounts for the low average $CaCO_3$ in the cores. The occasional elevated values found in some of the deeper core sub-sections may be a reflection of periods of less intense upwelling, when oxygenated, foraminiferal-bearing surface waters were able to penetrate into the nearshore zone. Baturin (1971e) has attributed a marked temperature difference between the top 5 cm of the diatomaceous mud and that immediately below it, to rapid changes in the character of the overlying waters.

Except for core No.32, all the P_2O_5 values are low, usually less than 1%, and show negligible variation down the length of the cores. Core No.32 averages 2,6% P_2O_5 and contains widely divergent sub-section values, with a maximum of 12,1% at the bottom (50-53 cm). Close proximity of this core to the thin strip of cP-containing diatomaceous mud (Chapter 5) is probably the reason for these elevated P_2O_5 values, and the erratic variations of P_2O_5 in the core would then reflect the random distribution of concretions and silt-size phosphatic clots in the mud. The dramatic increase of P_2O_5 at the bottom of the hole indicates that one or more large concretions were sampled by the corer.

Since potash-bearing minerals other than mica are virtually non-existent in the diatomaceous mud belt (Chapter 5), the abundance of K_2O is taken to reflect the influx of this terrigenous component during the advent of bergwind conditions (Chapter 1). Indirect evidence for this is provided by the highest concentration of K_2O being recorded in core No.24 (1,1%) which is located closest to shore, and by the presence of a biotite-rich strip of sediment in shallow water farther to the north (Chapter 5).

(b) Group associated with online Core No.34

In general, this group of cores is much richer in $CaCO_3$ and C_{org} than the group described above, but the P_2O_5 and K_2O values are still low and of the same order of magnitude. The spatial relationship noted earlier between the average $CaCO_3$ content of the cores, and their distance from shore is again

noticable in this set e.g., core No.26 at 129 cm depth has 6,5% CaCO_3 , and core No.34 at 135 cm depth has 34,4% CaCO_3 . The C_{org} content however, in addition to being very rich, differs from the previous set in being correlatable with CaCO_3 . This is apparent not only in the average C_{org} and CaCO_3 values of the cores (Table 6.1) but also down the lengths of some of them e.g., core Nos.26 and 27, between 15 and 25 cm (Appendix B.16). The most westerly core of the set, core No.34, simply reflects uniform and extremely high concentrations of both components. Correlation between CaCO_3 and C_{org} does not indicate that organic matter is foraminiferal-derived, but rather that the two components increase independantly for similar reasons. The factor controlling the abundance of both components is the degree to which the diluting diatom frustules were dissolved, and in the case of CaCO_3 , planktonic foraminifera also reach maximum densities west of the diatomaceous mud belt. The association between the two chemical components is therefore essentially fortuitous.

6.2.2 Online cores

These cores are not restricted to the diatomaceous mud belt as with the grouped cores but extend across the full width of the continental shelf (Fig. 6.1). Cores from the eastern end of each of the sample lines do however, coincide with the mud belt, and generally possess greater lengths than those recovered farther to the west (Fig.6.2). Because of the similarity in composition between cores disposed approximately equidistant from shore, it is more convenient to discuss them in this way rather than to discuss each of the sample lines individually.

(a) Cores from the eastern end of the sample lines

These cores were collected from between $1\frac{1}{2}$ and 30 n.miles from shore (Nos.45,43,50,33,42 and 37). With minor exceptions, C_{org} is dominant amongst the four components analysed for and invariably is present in concentrations >5%. Only in core No.37 adjacent to Conception Bay is CaCO_3 consistently higher than C_{org} . The reason for this is probably related to the local hydrological conditions in the lee of the foreland (Fig.6.1) e.g., weaker wave energies and the presence of a slack counter current (Chapter 1).

The concentration of P_2O_5 and K_2O in these cores is low, generally <1%, with the latter (from windblown terrestrial mica) usually showing more consistent and fractionally higher values than P_2O_5 . In core Nos.43 and 37 an inverse relationship exists with P_2O_5 increasing from about 1% at 20 cms depth, to approximately 3,5% at the surface. The regularity of the increments suggest that they are not due to randomly distributed concretionary phosphorite nodules, but rather to entrapment of P_2O_5 in the soft-body parts of diatom frustules, and possibly in silt-size phosphatic clots. Calvert and Price (1971b) have

CHEMICAL COMPOSITION OF ONLINE SARDINOPS CORES

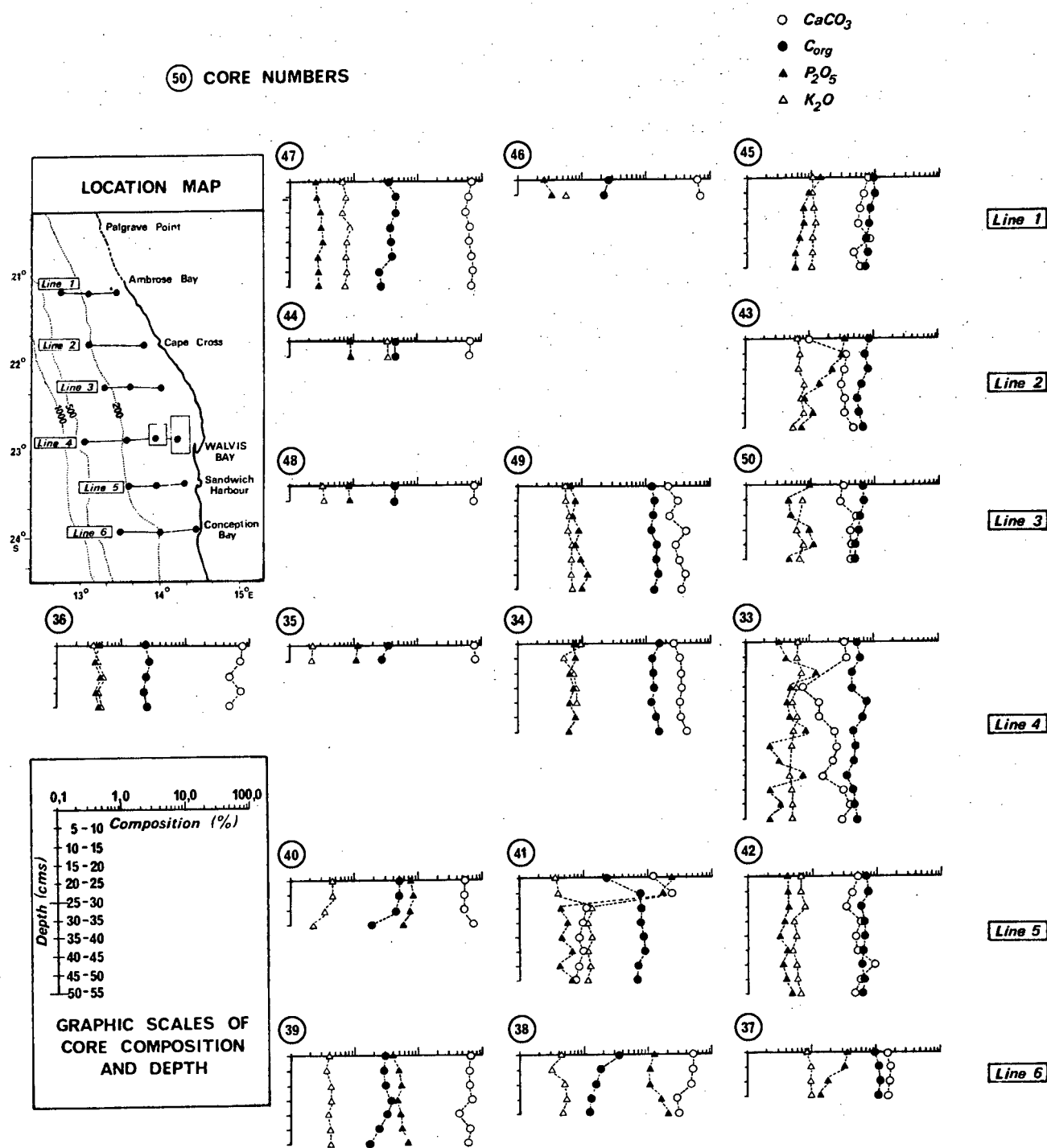


Figure 6.2

found that P_2O_5 is normally released more rapidly than other nutrients (Chapter 2), and it must therefore be assumed that fish scales or other fine-grained nucleation sites exist for the retainment of P_2O_5 .

(b) Cores from the middle of the sample lines

These cores lie at a distance not exceeding 40 n.miles from the coast (Nos.46,49,34,41 and 38). As a group they differ from each other fairly considerably, and most of them merit individual discussion.

Starting with the most northerly core, No.46, its 5 cm length is identical in composition to the suite from the western end of the sample lines, and its discussion is therefore delayed till later.

The next two cores, Nos.49 and 34, possess very similar compositions and are consequently discussed together. They lie along the edge of the western flank of the diatomaceous mud belt, and the regularity of their compositions with depth indicate that the overlying water mass in this region is relatively stable. The C_{org} content of the two cores is the highest on record (12,3 and 16,6% respectively), however, their $CaCO_3$ contents are even higher (21,8 to 42,4% respectively). These attributes reflect dense populations of benthic foraminifera, particularly Bolivina sp., in this region (Chapter 5) which apparently thrive on the diatomaceous organic matter accumulating there. The P_2O_5 and K_2O concentrations in the cores is low, usually <1% and show no variations with core-depths at all.

Core No.41 is the most interesting of all the cores because of a dramatic compositional change that occurs 5 to 10 cm below the sediment-water interface. The sediment below this transition depth is diatomaceous as indicated by relatively high and consistent C_{org} , and low P_2O_5 contents (~7,5% and ~0,5% respectively). The $CaCO_3$ content however is abnormally low (~1%), and the K_2O values are abnormally high (~1,3%) for this part of the shelf. Above the transition depth, the concentrations of $CaCO_3$ and P_2O_5 increase dramatically to 11,8% and 22,0% respectively (Appendix B.16), and the C_{org} and K_2O values drop suddenly to 2,3% and 0,4% respectively. This core, which was recovered from a depth of 146 m, lies just seaward of the western edge of the diatomaceous mud belt and therefore represents the only evidence for the existence of sub-surface, relict, diatomaceous mud. The sequence of events that gave rise to the chemical changes seen in core No.41 are envisaged as having occurred roughly as follows: the diatomaceous sediment below the transition depth (5-10 cm) was deposited at a time when the coastline was located close to the present site of the core. This deduction is based on the similarity in composition between it and the landward edge the diatomaceous mud belt as it exists today, i.e., low $CaCO_3$ and high K_2O . With rise in sea level, the upper portion of the diatomaceous mud deposit was eroded by storm-wave-induced bottom currents,

and relict sand-size pelletal phosphorite (pP) was washed over its lower semi-indurated part. At the same time, the abundance of CaCO_3 increased due to the influx of foraminiferal tests, and the sediment above the transition depth in the core therefore reflects P_2O_5 and CaCO_3 concentrations which are consistent with the present-day unconsolidated sediments of the Southern Mineral Province (see Chapter 5, Section 4).

The last core, No.38, also comes from the Southern Mineral Province, and simply reflects high CaCO_3 and P_2O_5 derived from mollusca, foraminifera, pP, and gpP.

(c) Cores from the western end of the sample lines

These cores (Nos.47,44,48,35,40 and 39) come from a maximum distance of 60 n.miles from the coast. Two other cores are included in the discussion of this group because of their similarity in composition. These are core No.46 (middle of Line 1), and core No.36 (Line 4, 90 n.miles from the coast). With few exceptions, the cores are short, probably reflecting the presence of stiff Neogene and Quaternary muds along the outer parts of the continental margin (Fig. 3.1).

The dominant chemical component at all depths in these cores is CaCO_3 , and this is due to the high concentrations of planktonic foraminifera in the sediments of the outer margin. The order of abundance of other constituents is $\text{C}_{\text{org}} > \text{P}_2\text{O}_5 > \text{K}_2\text{O}$, and only in a few instances is this general trend modified. For example, core No.44 has relatively high K_2O values because of its close proximity to a glauconite deposit on the upper slope off Cape Cross, and core Nos.40 and 39 reflect high P_2O_5 values due to their locations in the Southern Mineral Province.

Chapter 7. MINERALOGY AND GEOCHEMISTRY OF THE CLAY FRACTION

7.1 INTRODUCTION

In this Chapter, the results of a mineralogical and geochemical investigation on the $<2\mu\text{m}$ sediment-size fraction are reported in two sections. Fifty one samples from the hinterland and continental margin were selected for study, and consideration of their geographic locations facilitated their grouping into 7 different lithofacies types. These are: river silts (4 samples), inner shelf Kunene muds (4 samples), inner shelf diatomaceous muds (19 samples), mid shelf sands (9 samples), upper slope muds (5 samples), outer margin stiff muds (7 samples) and upper slope piston core muds (3 samples). The river samples were obtained from the four largest drainage systems in the hinterland (Table 1.2), and, apart from the Kunene River sample, were collected from between 2 and 10 km from coast. Because of inaccessibility, the Kunene River sample was collected from an area of swampy lowlands approximately 300 km from the coast. The stiff mud samples are pre-Holocene in age, some having dates as old as Miocene (Appendix B.3), and were recovered from the Kunene Margin and the southern part of the Walvis Margin (Fig. 3.1). The piston core samples were obtained from Dr. C.P. Summerhayes who recovered piston core No.2 in 1973/74 during Cruise 115 of the R.V. Chain. Although undated, the top section of the core (14-16 cm) has been considered together with the other continental margin sediments, whereas the middle (44-46 cm) and bottom (75-77 cm) sub-sections, which may well be Holocene in age, have been grouped together with the stiff muds.

The methods used for sample collection, storage and salt removal are discussed in Appendix A.24, and the procedures used to concentrate the clay-size sediment are described in Appendix A.25. After homogenization, each of the clay-fraction concentrates was split into two sub-samples, one half of which was utilized for the mineralogical investigation, and the other for the geochemical study.

One of the principal aims of this study was to contrast the geochemical character of terrigenous sediments on the Kunene Margin with that of the biogenic sediments on the Walvis Margin. To this end, it was considered more appropriate to compare similar sediment size fractions rather than bulk samples as dilution by quartz and CaCO_3 may considerably alter the metal content of some of the samples. Recently, several papers have been published in which, for similar reasons, geochemical analyses have been confined to the clay fraction of the sediment. For example, Wright (1974a, 1974b) in his study of the Barents Sea sediments, and Parker (1974) who examined the Speeton clay in Yorkshire, have both extracted the clay fractions for geochemical study. Some workers, eg., Burnett (1971), in his study of the sediments of the central

Pacific, have determined the geochemistry of bulk samples, and then expressed the analyses on a carbonate-free basis, but this greatly increases the relative error of samples with high carbonate values.

7.2 MINERALOGY OF THE CLAYS

7.2.1 Introduction

The composition of clay-size sediment on the continental margin is highly diversified, and consists for the most part of terrigenous clay minerals, quartz, juvenile and partially dissolved diatom tests, comminuted foraminiferal shells and organic matter. Texturally, the clay fraction ranges from nil to 77,8% of the dry weight of the sediment, and averages 18,7% for the 521 samples analysed (Table 5.1). It therefore constitutes a significant portion of the total sediment, and this part of Chapter 7 is devoted to an examination of the distribution and origin of the most commonly occurring terrigenous clay minerals in 51 selected samples.

Pre-treatment of the clay samples for X-ray diffraction analysis is described in Appendix A.26, and procedures followed for determining the semi-quantitative proportions of the three most commonly occurring minerals, montmorillonite, illite and kaolinite (+ minor chlorite), are discussed in Appendix A.27. A fourth clay mineral, vermiculite, has been found to occur in the south-central part of the continental shelf, and its abundance has been calculated as a ratio in terms of illite. Instrument settings used on the X-ray diffractometer are described in Appendix A.28, and a complete listing of the clay mineral proportions in the samples is given in Appendix B.17. A summary of the results in the form of averages and ranges is given in Table 7.1.

7.2.2 Regional distribution

(a) River clays

The clay mineral assemblage characterising the hinterland was obtained by analysing sediment from the four largest rivers draining from the Great Escarpment, viz., the Kunene, Hoanib, Ugab and Swakop (Table 1.2). An important observation to emerge from this study is that the climate appears to exert a stronger influence on the overall composition of the clays than the underlying bedrock geology. This climatic influence has been widely observed in the field and experimented with in the laboratory, and a voluminous literature exists on the subject (Milne and Earley, 1958; Weaver, 1958; Correns, 1963). In this particular case, it is expressed by a progressive change in the clay mineral assemblage from north to south across the study area, thus reflecting the increased aridity of the climate towards the south.

In the north of the area, the Kunene River is dominated by montmorillonite

Table 7.1 The average clay mineral composition of seven related sedimentary facies*

	Terrestrial sediment	Modern continental margin sediment				Pre-Holocene continental margin sediment	
	River silt	Inner shelf Kunene mud	Inner shelf diatomaceous mud	Mid shelf sand	Upper slope mud	Outer margin stiff mud	Upper slope piston core No.2**
No. of samples	4	4	19	9	5	7	3
17 ⁰ _A	23 (4 - 59)	27 (13 - 34)	11 (0 - 28)	15 (0 - 35)	24 (12 - 36)	34 (16 - 71)	19 (13 - 29)
10 ⁰ _A	62 (9 - 87)	57 (50 - 73)	81 (66 - 87)	74 (47 - 94)	53 (43 - 67)	53 (20 - 74)	70 (59 - 75)
7 ⁰ _A	16 (9 - 32)	16 (13 - 19)	8 (4 - 16)	12 (6 - 19)	22 (21 - 24)	12 (9 - 18)	11 (10 - 12)
14 ⁰ _A / 10 ⁰ _A	,14 (0,03-0,17)	,31 (0,27-0,38)	,51 (0,27-1,00)	,62 (0,29-1,18)	,57 (0,36-0,83)	,37 (0,21-0,76)	,14 (0,09-0,20)
17 ⁰ _A crystallinity	,39 (0,21-0,46)	,37 (0,30-0,56)	,53 (0,50-0,57)	,36 (0,29-0,52)	,40 (0,38-0,44)	,40 (0,23-0,57)	,61 (0,42-0,73)

* All measurements made on glycolated X-ray traces

** Except top subsection (14-16 cms)

17⁰_A = montmorillonite

10⁰_A = illite

7⁰_A = kaolinite (+ small amounts of chlorite and vermiculite)

14⁰_A/10⁰_A = vermiculite (+ small amounts of chlorite)/illite ratio based on peak heights

17⁰_A = montmorillonite crystallinity = $\frac{1}{2}$ peak width/peak height ratio

(59%), followed by kaolinite (32%), and contains only minor amounts of illite (9%) (Figs. 7.2 and 7.3). This clay mineral assemblage reflects strong leaching of the bedrock in the sub-tropical climate of southern Angola, with consequent release of Mg^{2+} and K^+ ions, and the formation of montmorillonite and kaolinite. Southwards from the Kunene River, the abundance of these two clays decreases rapidly to 18% and 11% respectively at the Hoanib River, and then continues to decrease more gradually towards the Swakop River, the most southerly of the four drainage systems (4% and 9% respectively). The illite content of the clay mineral assemblage shows an antipathetic relationship to montmorillonite and kaolinite, increasing progressively from north to south across the study area from 9% at the Kunene River to 87% at the Swakop. This great abundance of illite in the south is due to mechanical disintegration of bedrock in the arid climate of the Namib Desert (Chapter 5).

Because of the importance of the hinterland in providing terrigenous clay material to the continental margin, X-ray diffractograms of the four river clays are presented in Fig. 7.4. It is apparent from this diagram, that in addition to the clay minerals already discussed, small amounts of chlorite occur in the two central rivers, the Hoanib and the Ugab, but evidently not in the Kunene or Swakop River clays. Close proximity of the Kaoko lavas to the two central rivers (Fig. 1.2) probably accounts for these differences.

Finally, the crystallinity of the montmorillonite, as determined from ratios of half peak-width/peak-height, is directly proportional to the abundance of the clay mineral (Fig. 7.1), being best for the Kunene River (0,21) and worst for the Swakop River (0,46) (Appendix B.17).

(b) Continental margin clays

The distribution of clay material on the continental margin is determined by four main factors: (i) the incidence of easterly bergwind conditions during the autumn months (Chapter 1), (ii) the presence of a single, comparatively large perennial river, the Kunene, at the northern boundary of the study area, (iii) the influence the Angola and Benguela current systems, which converge and intermingle in a complex series of streams and eddies in the central part of the study area (Chapter 2) and (iv), the flocculation rates of different clay minerals on entering the marine environment. Each of these factors is considered in appropriate sections below. In general it may be said that illite is the dominant clay mineral in the study area, this being followed in decreasing order of abundance by montmorillonite, kaolinite, vermiculite, and chlorite. On a regional basis, the clay mineral composition of the shelf sediments closely parallels the composition of the onshore sediments, but on the upper slope, the clay minerals are dispersed much more uniformly.

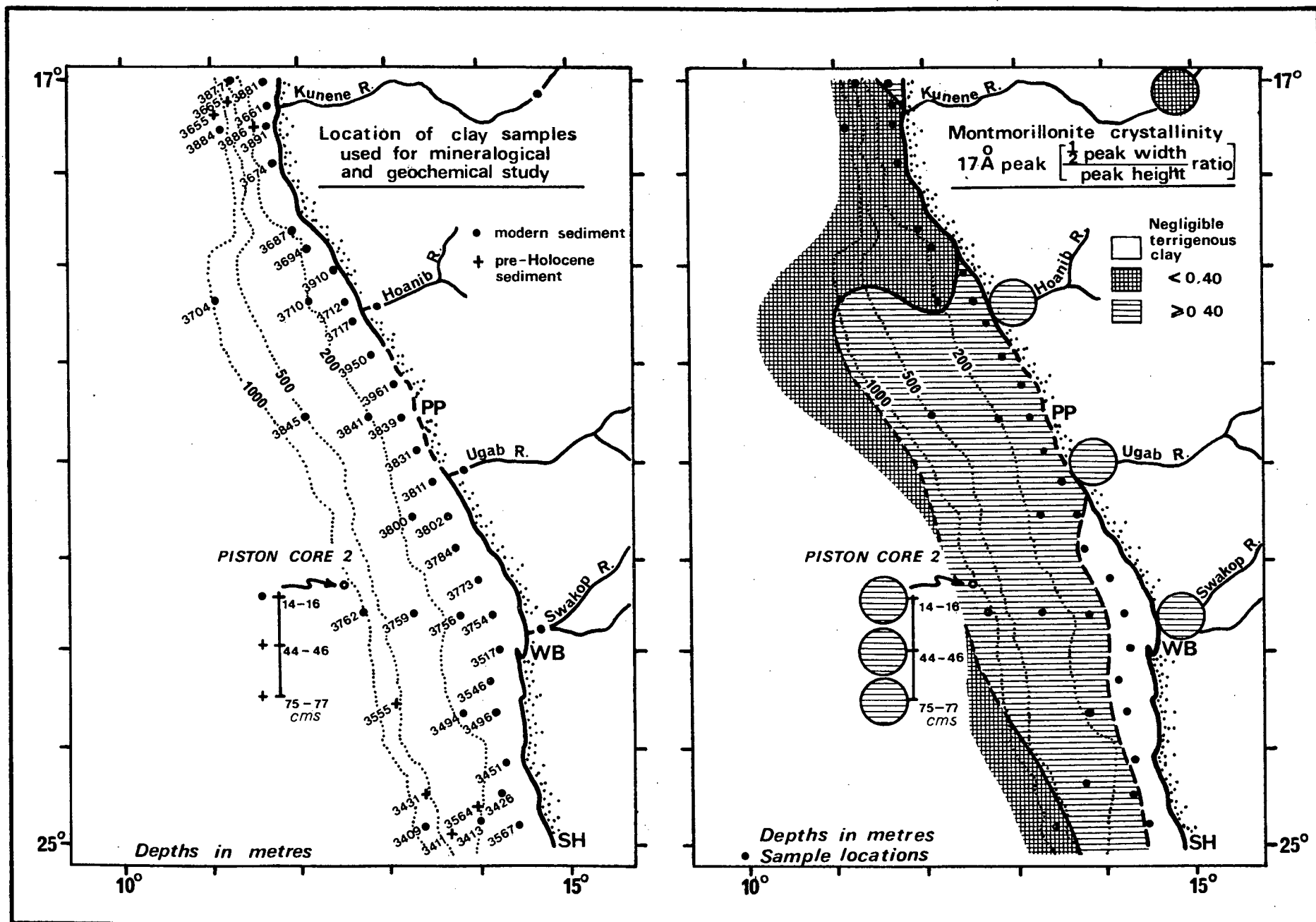


Figure 7.1

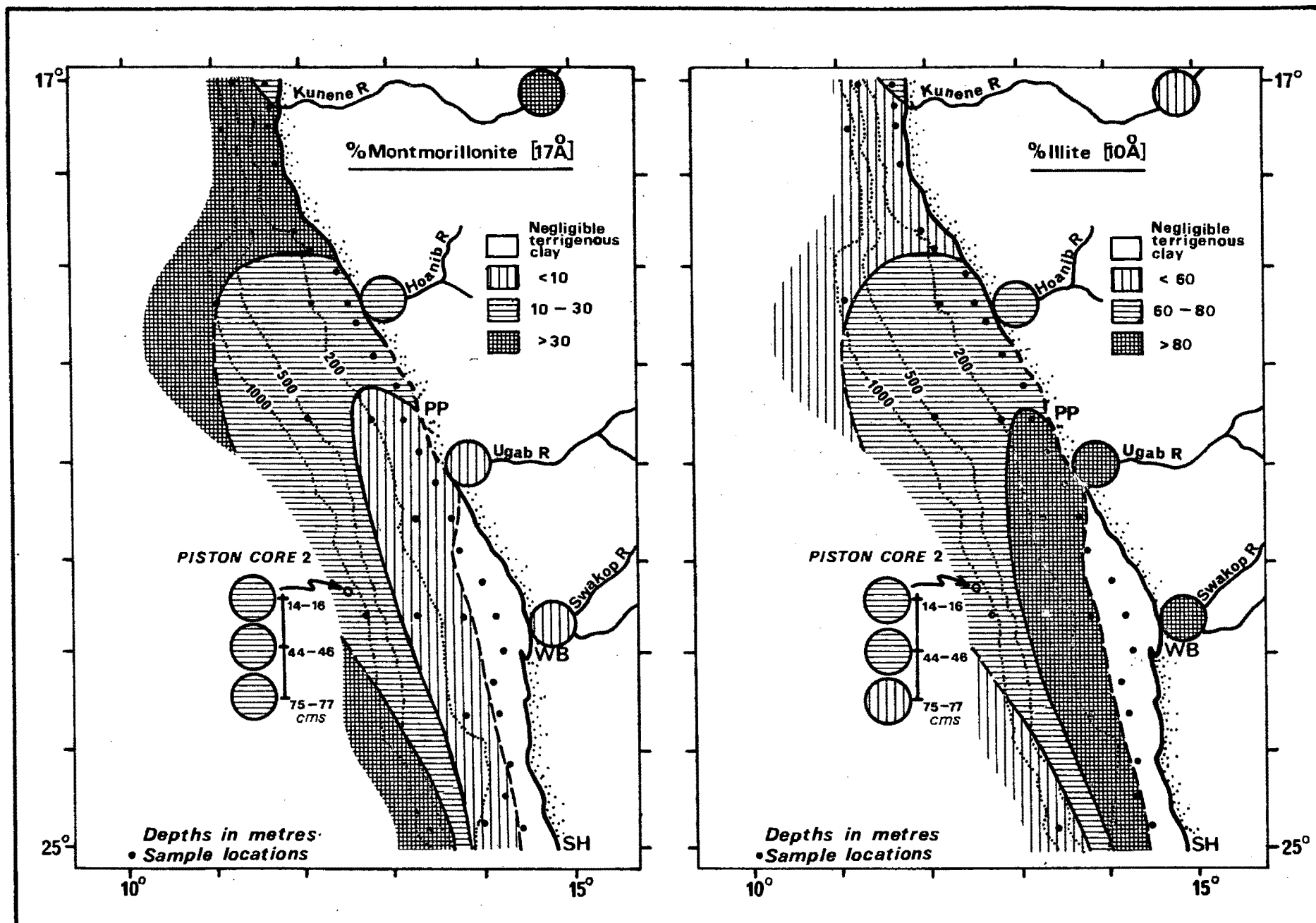


Figure 7.2

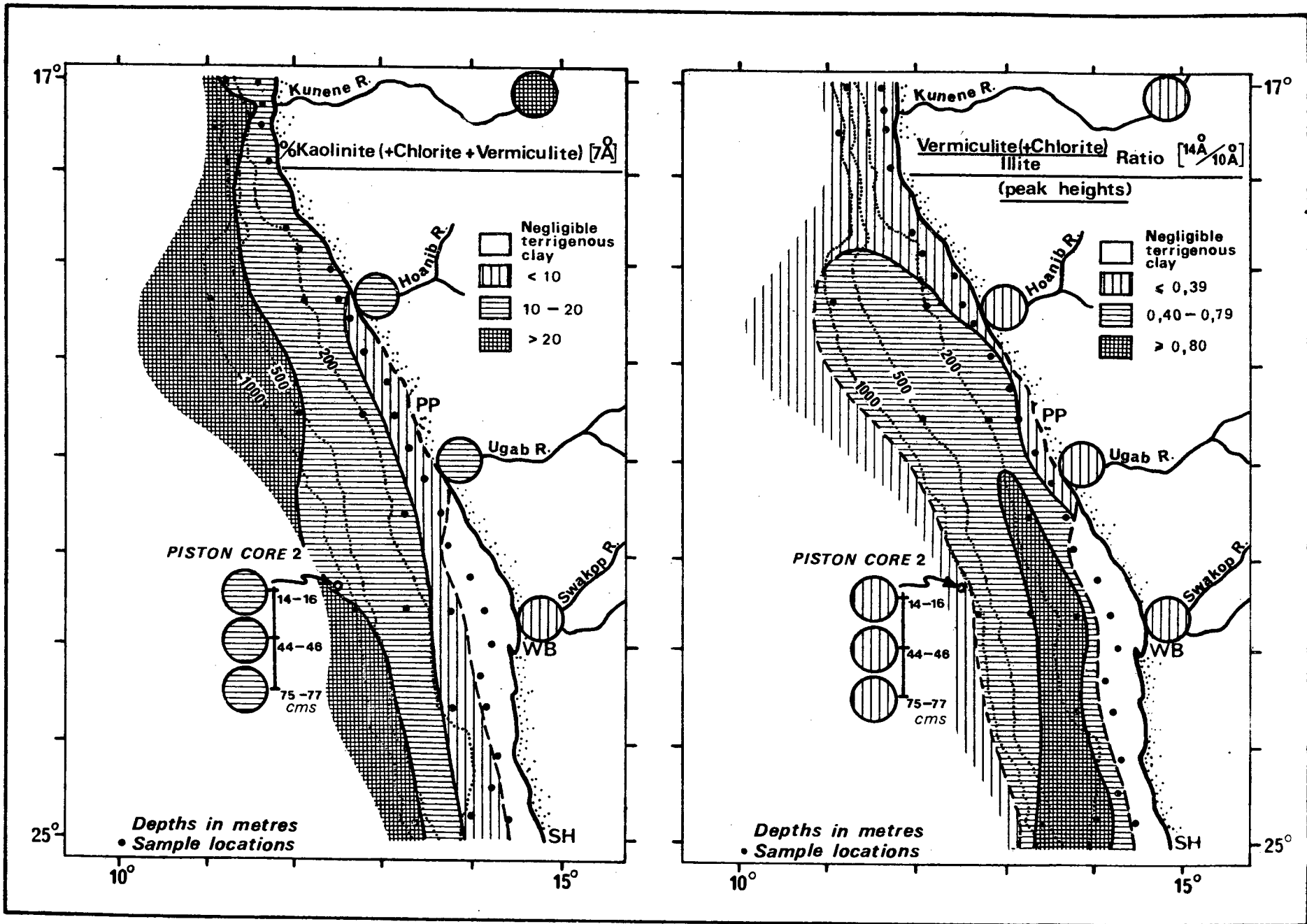


Figure 7.3

Maximum concentrations of illite are found on the Walvis Inner and Mid Shelves in close proximity to the Namib Sand Sea (Fig. 7.2), and values as high as 94% are recorded for the area west of Sylvia Hill (Appendix B.17). Based on evidence presented in Chapter 5 regarding the distribution of mica on the continental shelf, it would appear that on an opal-free basis, the concentration of illite would show a progressive increase towards the coast whereas instead, negligible terrigenous clay is found to exist due to the heavy dilution rate from opal. The lowest illite concentrations are associated with the Kunene Shelf and upper slope sediments, but even in these regions, it still constitutes approximately 50% of the total clay mineral assemblage. This value agrees well with the findings of Biscaye (1965), Griffin et al. (1968) and Bornhold (1973) for sediments of the Cape Basin and the southern part of the Angola Basin.

The distribution of montmorillonite bears a strong antipathetic relationship to that of illite (Fig. 7.2), being most concentrated in the Kunene Shelf and upper slope sediments (30-36%), and virtually absent from the Walvis Mid and Inner Shelves. Immediately north of the Kunene River mouth, the clay mineral composition contrasts markedly with the rest of the Kunene Shelf sediments (sample 3881) being abnormally poor in montmorillonite and rich in illite (13% and 73% respectively). It also differs geochemically from its neighbours (see next section), and in composition, is more closely akin to the diatomaceous muds than to the terrigenous sediments of the Kunene Shelf (Chapter 5). These differences are probably a reflection of different flocculation rates of the various river-borne clays, and are discussed in more detail in the following sections. The crystallinity of montmorillonite in the shelf sediment appears to increase directly in proportion with the abundance of the clay mineral (Appendix B.17) as was found to be the case with the onshore sediments, and as reported by Biscaye (1965) for sediments from the equatorial Atlantic.

In broad outline, the distribution of kaolinite (Fig. 7.3) resembles that of montmorillonite and shows a gradual increase in concentration with distance from shore (Bremner, 1974). The highest concentrations are found on the outer shelf and upper slope (21-24%), and correspond with the values indicated by Griffin et al. (1968) for the southern Angola Basin. They are however, somewhat higher than the ~10% reported by Biscaye (1965) and Bornhold (1973) for these deep-water sediments.

Vermiculite closely follows the distribution of illite, and increases at nearly the same rate as the latter towards the southern part of the Walvis Mid Shelf (Fig. 7.3). West of Sylvia Hill, a maximum $14\text{\AA}/10\text{\AA}$ peak height ratio (glycolated trace) of 1.2 was obtained indicating considerable vermicu-

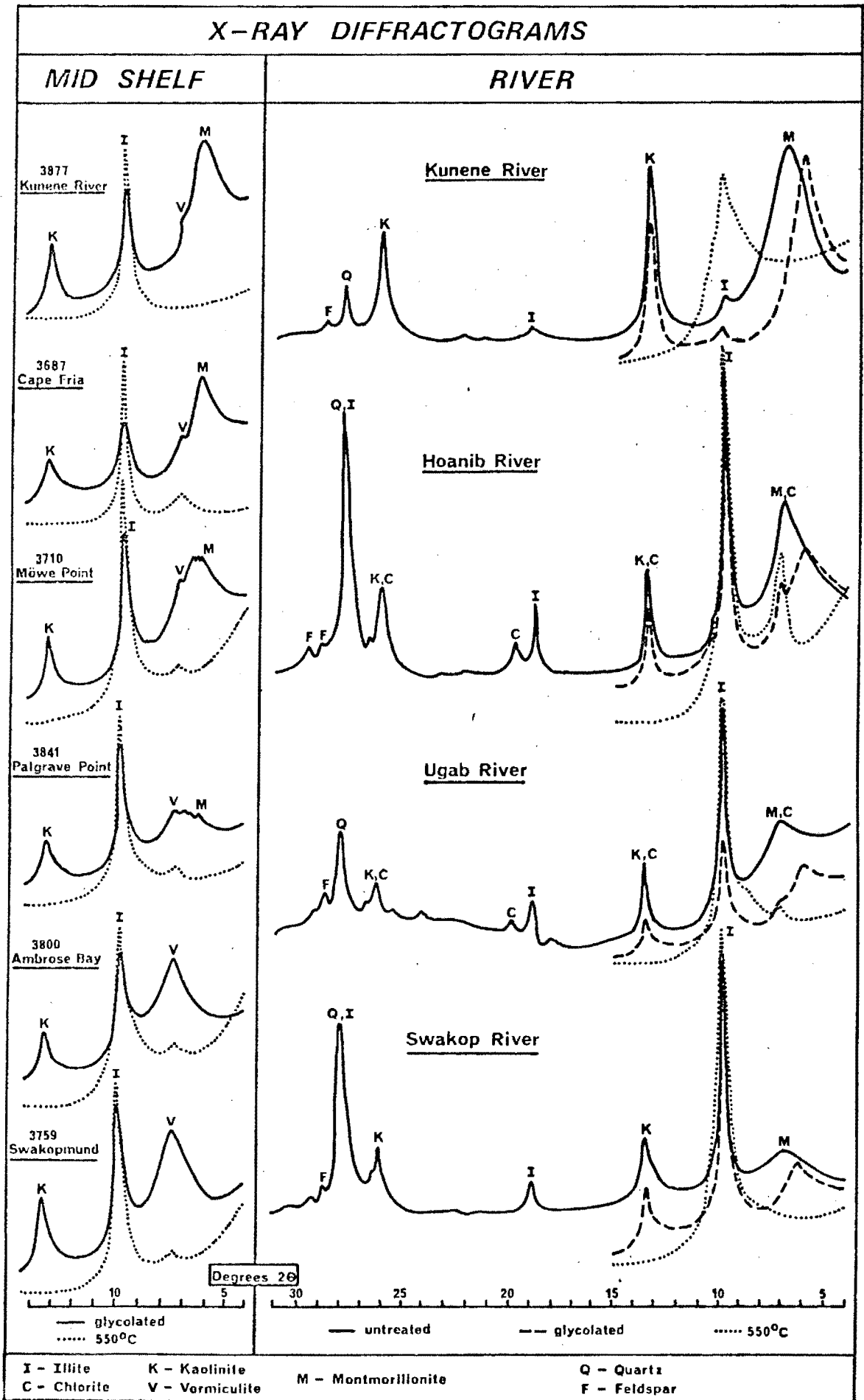


Figure 7.4

lite enrichment at this location (sample 3413 contains 94% illite).

A series of X-ray diffraction traces of mid shelf clay samples is shown in Fig. 7.4, from where it is clearly apparent that a southward increase in the abundance of vermiculite is accompanied by a corresponding decrease in the abundance of montmorillonite.

The occurrence of chlorite in the study area is very minor, and most often the mineral is entirely absent. This finding is in general agreement with values reported by Biscaye (1965), Griffin et al. (1968) and Bornhold (1973) for the adjacent deep-sea sediments (~5% chlorite).

(c) Pre-Holocene continental margin clays

Two sets of pre-Holocene sediments from the outer margin have been examined for their clay mineralogy and geochemistry. These include seven stiff mud samples recovered during routine sediment sampling (Fig. 3.1), and two sub-surface samples from piston-core No.2 (collected by Dr. C.P. Summerhayes at a depth of 1 017 m off Swakopmund). Despite the fact that the stiff muds are exposed on the sea floor, samples of this material were not included in the compilation of regional distribution maps (Figs. 7.1, 7.2 and 7.3) since lithostratigraphically they differ from the unconsolidated sediments. The clay mineralogy and age of the stiff mud samples are shown in Table 7.2 and the sub-surface piston-core samples are discussed separately later on.

Table 7.2 Clay mineralogy and age of some stiff mud samples*

	Percentages					
Sample No.	17Å	10Å	7Å	14Å/10Å ratio	17Å crystallinity	Age
Northern group of stiff mud samples						
3655	71	20	9	,76	,23	Miocene
3665	43	41	16	,45	,24	Miocene-Pliocene
3886	35	46	18	,35	,45	Quaternary
Mean	50	36	14	,52	,31	
Southern group of stiff mud samples						
3411	28	60	12	,30	,30	Miocene-Pliocene
3431	16	74	9	,21	,57	Miocene-Pliocene
3555	28	63	9	,29	,55	Pliocene
3564	19	70	11	,23	,44	Quaternary
Mean	23	67	10	,26	,40	

* The location of all stiff mud samples recovered is shown in Fig. 3.1, and a complete listing of their ages is given in Appendix B.3.

Considered as a whole, the northern group of stiff mud samples is typically montmorillonite-rich, the southern group illite-rich, and kaolinite occurs as a minor component in both groups. In isolation, samples of the northern group show a marked decrease in the concentration of montmorillonite with decreasing age and this is accompanied by an equivalent increase in the concentration of illite. This suggests that the hinterland adjacent the Kunene Continental Margin underwent increasing aridification from Miocene times, and furthermore, that the introduction of the Kunene River to the marine environment in Late Tertiary times (Chapter 1) did little to mask this climatic trend. The attendant changes in clay mineral composition are towards a closer similarity with the composition of the modern continental shelf sediments (Table 7.1). The crystallinity of montmorillonite appears to be proportional to the abundance of the mineral in the samples as was found to be the case with the modern sediments. The concentration of vermiculite differs from the modern sediment however, in that it does not parallel illite in concentration.

The southern group of stiff mud samples differs from the northern group in that no progressive changes in mineralogy are apparent with decreasing age. The variations that do occur are all minor and restricted to changes in the abundance of montmorillonite and illite.

Piston core No.2 was obtained from an area of comparatively heavy modern sedimentation between the two regions where stiff muds are found (Fig.3.1). Apart from a slight increase in the proportion of montmorillonite and a corresponding decrease in illite at greater depths in the core (Fig.7.2), the compositional changes are in general, small. As with the stiff muds, kaolinite is a minor component and averages only about 10% for all three core subsections.

7.2.3 Origin of the continental margin clays

The relative abundance of clay minerals in marine sediments is primarily dependent on the composition of source rock in the adjacent hinterland, and on the nature of the prevailing climate in the region (Kunze et al., 1968; Griffin et al., 1969). The distribution of clay material on continental shelves depends on the transporting medium in the hinterland (aeolian or fluvial), the current systems operative on the shelf, and on the flocculation rates of the different clay minerals in sea water (Biscaye, 1965; Whitehouse, 1960; Pryor, 1975). It has generally been supposed that clay minerals undergo rapid and in some cases extensive diagenesis when introduced into the marine environment (Folk, 1968; Carrol, 1970), but recent evidence suggests that these changes are actually very minor. For example, Savin and Epstein (1970), using isotopes of certain trace elements, have found that clay minerals in the marine environ-

river-borne montmorillonite and kaolinite.

(b) Montmorillonite

Montmorillonite may form under a wide variety of climatic conditions by stripping K^+ ions from illite and chlorite in the zone of weathering (Griffin and Goldberg, 1963; Kunze et al. 1968). Alternatively, it has been well established that montmorillonite can form as an alteration product from basic lavas in either subaerial or submarine environments (Griffin et al., 1968, 1969). Of these two possible modes of origin, the former is probably the most common in the study area because of the general lack of extensive fields of basic igneous rocks within the Kunene catchment area (Chapter 1). Other factors supporting this contention are the high concentrations of liberated muscovite in the southern part of the study area (Chapter 5), the prevailing southerly winds along the coast (Chapter 1), and the relatively high rainfall intensity in the northern part of the study area (Chapter 1). Unfortunately, the samples were not saturated with K^+ in the laboratory, to test whether the $14\text{\AA}$ clay mineral ($17\text{\AA}$ on glycolation) would collapse to $10\text{\AA}$ or not, but the evidence outlined above suggests that dioctahedral muscovite mica is transported northwards from the Namib Desert by wind, and that it then undergoes leaching of weakly-bonded K^+ ions in the humid Kunene catchment area. The widespread Kaoko Lavas (Fig. 1.2) have apparently had little effect on the montmorillonite content of the two central rivers, the Hoanib and Ugab, probably because of the insignificance of chemical weathering in the arid climate. In the Kunene River area, the Kunene Igneous Complex (downstream from the sample location), and small bodies of amphibolite gneiss may have contributed to some extent to the montmorillonite content of the river clays.

The comparatively high concentration of montmorillonite in the clay-size sediment of the Kunene Margin (>30%) is a direct result of input from the Kunene River. Its dispersal across the width of the shelf there probably reflects the slow flocculation rate of montmorillonite in saline waters compared to the flocculation rates of other clay minerals (Whitehouse et al., 1960). A slow flocculation rate would also promote the formation of fairly large montmorillonite crystallites (Griffin, 1971) where the suspension concentration is high, thus accounting for the improved crystallinity of the clay mineral in the Kunene Margin sediments. Fairly high concentrations of montmorillonite also occur along most of the upper slope, particularly off Sylvia Hill, and this was originally thought to be due to its northward transportation from the Orange River mouth by the Benguela Current. Very low levels of montmorillonite on the Orange Shelf (Rogers, 1975) however, argue against this source for the clay mineral, and it therefore seems more likely that it gets

transported southwards from the Kunene River mouth by the Angola Current (Chapter 2).

Chester et al. (1971, 1972) have found that montmorillonite in aeolian dust occurs only in minor and highly variable amounts off the west coast of southern Africa, and this led them to conclude that montmorillonite in the mid-ocean areas is not of detrital origin. The results of this study support their findings to the extent that the Namib Desert is a low source of montmorillonite, and that in the north-eastern part of the hinterland, where montmorillonite is dominant in the clay mineral assemblage, the area is protected from wind erosion by a dense foliage cover. Since montmorillonite on the continental margin is a direct result of detrital input from the Kunene River however, it is not impossible that some of this clay material eventually finds its way to the mid-Atlantic Ocean areas as well.

(c) Kaolinite

Kaolinite is a secondary mineral that reflects the intensity of soil-forming processes in the hinterland, and therefore occurs most abundantly in regions undergoing strong chemical weathering (Yeroshchev-shak, 1961; Griffin et al., 1968). Chemical degradation of bedrock in the Namib Desert, although of minor importance, does manifest itself in the form of iron stainings on marble, case-hardening on granite, and the formation of an 'iron-hat' on ultrabasic rocks (Goudie, 1972). The agent responsible for these effects is the early morning fog (Chapter 1), which according to Koch (reported in Goudie, op.cit.), contains a very high salt content, viz., 9 860 ppm total dissolved solids at Walvis Bay, 1 175 ppm at Gobabeb, and also sulphate as a major component. A deposit of kaolinite, which probably formed in pre-Holocene times has been reported by Kaiser (1923) in the vicinity of Luderitz. In general however, van der Merwe (1966) states that the illitic soils of the arid west coast gradually give way to kaolinitic soils closer towards the Equator. This finds strong support from the present study as indicated by the increasing kaolinite content of the river clays from 9% for the Swakop, to 32% for the Kunene.

Analysis of clay material in aeolian dust has indicated that kaolinite constitutes approximately 25% of the total clay mineral assemblage offshore from the study area (Chester et al., 1971, 1972). As with montmorillonite however, it is probable that most of the kaolinite on the continental margin is derived from the Kunene River. Minor differences in the dispersion pattern of these two clay minerals on the continental margin is attributable to their different flocculation rates. In this connection, Whitehouse et al. (1960) have found that kaolinite forms larger floccules than montmorillonite, but when introduced into a saline environment, the rate of montmorillonite floccu-

lation increases faster than that of kaolinite. This latter observation provides a satisfactory explanation for the absence of kaolinite on the Kunene Inner Shelf south of the river mouth.

(d) Vermiculite

Both dioctahedral and trioctahedral vermiculites occur in nature. The former originates from weathering of muscovite mica with concomitant fixation of Al^{3+} in the interlayer positions (Hathaway, 1955), and the latter forms either from leaching of brucite layers in trioctahedral chlorite lattices (Johnson, 1964), or else from the alteration of finely comminuted biotite flakes. Trioctahedral vermiculite is by far the most commonly occurring variety (Carrol, 1970), and because of its unit cell being analogous to that of biotite, although of slightly larger dimensions, the transformation from biotite to vermiculite probably proceeds relatively easily (Kazantzev, 1934; reported in Walker and Brown, 1963). According to Kazantzev (op.cit.) the reactions involved would be replacement of K^+ by H^+ and Fe^{3+} , Fe^{2+} by Mg^{2+} .

Two factors favouring a biotitic origin for the vermiculite in the continental shelf sediments are the abundance of biotite and sparseness of chlorite in the terrestrial sediments, and the lack of strong chemical weathering necessary for the transformation of fine-grained muscovite to vermiculite (Hathaway, 1955). In Chapter 5 it was seen that sand-size biotite is stable in a chemical as well as a hydrodynamic sense in the nearshore zone, but finely comminuted particles, because of their greater surface area, would be much more susceptible to chemical reaction. No vermiculite was found to occur in the river samples (the 14 μ material there being chlorite), and its mode of formation is therefore postulated to be due to partial stripping of K from fine-grained biotite in the arid hinterland, followed by diagenetic replacement of Fe by Mg in the marine environment.

Nilolayev and Senin (1972) have reported the presence of a trioctahedral mineral, which they call 'hydrobiotite-vermiculite', on the West African shelf northwards from 18°S. On the basis of X-ray diffraction and chemical analyses, they suggest an authigenic origin for this mineral, and consider it to be a possible precursor of protoglaucinite. Since their data were derived from only a few samples, their limit at 18°S should be extended southwards to include the Walvis Mid Shelf, where, from the present study, the concentration of vermiculite has been found to be greatest.

(e) Chlorite

Most chlorite found associated with marine sediments is the trioctahedral variety of detrital origin (Carrol, 1970), and its introduction to the marine environment is mainly through the medium of glacial rock flour. It is

classified as a typical high-latitude mineral (Griffin et al., 1968) and would therefore not be expected to occur off the coast of South West Africa.

The small amounts of chlorite found in the Hoanib and Ugab River clays are probably derived from the basic Kaoko lavas and from the many low-grade metamorphic schists exposed in their catchment areas. The abundance of iron in the hinterland, as portrayed by the red colouration of the interior longitudinal dunes, suggests that the chlorite, where it occurs, is probably of the Fe-rich variety.

7.3 GEOCHEMISTRY OF THE CLAYS

7.3.1 Introduction

The 51 samples that were analysed by X-ray diffraction for their clay mineralogy, were also analysed geochemically by means of atomic absorption spectrophotometry. Nine trace elements, viz., Cu, Ni, Pb, Zn, Co, Cd, Rb, Sr and Mn, and five major elements, viz., Ca, Mg, Fe, Al and K were determined. In addition, three other elements, viz., Mo, Ba and I were analysed for qualitatively by X-ray fluorescence. Methods used for collecting, storing and dialysing the samples for geochemical study are described in Appendix A.24, and the techniques employed for separating the clay fractions, and for dissolving them, are covered in Appendices A.25 and A.29 respectively. The method of analysis is described in Appendix A.30, and the instrument settings used on the atomic absorption spectrophotometer are listed in Appendix B.19.

In order to correct for matrix differences between the samples, and also between the dissolved sample solutions and the prepared standard solutions, six international standards were prepared and analysed in exactly the same way as the samples. All the elements determined in the samples were also analysed for in the standards, except Cd for which no published data exist. The standards used were NIM-G, NIM-N, NIM-S, AGV-1, BCR-1 and W-1. The accuracy of the atomic absorption method is discussed in Appendix A.31, and a listing of the results is given in Appendix B.20.

The reproducibility of the geochemical process, from the sub-sampling stage to the final result, was examined by re-analysing the clay fractions of four diatomaceous samples (3426, 3754, 3756 and 3950). The results are discussed in Appendix A.32, and are listed in Appendix B.21. These same samples were also used to investigate the partition of elements between gravel/sand, silt and clay fractions of diatomaceous mud. The results of this study are described in Appendix A.33, and the results are shown in Appendices B.21 and B.22.

Table 7.3 The average concentration of trace and major elements in seven related sedimentary facies

	Terrestrial sediment	Modern continental margin sediment				Pre-Holocene continental margin sediment		Average deep sea	
	River silt	Inner shelf Kunene mud	Inner shelf diatomaceous mud	Mid shelf sand	Upper slope mud	Outer margin stiff mud	Upper slope piston core No.2	clay sediment	carbonate sediment
No. of samples Element	4	4	19	9	5	7	3		
Cu*	51 (25-83)	33 (28-36)	43 (25-87)	49 (38-60)	56 (51-69)	46 (29-63)	56 (55-57)	250	30
Ni*	52 (45-64)	63 (59-70)	74 (27-226)	101 (64-129)	99 (72-126)	88 (56-128)	104 (100-108)	225	30
Pb*	85 (34-86)	23 (18-28)	18 (Tr-41)	40 (21-61)	29 (26-32)	36 (19-54)	44 (32-65)	80	9
Zn*	243 (104-360)	84 (74-91)	94 (27-256)	98 (57-207)	122 (87-159)	137 (110-184)	105 (87-118)	165	35
Co*	35 (20-44)	9 (Tr-15)	2 (0-11)	7 (Tr-21)	16 (10-28)	13 (Tr-28)	19 (15-21)	74	7
Cd*	2 (Tr-6)	11 (3-34)	30 (13-60)	8 (Tr-15)	3 (Tr-5)	8 (Tr-38)	6 (4-8)	0,21	0,23
Rb*	179 (153-232)	107 (76-127)	47 (Tr-134)	71 (25-126)	77 (54-101)	161 (54-101)	53 (121-232)	110	10
Sr*	121 (72-182)	121 (82-137)	209 (41-1080)	619 (145-1240)	740 (180-1870)	266 (149-414)	1,050 (1030-1090)	180 ⁺	2000
Ca	5,5 (2,6-10,2)	3,4 (2,1-4,5)	5,2 (1,3-23,0)	15,4 (2,5-25,6)	15,3 (5,2-29,6)	6,8 (3,0-9,7)	25,6 (23,0-28,3)	2,9 ⁺	31,2 ⁺
Mg	5,3	4,0	1,4	2,3	3,7	4,1	2,0	0,4 ⁺	2,1 ⁺
Mn*	831 (458-1080)	200 (132-280)	74 (32-206)	134 (49-225)	138 (88-171)	214 (194-232)	104 (56-131)	6700	1000
Fe	8,7 (6,1-10,4)	6,6 (3,2-9,0)	1,8 (0,4-4,7)	3,2 (0,8-7,1)	5,6 (2,6-8,3)	6,0 (4,9-7,4)	2,4 (2,1-2,5)	6,5	0,9
Al	16,2 (10,0-23,4)	9,7 (5,6-13,2)	3,9 (1,5-8,0)	5,4 (2,0-10,0)	8,3 (6,7-10,4)	13,1 (8,9-15,5)	6,2 (5,2-7,4)	8,4 ⁺	2,0 ⁺
K	2,6 (1,4-3,4)	1,5 (1,1-1,6)	0,7 (0,2-1,8)	1,3 (0,2-3,5)	1,2 (1,1-1,6)	2,3 (1,3-3,4)	1,1 (1,0-1,3)	2,5 ⁺	0,3 ⁺

* Elements reported in ppm, others in %

+ Data on deep sea sediments from Turekian and Wedepohl (1961); those with asterisks from Riley and Aston (1976)

A complete listing of corrected results obtained from analysis of the clay samples is given in Appendix B.18, and a summary of this data is given in Table 7.3.

7.3.2 Regional distribution and origin of the elements

(a) River clays

The river clays are richer than the marine clays in 10 of the 14 elements examined, viz., Cu, Pb, Zn, Co, Mg, Mn, Fe, Al, K and Rb (Table 7.3), but because of the considerable variability between sample concentrations in any particular environment, many exceptions to this broad generalization occur. The progressive regional changes that were apparent with the clay mineral distributions are not repeated with the element abundances, thus suggesting that the geochemistry of the clays is less dependent on climatic conditions, and more a function of the bedrock composition.

In the northern part of the study area, the Kunene River reflects higher concentrations of Pb, Ca and Al than the other three rivers (Appendix B.18), and these values exceed the 'average shale' of Turekian and Wedepohl (1961) and Chester and Aston (1976) (see Table 7.3) by factors of 9, 5 and 3 respectively. The significant enrichment of Pb in the sediments cannot be related to any known mineral deposits in the river catchment, and the possibility therefore exists for a Tsumeb-type orebody in the limestones of the Otavi System (Fig. 1.2) (Bembi System in Angola, Hamilton and Cooke, 1962). This supposition receives indirect support from the association of Pb with high concentrations of Ca. The Al enrichment of the Kunene River clays reflects the sub-tropical chemical weathering of K-feldspars in basement granite-gneisses in the area. Some of the Al may also be derived from kaolinitization of muscovite micas introduced from the Namib Desert by the prevailing winds.

The clays of the two central rivers, the Hoanib and the Ugab, contain few elements in concentrations above normal background levels (Table 7.3). Exceptions to this are Mg, which is 5 times more concentrated in the Hoanib River clays than the average shale, and Zn, which is 3 times more concentrated in the Ugab River clays. The Mg enrichment probably reflects its introduction from the Kaoko tholeiitic basalts (Fig. 1.2), and the elevated Zn levels in the Ugab River clay may be indicative of sulphide mineralization in its catchment area. It is interesting to note that the influx of Zn to the marine environment has had a significant effect on the concentration of this element in presently forming concretionary phosphorite (Chapter 8).

Clay from the southernmost river, the Swakop, contains the greatest number of elements in a comparatively enriched state, viz., Cu, Ni, Co, Rb, Mn, Fe and K. Of these, Cu, Co, Rb and Fe are about twice as concentrated

as in the average shale (Table 7.3), and the others are of the same order of magnitude. The distinctive red coloration of the inland dunes of the Namib Sand Sea, as well as of sands of the Kalahari Desert (Poldervaart, 1957; Logan, 1969), is clear evidence of the abundance of iron in the arid interior. It is possible that this iron hydroxide coating on the grains (Scholz, 1972) has served as a scavenger for the elements Cu and Co (Goldberg, 1961). The relatively high concentration of Rb in the Swakop River clay material is attributable to the abundance of muscovite and biotite micas in the Namib Sand Sea (Chapter 5).

(b) Continental margin clays

The regional distribution of absolute element abundances in the clay-size sediment of the continental margin are shown in Figs. 7.5 to 7.11. R-mode factor analysis has been used to establish the degree of association between the various major and trace elements, and also to determine the extent to which the geochemistry is controlled by the clay mineralogy, the sediment texture and the sediment composition. Background information to the factor analysis (principal components procedure) has been outlined in its application for synthesising regional sedimentological data obtained in Chapter 5 (see Appendix A.22).

(i) R-mode factor analysis

The 25 variables considered in the factor analysis included 14 major and trace elements; 3 clay minerals, viz., montmorillonite, illite and kaolinite; 4 sediment textural fractions viz., gravel, sand, silt and clay; and 4 sediment compositional facies viz., CaCO_3 , opal, C_{org} and terrigenous. The samples involved come from the four sedimentary environments classified under the heading 'modern continental margin clays' in Tables 7.1 and 7.3 i.e., 37 samples in all. One additional sample from the top of piston core No.2. was also included making a grand total of 38 samples involved in the factor analysis.

The factor analysis procedure becomes statistically unreliable when the number of variables exceeds half the number of samples, and it was therefore decided to run the 14 major and trace elements separately against the three other groups of variables. These results are shown in Fig. 7.12 in the form of three independent factor matrices. In each of the factor matrices, the number of geochemical variables (the 11 elements) exceeds the number of other variables considered (3 clay minerals or 4 textures or 4 compositions), and consequently, the loadings on the former are all very similar, though the sequencing of the factors is not always the same. This has allowed synthesis of the variable associations in each of the factor matrices into a single

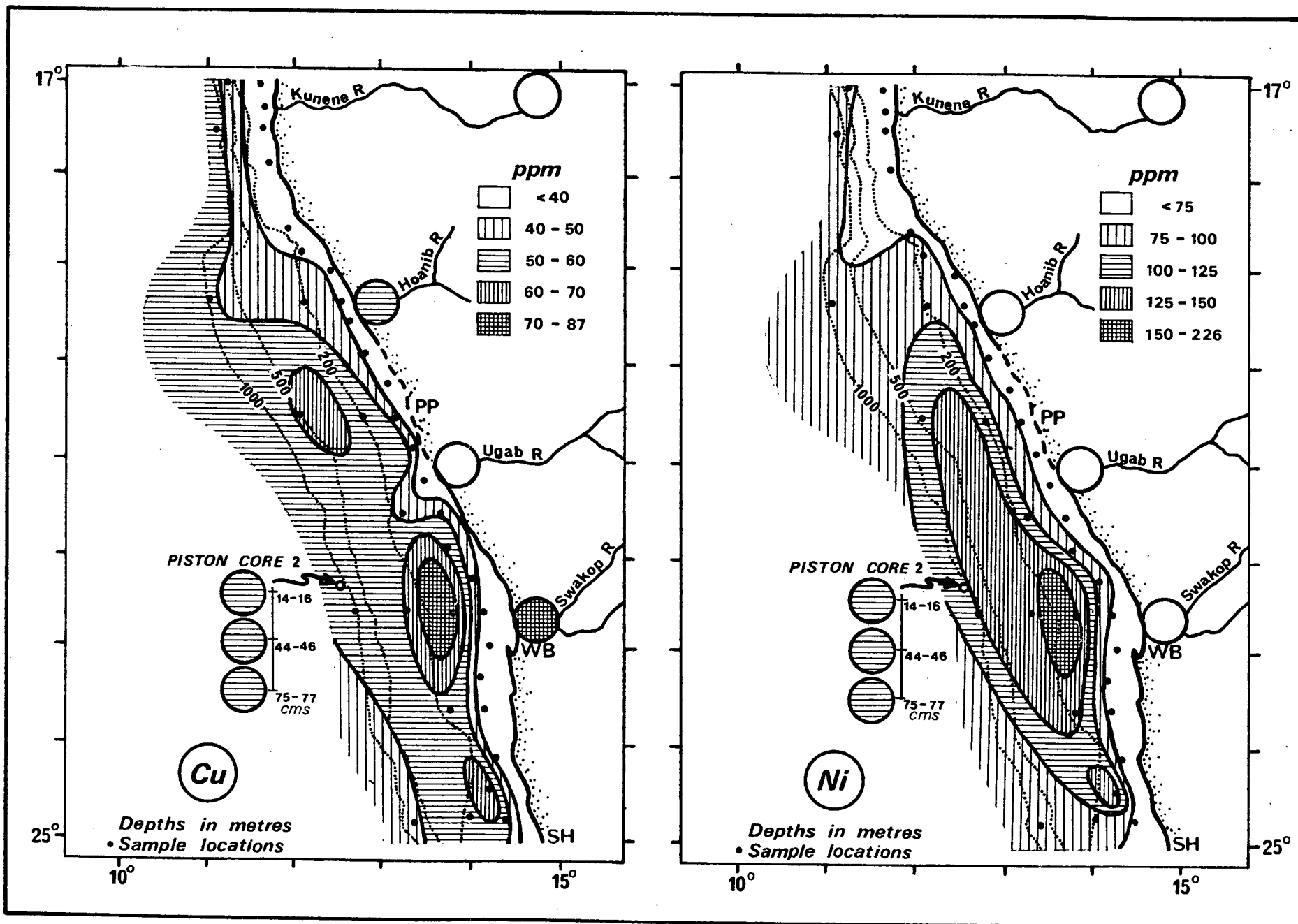


Figure 7.5

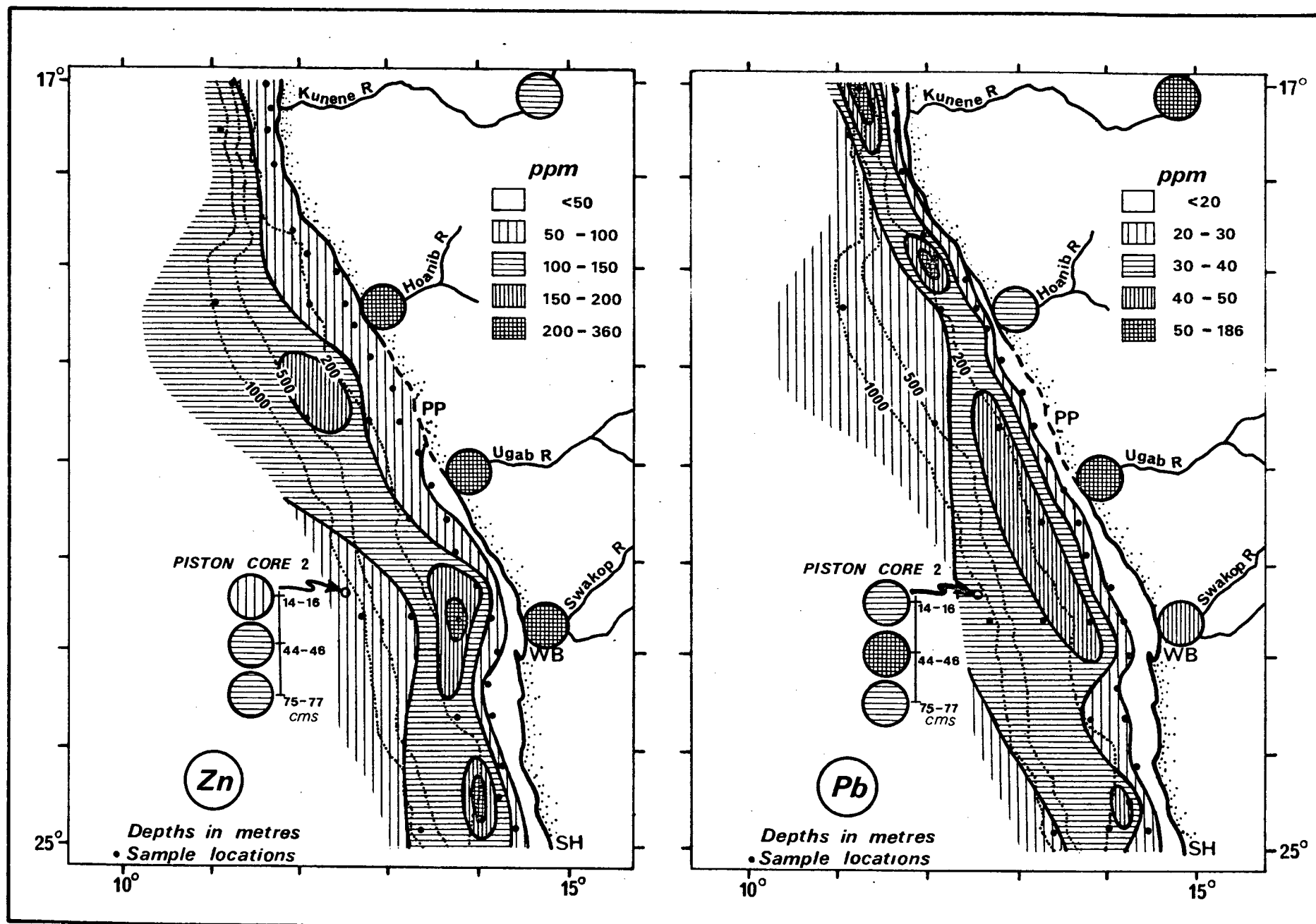


Figure 7.6

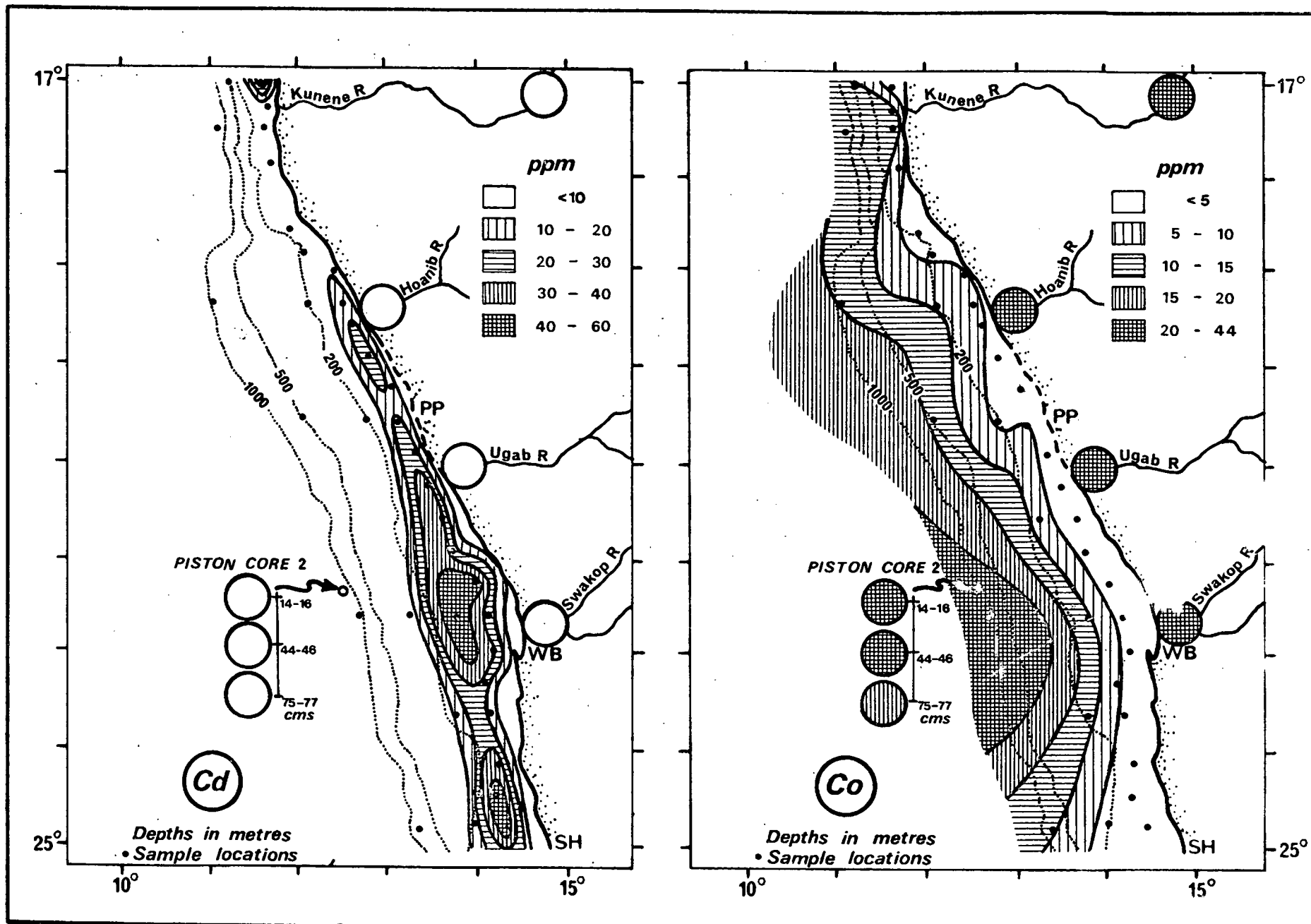


Figure 7.7

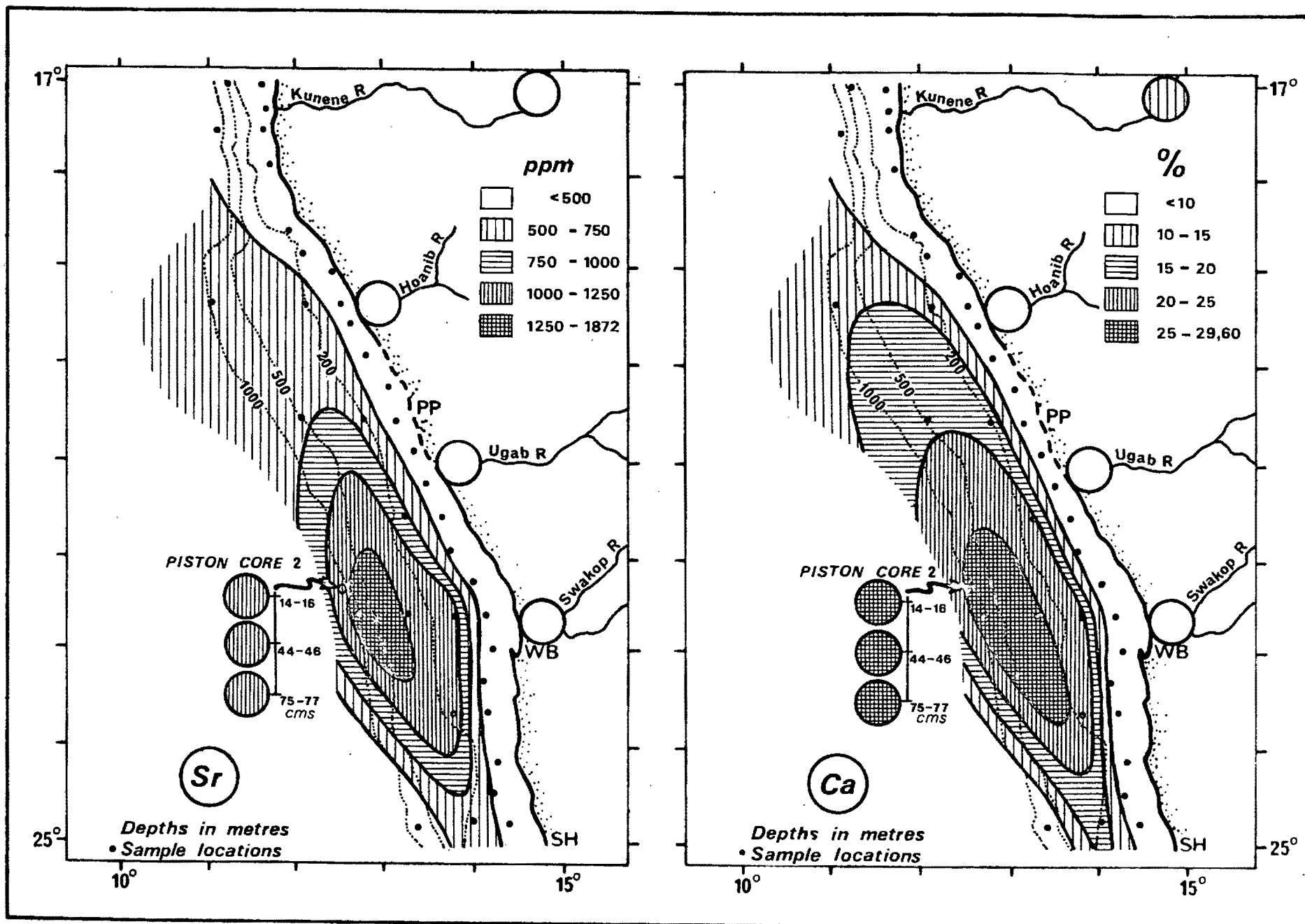


Figure 7.8

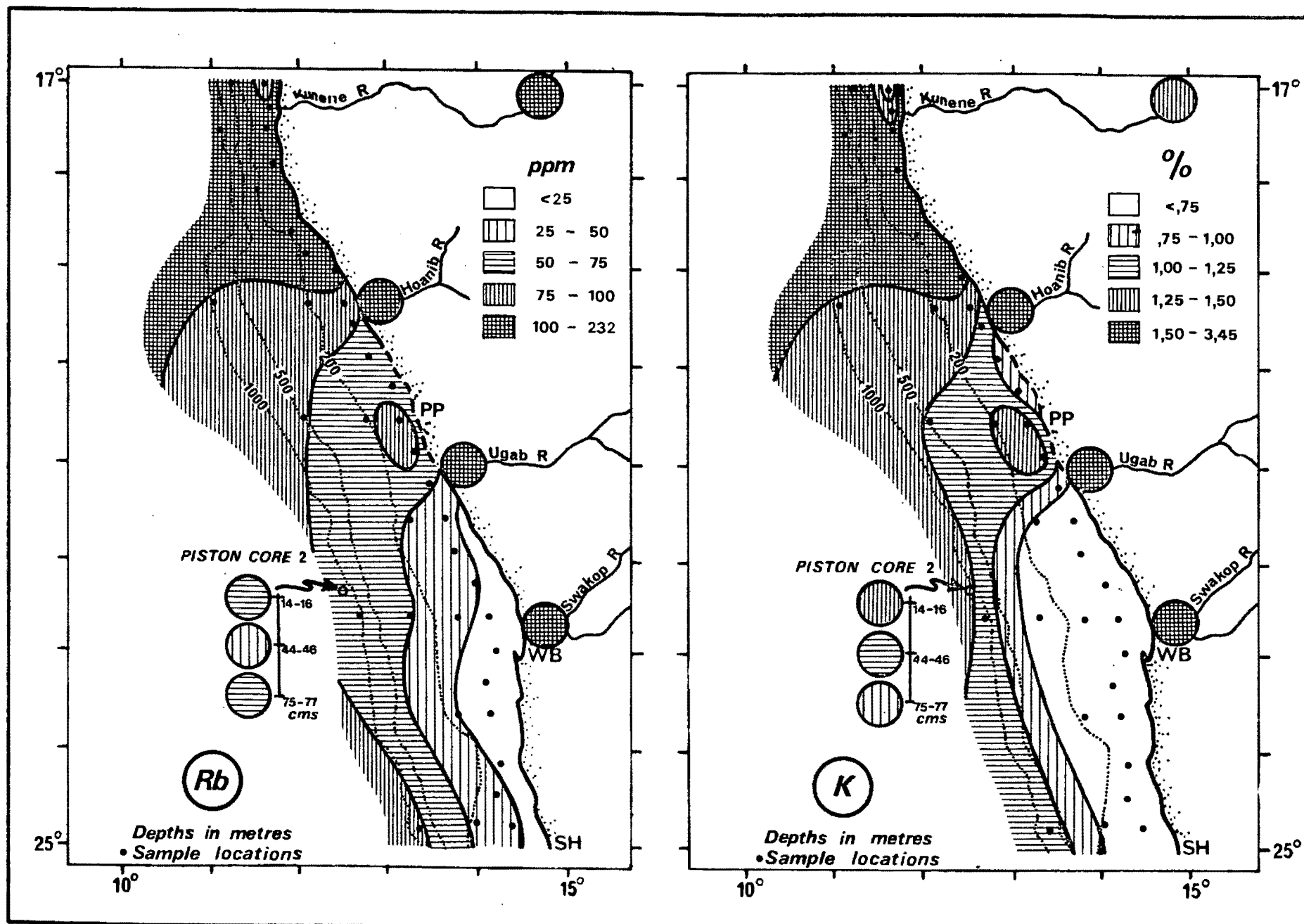


Figure 7.9

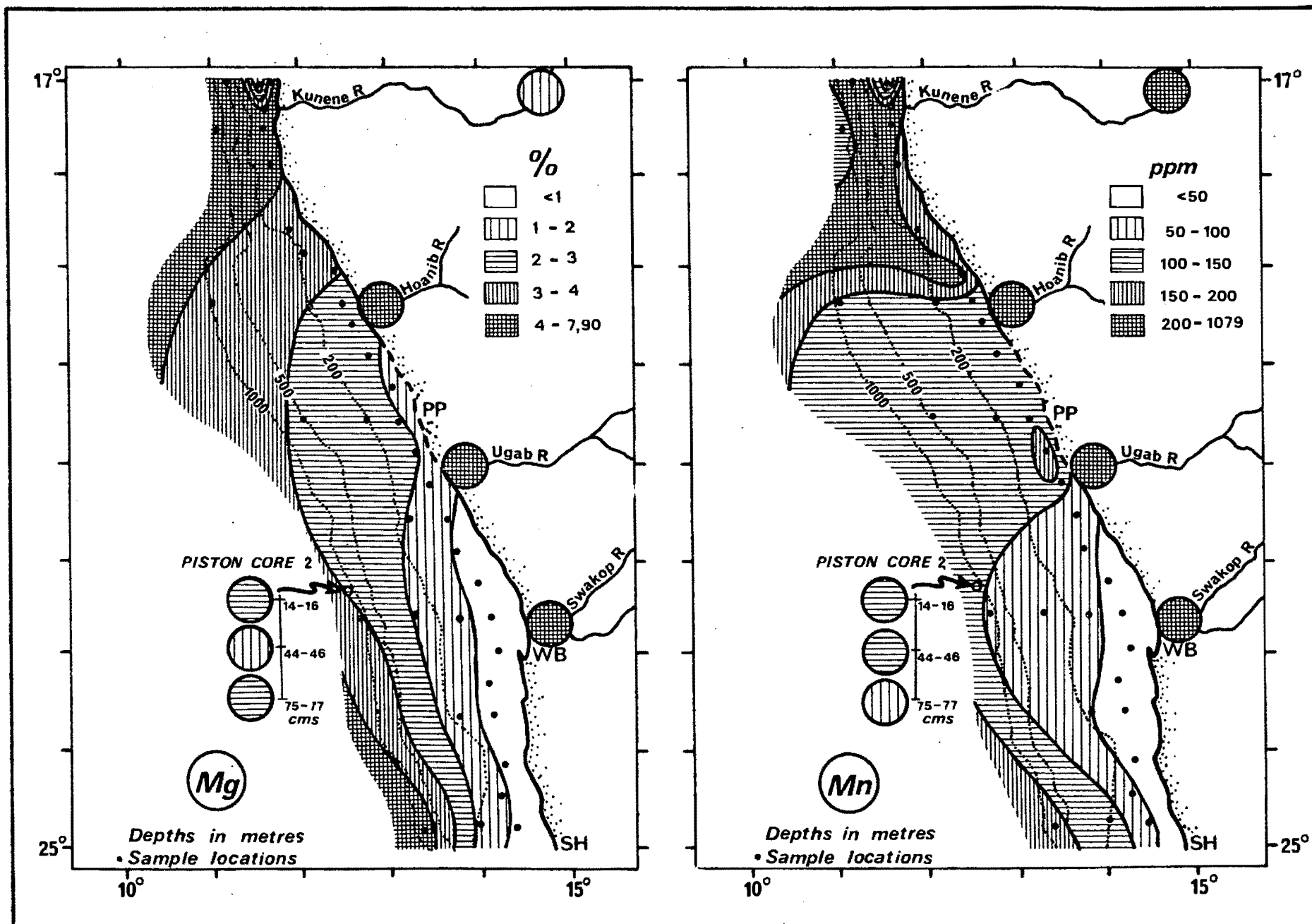


Figure 7.10

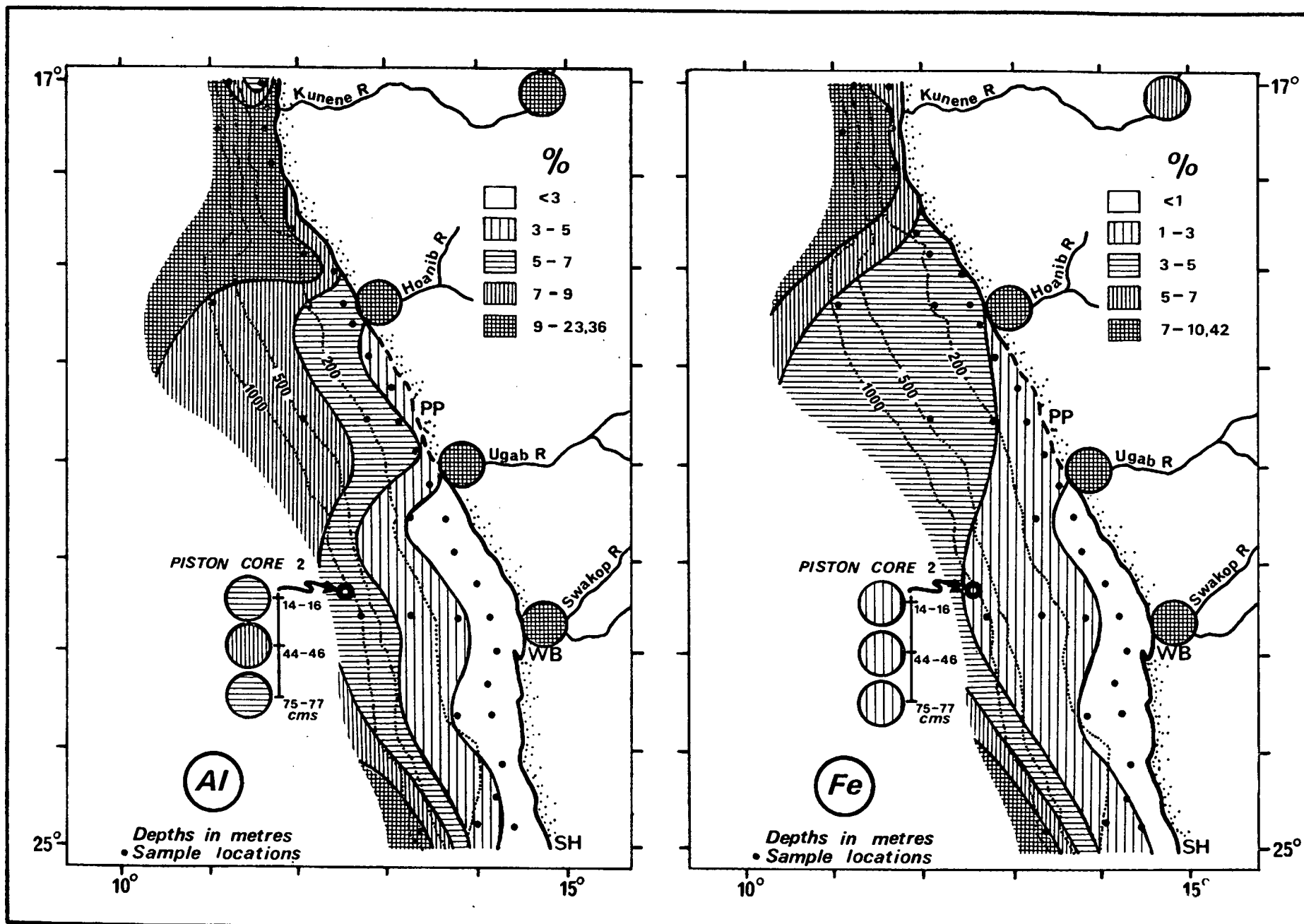


Figure 7.11

table, Table 7.4, as though all 25 of the variables had in fact been processed by a single factor-analysis run.

An important point emerged from this analysis that is worth commenting on. The three sedimentological lithofacies arbitrarily chosen for individual classification in Chapter 5, viz., >5% opal (diatomaceous sediments), >50% CaCO_3 (calcareous sediments), and Balance (terrigenous and authigenic sediments), are all represented in factors 1, 2, and 3 of the three factor matrices, and thus give considerable support for the original assumptions made in choosing them (see Chapter 5, section 1). Apart from the element Pb, which constitutes a fourth factor in matrix B, and shows no particular affiliations with any of the sedimentological lithofacies (Fig. 7.6), the geochemistry of the clay closely follows the composition of the sediments whereas the texture of the sediment appears to play only a minor role (see Appendix A.33). The names of the sedimentological lithofacies have been included in Table 7.4 to give geographical meaning to the positively and negatively loaded variables in each of the variable groups, and the groups themselves represent summaries of similar factors from each of the factor matrices shown in Fig. 7.12.

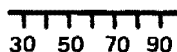
Finally it should be pointed out that although factor analysis provides a statistically valid set of numbers descriptive of the degree of association between different variables, interpretation of these numbers is entirely subjective, and a priori knowledge of the sediment character in this particular study has been a distinct advantage in drawing sound conclusions.

(ii) Group I variables

Of the nine positively loaded variables in this group, only Cu, Ni, Zn and illite are strongly correlated with each other (Table 7.4). This grouping is interpreted as being determined largely by the organic-rich seaward flank of the diatomaceous mud belt (Figs. 7.2, 7.5 and 7.6), where the concentration of all four components reaches a maximum (sample 3756 - 87 ppm Cu, 226 ppm Ni, 256 ppm Zn and 91% illite). A weak positive loading on C_{org} is probably a response brought about by the presence of relatively organic-rich, but trace element-poor, faecal pellet sand in the general neighbourhood. The association between illite and the trace elements furthermore, does not necessarily imply that the latter are adsorbed onto the surfaces of the clay-size mica particles, but rather that their concentrations are both high due to minimum dilution from diatom frustules. This is corroborated by weak negative loadings on the clay and opal variables in this group. Weak positive loadings on Pb, Ca and Sr, and a very weak loading on Cd reflect modest concentrations of these elements along the seaward flank of the diatomaceous mud belt, particularly in the vicinity of sample 3756. These elements

R-MODE FACTOR MATRICES OF CLAY GEOCHEMISTRY WITH THE CLAY MINERALOGY, SEDIMENT TEXTURE, AND SEDIMENT COMPOSITION

FACTOR LOADINGS



+ ve loading - ve loading

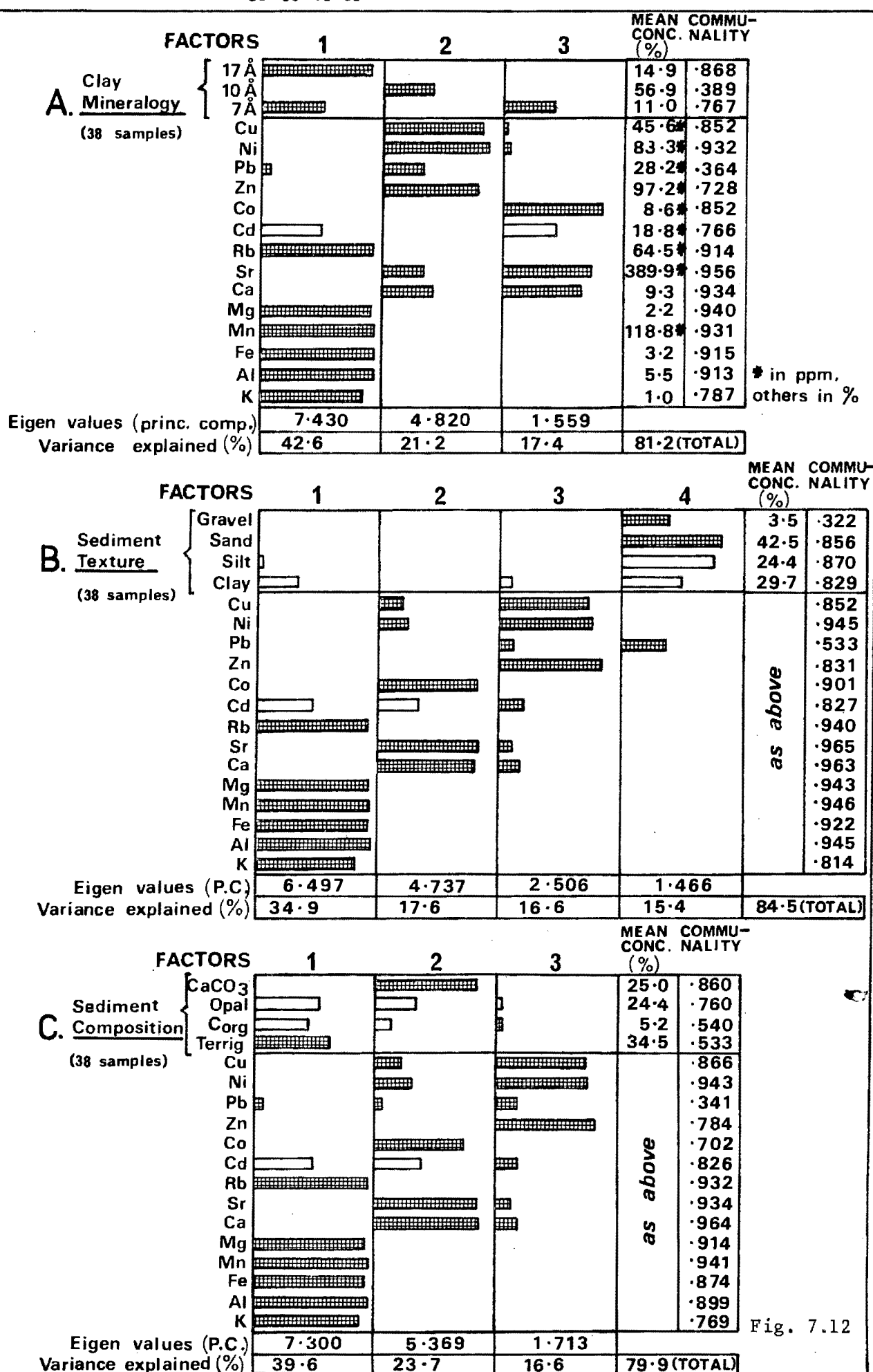


Fig. 7.12

Table 7.4 Summary of the three factor matrices depicted in Fig. 7.12

			Matrix variables				
			Clay fraction		Total sediment		
Variable groups	Matrix and factor numbers	Loading	Geochemistry	Mineralogy	Texture	Composition	Sedimentological lithofacies
I	A2, B3, C3	+	Cu-Ni-(Pb)-Zn-(Cd)*-(Sr)-(Ca)	10Å		(C _{org})	Diatomaceous mud
		-			(clay)	(Opal)	_____
II	A3, B2, C2	+	(Cu)-(Ni)-(Pb)*-Co-Sr-Ca	7Å		CaCO ₃	Calcareous sediments
		-	Cd			Opal-(C _{org})	Diatomaceous muds
III	A1, B1, C1	+	(Pb)*-Rb-Mg-Mn-Fe-Al-K	17Å-7Å		Terrigenous	Terrig. and authig. sediments
		-	Cd		(silt)-clay	Opal-C _{org}	Kunene mud
IV	B4	+	Pb		gravel-sand		Unaffiliated
		-			silt-clay		_____

Notes: - Only variables with a loading greater than 25% are shown.
 - Variables between brackets have average loadings of less than 50%.
 - Variables marked with an asterisk do not occur in all three factor matrices, and are therefore very weakly associated with the other variables in the positively or negatively loaded groups.
 - In the column listing the clay mineral variables, 17Å implies montmorillonite, 10Å implies illite and 7Å implies kaolinite.

are discussed more appropriately where they occur as strongly loaded variables in other groups.

(iii) Group II variables

Two inversely related variable associations exist in this group (Table 7.4), viz., a Co-Sr-Ca-Kaolinite- CaCO_3 association, and a Cd-opal association. Strong positive loadings on variables of the former association clearly indicate the calcareous sediments of the Walvis Outer Margin where the concentration of the first four variables all attain maxima (sample 3762 - 28 ppm Co, 1 872 ppm Sr, 29.6% Ca, 24% kaolinite), and the concentration of CaCO_3 is also very high. The regional distribution of the elements is shown in Figs. 7.7 and 7.8, from where it is apparent that the trends are all very similar particularly for Sr and Ca. Compared with the average carbonate rock (Table 7.3), sample 3762 is enriched in Co, Sr and Ca by factors of 280, 3 and 1, but in relation to the average shale, the Co content is about normal.

The Cd-opal association (Table 7.4), is well illustrated in the regional distributions of the two components (Figs. 7.7 and 5.21 respectively). The level of Cd enrichment in the diatomaceous muds is exceptionally high (sample 3773 - 60 ppm Cd), this being enriched by a factor of 200 compared to the average shale (Table 7.3). A weak negative loading on the C_{org} variable (Table 7.4) indicates that Cd is not associated with organic matter in the diatomaceous muds, but rather with the opal.

Weak positive loadings on Cu and Ni and a very weak loading on Pb indicate modest concentrations of these elements in the calcareous sediments of the Walvis Outer Margin and as described above, the first two of these elements are specifically concentrated in the diatom-derived organic matter.

(iv) Group III variables

This group is statistically dominant, and accounts for an average of 39% of the total variance amongst the variables (factors 1 of matrices A, B and C in Fig. 7.12). Nine variables are present with strong positive loadings viz., Mg, Mn, Fe, Al, K, Rb, montmorillonite, kaolinite and terrigenous; and inversely related to this association are the four negatively loaded variables Cd, clay, opal and C_{org} . The first of these antipathetic associations clearly reflects the chemical and mineralogical character of the terrigenous and authigenic (principally glauconitic) sediments of the Kunene Continental Margin. From the regional distribution diagrams of the elements (Figs. 7.9, 7.10 and 7.11), it is apparent that their concentrations fall off fairly rapidly near the $18^{\circ}40'S$ Kunene-Walvis boundary (see Chapters 3 and 5), and this is due to the heavy influx of biogenic detritus on the Walvis Continental Margin. The abundance of these elements in the marine clays, although intim-

ately related to supply from the perennial Kunene River, differs from the river in being richer in Mg, Fe and K, and poorer in Mn, Al and Rb. This discrepancy probably reflects the concentration of certain elements by different minerals on the shelf. For example, K, Mn, Fe and Mg are most enriched in glauconitic sands (sample 3877 - 3,45% K, 225 ppm Mn, and sample 3674 - 8,14% Fe, 4,93% Mg), Al is most concentrated in terrigenous silt adjacent to the Kunene River mouth (sample 3661 - 13,18% Al), and Rb is most abundant in terrigenous sand 20 n.miles north of the mouth of the Hoanib River (sample 3910 - 134 ppm Rb). Compared to the average shale (Table 7.3), these concentrations are enriched by factors of 1, 0,25, 2, 3, 2 and 1 respectively. A weak correlation between Pb and the positively loaded variables of this group reflects the high concentration but patchy distribution of this element in the Kunene Margin sediments, and as with the Group I and Group II variable associations, it exhibits only a very weak positive loading.

Immediately north of the Kunene River mouth on the inner shelf, a small deposit of biogenic sediment exists as part of the Kunene mud belt, and contrasts strongly with the terrigenous silty character of the main body of the mud belt south of the river mouth (see Chapter 5). All the elements associated with the terrigenous/authigenic sediments, as described above, are impoverished in the biogenic deposit, and this is indicated by hiatuses in their regional distributions at this particular location (Figs.7.9, 7.10 and 7.11). It is however, enriched in Cd (Fig.7.7), and a strong negative loading on this element (Table 7.4), as well as on the variables clay, opal and C_{org} indicate that compositionally, it closely resembles the diatomaceous mud belt farther to the south. The fact that it occurs only to the north of the Kunene River mouth suggests that the supply of nutrients for diatom productivity may be river-derived and not upwelling-derived, and furthermore, that a weak northward moving counter-current exists in the general vicinity (see Chapter 2). Offshore from the Amazon River mouth however, increased productivity has been attributed to shallow-water upwelling produced dynamically by the presence of a large mass of freshwater there.

(v) Group IV variables

This group contains only one element variable, Pb, whose concentration in the clay fraction of the sediments appears to be uninfluenced by the composition of the sediment but effectively controlled by its texture (Table 7.4). The strong positive correlation of Pb with gravel and sand is given expression by the occurrence of maximum Pb concentrations in glauconitic sand west of the Kunene River (sample 3877 - 61 ppm Pb) and by fairly high concentrations in terrigenous sand off Rocky Point, molluscan gravel off Palgrave Point, shelly diatomaceous mud off Walvis Bay, and terrigenous sand off Meob Bay (Fig.7.6). Although the glauconite occurrence is $\frac{1}{3}$ as concentrated as the Kunene River clay-size sediment, it is still 3 times more concentrated than the average shale (Table 7.3).

(c) Pre-Holocene continental margin clays

For reasons set out in the previous section dealing with the mineralogy of the clay fraction, neither the stiff mud samples nor the core sub-surface samples were utilized in compiling the clay mineral and element distribution maps shown in Figs. 7.2, 7.3 and 7.5 to 7.11. The following table, Table 7.5, which gives the abundance of the 14 trace and major elements in the clay fraction of the stiff mud samples should therefore be viewed together with Table 7.2, which lists the clay mineralogy and ages of the samples. The core sub-sections are discussed after the stiff muds.

Table 7.5 Trace and major element abundances of some stiff mud samples

Sample No.	Cu*	Ni*	Pb*	Zn*	Co*	Cd*	Rb*	Sr*	Ca	Mg	Mn*	Fe	Al	K
<u>Northern group of stiff mud samples</u>														
3655	44	84	42	184	28	4	165	382	9,70	4,36	208	7,05	13,7	2,82
3665	29	56	28	146	11	Tr	132	355	8,37	4,76	214	7,41	8,8	72,11
3886	39	83	38	125	11	4	141	171	6,38	4,29	223	6,14	12,1	1,83
Mean	37	74	36	152	17	3	146	303	8,15	4,47	215	6,87	11,6	2,25
<u>Southern group of stiff mud samples</u>														
3411	44	82	48	114	18	Tr	188	149	3,49	4,24	215	5,68	15,0	3,39
3431	47	70	54	110	7	4	232	216	7,04	4,07	232	5,45	15,5	1,28
3555	63	114	24	167	13	4	148	414	9,70	3,95	194	4,94	11,1	2,77
3564	59	128	19	114	Tr	38	121	172	2,03	3,02	209	5,46	15,5	1,88
Mean	53	99	36	126	10	12	172	238	5,82	3,82	213	5,38	14,3	2,33

* These elements reported in ppm, the others in %.

Although the element abundances vary over quite considerable ranges, some interesting comparisons can be drawn between the two groups of samples. The northern group reflects enrichment in Zn, Co, Sr, Ca, Mg and Fe, and all of them except the last two decrease progressively in abundance with decreasing age. This decrease, particularly in Ca, suggests that the waters overlying the Kunene Margin may have been more productive in Miocene times (the age of the oldest stiff mud samples) than the present, and that calcareous sediments slowly gave way to the terrigenous material found on the shelf today. The mineralogy of the same samples suggested increasing aridity of the hinterland in post-Miocene times (see Section 7.7.2(c)), thus implying that correlation between sea-water temperature and coastal aridity (Siesser, 1977a) is not generally valid along the west coast of southern Africa. The reason for lithified limestone rocks of Middle to Late Miocene age (Chapter 4) existing on the inner shelf, and stiff

muds of similar age occurring on the outer margin is also enigmatic. Perhaps this difference reflects the desiccation of lime-mud on the inner shelf during repeated sea-level regressions rather than lithification through compaction. The youngest of the stiff mud samples (3886) has a chemical composition very similar to that of the modern sediments accumulating in the general vicinity (Appendix B.18).

The southern group of stiff mud samples is enriched in Cu, Ni, Cd, Rb, K, and Al, and except for the last three, the others show a rough increase in abundance with decreasing age. From the discussion of modern continental shelf sedimentation, the Cu-Ni-Cd association immediately suggests a relationship with organic-rich diatomaceous mud, and the conclusion drawn, is that primary productivity of the Walvis Shelf waters (the Benguela Current) has apparently increased since the Miocene. This situation is therefore in direct contrast with the changes that took place on the Kunene Margin, and implies that diatomaceous sedimentation on the Walvis Margin increased progressively in post-Miocene times. (It will be recalled from Chapter 4, that the highly reducing environments that gave rise to pelletal phosphorite in Middle to Late Miocene times was considered, based on petrographic evidence, to have formed in nutrient-rich lagoons with estuarine circulation, and not on the open shelf). Finally, erratic but high Al concentrations in the southern group of stiff mud samples and relatively high, but decreasing concentrations of K and Rb imply that much more humid conditions prevailed in the past, when leaching of acidic basement rocks and formation of thick soil horizons must have occurred where the Namib Sand Sea exists today. The effects of Holocene climatic changes on the development of the inner shelf have been discussed in Chapter 3.

The remaining two elements, Pb and Mn, show neither enrichment nor impoverishment and with the data at hand, it is not feasible to speculate further as to why these elements appear to be evenly distributed in the pre-Holocene clays.

In Piston Core No.2, no clear trends in element abundance values are evident (Appendix B.18) except that Co and Mn are relatively richer in the top two sub-sections, Zn in the bottom two sub-sections, and Pb and Al in the middle sub-section.

7.3.3 Mechanisms of element enrichment in the clays

Chemical elements in marine waters exist either in association with a solid phase, or in solution (Goldberg, 1957). They are incorporated into the sediment in three main ways: (i) in the crystal lattices of solid particles, by adsorption on to the surface of solid particles, or by absorption within inter-layer positions of the solid particles, (ii) in biogenic remains such as calcareous and siliceous shells, soft-body parts, and metabolic waste products,

and (iii) as a result of hydrogenous processes involving oxidation or hydrolysis of elements in solution (Goldberg, 1957; Riley and Chester, 1971). The type of solid phase with which an element is likely to become associated depends on its ionic potential (Goldschmidt, 1954) i.e., ionic charge/ionic radius. Elements with low and high potentials form stable cations and complex anions respectively, and those with intermediate potentials tend to form insoluble hydrolysates (Day, 1963; Mason, 1966).

Possible mechanisms whereby the 14 elements studied here were incorporated into the sediments are now briefly described, and the elements are dealt with in the same groups that were indicated by factor analysis as being naturally associated (Table 7.4).

(a) Cu, Ni and Zn

Statistically, these elements have been found to be significantly correlated with the organic fraction of marine sediments from many parts of the world (Hirst, 1962; Gross, 1967; Baturin and Kochenov, 1967; Calvert and Price, 1971b, 1972). They are initially taken up by phytoplankton and zooplankton in regions of upwelling (Brongersma-Saunders, 1965, 1968, 1969) and then transported to the sea floor by a variety of methods. The most important of these are: in association with skeletal structures, in the contained organic matter, in moulted exoskeletons, and in fast-sinking faecal pellets (Martin and Knauer, 1973; Smayda, 1971).

The levels of element enrichment in phytoplankton and zooplankton are complicated by the fact that not only do they vary widely between different taxa of the same phyla (Martin, 1969), but that the composition of individual species can change depending on the place, depth and time of sample recovery (Martin and Knauer, 1973). An example of the exceptionally high metal content of some planktonic species is provided by the diatom Chaetoceros curvisetus which is present in South West African waters, and contains 300-600 ppm Cu, 60-90 ppm Ni and 6000-9000 ppm Zn (Calvert and Price, 1971a). Furthermore, Cu is found in the blood of many marine invertebrates and is an essential component in the respiratory pigment hemocyanin (Burnett, 1971); Ni is found in porphyrin pigments from petroleum deposits (Emery, 1960; Calvert and Morris, in press); and Zn is particularly concentrated in the exoskeletons of some copepoda like Euphausia pacifica (Paquegnat et al., 1969; in Calvert and Morris, in press). In general, it appears that organisms of lower organizational levels are able to accumulate trace metals to a greater extent than the vertebrates (Goldberg, 1957).

Diagenesis of organic matter appears to be an important process in raising the levels of concentration of sorbed trace metals. Calvert and Morris (in press) have obtained evidence that low molecular weight degradation products of

marine organism (amino acids, carbohydrates, lipids, polycarboxylic acids) are responsible for complexing metals at an early stage, and that polymerisation of this material through diagenesis results in transfer and concentration of the metals in the insoluble, high molecular weight, humic acids.

Two main processes have probably been responsible for the concentration of Cu, Ni, Zn, and to some extent Pb, in the carbon-rich seaward flank of the diatomaceous mud belt (Figs. 7.5 and 7.6). The first, described in Chapter 5, involved the rapid rate of diatom frustule dissolution relative to the rate of organic matter oxidation. This difference has resulted in rich accumulations of C_{org} along the seaward flank of the diatomaceous mud belt, particularly west of Walvis Bay, whereas closer to shore, organic matter is diluted by opal. The lower C_{org} and trace metal concentrations in faecal pellet sand are probably a reflection of increased organic matter oxidation during transit to the deeper mid-shelf floor and concomitant regeneration of trace elements associated with it.

The second process involves the geochemical affinity of Cu, Ni and Zn for S, an element which is extracted from sea water by bacteria (Siesser, pers. comm.), and released from decaying organic matter as H_2S (Copenhagen, 1953; Baturin, 1974b). Introduction of Cu, Ni and Zn into the reducing environment of the diatomaceous mud (negative Eh and pH >7), possibly as ions scavenged by Fe hydroxides and Mn oxides (Goldberg, 1961), would result in their immediate release as the host elements went into solution, and they would then be available for precipitation in the form of insoluble sulphides (Nichols and Loring, 1962; Wedepohl, 1964). The role of pyrite in concentrating minor elements has recently been examined by Volkov and Fomina (1972) who found that pyrite in Black Sea sediments accommodates exceptionally high concentrations of Cu and Ni, viz., up to 1 562 ppm and 3 133 ppm respectively. On the other hand, because of similar ionic radius to that of Fe (Mason, 1966), Zn can readily replace it, or Mg, in mineral structures (Burnett, 1971).

Adsorption of the trace elements Cu, Ni and Zn on to the surfaces of clay minerals is probably not significant in the diatomaceous mud because of the general paucity of clays (excepting illite) and the abundance of organic matter. Nichols (1963) has shown that an organic film can be adsorbed on to the surfaces of clay particles, and this would tend to screen the latter from surrounding ions. Farther offshore, where montmorillonite and kaolinite increase in proportion to illite, adsorption of these trace elements may well be an important process.

(b) Cd

The occurrence of Cd in the clay fraction of the sediments is unusual

for two reasons: (i) it shows perfect correlation with the distribution of the diatomaceous mud belt (c.f. Figs. 5.21 and 7.7), and (ii) it occurs there in exceptionally high concentrations (maximum value of 60 ppm for sample 3773).

Data on Cd for comparative purposes are scarce but, in relation to the few published results on sediment studies elsewhere, the values obtained here are orders of magnitude higher. Since Cd was the only element not corrected against international standards (Appendix A.31), a single sample was analysed semi-quantitatively by X-ray fluorescence as a check on the previously obtained concentration (sample 3756 - 56 ppm). The results indicated approximately 50 ppm Cd, thus confirming the level of enrichment obtained by atomic absorption (J.P. Willis and A.R. Duncan, pers.comm.). The highest reports of Cd in the literature known to the writer are those of Jones (1973), who obtained a maximum of 19 ppm in boulder clay samples from Cardigan Bay (Wales), and Loginova (1959, in Wakita and Schmitt, 1970) who measured between 12 and 1 000 ppm in dry residues obtained from natural waters with low mineral content. Chester and Stoner (1974) report that the near-shore surface waters off South Africa and Japan contain higher concentrations of Cd than other parts of the world ocean, but the South African values are still only about 0,1µg/l (0,1 ppb). More recently, Alberts et al. (1976) have obtained substantially higher sea water values from near the Tongue of the Ocean (0,13 - 1,2 ppb), and they attribute this to riverine input from Puerto Rico. Eaton (1976) has found that about 60 ng/kg (0,6 ppb) is representative of the North Atlantic Ocean. It is thus apparent that some highly efficient enrichment mechanism exists for raising the Cd content of the South West African diatomaceous muds to such high levels.

In nature, Cd occurs in five known minerals, but the bulk of it resides as isomorphous impurities in other minerals, e.g., with zinc sulphides (Vlasov, 1964). It is therefore not unreasonable to assume that the source of Cd in the study area may be related to the suggested Zn mineralization in the Ugab River catchment area. Anthropogenic influence on the natural levels of Cd enrichment is unlikely because of the complete lack of industrial development along the coast other than fishing. During weathering, Cd^{2+} goes into solution containing sulphates or chlorides, and is capable of forming a large number of complex ions. The most important factors controlling its concentration in solution are apparently the pH and Eh (Wakita and Schmitt, 1970). Once introduced into the marine environment, it is probably taken up by diatom frustules since the degree of correlation between Cd and opal is significantly better than that between Cd and C_{org} (Table 7.4). It is unlikely to be associated with concretionary phosphorite in the mud despite the assertion of Goldberg (1957) that Cd may substitute for Ca in similar fashion to Sr, since Brooks and Ahrens

(1961) have indicated that the Cd-O bond contains a high degree of covalency. Furthermore, the distribution of Cd is entirely different to that of concretionary phosphorite (Fig. 5.23).

(c) Ca, Sr and Co

Sr^{2+} , with ionic radius of $1.12\text{\AA}$ (Mason, 1966), is only 15% larger than Ca^{2+} and can therefore be expected to follow a similar biochemical path to that of Ca (Goldberg, 1957; Krauskopf, 1967). Most Sr in marine sediments occurs together with calcium carbonate, apatite and phillipsite, and only 13% of it exists in the sorbed state in pelagic clays (Goldberg and Arrhenius, 1958). It is not surprising, therefore, that maximum concentrations of the two elements are found on the Walvis Outer Margin west of Swakopmund, where the highest concentrations of planktonic foraminifera are found (Chapter 5).

As was indicated earlier, the relatively high concentration of Co in the Swakop River clays is probably introduced into the marine environment in hydrogenous association with Fe. In the reducing environment of the diatomaceous mud, the Co would be released due to the formation of iron sulphides, but for some reason, it is not secured by diatomaceous organic matter as was the case with the chemically similar elements Cu, Ni, and Zn. Instead, the strong association of Co with Ca and Sr suggests that it is taken up by planktonic foraminifera, and whereas the Sr is situated in aragonite crystal structures, the much smaller Co^{2+} ion can only be accommodated by calcite (Mason, 1966). Some of the Co on the Kunene Margin, where both Ca and Sr concentrations are low, is probably adsorbed on to the surfaces of clay minerals as has been found by Hirst (1962) for sediments of the Gulf of Paria.

(d) Mg, Mn, Fe, Al, K, Rb

The strong positive correlation of all these elements with montmorillonite, kaolinite and the terrigenous fraction of the sediments (Fig. 7.12) is clear evidence of a primary terrestrial control. This is apparent from the regional distribution maps, Figs. 7.9, 7.10 and 7.11, which show maximum abundance levels on the Kunene Continental Margin and the Walvis Upper Slope.

Because of the great variety of isomorphous replacements possible in montmorillonite (Carrol, 1970), and also because of element uptake in interlayer positions to compensate the net negative charge, regional trends of Mg, Mn, Fe, and Al are probably largely accounted for by the distribution of this clay mineral. Some of the Fe and Mn however, may also occur as precipitated metal coatings on terrigenous grains; the findings of Gibbs (1973) indicate that between 40 and 50% of these elements are transported in the Amazon and Yukon Rivers by this means. Another source of Al is the clay mineral kaolinite, which is similarly dispersed to montmorillonite on the continental margin (Fig. 7.3), and is brought into the marine environment by the Kunene River. K, and

its geochemically related element Rb, is not determined by the wind dispersed, and most highly concentrated clay mineral, illite, because the regional distribution pattern of the latter (Fig. 7.3) is exactly the reverse to that of the two elements. This is confirmed by the lack of correlation between the clay mineral and the six elements of this Group (Fig. 7.12), which is in direct contrast with the findings of Griffin and Goldberg (1963) for the Pacific Ocean. The concentration of K and Rb in the clay fraction of the sediments does, however, reflect in broad outline, the distribution of glauconite (Fig. 5.25), this being due to the much greater volumetric abundance of glauconite relative to illite on the Kunene Margin and Walvis Upper Slope.

(e) Pb

The highest concentration of Pb is found associated with glauconite off the Kunene River mouth, and is probably related to the high influx of this element from the Kunene River clays. This, together with its occurrence in other sandy and gravelly deposits of varying composition and relict origin, suggests that it may be present as clay- and silt-size detrital particles that became associated with lag deposits during successive sea-level regressions and transgressions. Wright (1974) has found a similar situation in clay-size sediment from the Barents Sea where Pb is apparently partitioned between K_2O -bearing material and biogenic carbonate. Some Pb enrichment does occur in the carbon-rich western flank of the diatomaceous mud belt, but the degree of enrichment there is less than that occurring in the sandy and gravelly deposits of glauconitic and terrigenous and shelly sediment elsewhere on the continental shelf.

Chapter 8. GEOCHEMISTRY AND ORIGIN OF THE AUTHIGENIC MINERALS

8.1 INTRODUCTION

In this Chapter, the major and trace element geochemistry of the authigenic minerals is described, and this is followed by a discussion, using all available evidence, on their probable modes of formation. In Chapter 4, the petrography of phosphorite infillings (rock) was discussed, and such aspects as the age and physical character of the depositional environments that gave rise to it and the pelletal phosphorite were also described. In Chapter 5, the regional distribution of four unconsolidated sedimentary authigenic minerals cP, pP, gpP, and G was discussed as well as the P_2O_5 and K_2O contents of the sediment silt and clay fractions, the CO_2 , F and C_{org} concentrations in phosphorite, and the economic potential of the various authigenic mineral deposits.

The major element geochemistry of phosphorite and glauconite has been determined by two independent analytical techniques viz., X-ray fluorescence (XRF) and electron microprobe (EMP). Most published reports on the geochemistry of authigenic minerals have utilized the former method of analysis, and this has allowed comparison of their results with those obtained in the present study. The object of using the EMP was to study specific regions of some of the sedimentary particles, and also, to examine individual grains within the phosphorite infillings. Trace element abundances in the sedimentary particles were determined by XRF, and the previously obtained major-element concentrations were used for calculating mass absorption coefficients when necessary.

Glauconitized pelletal phosphorite (gpP), which has not been previously reported in the literature, constitutes 22% of the total phosphorite content of the unconsolidated sediments (Table 5.9), and as such, is an important component of the authigenic suite of minerals. Whereas pelletal phosphorite (pP) and glauconite (G) commonly occur in the granular fabric of limestones and phosphorite infillings, gpP does not.

Methods used for purification of the samples for XRF and EMP study are described in Appendix A.34, and the XRF procedures followed are given in Appendix A.35. Major element results obtained from XRF analysis are given in Appendix B.23, and the trace element concentrations are listed separately in Appendix B.24. Instrument settings employed on the XRF spectrometers are shown in Appendix B.25, and the major and trace element compositions of international and departmental standards used in the study are given in Appendices B.26 and B.27 respectively. Procedures followed on the electron microprobe are described in Appendix A.36, and the major element composition of standards employed is given in Appendix B.28. The results obtained from this study are

LOCATION OF SEDIMENTARY AUTHIGENIC MINERALS EXAMINED FOR THEIR TRACE AND MAJOR-ELEMENT GEOCHEMISTRY

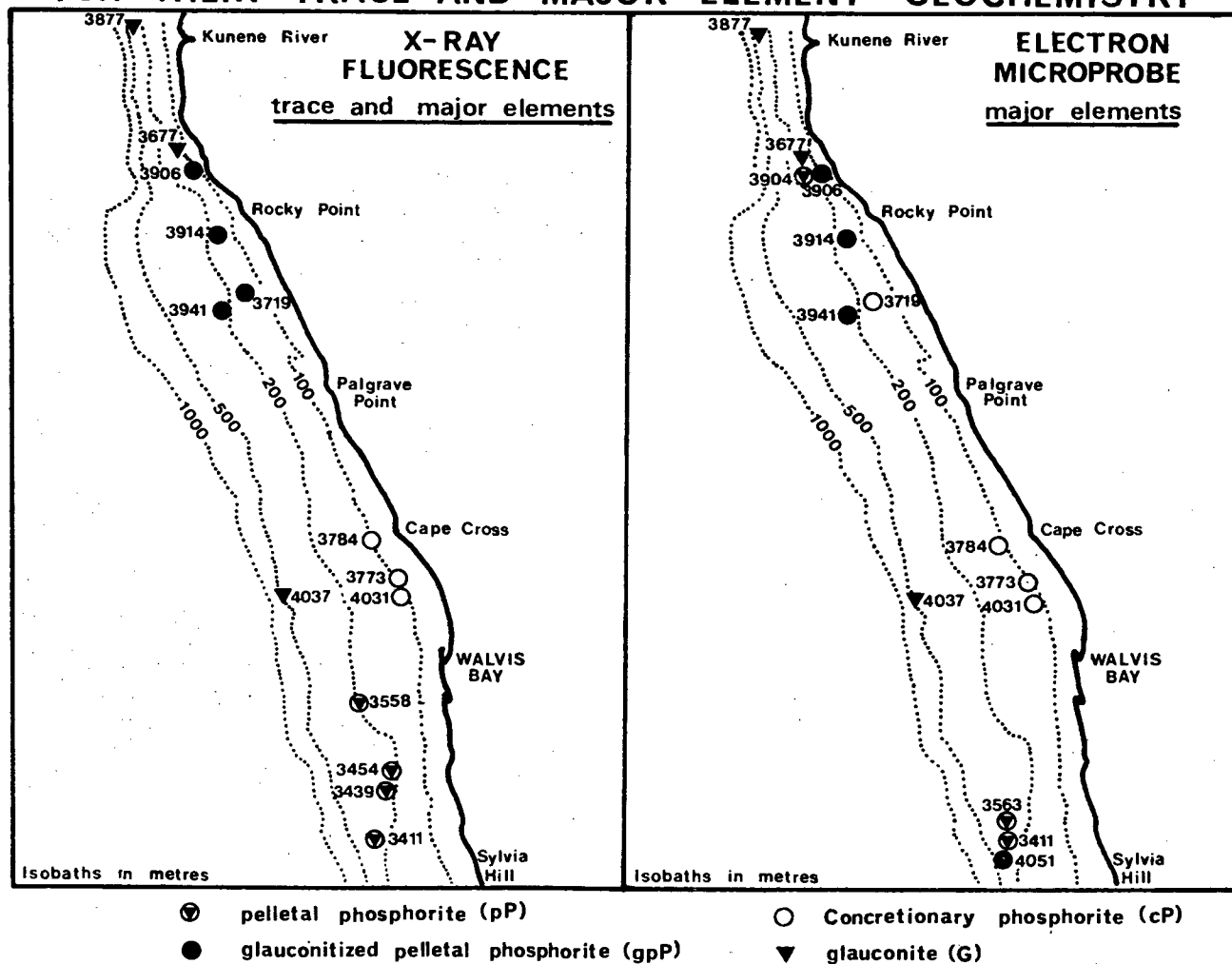


Figure 8.1

presented in Appendix B.29. Finally, a brief description of the advantages and disadvantages of the two analytical methods is given in Appendix A.37, and the degree of sample and element overlap between this study, and the geochemical study on the clay fraction of the sediments (Chapter 7) is described in Appendix A.38.

8.2 PETROGRAPHIC DESCRIPTION OF THE AUTHIGENIC MINERALS

Two principle types of concretionary phosphorite (cP) are found in the diatomaceous mud. These are: (i) hard brown concretions that break with difficulty by hand, and (ii) friable buff-coloured concretions that are usually smaller in size and disintegrate easily under finger pressure. The chroma of the hard brown concretions occasionally decreases in the interior of the particles suggesting that the colour of the outer surface is due to Fe-oxide staining. In thin-section, both types contain a few very-fine sand-size quartz grains and mica flakes, both totalling less than 1%, and no fishbones, fish-scales or diatom frustules were seen. The matrix of the concretions is homogeneous, cryptocrystalline and pale brown in colour, usually with a thin scattering of black organic matter.

Pelletal phosphorite (pP) and unfractured glauconitized pelletal phosphorite (gpP) are spherical, and rarely oval in shape. Whereas the former is always jet-black in colour with a resinous reddish lustre, the latter range from olive greens through yellowish browns to reds and have an earthy lustre. Additional features of the gpP are their deeply open-sutured rims and general similarity in appearance of their nuclei to the pP particles. In thin-section, the pP are black in colour owing to an abundance of organic matter, and generally possess a thin, clear, pale brown or pale green pellicle of collophane or glauconite. Approximately 20% of the pellets possess an oolitic internal structure, and roughly 5% contain an allogenic nucleus of quartz, glauconite, fishbone, etc. (Plates 8.1 and 8.11).

Glauconite (G) occurs as sub-rounded sand grains of varying shades of green, but samples from shallow water are generally smaller and angular due to fracturing along suture planes. Based on X-ray diffraction results (Chapter 5), and their high K_2O content (>8%, see later), they have all been classified as well-ordered and chemically mature (Burst, 1958a, 1958b). In thin-section, they are dark green to mottled yellowish-green with an homogeneous texture, and without inclusions of foreign material. Some of the grains, particularly from shallow water depths on the Kunene Shelf (e.g., sample 3677), exhibit some oxidation along sutures in the form of brown coatings (limonite of McRae, 1972).

8.3 MAJOR ELEMENT RESULTS

8.3.1 Comparison with similar material from other locations

Average major element compositions of the four authigenic minerals are listed in tables in the following order: cP - Table 8.1, pP and gpP - Table 8.2, and G - Table 8.3. Results obtained by other workers for the South West African authigenic minerals, as well as for minerals obtained from other locations, are included in these tables for comparative purposes.

The average bulk analyses obtained in the present study (XRF method) indicate that cP consists almost entirely of Ca and P, and the only other elements occurring above trace levels are Mg, Na and S. These results compare well with the results obtained by other workers (Price and Calvert, in press; Baturin, 1971c), and the small differences probably reflect variations in the abundance of detrital impurities in the different samples examined. Compared to phosphatic concretions from the diatomaceous muds off Chile (Baturin and Petelin, 1972), the South West African concretions are much less affected by detrital contamination as reflected by their lower concentrations of Si, Al, Fe and Mg, and higher concentrations of Ca and P.

The pP and gpP however, contain much higher concentrations of Si, Al, Fe, Mg and K than the cP (Tables 8.1 and 8.2), and for each of these elements, the levels of enrichment in gpP exceeds that in the pP. Conversely, the concentrations of Ca, P and Na are less in pP and gpP than in cP, and again, each of these elements reflect lower abundances in the gpP compared to pP. The only element to differ from these relative abundance trends, is S, which increases markedly from cP to pP, but then drops off slightly for the gpP. Comparison between EMP spot analyses of gpP nuclei and rims indicate that the nuclei are compositionally more closely akin to the pP, but even here the levels of Si and Fe enrichment are higher, and Ca, P and S are lower than in the pP. The average bulk analysis of pP, as found in the present study, is almost identical to that found by Price and Calvert (in press) for the same material except that they obtain a slightly lower average concentration for Ca. In comparison with the pP from the Cape West Coast (Birch, 1975), the South West African pellets, as with the S.W.A. - Chilean comparison of cP, are much purer in terms of allo-genic contamination as evidenced by lower levels of Si, Al, Mg and K. However, the South West African pP are relatively impoverished in P compared to the Cape West Coast pP, and this is apparently compensated for by considerably higher concentrations of S. Rough similarity in the Ca and Fe contents of pP from the two areas therefore suggests that the South West African mineral contains significant amounts of SO_4^{2-} substituting for PO_4^{3-} (Gulbrandsen, 1966), and this is supported to some extent by the relatively higher concentrations of Na in these particles. Unlike the rock phosphorites of the Agulhas Bank (Parker,

Table 8.1 Average major element composition of concretionary phosphorite(cP) from the study area, and from other locations (weight %)

Analytical method	This study		SWA ¹	SWA ²	Chile ³
	XRF	EMP	XRF	?XRF	?XRF
No. of analyses	3	8	2	?	?
SiO ₂	-	,11	1,40	,15	12,30
Al ₂ O ₃	-	,03	,37	,04	3,31
FeO*	,03	,01	,79	,18	2,01
MgO	,79	1,47	,60	1,70	1,60
CaO	48,36	50,31	51,25	46,42	38,64
Na ₂ O	,95	,96	-	-	-
K ₂ O	-	,04	,13	-	-
P ₂ O ₅	32,62	33,07	32,10	32,74	25,62
MnO	,01	ND	-	-	-
TiO ₂	,04	ND	,06	-	-
S	,79	,59	-	-	-
L.O.I.+H ₂ O ⁻	16,21	ND	-	12,20	8,65
CaO/P ₂ O ₅	1,48	1,52	1,60	1,42	1,51
F/P ₂ O ₅	,098	,097	,074	,092	,100
CO ₂ ^(a)	5,2		4,20	6,33	3,04
F ^(b)	3,2		2,39	3,02	2,55
C _{org} ^(c)	1,3		-	,92	,60

XRF = X-ray fluorescence, EMP = electron microprobe

* Total iron reported as FeO

- This study, not detected; other studies not reported

ND Not determined

1. Price and Calvert (in press). Consolidated phosphorite concretions

2. Baturin (1971c). Hard nodules

3. Baturin and Petelin (1972). Compact grey concretions

(a) This study and 1 - Gasometry and X-ray diffraction; 2, and 3 - not reported

(b) This study - specific ion electrode; 1 - XRF; 2, and 3 - not reported.

(c) This study - wet oxidation; 2 and 3 - not reported.

Table 8.2 Average major element compositions of pelletal phosphorite (pP) from unconsolidated sediment, bedrock and other locations, and of glauconitized pelletal phosphorite (gpP) from the sediment (weight %)

Analytical method of analyses	Pelletal phosphorite (pP)					Glauconitized pelletal phosphorite (gpP)			
	Unconsolidated sediment				Rock ⁺	Unconsolidated sediment			
	This study		SWA ¹	Cape West coast ²	This study	This study			
	XRF	EMP	XRF	EMP	EMP	XRF	EMP	EMP 24 (nucleus)	EMP 35 (rim)
	4	31	2	12	16	4	59		
SiO ₂	4,97	2,70	4,80	5,51	3,30	8,06	4,17	3,78	4,44
Al ₂ O ₃	1,12	1,11	1,21	1,40	,93	1,66	1,16	1,11	1,19
FeO*	2,29	4,95	2,63	4,13	8,48	6,02	6,31	6,57	6,13
MgO	,83	,90	,90	1,10	,80	,96	,68	,62	,72
CaO	46,93	45,18	44,15	44,90	43,26	38,73	39,70	41,52	38,46
Na ₂ O	,50	1,09	-	,84	1,06	,34	,61	,70	,55
K ₂ O	,38	,34	,39	,56	,34	,60	,42	,38	,45
P ₂ O ₅	28,04	28,62	28,30	34,00	25,05	25,25	25,12	27,65	23,38
MnO	,03	ND	-	-	ND	,09	ND	ND	ND
TiO ₂	,46	ND	,11	-	ND	,89	ND	ND	ND
S	2,31	4,27	-	1,67	8,16	2,00	1,98	2,68	1,50
.I.+H ₂ O ⁻	12,03	ND	-	-	ND	16,85	ND	ND	ND
/P ₂ O ₅	1,67	1,58	1,56	1,32	1,73	1,53	1,58	1,50	1,64
/P ₂ O ₅	,114	,112	,086	-	ND	,100	,100	ND	ND
CO ₂		3,6	3,70	-	ND		4,1		
F		3,2	2,42	-	ND		2,6		
C _{org}		2,7	-	-	ND		1,4		

Pelletal phosphorite in granular fabric of phosphorite infillings (Chapter 4)

= X-ray fluorescence, EMP = electron microprobe

Total iron reported as FeO

= not determined (this study), - = not reported (other studies)

Price and Calvert (in press)

Birch (1975)

Analytical methods for determining CO₂, F and C_{org}, see Table 8.1

Table 8.3 Average major element composition of glauconite(G) from unconsolidated sediment, bedrock and other locations(%)

Analytical method No. of analyses	This study			Cape West coast ¹	USA and Sweden ²	Israel ³
	Unconsolidated sediment		Rock ⁺			
	XRF	EMP	EMP	EMP	Miscell.	XRF
	3	13	5	20	4	8
SiO ₂	48,42	49,28	50,25	50,97	49,24	46,27
Al ₂ O ₃	5,59	5,28	4,45	4,29	11,09	7,13
Fe ₂ O ₃ *	24,35	23,38	25,66	21,01	20,80	24,61
MgO	4,29	4,48	4,96	5,45	3,42	4,21
CaO	,59	,19	,21	,18	1,31	,46
Na ₂ O	,02	,02	,03	,07	,12	,41
K ₂ O	8,05	8,16	8,72	9,01	8,13	7,50
P ₂ O ₅	,22	,10	,12	,15	-	,19
MnO	,01	ND	ND	-	-	,02
TiO ₂	,13	ND	ND	-	-	,08
S	,06	,03	,06	-	-	-
L.O.I.+H ₂ O ⁻	8,44	ND	ND	-	6,80	9,13
Al ₂ O ₃ /K ₂ O	,69	,65	,51	,48	1,36	,95
Fe ₂ O ₃ /K ₂ O	3,02	2,87	2,94	2,33	2,56	3,28

+ Glauconite in granular fabric of phosphorite infillings (Chapter 4)

XRF = X-ray fluorescence, EMP = electron microprobe, Miscell. = microchemical, spectrochemical, and colourimetric methods

* Total iron reported as Fe₂O₃

ND = not determined (this study), - = not reported (other studies)

1. Birch (1975). "Mature" glauconite

2. Burst (1958b). "Ordered" glauconite, samples 3,4,5 and 6, p.490

3. Benton and Kastner (1965). Recalculated analyses, samples 1,2,3,4,5,6,10,11, p.160.

1971), a weak negative correlation was found to exist between Na and S in the South West African pP, but this is largely due to the masking effect of pyrite, which is present in great abundance. The Fe not associated with S in the Cape West Coast pP may be occurring as ferric-hydroxy phosphate as has been suggested by Birch (1975) for some foraminiferal infillings in the area.

In contrast with the close geographic relationship of phosphorite to glauconite in the authigenic deposits on the Cape West Coast (Summerhayes, 1972a), the distribution of these two minerals off South West Africa is essentially separate (Chapter 5). Nevertheless, glauconite constitutes one pure end-member of the mineralogic series: cP - pP - gpP - G, and must be included in any study of the authigenic suite of minerals. In composition, G is most similar to the gpP, but naturally, contains much higher concentrations of Si, Al, Fe, Mg and K, and lower Ca, P, Na and S (Tables 8.2 and 8.3). Compared to well-ordered, mature glauconites from other parts of the world, the South West African G can be considered to be 'normal', and compared to the Cape West Coast glauconites in particular (Birch, 1975), it is relatively richer in Fe and Al, and poorer in Si, Mg and K.

8.3.2 Pelletal phosphorite and glauconite in phosphorite infillings

Only two of the four authigenic minerals commonly found in the unconsolidated sediments viz., pP and G, are also found in the granular fabric of the phosphorite infillings. cP is absent because of its Quaternary age, and gpP does not occur for reasons that are discussed below. Conversely, two authigenic materials commonly found in the phosphorite infillings are absent from the sediments viz., sand-size angular fragments of phosphorite, and light brown collophane which constitutes the matrix of the infillings (Chapter 4). Neither of these materials have been included in the present study because the aim was to examine the sedimentary authigenic mineral assemblage as defined by the mineralogic series shown above.

Of the infillings that were studied in Chapter 4 for their petrography, three were examined in the present study to determine whether the pP and G particles had undergone any chemical alteration. Two of these were small fragments <2 cm across, and came from the inner shelf off Cape Fria (sample 4729) and the mid shelf south of Sylvia Hill (sample 3232, Rogers, pers.comm.). The third sample, which was actually classified as a limestone in Chapter 4, was included in this study because it contained a large phosphorite-filled boring; it came from the continental shelf just south of the Kunene River mouth (sample 4744). Due to the small physical dimensions of samples 3232 and 4729, it is likely that they too were formed within the confines of limestone borings and for this reason, all of them are generally referred to as 'infillings'. Microprobe thin-sections of these infillings show clearly definable particles

action between the non-carbonate grains, the muddy matrix and the wall-rock of the borings, thereby transforming any included gpP to pP, and at the same time, modifying the compositions of the pP and G.

8.3.3 Major element inter-relationships

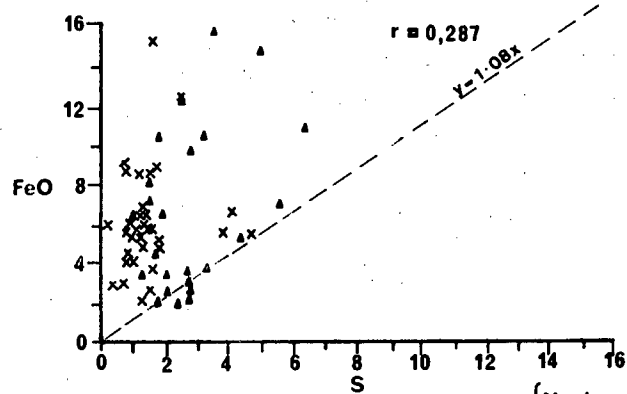
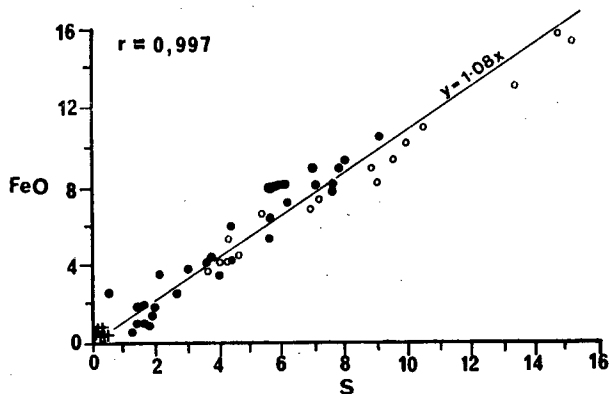
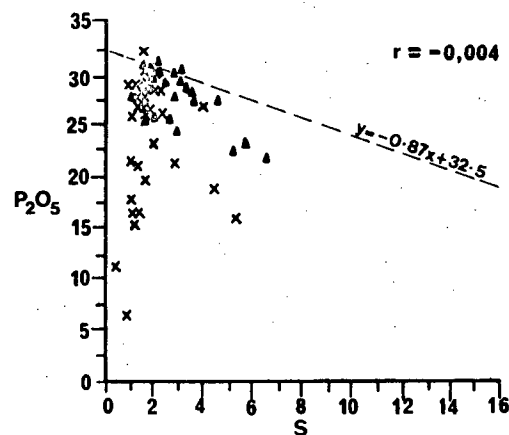
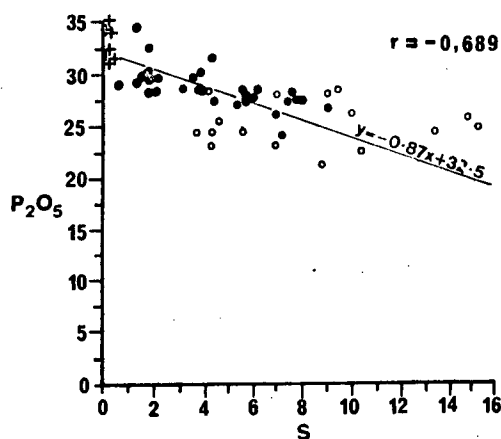
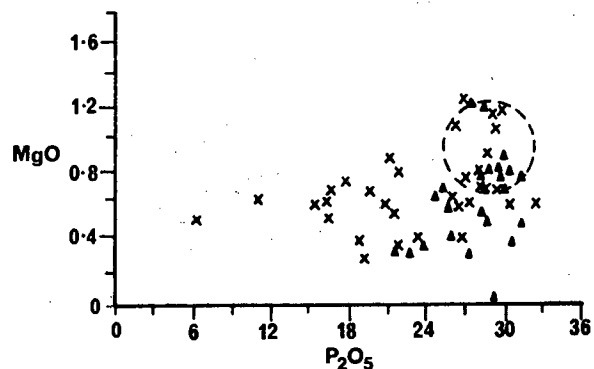
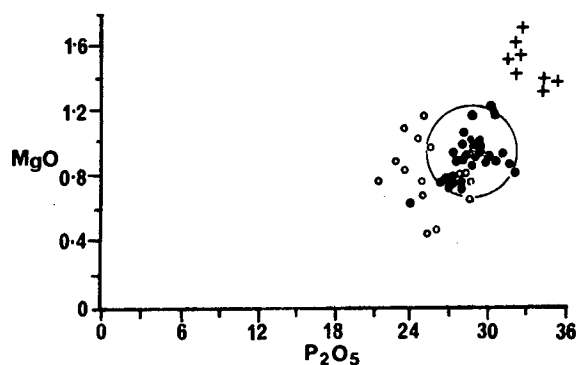
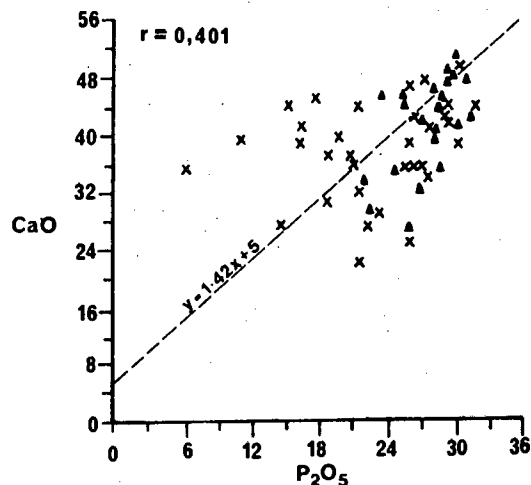
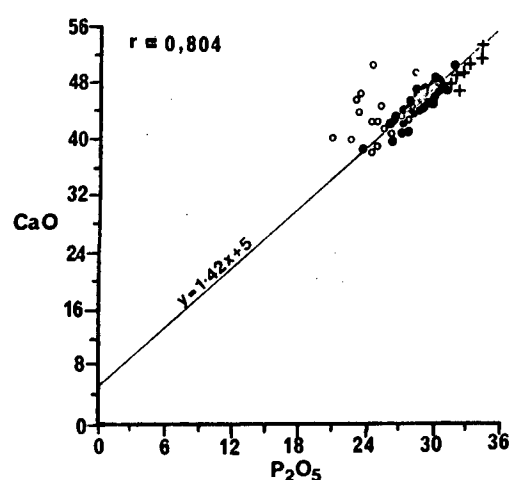
A number of bivariate plots have been compiled of EMP spot analyses in order to examine the degree of correlation among various major elements in the authigenic minerals. The cP, sedimentary pP and infilling pP are plotted together in the same diagrams (using different symbols), and the gpP nuclei and rims are plotted in adjacent diagrams to facilitate comparison between them (Figs. 8.2 and 8.3). The sedimentary G and infilling G are plotted together in Fig. 8.4.

(a) Phosphorite

From Fig. 8.2, it is evident that CaO and P_2O_5 are strongly positively correlated in cP and pP (CaO/P_2O_5 ratios = 1,52 and 1,58 respectively), whereas the infilling pP shows some impoverishment in P_2O_5 (CaO/P_2O_5 = 1,73). Since both Ca and P were previously seen to be impoverished in the infilling pP, the greater loss of P over Ca may be related to phosphatization of the limestone-boring walls (Plate 8.8). The equation of the best-fitting regression line through all these points in the diagram is identical to that obtained by Price and Calvert (in press) for South West African phosphorite minerals, and transfer of this regression line to the gpP plot reveals that these points are spread over a much wider area. The average CaO/P_2O_5 ratio however, has fortuitously remained the same as the ratio for pP viz., 1,58. Close inspection of the plot reveals that whereas both nuclei and rims are sometimes impoverished in Ca, only the rims are occasionally impoverished in P. The considerable variation in composition of these pellets indicate that the environment in which they were formed suffered marked chemical changes.

The MgO vs. P_2O_5 plot of Fig. 8.2 reveals that the Mg content of pP falls within a very narrow range, and whereas the infilling pP exhibit, on average, slightly lower concentrations of Mg, the cP are comparatively enriched in Mg. A possible explanation for the lower Mg content of infilling pP is that it may have been transferred to the infilling G, since Mg^{2+} ions are not easily accommodated in apatite (Martens et al., 1970) but commonly replace Al in the dioctahedral layers of glauconite (Foster, 1969). Regarding the high concentrations of Mg in cP, McLellen and Lehr (1969) have shown that increased carbonate substitution in apatite can be accompanied by increased uptake of Mg. The lack of terrigenous impurities in the cP, together with the high CO_2 content, therefore suggests that Mg does in fact occur in the carbonate-fluorapatite lattice. This has been specifically suggested by Price and Calvert

RESULTS OF ELECTRON MICROPROBE ANALYSES ON cP, SEDIMENTARYpP, INFILLING pP, AND gpP NUCLEI AND RIMS



Concretionary phosphorite (cP) +
Pelletal phosphorite (pP) { Sediment •
Infillings ○

Glauconitized pelletal phosphorite (gpP) { Nucleus ▲
Rim x

Figure 8.2

(in press) in their study of South West African concretionary phosphorites. The pP and gpP particles contain an abundance of silt and clay size terrigenous material (Plates 8.1, 8.2, 8.3, 8.4), yet their Mg contents are lower than the cP, as are also their CO_2 contents (Fig. 8.5). The gpP furthermore, contain slightly less Mg than the pP (Fig. 8.2), and this fact is considered to be of major importance in the interpretation of the origin of these particles (see Section 8.5 of this Chapter).

The P_2O_5 vs. S plot (Fig. 8.2) shows strong negative correlation between these variables for cP, sedimentary pP and infilling pP, with the latter containing most S, and the cP containing most P. In direct contrast with this plot, Fe vs. S exhibits a strong positive correlation. These two diagrams together indicate that most of the Fe and S coexist in pyrite, that cP contains negligible quantities of this mineral (Plate 8.5), that infilling pP contains the most (Plates 8.7 and 8.9), and that the abundance of pyrite is inversely related to the abundance of apatite. A slightly wider scatter of points in the P_2O_5 vs. S plot compared to the Fe vs. S plot probably reflects the presence of some S in the carbonate-fluorapatite lattice (Gulbrandsen, 1966), and some in association with organic matter (Powell et al., 1975). The two equivalent gpP plots in Fig. 8.2 diverge markedly from the previously established regression lines. This is due, in most cases, to lower concentrations of P_2O_5 and S, and higher concentrations of Fe. In general, the enrichment in Fe is most pronounced in the rims of the gpP particles (Fig. 8.2, Plate 8.3), but in a few of them, the reverse is true (see Plate 8.4).

In the remaining element plots for these phosphorite minerals (Fig. 8.3), Al_2O_3 and CaO show some degree of correlation with K_2O but FeO and MgO do not. The weak positive correlation between Al and K indicates that these elements are mostly bound up in terrigenous phases in the sedimentary and infilling pP, as well as in gpP (the cP being virtually devoid of terrigenous material, Plate 8.5). On the other hand, Ca shows a weak negative correlation with K for these minerals, and this most likely reflects apatite dilution by the terrigenous phases. Relative to the previously established regression lines, most of the gpP are impoverished in Ca, which is due in part to glauconitization of the rim. Some of them however, are significantly enriched in Ca due to the presence of gypsum in the sutures of the rims (Plates 8.3 and 8.4). The reason for FeO and MgO not being correlated with K_2O is probably because most of the Fe occurs with S (in the sedimentary and infilling pP) or with P (in the gpP rims), and most of the Mg occurs in the carbonate-fluorapatite lattice of the minerals.

Regarding the occurrence of Fe and Al in phosphorite, Stumm and Morgan (1970) state that phosphate has a strong tendency to react with ferric iron,

RESULTS OF ELECTRON MICROPROBE ANALYSES ON cP, SEDIMENTARY pP, INFILLING pP, AND gpP NUCLEI AND RIMS

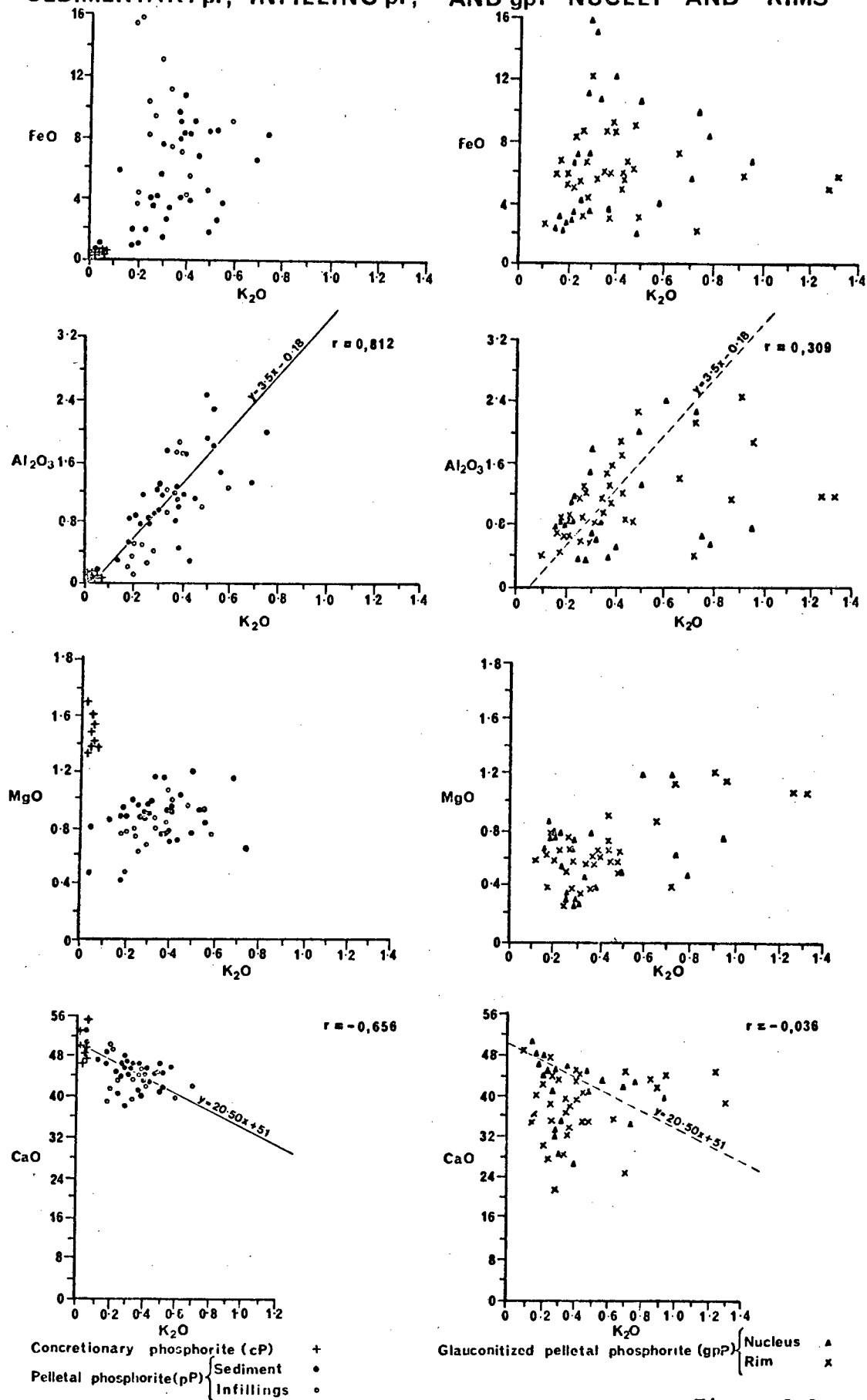


Figure 8.3

and the solubility of FePO_4 is minimal at a pH of 5.5. Van Riemsdijk (1975) has found experimentally that at the same pH, and relatively warm temperatures (20.5°C), phosphate will adsorb onto alumina, and subsequently crystallize as aluminium phosphate at a rapid rate. Deer et al. (1962) have suggested that a possible replacement mechanism may be $\text{Ca}^{2+}\text{P}^{5+} \rightleftharpoons 3(\text{Al}, \text{Fe})^{3+}$. The two essential criteria are therefore an acidic and oxygenated environment, both of which are contrary to the generally accepted conditions thought to be necessary for apatite precipitation (Gulbrandsen, 1969; Tooms et al., 1969; Burnett, 1974). These factors are examined further in the last Section of this Chapter.

(b) Glauconite

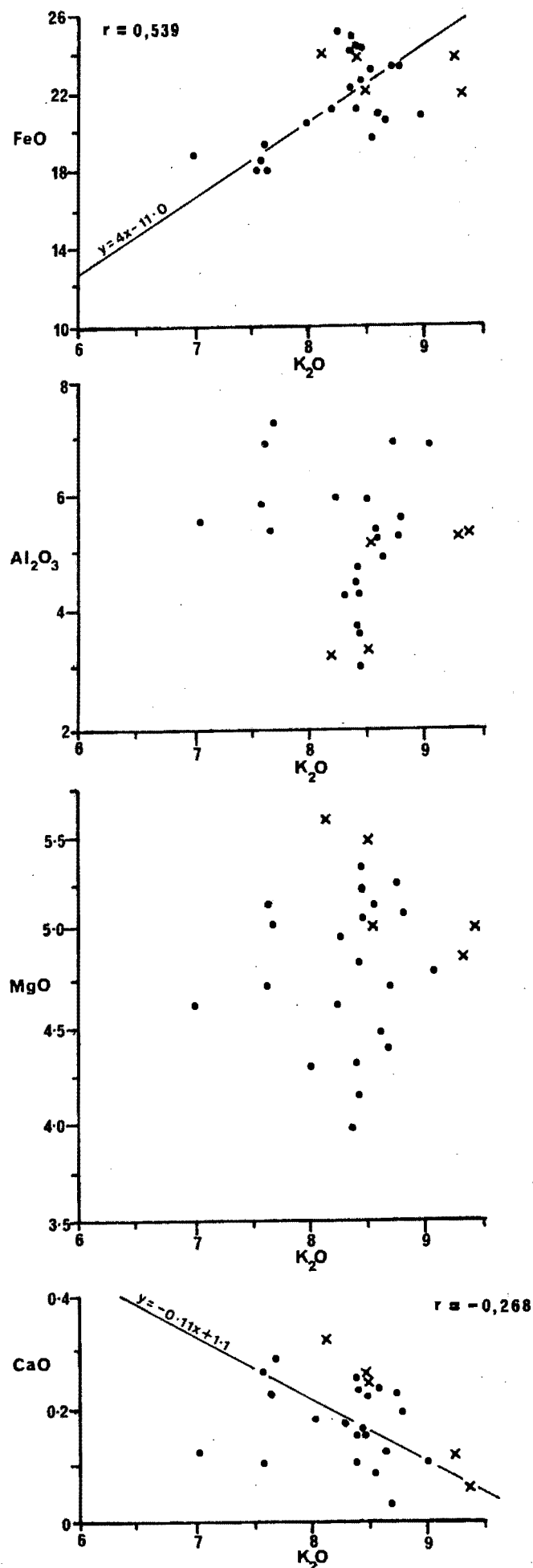
The roles played by Fe and K in the authigenesis of glauconite is a highly contentious subject. From evidence gained in the present study, the two elements appear to show a weak positive correlation with each other (Fig. 8.4), which therefore tends to support the 'layer lattice theory' of Burst (1958a, 1958b) and Hower (1961). This theory holds that Fe slowly substitutes for Al in octahedral positions of partially degraded 2:1 layer-lattice minerals, and the resulting increase in layer-lattice charge results in the uptake of K, first by adsorption in the interlayer positions, and subsequently by fixation in the lattice. Foster (1969) however, maintains that any proportionality between Fe and K is purely coincidental. Bentor and Kastner (1965) have suggested that non-structural Fe may be responsible for obscuring the true relationship between Fe and K in glauconite, and Ehlmann et al. (1963) have found evidence that Fe is necessary at an early stage for the authigenesis of glauconite.

Al_2O_3 and MgO exhibit no correlation with K_2O at all (Fig. 8.4). Hendricks and Ross (1941) assumed that all the Mg in glauconite replaces Al in the octahedral layers, but more recently, Bentor and Kastner (1965) have found that adsorbed K^+ ions can only balance the negative lattice charge if some of the Mg in the octahedral layers is additional to that replacing Al. It therefore appears that whereas Fe exclusively replaces Al in octahedral layers, Mg is partitioned there, and this probably accounts for the scatter of points seen in the two plots both for the sedimentary G and the infilling G.

CaO and K_2O are weakly negatively correlated in the plot shown in Fig. 8.4. Ca, together with Sr and Na, are exchange ions in the expandable layers of glauconite (Hower, 1961; Weaver and Pollard, 1973), and under normal marine conditions, all three would tend to be replaced by K and Rb.

Element distribution images of sedimentary G are shown in Plate 8.6, and of infilling G in Plates 8.8 and 8.10. No significant differences between them are apparent except that sutures in the latter are filled with apatite or

RESULTS OF ELECTRON MICROPROBE ANALYSES ON G



Glauconite (G) { Sediment • Infillings x Figure 8.4

pyrite, and occasionally, the rims are replaced (or ?coated) with apatite or pyrite.

8.4 TRACE ELEMENT RESULTS

A large body of literature has been published on the mineralogy, distribution and origin of phosphorite and glauconite deposits around the world, and as an adjunct to some of these studies, their major-element geochemistry has come to be fairly well understood (Hendricks and Ross, 1941; Hower, 1961; Gulbrandsen, 1966; Parker, 1971; Birch, 1971, 1975; Burnett, 1974). The trace element geochemistry has, by contrast, received only cursory attention, mainly because of the tedium involved in removing contaminant phases prior to their analysis. However, Price and Calvert (in press) have made a detailed geochemical study of some of the South West African authigenic minerals, and their work has been invaluable to a proper understanding of the results obtained here. All together, 14 trace elements were analysed for viz., Ba, Co, Cr, Cu, Mn, Nb, Ni, Rb, Sr, Ti, V, Y, Zn and Zr, and since the determinations were made on bulk samples (XRF) (Appendix A.35), only the unconsolidated sedimentary authigenic minerals have been considered in this study.

8.4.1 Authigenic minerals compared to sea water

Tooms et al. (1969) have compared published data on trace element enrichment levels in phosphorite rock with reported values for sea water. They found that with few exceptions the elements enriched in sea water were also enriched in phosphorite (relative to the average crustal rock), and those elements impoverished in sea water were also impoverished in phosphorite (relative to the average crustal rock). They therefore concluded that sea water strongly influenced the trace element composition of phosphorite. Based on this deduction, it was decided to test the three phosphorite minerals as well as glauconite from the study area, using the sea-water values published recently by Brewer (1975).

Average trace element concentrations and ranges for each of the different authigenic minerals, are presented in Table 8.4 together with additional information on the Phosphoria Formation, average crustal rock and sea-water. In relation to the Phosphoria Formation, the South West African phosphorites contain lower concentrations of each of the trace elements except Mn in gpP, and Sr in cP, pP and gpP. However, judging from the 'rounded' values reported by Gulbrandsen (1966), the accuracy of the spectrographic method appears to be rather poor.

The average trace element abundances of South West African authigenic minerals are contrasted with sea water by relating both of them to the element abundances in average crustal rock (Mason, 1966). Since the trace element

Table 8.4 Average trace element concentrations in the authigenic minerals, and in some other deposits and environments (ppm)

	South West Africa ¹				Phos- phoria ² U.S.A.	Average ³ crustal rock	Sea ⁴ water
	cP	pP	gpP	G			
No. of samples	3	4	4	3			
Ba	79 (74-83)	66 (43-100)	62 (48-77)	12 (6-17)	100	425	,002
Co	<3	<10	<12	<10	ND	25	,00005
Cr	14 (10-18)	195 (182-218)	300 (210-382)	714 (473-894)	1000	100	,003
Cu	4 (<2-9)	28 (23-38)	48 (25-86)	4 (<2-6)	100	55	,005
Mn	12 (0-35)	30 (20-45)	90 (40-160)	135 (90-220)	30	950	,002
Nb	<3	<3	<3	<3	ND	20	,00001
Ni	7 (6-8)	60 (43-75)	80 (33-117)	9 (3-18)	100	75	,0017
Rb	<3	7 (5-8)	20 (16-23)	185 (167-202)	ND	90	,12
Sr	2350 (2300-2410)	2260 (2250-2270)	1630 (1160-1860)	18 (14-23)	1000	375	,008
Ti	43 (30-50)	463 (380-520)	889 (590-1420)	1310 (870-2090)	ND	4400	,001
V	20 (12-24)	40 (38-43)	67 (49-79)	180 (159-222)	300	135	,0025
Y	7 (6-8)	206 (187-220)	284 (204-348)	10 (7-14)	300	33	,000013
Zn	84 (66-108)	27 (24-29)	46 (41-56)	30 (30-31)	300	70	,0049
Zr	<3	29 (17-44)	28 (11-37)	44 (33-55)	30	165	,00003

< Average value = lower limit of determination

ND = not determined

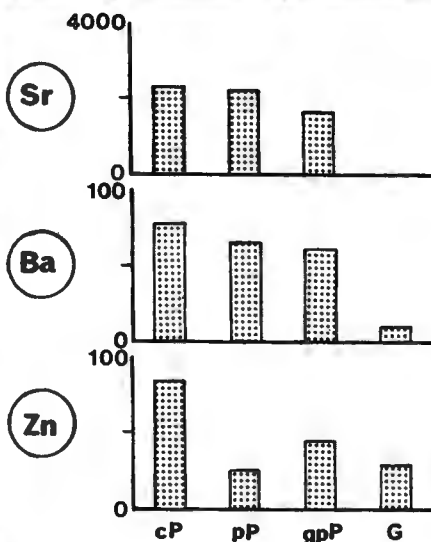
¹ = this study; average values and ranges shown² = data from Gulbrandsen (1966). (Spectrographic analysis)³ = data from Mason (1966)⁴ = data from Brewer (1975)

CONCENTRATION OF SOME CHEMICAL COMPONENTS IN PHOSPHORITE AND GLAUCONITE

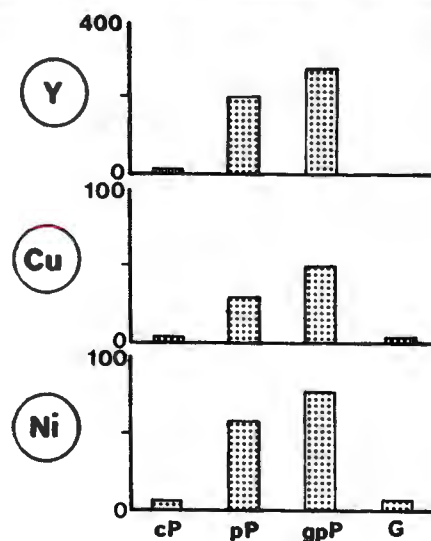
TRACE ELEMENTS

Phosphorite-group elements

cP-dominant

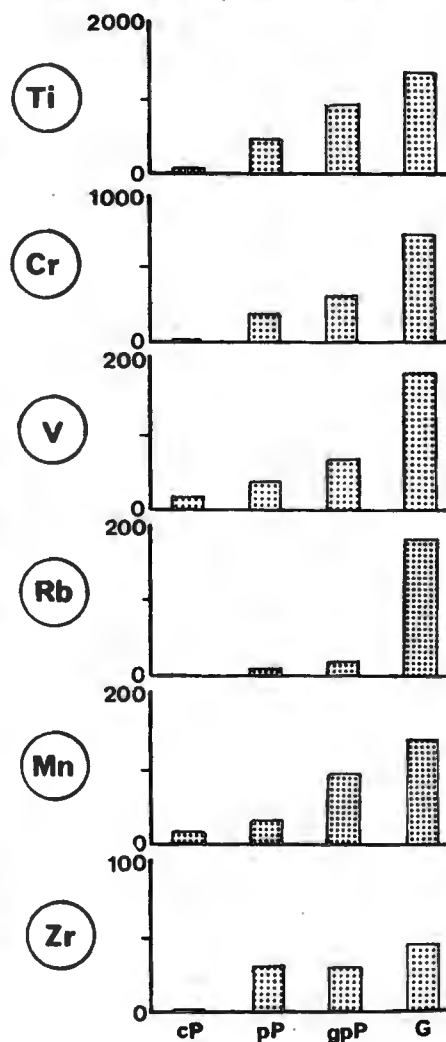


pP-and gpP- dominant

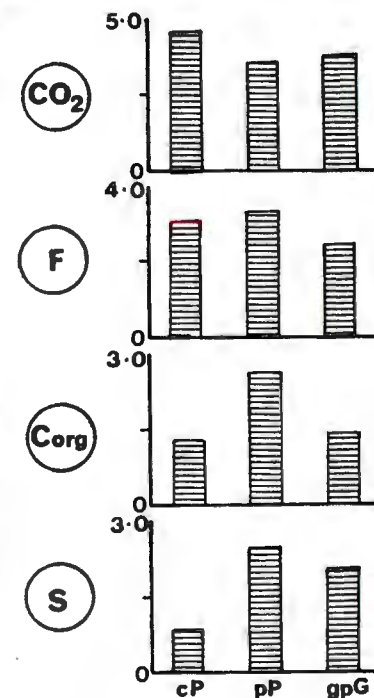


Glauconite-group elements

G-dominant



MAJOR COMPONENTS



cP - concretionary phosphorite (modern)
pP - pelletal phosphorite (relict)
gpP - glauconitized pelletal phosphorite (relict)
G - glauconite (relict)

Heights of histogram blocks indicate average element concentrations in the four mineral types

Trace elements in ppm, major components in %.

Co and Nb - not plotted
(concentrations below limits of determination)

Figure 8.5

some of these components exert on trace-element enrichment. This diagram allows direct comparisons to be drawn between the absolute element concentrations within each of the hierarchical groups, and is used to advantage in the discussion of trace element associations in the next section. To facilitate comparison of the trace element enrichment levels between various phosphorite minerals and between each of them and glauconite, Table 8.6 was constructed along the same lines as Table 8.5. The element abundance ratios used for classifying the elements are again those of Nicholls (1967).

Table 8.6 Comparison of trace element abundances in the various authigenic minerals (Data from Table 8.4)

Mineral comparisons	Enriched	Equivalent	Impoverished
cP : pP	Zn	Ba Sr	Cr Cu Mn Ni Rb Ti V Y Zr
cP : gpP		Ba Sr Zn	Cr Cu Mn Ni Rb Ti V Y Zr
pP : gpP		Ba Cr Cu Ni Sr Ti V Y Zn Zr	Mn Rb
cP : G	Ba Sr Zn	Cu Ni Y	Cr Mn Rb Ti V Zr
pP : G	Ba Cu Ni Sr Y	Zn Zr	Cr Mn Rb Ti V
gpP : G	Ba Cu Ni Sr Y	Mn Ti Zn Zr	Cr Rb V

cP = concretionary phosphorite, pP = pelletal phosphorite, gpP = glauconitized pelletal phosphorite, and G = glauconite.

Enriched elements = $(x \geq 2)$, equivalent elements = $(2 > x > \frac{1}{2})$, impoverished elements = $(x \leq \frac{1}{2})$

Note: The element classifications 'enriched', 'equivalent' and 'impoverished' apply to the first-named mineral in each of the comparisons. The 'enriched' and 'impoverished' classifications are naturally reversed for the second-named mineral.

With regard to the phosphorite comparisons, it is apparent that Zn is the only element in an enriched state in cP, and then only with respect to the pP. The two pelletal phosphorites, pP and gpP, have very similar trace element compositions, both being enriched relative to cP in Cr, Cu, Mn, Ni, Rb, Ti, V, Y and Zr. The gpP however, are enriched in Mn and Rb relative to the pP.

In the phosphorite-glauconite comparisons, the former are all enriched in Ba and Sr, and in addition, cP are also enriched in Zn, and pP and gpP in Cu, Ni and Y. Glauconite on the other hand, reflects a trace element composition closely related to gpP, and in relation to it, is enriched in only 3 of the 14 trace elements examined viz., Cr, Rb and V. In addition to these elements, G is also enriched in Mn and Ti relative to the cP and pP, and in Zr as well relative to cP.

Combining the results of Table 8.5 and Table 8.6, it appears that the only trace elements significantly enriched in the authigenic minerals relative to the average crustal rock and sea water are: Sr in cP, pP and gpP, Y in pP and gpP, Cr in G, and Rb is enriched in G relative to crustal material, but not relative to sea water.

8.4.3 Associations between the trace and major elements

The manner in which the trace elements were taken up by the various authigenic minerals is examined in relation to the major element geochemistry using correlation matrices shown in Tables 8.7 and 8.8. The matrices were derived with the aid of a computer program called BMD02D published by the Health Sciences Computing Facility, U.C.L.A. Because of the small number of samples that were analysed by X-ray fluorescence (3 cP, 4 pP, 4 gpP and 3 G), it was decided to run the three phosphorite minerals together, and subsequently, to run them with glauconite in order to obtain realistic correlations. In the following discussion, the trace element associations in each of the hierarchical groups shown in Fig. 8.5 are discussed separately.

(a) cP-dominant trace elements

Sr, the most abundant and only trace element selectively enriched in all three phosphorite minerals is, not unexpectedly, associated with the major elements of the carbonate fluorapatite lattice viz., Ca, P, F and Na (Tables 8.7 and 8.8). Price and Calvert (in press) have found evidence to suggest that Sr is incorporated in the apatite structure at the time of its formation, and that it remains fixed during postdepositional changes that may affect the phosphorite. Close similarity of the Sr/Ca ratios, as indicated by the present study, for the three different phosphorite minerals, supports this contention, and in relation to sea water, the minerals are enriched in Sr by a factor of approximately 3, viz., cP:pP:gpP:sea water = $6,80 \times 10^{-2}$: $6,74 \times 10^{-2}$: $5,85 \times 10^{-2}$: $1,90 \times 10^{-2}$. Relative to the ambient sediment (Appendix A.38), cP is enriched in Sr by a factor of 14, pP by a factor of 15, and G by a factor of 0,1.

Ba is not significantly correlated with any of the major or trace elements (Tables 8.7 and 8.8). Possible mechanisms of incorporation in the apatite are: in association with feldspar and clay mineral contaminants (Willis, pers.comm.), as a sequestered element with Mn (McConnell, 1973), or concentrated by phytoplankton e.g., Chaetoceros sp. (Brongersma-Saunders, 1967b; Vinogradova and Koval'skiy, 1962). Although the ionic radius of Ba^{2+} is considerably larger than Ca^{2+} (Mason, 1966), it has been successfully substituted in synthetic apatites (Deer et al., 1962), and in the opinion of Price and Calvert (in press), the uptake of Ba is penecontemporaneous with the formation of carbonate-fluorapatite.

Zn is correlated with CO_2 in the phosphorites (Table 8.7), thus suggesting that it substitutes for Ca as CO_3^{2-} substitutes for PO_4^{3-} in the carbonate-fluorapatite lattice. Indirect evidence to support this is that cP contains the highest concentration of Zn and also, the highest concentration of CO_2

Table 8.7 Correlation matrix* of major and trace elements in the phosphorite minerals (cP, pP and gpP)

Major Elements												Trace Elements											
SiO ₂	Al ₂ O ₃	FeO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	S	F	CO ₂	C _{org}	Sr	Ba	Zn	Y	Cu	Ni	Ti	Cr	V	Rb	Mn	Zr
				,86	,79		,91		,93			1,00											
										,76			1,00	1,00									
,92	,93	,87					,89								1,00								
,80	,79						,82									1,00							
,88	,88						,87									,87	1,00						
,87	,89	,81					,81								,87		,76	1,00					
,93	,94	,89					,89								,98			,93	1,00				
,87	,85	,92					,85								,92			,85	,94	1,00			
,91	,87	,98					,94								,83			,77	,84	,90	1,00		
															,76			,91	,83	,84		1,00	
															,81				,80				1,00

Table 8.8 Correlation matrix* of major and trace elements in the phosphorite minerals and glauconite (cP, pP, gpP and G)

Major Elements												Trace elements											
SiO ₂	Al ₂ O ₃	FeO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	S	F	CO ₂	C _{org}	Sr	Ba	Zn	Y	Cu	Ni	Ti	Cr	V	Rb	Mn	Zr
				,97	,82		,98		,98			1,00											
													1,00	1,00									
														1,00									
															1,00								
																1,00							
,89	,94	,90					,88											1,00					
,95	,94	,97					,93											,83	,83	1,00			
,99	,96	,98					,99												,85	,96	1,00		
																		,96		,82		1,00	
																			,76				1,00

Only positive correlations >0,75 are shown, which for the number of samples considered, are significant to 99% (Lewis,1966)

amongst the various phosphorite minerals (Fig. 8.5). In Chapter 7 it was seen that the Ugab River is a rich supplier of this element to the diatomaceous mud belt, and it is interesting to note that the mud is almost twice as rich in Zn than the cP (Appendix A.38). This suggests that sorption of Zn by the organic matter in the mud is a much more effective process than Zn substitution in the apatite lattice.

(b) pP and gpP-dominant trace elements

Y is most abundant in the gpP, and is significantly correlated with Si, Al, Fe, K and the trace elements Ti, Cr, V, Rb, Mn and Zr (Table 8.7). Although Y is readily able to replace Ca in marine apatites because of the similarity in their ionic sizes (Day, 1963; Deer et al., 1962), it is clearly associated with 'glauconite-type' elements in the pP and gpP. However, Y is virtually absent in glauconite itself, and is present in cP in very low abundance. Price and Calvert (in press) consider the behaviour of Y to reflect either on the environmental conditions that gave rise to the phosphorites, or else on the post-depositional changes that may have affected them.

Cu and Ni are strongly correlated with each other in the phosphorites and glauconite, but reflect significant correlations with major elements only in phosphorite i.e., with Si, Al and K (Tables 8.7 and 8.8). Furthermore, both elements are enriched in the gpP relative to pP and occur in cP and G in very low abundance (Fig. 8.5). Whereas Cu reflects a very low propensity for substitution in silicate minerals (Mason, 1966), non-hydrogenous Ni is believed to be restricted to structural positions (Hirst, 1962). The abundance of Cu and Ni in pP and gpP, although differing from Y in not being correlated with other trace elements and Fe, is probably related to the same set of conditions, either formational or postdepositional, that resulted in the enrichment of Y. Cu and Ni show no relationship to C_{org} as they did with the clay fraction of the diatomaceous muds (Chapter 7), and their uptake in carbonate-fluorapatite may therefore be a result of lattice distortions created by the 'glauconite-type' element substitutions.

(c) G-dominant trace elements

In the phosphorites, Ti correlates with Si, Al, Fe and K, and also with the trace elements Y, Ni, Cr, V, Rb and Mn, but in glauconite, it is only correlatable with V and Mn (Tables 8.7 and 8.8). This suggests that it may be situated in admixed detrital phases in the phosphorites. although some of it may, together with the other trace elements, be associated with hydrated oxides of Fe. In glauconite, Ti can replace Al in six-fold coordination, and is probably captured on account of its higher charge ($Ti^{4+}-Al^{3+}$) (Mason, 1966). It is also an element typically found in biotite (Mason, op.cit.), which may be

indicative of the origin of the glauconite. However, the bulk of Ti in nature apparently occurs as finely disseminated cryptocrystalline needles of rutile and other polymorphs (Degens, 1965), and Allen (1937, in McRae, 1972) has actually observed the presence of rutile crystallites in glauconite.

Cr, V and Rb exhibit almost identical relationships with regard to their element associations in phosphorite and glauconite, and are therefore considered together. They are strongly correlated with Si, Al, Fe, K, as well as with each other, and additional elements belonging to the pP + gpP and G hierarchical groups. The association of these three elements in the different phosphorite minerals is obviously dominated by the influence of gpP in Table 8.7 because of the close similarity between the latter and the phosphorite + glauconite correlation matrix in Table 8.8. Cr and V possess very similar behavioural patterns for example, they both replace Fe^{3+} in silicate minerals (Day, 1963), they are typically found in biotite (Mason, 1966), and both are easily sequestered by Al, Fe and Mn oxides and hydroxides (Degens, 1965). Compared to the average concentrations of Cr and V reported from five glauconite deposits on the Russian Platform (Yasyrev, 1966), the South West African glauconites are enriched by factors of 10 and 3 respectively. With regard to Rb, its ability to replace K is well recognized and as will be recalled, it is the only element in the present study found to be enriched in sea water relative to crustal rocks (Table 8.5). According to Hower (1961), most Rb in glauconite occurs as non-exchangeable cations, but that which is taken up by the expandable layers is more firmly held than K. The preferential uptake of Rb by glauconite is well shown by its enrichment factor of two relative to the ambient sediment.

Mn is not associated with any of the major elements, but correlates with Ti and V in both the phosphorites and glauconite, and additionally, with Y and Cr in the phosphorites (Tables 8.7 and 8.8). Some of the Mn may be replacing Ca in the apatite (Deer et al., 1966) and some of it may be replacing ferrous Fe in glauconite (Day, 1963), but because the levels of Mn enrichment in all of the authigenic minerals is low, it probably was affected by factors such as the pH and Eh in the depositional environment (Mason, 1966). For example, unlike Fe, which would precipitate as a sulphide in the high pH, low Eh, diatomaceous environment, Mn would tend to remain in solution. In comparison with the ambient sediment, cP and pP are both impoverished in Mn, whereas the G contains exactly equivalent amounts.

Zr correlates only with other trace elements viz., Y and Cr in the phosphorites, and Cr alone in glauconite. Arrhenius (1963) has found that Zr can substitute for Ca in the lattice of marine apatite despite its much smaller ionic radius. The significance of this process however, is probably very minor because of its virtual absence in the cP (Fig. 8.5). Compared to glau-

conites from five Russian Platform deposits (Yasyrev, 1966), the South West African mineral is about equally enriched.

Finally, the concentrations of Co and Nb in the authigenic minerals were below the determination limits of the XRF method, and for this reason were excluded from the hierarchical element groups shown in Fig. 8.5.

8.5 ORIGIN OF THE AUTHIGENIC MINERALS

8.5.1 Concretionary phosphorite (cP)

From textural analysis of 142 diatomaceous mud samples, it was found that gravel-size material, consisting for the most part of phosphorite concretions and mollusc shells, constitutes 0.9% of the total sediment (Table 5.1). A number of these gravel-size components were submitted to FOSKOR for P_2O_5 and K_2O analysis the results of which are shown in Table 8.9.

The various components are listed in decreasing order of abundance of their average P_2O_5 concentrations which establishes that hard brown concretions are the richest in P, and one of the poorest in K. The next three materials, friable concretions, fish scales and coprolites, all contain roughly equivalent amounts of the two elements, whereas the fishbones, some of which appeared to be relatively fresh, contain less P and similar K. Mica-rich diatomaceous sediment from the landward edge of the mud belt, and near to the region where concretionary phosphorite occurs most abundantly (Chapter 5), reflects appreciably lower P and much higher K values than the previously described gravel components, but is still significantly richer in P than C_{org} -rich diatomaceous mud from the seaward edge of the mud belt. The two shell samples illustrate that relict mollusc shells lying within the diatomaceous mud have undergone no phosphatization at all, whereas the modern phosphatic brachiopoda not associated with the mud belt are significantly enriched in P. The results of this Table give a number of clues as to the probable mode of formation of concretionary phosphorite in the diatomaceous muds.

Hard brown concretions are more mature than the friable buff-coloured ones, both in terms of their age and their composition. Veeh et al. (1974) have dated them radiometrically in excess of 7×10^5 years, and Baturin et al. (1972) have obtained an age of approximately 24×10^3 years for other concretions. They were therefore formed in pre-Holocene times when the diatomaceous mud belt occupied roughly the same position on the shelf as it does today.

All the concretions recovered in the present study came from the surface of the diatomaceous mud belt, and this was attributed in Chapter 5 to H_2S accumulation within the body of the deposit, and consequent uplift of concretion-bearing mud to the surface of the sea. Waldron (1900) has described the appearance and disappearance of a large mud island that measured 150ft in length,

Table 8.9 P₂O₅ and K₂O concentrations of gravel-size components and mud from the diatomaceous mud belt (%)

Particle description	No. of Samples	P ₂ O ₅		K ₂ O	
		Average	Range	Average	Range
Concretionary phosphorite (hard, brown)	4	30,5	30,0-31,0	0,14	0,10-0,25
Concretionary phosphorite (friable, buff-coloured)	8	27,6	24,4-29,5	0,31	0,16-0,55
Fish scales	3	26,5	26,1-27,0	0,45	0,27-0,76
Grey, loosely-bound lumps (? seal coprolites)	3	25,9	24,2-27,0	0,32	0,27-0,35
Modern phosphatic brachiopoda (<u>Disciniscus tenuis</u>) [*]	2	23,5	23,2-23,8	0,39	0,31-0,46
Fish bones (some partially phosphatized)	5	20,7	12,6-27,2	0,38	0,18-0,75
Micaceous diatomaceous mud (eastern flank) ^{**}	2	6,5	2,0-10,9	3,29	2,94-3,63
C _{org} -rich diatomaceous mud (western flank) ^{***}	2	0,6	0,5-0,6	0,69	0,68-0,69
Relict mollusc shells (<u>Venus chevreuxi</u>) ^{***}	2	0,2	0,1-0,2	0,08	0,06-0,10

P₂O₅ analyses by colourimetry (FOSKOR)

K₂O analyses by X-ray fluorescence (FOSKOR)

* Detached from relict storm-beach cobbles at 20 and 38 m depth near Conception Bay.

** From 68 and 76 m depth near Conception Bay. Average mica = 10% (samples 3443, 3835)

*** From 128 and 129 m depth near Swakopmund. Average C_{org} = 10.6%, CaCO₃ = 53.1% (samples 3756, 4033)

30ft in width and 15ft above the sea surface. This particular occurrence took place in the lee of the sand-spit at Pelican Point, and may therefore have been the result of a density inversion of terrigenous sand over lighter diatomaceous mud. Inversion processes such as this have been suggested by King (1974) to explain the emergence of mud islands on the seaward side of the Mississippi River delta. In effect, both methods of mud 'uplift' would bring concretions from the interior of the deposit to the surface. The concentration of concretions near the landward edge of the mud belt however, is more likely due to wave-induced bottom currents sorting the associated fine-grained diatomaceous debris to greater depths.

Baturin (1974) has shown that diagenesis of the concretions results in loss of terrigenous contaminants, amorphous silica, organic matter and water, and this is accompanied by an increase in the concentration of P_2O_5 and CO_2 . The results obtained in the present study support these findings by demonstrating their chemical composition to be essentially pure carbonate-fluorapatite, and X-ray diffraction analysis (Chapter 5) indicated that they were better crystallized than either of the pelletal phosphorites.

The abundance and distribution of concretions and fish remains in the gravel fraction of the mud samples were assessed semi-quantitatively by visual examination of the 142 diatomaceous samples. The results are shown in Fig. 8.6 from where it is readily apparent that considerable agreement exists between the P_2O_5 content of the muds (P_2O_5 determined by FOSKOR on untreated subsamples - see Fig. 5.26), and the presence of concretionary phosphorite nodules (determined from visual estimates on the isolated gravel fractions). Furthermore, the distribution of fish remains, particularly fish scales, corresponds with the distribution of concretions as well. It is therefore postulated that any phosphatic solid material settling into the mud, be it guano from sea birds (Summerhayes, 1974, 1976), seal coprolites, or actual fish remains, all serve as nucleation sites for the initiation of authigenic apatite growth. Tiny apatite crystals growing authigenically on the surface of diatom frustules in a phosphorite rock from Peru have actually been photographed by Burnett (1974).

Calvert and Price (1971b) have shown that P is regenerated at a rapid rate in the water column (Chapter 2). This probably accounts for the low P_2O_5 content of diatomaceous muds along the seaward flank of the deposit (Table 8.9) and also for the general absence of concretionary phosphorite in this area. The high pH and low Eh of the muds (7.5 - 7.6 and -200mV respectively, Baturin, 1971b) results from decomposition of organic matter by sulphate reducing bacteria (Berner, 1969; Baturin, 1972), and these conditions would tend to lower the solubility of apatite and that of $CaCO_3$ as well. The fact that apatite and not $CaCO_3$ is found in the mud, reflects on the high degree of P

CONCRETIONARY PHOSPHORITE (cP), FISH REMAINS AND ?SEAL COPROLITES IN THE DIATOMACEOUS MUD BELT

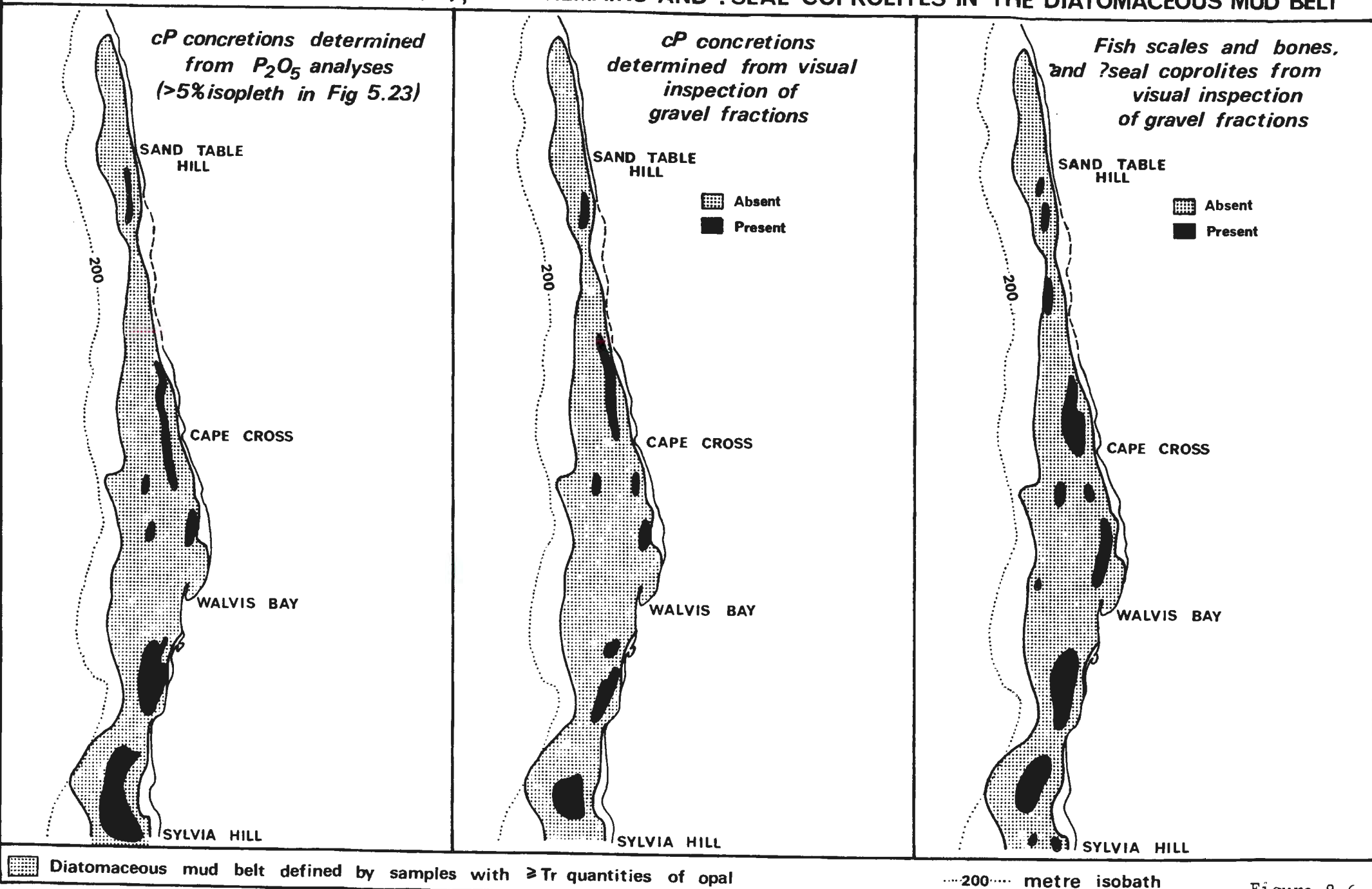


Figure 8.6

supersaturation that is attained there. Calvert and Price (1971b) have found that dissolved P concentrations in the interstitial waters are up to 26 times higher than the overlying bottom waters, and Baturin (1972) found that the interstitial waters are, on average, 20 times higher than the remaining sediment.

The high Mg and Zn contents of concretionary phosphorite may be a reflection of its comparatively young age relative to that of the relict pelletal phosphorites. Both elements probably substitute for Ca in the carbonate-fluorapatite structure as CO_3^{2-} substitutes for PO_4^{3-} , but diagenesis of the concretions through time would probably work to remove them in favour of Ca^{2+} . It is interesting to note that the Ca/Mg ratios of sea water (Brewer, 1975) : diatomaceous mud (19 samples - atomic absorption):concretionary phosphorite (8 analyses - electron microprobe) = 0,3 : 3,7 : 40,7, which puts the diatomaceous mud environment just outside of the critical Ca/Mg ratio of 4,5 - 5,2 (Martens et al., 1970) where apatite would be able to precipitate inorganically from sea water.

In summary, the main conclusions regarding the origin of cP are as follows:

- (i) They were formed initially by authigenic growth followed by diagenetic enrichment of apatite in the interstitial waters, and not by inorganic precipitation from the overlying water column.
- (ii) The hard, brown phosphorite concretions are the most mature in age and composition, and formed in pre-Holocene times when the diatomaceous mud belt occupied its present position on the inner shelf.
- (iii) The small, friable, buff-coloured concretions are modern equivalents of the hard brown ones, and form by natural seeding of the P-supersaturated interstitial waters with phosphatic solids such as fish scales, fish bones, coprolites and guano.
- (iv) The Mg content of the muds is sufficiently high to inhibit direct precipitation of apatite, and the average temperature of the upwelled water ($\sim 11^\circ\text{C}$, see Chapter 2) is also probably too low.
- (v) Phosphate replacement of pre-existing CaCO_3 does not occur in the diatomaceous muds as evidenced by the unaltered relict mollusc shells in the western flank of the mud deposit.

8.5.2 Pelletal phosphorite (pP) and glauconitized pelletal phosphorite (gpP)

It has been shown that concretionary phosphorites do not conform to either of the two mechanisms that have been proposed for the origin of marine apatites. One of these mechanisms advocates direct inorganic precipitation from sea water (Kazakov, 1937; Dietz et al., 1942; McKelvey et al., 1953; McConnell, 1965), and the other favours phosphatization of pre-existing CaCO_3

(Ames, 1959; Summerhayes, 1967; Pevear, 1967; D'Anglejan, 1968; Parker, 1971; Birch, 1975; Manheim et al., 1975). Ample field evidence exists to support both of these theories and experimental work has been done to confirm them (Ames, 1959; Simpson, 1964; Gulbrandsen, 1969; Martens et al., 1970; van Riemsdijk, 1975).

The Middle to Late Miocene phosphorite pellets and Pliocene phosphorite infillings are both regarded as having originated from the first of these two mechanisms based on their morphology, and evidence gained on their petrography and geochemistry. Some of the pellets possess an oolitic internal structure and others contain a nucleus of allogenic material, but they all reflect a high degree of sphericity and are uniformly fine-grained in size. Bushinsky (1966) is of the opinion that most 'phosphate grains' originated through phosphatization of faecal pellets, and D'Anglejan (1967) has found indications of this as well. Senin (1970) reports that phosphatized and glauconitized faecal pellets have been found on the South West African continental shelf but considers the former to be unrelated to the pelletal phosphorite because of their ellipsoidal shape. Geochemical evidence against a faecal pellet origin for the pelletal phosphorites, is their extremely high organic matter and pyrite contents. In Chapter 4, a laminated rock specimen was described which consisted of several layers of micrite of approximately 1mm thickness, and capped by a collophane layer with well-preserved mud-cracks. The material composing this collophane layer is identical petrographically to the phosphorite infillings, and represents clear evidence for precipitation in shallow water. Further evidence against a replacement origin for the phosphorite infillings is the small amount of phosphatization that occurs in the walls of some of the limestone borings.

It is envisaged that the pelletal phosphorites were formed in a shallow, semi-restricted lagoon that allowed phosphate-rich upwelled waters from outside of their mouths to be drawn in through estuarine circulation (Brongersma-Saunders and Groen, 1966; Brongersma-Saunders, 1967a; Bushinsky, 1966). The temperature of the cold upwelled waters would have been warmed by solar radiation in the shallow lagoon depths, and the pH would have conceivably been quite high due to the abundance of organic matter and pyrite (Berner, 1969; Baturin, 1972). The relatively high concentration of silt and clay material in the pellets would have lowered the Mg content of the environment (Drever, 1971), and this is suggested by the higher Ca/Mg ratios of pP (31 analyses - electron microprobe) and gpP (59 analyses - electron microprobe) compared to cP, viz., 59,4 : 69,1 : 40,7. Thus an optimum set of conditions were created for the direct precipitation of apatite from sea water.

The precise mechanism of precipitation is not known with certainty, but McConnell (1965) has found experimentally that the common enzyme carbonic anhydrase causes precipitation of carbonate hydroxyapatite, and mentions in addition, that certain bacteria are capable of initiating similar reactions. Stumm and Morgan (1970) state that micro-organisms are probably instrumental in determining such factors as pH, Eh, the type of residual organic matter and the proportions of particulate P to dissolved inorganic P. These micro-organisms would therefore have played an essential role in stimulating the precipitation of apatite from the P-saturated waters in the lagoon.

The reason for some pellets possessing concentricity and others possessing allogenic nuclei must now be explained. In Chapter 4, it was postulated that a layer of collophane mud on the floor of the lagoon was broken up by the periodic entry of abnormal storm waves. Once these semi-plastic, angular fragments had been formed, they would either have suffered erosion or accretion in the surf zone until a stable grain-size was attained with respect to the normal wave regime. It is significant that the central portion of the oolitic pellets (Plate 8.1) is similar in texture and lack of structure to the non-oolitic pellets (Plate 8.2) because this indicates these fragments were originally small and grew by accretion, whereas the larger non-oolitic fragments were simply eroded. The allogenic nuclei exhibited by some of the pellets probably reflects the original presence of these particles in the mud layer prior to its break-up, and subsequently, would have served as ideal loci for accretion.

In Chapters 4 and 5 it was seen that the gp and gpP were formed at the same time, and in the same manner, based on the similarity of their morphology and distribution on the shelf. Dissimilarity in the chemical composition of the two pellets however, reflects non-uniformity of the environment of formation. It is conceivable that one or more rivers may have been responsible for the chemical inhomogeneity of the semi-restricted lagoon as this would also explain the high proportion of terrigenous silt in the pellets. Further indirect evidence for this is obtained from the low Na content of gpP relative to the other phosphorite minerals, which suggests a lower salinity in the environment that produced them, viz., cP : pP : gpP = 0,71 (8 analyses - Electron microprobe) : 0,81 (31 analyses - electron microprobe) : 0,45 (59 analyses - electron microprobe).

The overriding chemical difference between the pP and gpP is the disproportionality in their Fe contents. Higher levels of Fe in the gpP, particularly in the rims, probably resulted in the suturing and fracturing seen there (Plates 8.3 and 8.4) in a manner similar to glauconite, and likewise, most probably accounted for the higher concentrations of Cu and Ni in these

particles. Significant quantities of Fe are introduced into the marine environment by the four largest rivers in the study area at the present time (between 6 and 11%, see Chapter 7), but negligible pyrite is found to occur in the cP because of the slowness of their authigenesis. In contrast to this, the abundance of pyrite and fine terrigenous sediment associated with the pP and gpP suggests that the inorganic precipitation process, which was probably responsible for their formation, proceeded at a relatively rapid rate. In an environment conducive to direct inorganic precipitation from sea water, any colloidal $\text{Fe}(\text{OH})_3$ or Fe^{3+} ions introduced by this proposed river would immediately react with phosphate in the oxygenated and low pH environment at its mouth to form $\text{Fe}(\text{PO}_4)$ and other iron phosphates (Day, 1963; Stumm and Morgan, 1970).

The main conclusions regarding genesis of the pelletal phosphorites are as follows:

- (i) Both the pP and gpP were formed by direct inorganic precipitation from sea water, and not in interstitial waters as occurs with the cP.
- (ii) The pellets formed in the surf zone of a semi-restricted lagoon by physical disruption of a phosphatic mud layer through storm waves. Small mud fragments then accreted to form oolitic pellets, and the larger fragments eroded to form unstructured pellets.
- (iii) The conditions created in the lagoon that were favourable for direct precipitation were: influx of phosphate-rich waters through estuarine circulation, high pH from decomposing organic matter, high temperatures from solar heating of the shallow waters, a high Ca/Mg ratio, and some biochemical agent to stimulate the reaction.
- (iv) A river source introduced terrigenous silt to the environment, and also an abundance of Fe and trace elements in hydrogenous association with it.
- (v) Close to the river mouth in relatively well oxygenated, slightly acidic and poorly saline water, the Fe reacted with PO_4^{3-} to form various iron phosphates. In the deeper parts of the lagoon, it reacted with S to form FeS_2 .

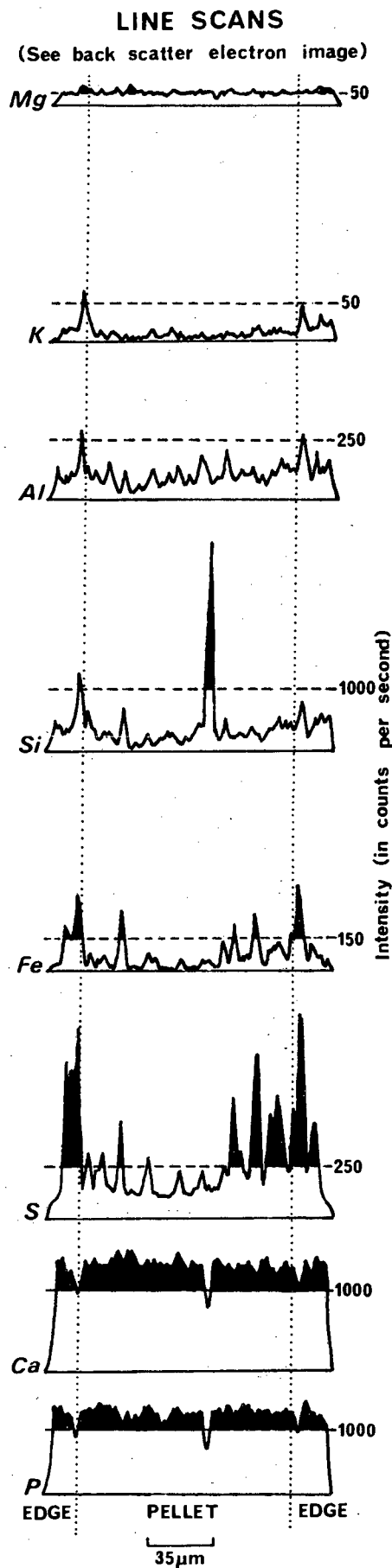
8.5.3 Glauconite (G)

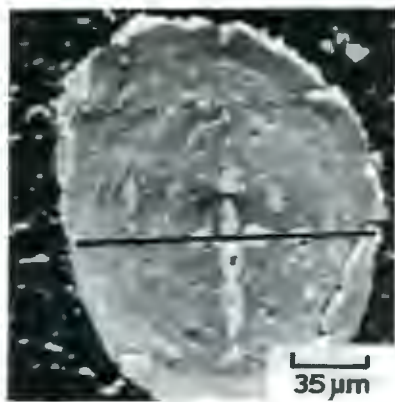
Whereas the cP is currently forming in interstitial waters of the diatomaceous mud, and relict pP and gpP formed by direct precipitation from the overlying water column, glauconite occurs exclusively at the sediment/water interface, and rapid burial brings its authigenesis to a halt. Ehlmann et al. (1963) and Porrenga (1967) have indicated that the most suitable environment for glauconite formation is one which is oxygenated, and at intermediate to shallow water depths. Several starting materials have been proposed for

X-ray element distribution images and line scans of pelletal phosphorite (pP)
(unconsolidated sediment from Sandwich Harbour, Sample 3558, grain A-14)

An oolitic internal structure is indicated by the concentric 'halo-like' rings of pyrite (Fe and S images) along the outer portion of the pellet. The central region is non-oolitic, with silt- and clay-size pyrite randomly scattered throughout the matrix. Si and Al reflect the random distribution of quartz and clay particles as well, and slight enrichment of Si, Al, K and Fe along the outer edge of the pellet indicates incipient glauconitization and loss of S. The Ca and P images simply reflect homogeneity of the apatite matrix.

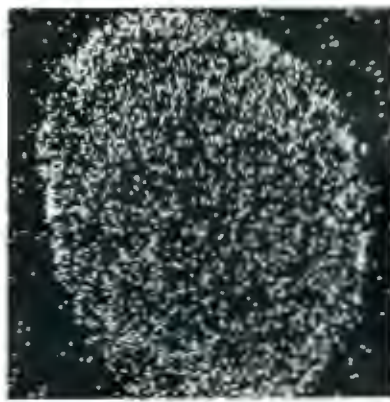
Line scans shown adjacent indicate that the increments in Mg, K, Al, Si and Fe actually occur slightly inwards from the very edge of the pellet, and this region of incipient glauconitization corresponds with a decrease in the abundance of apatite (Ca and P images). Apparent superposition of S at these locations is probably due to the X-ray beam impinging on juxtaposed pyrite and glauconitic grains. Similarly the high Si peak in the centre of the pellet is due to a silt-size quartz particle, which has resulted in a coincident decrease in the abundance of Ca and P.





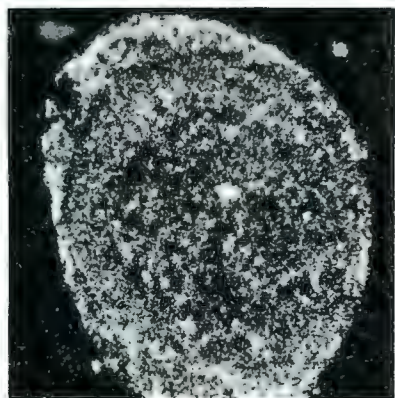
BSE

a



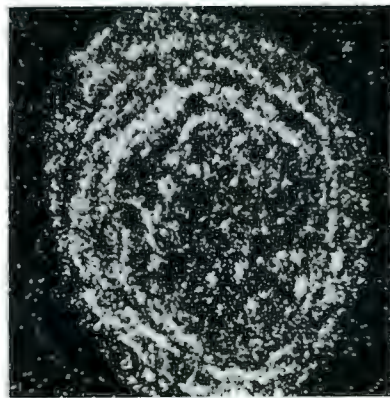
K

b



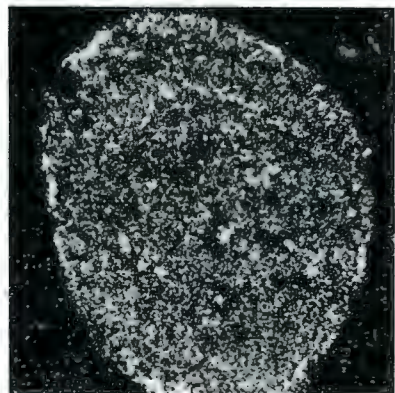
Si

c



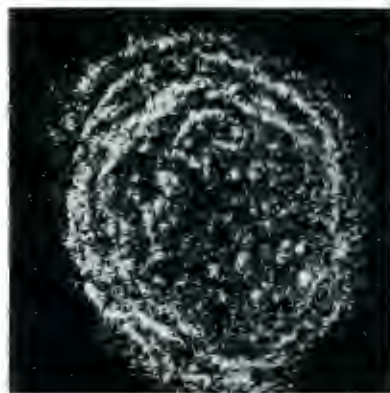
Fe

d



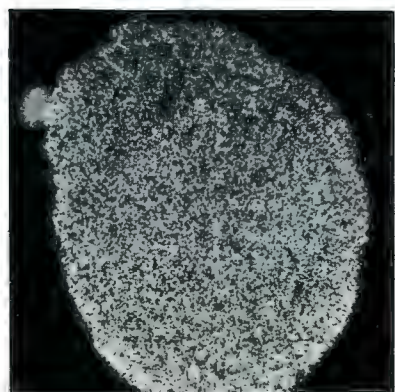
Al

e



S

f



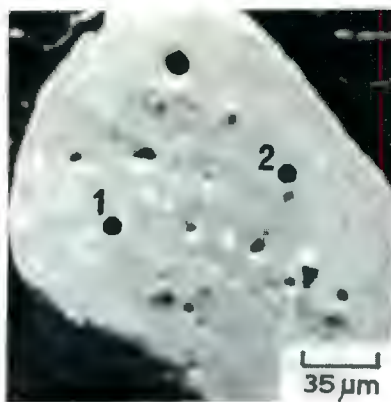
P

g



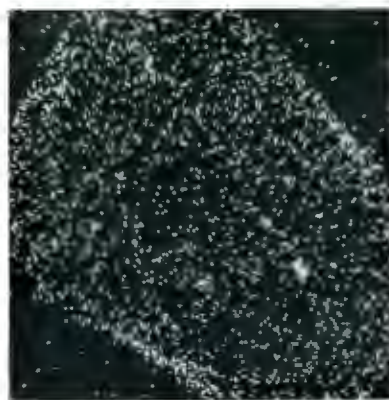
Ca

h



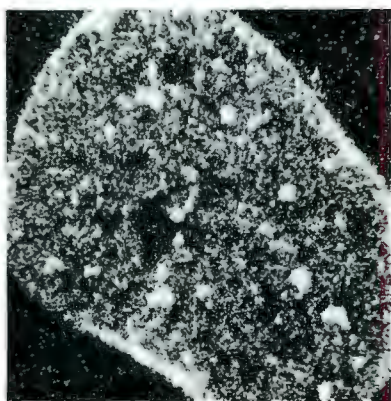
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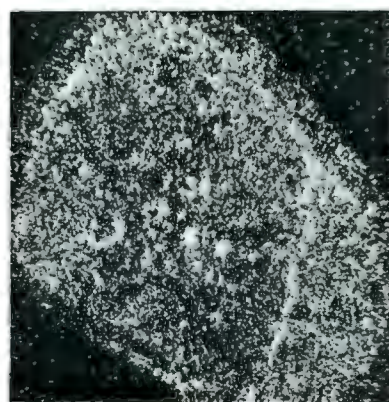
K

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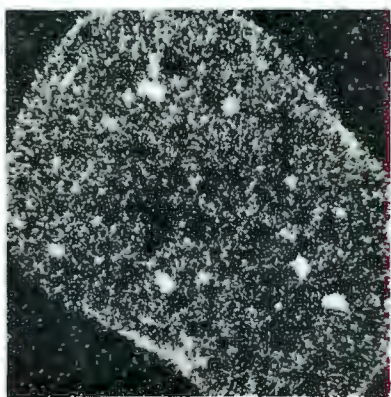
Si

c



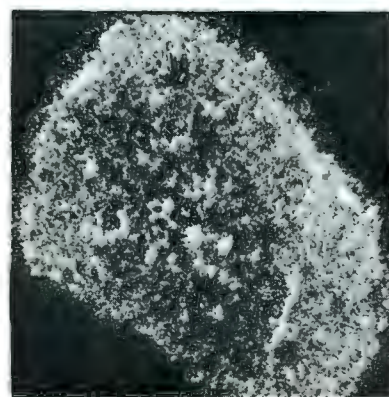
Fe

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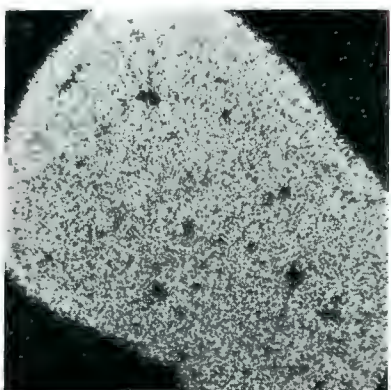
Al

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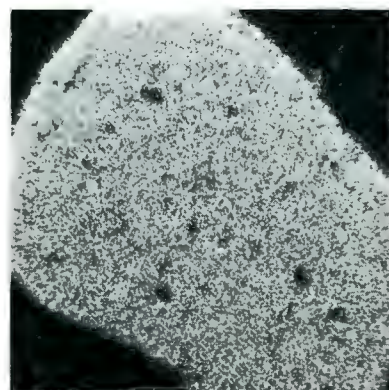
S

f



P

g



Ca

h

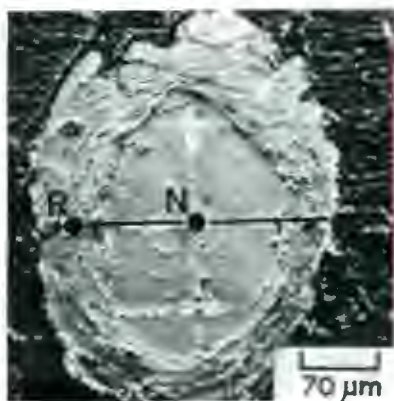
X-ray element distribution images and line scans of glauconitized pelletal phosphorite (gpP)

(unconsolidated sediment from Møwe Point, sample 3941, grain N-17)

Numerous inter-connecting concentric fractures, and a few large, open, radial sutures are evident in the rim of this pellet (see BSE). In thin-section, the rim is a 'moderate brown' colour (5 YR 4/4), and in composition, it reflects a much higher proportion of Fe than the nucleus. In contrast to the pP particle shown in Plate 8.2, S is antipathetically related to Fe in being most abundant in the rim. Quartz and clay minerals however, are randomly distributed as before (Si, Al and K images), and no difference in the abundance of these components is evident between the nucleus and rim. Strong glauconitization of the edge of the rim is indicated by marked increases in Si, Al and K (the Fe occurring right across the rim), and whereas Ca is evenly distributed across the pellet, P is depleted in the sutures and the fractures of the rim.

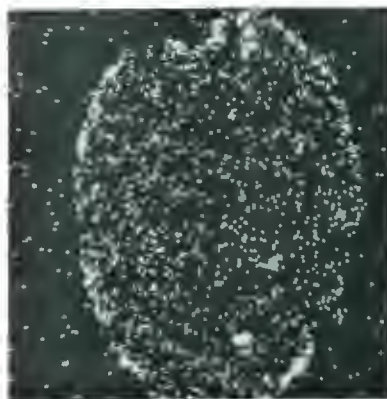
In the line scans shown adjacent, glauconitization of the very outer edge of the rim, and to a lesser extent the inner margin of the rim, is indicated by increased concentrations of Mg, K, Al, Si and Fe and corresponding decreases in the abundance S, Ca and P. Fe however, is distinct in being most concentrated along the inner margin of the rim, whereas the other 'glauconite' elements are most concentrated along the outer edge. Most Fe and S peaks correspond in the nucleus of the pellet; the highest S peak however, is not relatable to any of the other elements, and may perhaps be due to a particle of free sulphur.

continued over/..



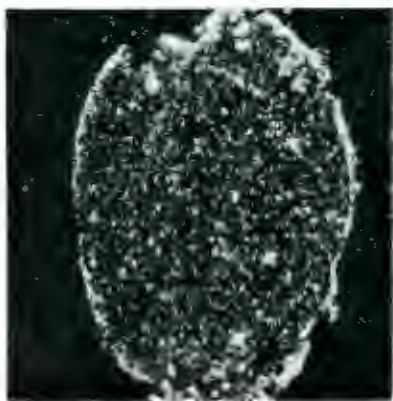
BSE

a



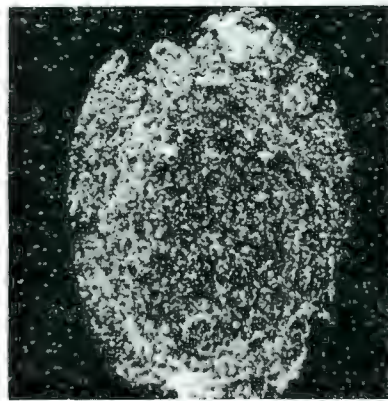
K

b



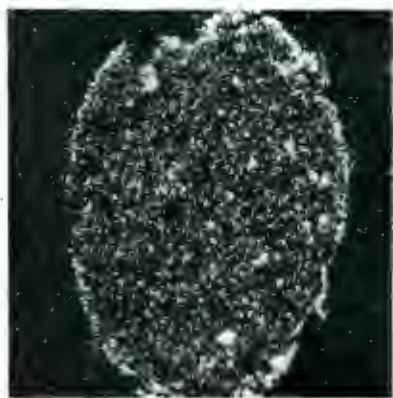
Si

c



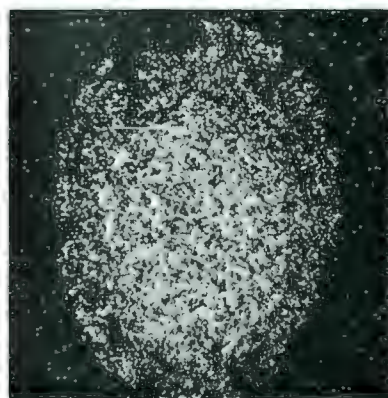
Fe

d



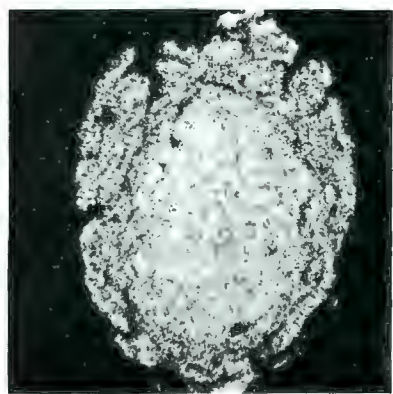
Al

e



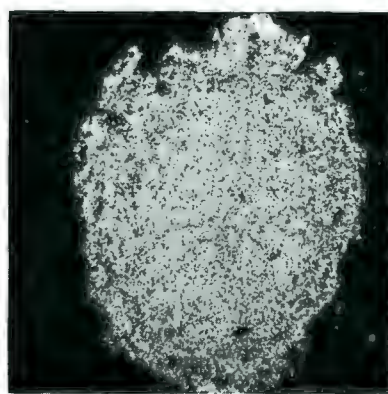
S

f



P

g



Ca

h

X-ray element distribution images of pelletal phosphorite (pP)
(unconsolidated sediment from Mbwe Point, Sample 3719, grain V-18)

This non-oolitic pellet contains silt-size quartz, pyrite and clay minerals, randomly scattered throughout the entire matrix. A slight increase in the size of the pyrite is evident towards the centre of the pellet, and a fall-off in concentration of both Fe and S occurs along its outer edges. A small veinlet of pyrite is also evident near the bottom right-hand edge of the pellet. Incipient glauconitization of the very edge of the pellet is shown by increased concentrations of Si, Al, K and Fe, and the Ca and P images reflect homogeneity of the apatite matrix.

The chemical composition of the pellet was obtained from two microanalyses at the locations shown on the back scatter electron image.

Analyses	1	2
SiO ₂	4.07	4.26
Al ₂ O ₃	.99	1.13
FeO*	6.73	6.81
MgO	.86	.74
CaO	44.27	42.81
Na ₂ O	1.18	1.16
K ₂ O	.33	.43
P ₂ O ₅	28.41	27.59
SO ₃ **	13.41	14.21
Totals	100.25	99.14

* Total Fe reported as FeO

** Total S reported as SO₃. Since most of the S is present as pyrite, the average S content from the two analyses is $\Sigma(\text{SO}_3 \times 0.4)/2 = 5.52\%$.

X-ray element distribution images and line scans of glauconitized pelletal phosphorite (gpP)

(unconsolidated sediment from M^Howe Point, sample 3941, grain N-17)

Numerous inter-connecting concentric fractures, and a few large, open, radial sutures are evident in the rim of this pellet (see BSE). In thin-section, the rim is a 'moderate brown' colour (5 YR 4/4), and in composition, it reflects a much higher proportion of Fe than the nucleus. In contrast to the pP particle shown in Plate 8.2, S is antipathetically related to Fe in being most abundant in the rim. Quartz and clay minerals however, are randomly distributed as before (Si, Al and K images), and no difference in the abundance of these components is evident between the nucleus and rim. Strong glauconitization of the edge of the rim is indicated by marked increases in Si, Al and K (the Fe occurring right across the rim), and whereas Ca is evenly distributed across the pellet, P is depleted in the sutures and the fractures of the rim.

In the line scans shown adjacent, glauconitization of the very outer edge of the rim, and to a lesser extent the inner margin of the rim, is indicated by increased concentrations of Mg, K, Al, Si and Fe and corresponding decreases in the abundance S, Ca and P. Fe however, is distinct in being most concentrated along the inner margin of the rim, whereas the other 'glauconite' elements are most concentrated along the outer edge. Most Fe and S peaks correspond in the nucleus of the pellet; the highest S peak however, is not relatable to any of the other elements, and may perhaps be due to a particle of free sulphur.

continued over/..

LINE SCANS

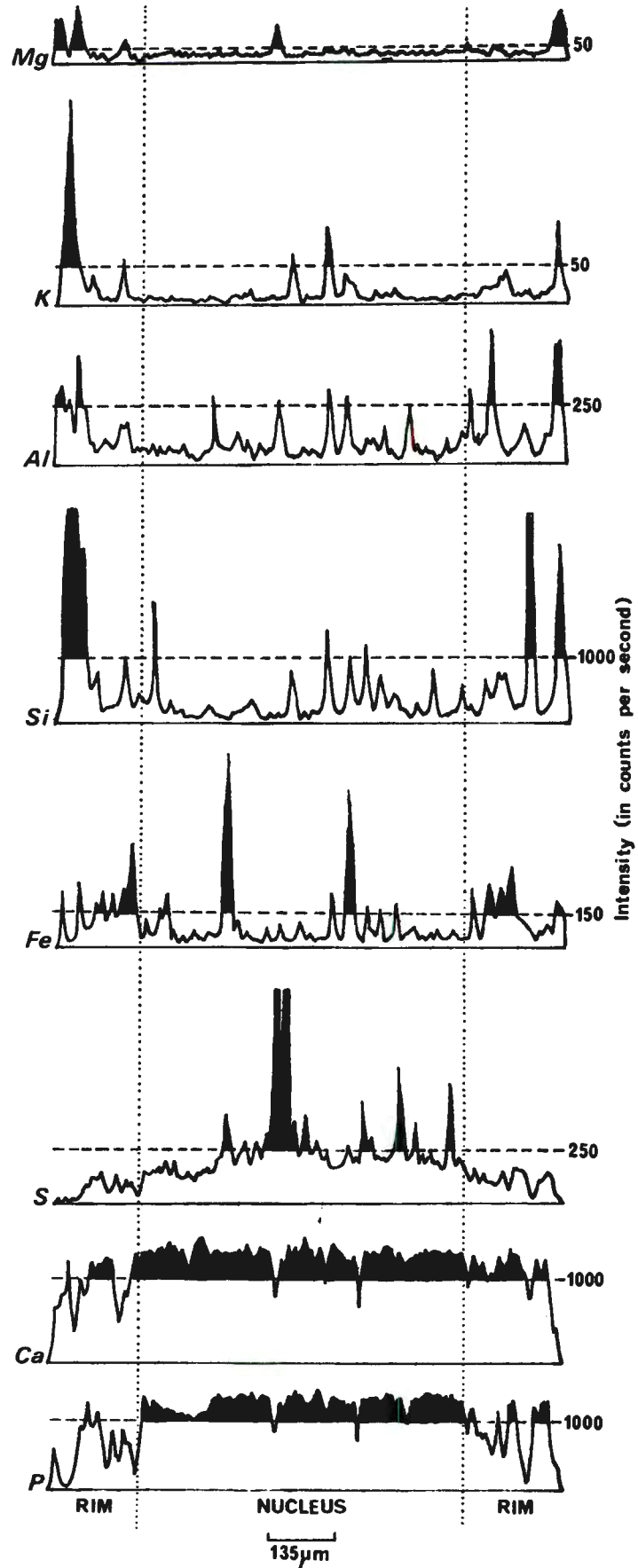
(See back scatter electron image)

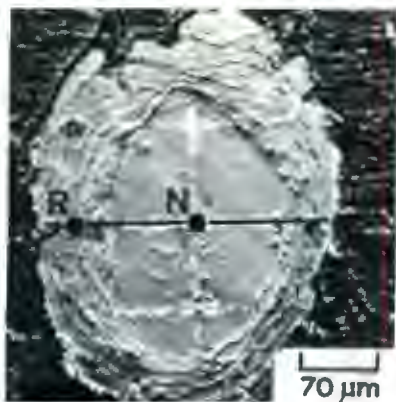
The chemical composition of the nucleus and rim at the locations shown on the back scatter electron image, is given below:

Analyses	Nucleus (N)	Rim (R)
SiO ₂	3,22	2,32
Al ₂ O ₃	,81	,91
FeO*	2,28	5,09
MgO	,77	,61
CaO	48,11	46,29
Na ₂ O	,68	,56
K ₂ O	,18	,19
P ₂ O ₅	29,81	26,12
SO ₃ *	6,60	4,40
Totals	92,46	86,49

* Total Fe reported as FeO, and total S as SO₃²⁻.

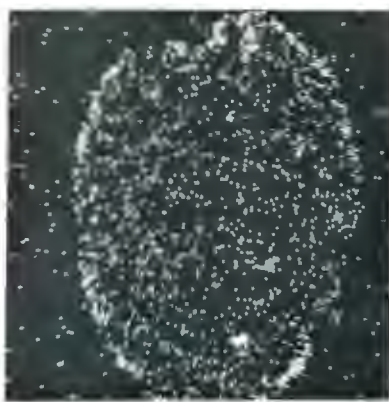
The low totals are due mainly to associated H₂O.





BSE

a



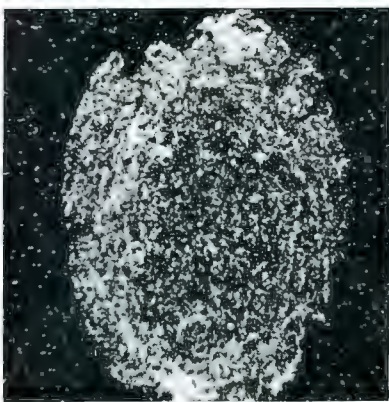
K

b



Si

c



Fe

d



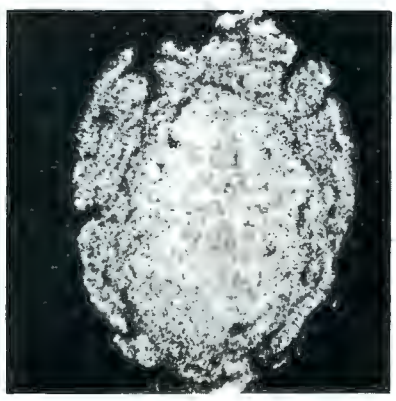
Al

e



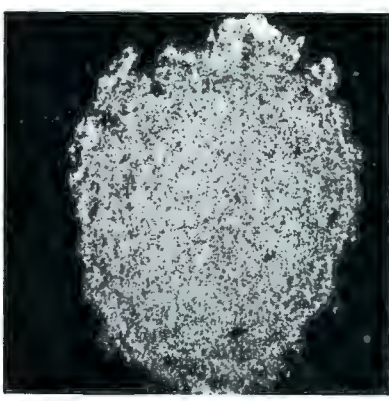
S

f



P

g



Ca

h

Plate 8.4

X-ray element distribution images of glauconitized pelletal phosphorite (gpP)
(unconsolidated sediment from Cape Fria, sample 3906, grain H.J-11.12)

This pellet shows similar fracturing and suturing of the rim to the gpP grain shown in Plate 8.3, but differs from it in being pale green (5 G 7/2) in colour. The concentration of Fe in this pellet, although showing some drop-off in the rim, is exceptionally high. The distribution of S, which occurs as large blebs and stringers, is not correlatable with the Fe at all. The Si, Al and K images reflect evenly dispersed quartz and clay minerals in the matrix of the grain, and minor glauconitization is evident along the very edge of the rim. As with the gpP grain shown in Plate 8.3, P is absent in the sutures of the rim, but Ca and S correlate there indicating the presence of gypsum.

Micro-analyses of the nucleus and rim are shown below. Compared with gpP grain in Fig. 8.3, both the nucleus and rim contain significantly more Fe and P, and significantly less Ca.

Analyses	<u>Nucleus</u>		<u>Rim</u>	
	N1	N2	R1	R2
SiO ₂	1,26	2,39	3,09	1,66
Al ₂ O ₃	,35	1,33	,92	,62
FeO*	7,18	10,43	6,69	8,60
MgO	,31	,52	,60	,42
CaO	44,64	40,36	43,84	38,06
Na ₂ O	,74	,99	,93	,72
K ₂ O	,24	,50	,43	,26
P ₂ O ₅	33,26	28,29	32,20	30,31
SO ₃ **	13,70	7,80	2,50	3,23
Totals	101,68	92,61	91,20	83,88

* Total Fe reported as FeO, and total S reported as SO₃²⁻.

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Appendix A.1 Wind parameters

Wind measurements at Mbuwe Point were made by the Fisheries Development Corporation of South Africa, and made available to the Hydraulics Research Unit of the C.S.I.R. for analysis (van Schaik et al., 1970). Hourly recordings of wind direction and speed were obtained from a Lambrecht Recorder established on the coast, and the information used in the present study covers the period July 1966 to June 1970. For Pelican Point, wind data came from the National Climatic Centre, Asheville, N. Carolina, and were kindly furnished by S. Fryberger of the U.S. Geological Survey to J. Rogers of this Institution for the periods 1949 - 1953 and 1966 - 1967. Although no acknowledgement of original data sources were made on the furnished data sheets, the measurements were in all probability taken by the South African Weather Bureau.

Methods used here are those developed by Fryberger (in press) as part of a major study on wind regimes and desert dunes at a number of locations around the world. Following is a summary of the definitions and methods as conceived and used by him:

Data - The data are arranged in the form of percentage frequency listings for each velocity category (usually expressed in knots on the Beaufort Scale), and for each direction sector (usually $22\frac{1}{2}^{\circ}$).

Weighting Factors - are determined for each velocity category using the formula:

$$\frac{V^2 (V - V_t)}{100}$$

where V = the mean velocity for each category $(\frac{V_{\max} + V_{\min}}{2})$

V_t = threshold velocity = 12 knots, and extrapolated to 10 metres above the desert floor where most wind data are collected.

Drift Potential (DP) - each of the direction sectors, expressed as vector units, are obtained from:

the percentage occurrence in each velocity category $\times$ the weighting factor.

The drift potentials are plotted on the perimeter of 1-cm diameter circles in Fig. 1.3.

Resultant Drift Potential (RDP) - all the directions are obtained by resolving the DP vectors for each direction sector into x and y components, and calculating it from $(\sum x)^2 + (\sum y)^2)^{\frac{1}{2}}$. In Fig. 1.3 the RDP's are plotted from the centre of the 1-cm diameter circles.

Resultant Drift Direction (RDD) - obtained from $\tan^{-1} x/y$ (in degrees).

$\frac{RDP}{DP}$ - a number which gives a measure of the constancy of the wind direction.

Appendix A.2 Wave-induced bottom currents

Wave-recording stations have been operational at Pelican Point (Walvis Bay) and at Mbe Point since June 1969 and March 1970 respectively. Data from these stations, although available, were not utilized in the present study because the buoys at both locations were anchored in very shallow water viz., 16,5 m at Pelican Point, and 12 m at Mbe Point. The data chosen for study involved a total of 3,425 ship-board observations of swell direction, height and period, made routinely by officers aboard merchant ships sailing through the study area. The observations were recorded every three hours for the year 1965, and the results collated into histograms by van Schaik et al. (1970). Thus although these data probably include many inaccuracies inherent to human estimation, the great number of recordings increases their usefulness for semi-quantitative evaluation of wave-induced bottom currents.

The histogram data of van Schaik et al. (1970) have not been resolved into different components, so following on their statement that high waves with short periods come from the southeast, and low waves with long periods originate in the southwest, the following assumptions were made:

Average sea conditions - taken as being represented by the median wave height and median period. $H_{med} = 1,85$ metres, and $T_{med} = 8,0$ seconds.

Local storms - taken as being represented by the maximum wave height and median period. $H_{max} = 5,24$ metres.

Distant storms - taken as being represented by the median wave height and maximum period. $T_{max} = 21,4$ seconds.

The mass transport velocities, at a number of different depths, have been calculated for each of the three cases listed above using the equation of finite-amplitude Stokesian theory (Allen, 1970; Shepard, 1963):

$$U_m = \frac{H}{L} \cdot \frac{C}{2} \cdot \frac{\cosh 2k(d+z)}{\sinh^2 kd}$$

U_m = mass transport velocity

L = wavelength

H = wave height

C = celerity

k = wave number ($= 2\pi/L$)

d = distance between sea surface and sea floor

z = distance below sea surface

When $d = z$, $\cosh 2k(d+z) = 1$; and since the wavelength and celerity both decrease in shoaling water, $C/L = 1/T$ (Cook and Gorsline, 1972).

The equation then reduces to:

$$U_m = \frac{\bar{U} H}{T \sinh^2 \left(\frac{2\pi d}{L} \right)}$$

Intermediate water depths, with which we are concerned, are defined as $0,5 < d/L_0 < 0,05$, where the deep water wavelength $L_0 = 1,56T^2$ metres (Shepard, 1973; Allen, 1970). Since Stokesian theory is only valid for $d/L_0 \geq 0,1$ (Allen, op.cit.), the mass transport velocities for each of the three chosen cases were calculated for the range $0,5 < d/L_0 \leq 0,1$.

The results are listed in Appendix B.1, and shown graphically in Figure 2.5.

Appendix A.3 Bathymetry

Bathymetric data were obtained using a conventional wide-beam, deep-sea echosounder, an instrument that has recently been criticized as inadequate for anything other than a flat smooth sea floor. Belderson et al. (1972) have published an example of the inaccuracies involved in interpreting detail from blocky relief using conventional deep-sea echo-sounders, and Krause and Kanaev (1973) have shown that for a sloping or uneven sea floor, the recorded depth is always less than the true depth because the sound impulses are reflected from the nearest bottom. No corrections to the recorded depths have been made in the present study as the gradients are generally quite small. The regional picture presented in Fig. 3.2 however, is considered to be fairly accurate, and only minor changes of detail will probably be necessary in the few regions of rugged relief.

The instrument used is permanently installed on the University of Cape Town research vessel Thomas B. Davie. It is equipped with master and daughter recording sets, operates at 12 000 Hz, and coupling through a transducer measuring 36 cms in diameter, produces a beam width of about 20° .

Decca navigation was used throughout the study area except in the extreme north where the lines approach parallelism due to the distant location of slave stations. Dead reckoning with celestial fixes and radar, were therefore resorted to in this area.

Appendix A.4 Compilation of bathymetric and physiographic maps

Compilation of the bathymetric data onto maps was done first by drawing the ship's track at a scale of 1:150 000 between 15-minute time marks, and between the station 'heave to' and 'under way' positions. The water depth at these locations were then plotted onto sheets superimposed over the track charts, and the inter-time-mark positions and depths established at 5-minute intervals with a ten-point divider. All together, 46 lines oriented transverse to the shelf were plotted in this manner, and several cross-lines parallel to the coast were used as a check on the position-depths. Plotting at this scale resulted in 8 large position-depth charts which after hand-contouring, were reduced photographically to a scale of 1:1 000 000 at 33°S. The final bathymetric map shown in Fig. 3.2 was draughted from a compilation of these reductions.

The physiographic map (Fig. 3.3) was drawn using the bathymetry map (Fig. 3.2), and World Aeronautical Charts compiled by the Trigonometric Survey (1964). The profiles, both onshore and offshore, were constructed by scaling the distances between 50 m elevation and depth intervals respectively, and regions of rugged relief between them were simply sketched in. River drainage systems were superimposed on the hinterland topography using the Geological Map of South West Africa, Dept. of Mines (1963).

Appendix A.5 Sediment size fractionation and $\frac{1}{2}\phi$ sieve analysis

The 'T' subsamples, partially processed on board ship (Chapter 5.1), were treated in the laboratory in the following way: First the coarse fractions were wet-sieved through a 2mm screen to separate the gravel and sand fractions, and care was taken to minimise disaggregation of fragile components such as faecal pellets and diatom frustules. This was followed by pipetting representative volumes of silt and clay from a one litre burette containing the mud fractions, and this was done through employ of an Andreasen Pipette. The latter procedure involved the use of Calgon as a deflocculant, and the method used was that of Anonymous (1967) and Folk (1968). All the analytical operations performed in size fractionation of the sediments are shown in flowchart form in Fig. 5.1, and data reduction was achieved using a short computer programme (Bremner, 1972) that made correction for the weight of Calgon added to the mud.

Precision tests on the method have established that for faecal pellet mud, foraminiferal sand and glauconitic sand, the relative deviations are 38%, 4% and 1% respectively (Birch, 1975). These results emphasise the dependence of precision on the composition of the sediment and as a result, similar tests have been carried out on four samples of the rarer diatomaceous muds:

Replicate sediment size fractionation

Sample	Statistic	Gravel	Sand	Silt	Clay
3426	$\bar{X}$ σ_x RD	1,0	56,8	28,0	14,2
		1,0	61,5	25,7	11,8
		3,5	57,2	24,9	14,5
		1,0	59,3	27,6	12,1
		1,9	55,5	28,3	14,2
		1,7	58,1	26,9	13,4
		1,1	2,4	1,5	1,3
		64,7	4,1	5,6	9,7
3754	$\bar{X}$ σ_x RD	-	25,1	18,7	56,2
		-	22,4	17,5	60,1
		-	20,6	19,5	60,1
		-	24,3	18,1	57,6
		-	23,2	19,1	57,7
		-	23,1	18,5	58,3
		-	1,8	,7	1,7
		-	7,5	4,0	2,9
3756	$\bar{X}$ σ_x RD	8,4	46,7	26,5	18,4
		12,4	42,3	27,3	18,0
		10,4	43,6	24,6	21,4
		6,6	47,9	22,7	22,8
		9,3	43,5	28,5	18,7
		9,4	44,8	25,9	19,9
		2,2	2,4	2,3	2,1
		23,2	5,3	8,8	10,6
3950	$\bar{X}$ σ_x RD	-	36,8	24,6	38,6
		,2	30,7	24,0	45,1
		,3	38,1	27,6	34,1
		-	32,7	23,4	43,9
		4,7	31,5	24,3	39,5
		1,0	34,0	24,8	40,2
		2,1	3,3	1,6	4,4
		100,0	9,7	6,6	11,0

where $\bar{X}$ = mean = $\frac{1}{n} \sum_{i=1}^n x_i$

σ_x = standard deviation = $\sqrt{\frac{\sum x_i^2 - n\bar{X}^2}{n-1}}$

RD = relative deviation = $\frac{\sigma_x}{\bar{X}} \cdot 100\%$ at 66% confidence level

Two facts emerge from these results. Firstly, high relative deviations obtained for the gravel analyses are due to the occasional presence of mollusc shells and/or concretionary phosphorite nodules in the diatomaceous mud. Secondly, although diatom frustules are subject to disintegration and the organic matter is susceptible to clotting, the relative deviations exhibited by different size fractions are roughly proportion dependent i.e., the greater the abundance of any particular size fraction in a sample, the better is the precision of its determination. Similar observations have been made and commented on by Ahrens (1957) in connection with geochemical analysis of samples, and as will be seen in subsequent precision tests, this phenomenon is a general feature.

Half phi sieve analysis of the sediment was undertaken in order to be able to describe the main textural units, and also to examine the relationship between the textural parameters and the overall composition of the sediment. All together, 132 widely spaced samples were selected for study, which involved mechanically dry-sieving their $>63\mu\text{m}$ fractions at $\frac{1}{2}\phi$ intervals, for 15 minutes. The mud fractions were not pipetted systematically according to established settling procedures, because the organic-rich nature of the sediments rendered them unsuitable for rigorous analysis. The results of the study therefore simply provide a first-order approximation of the sediment textural parameters. Interpolation of the $\frac{1}{2}\phi$ mud fractions was accomplished by proportioning the weight percentages of silt and clay (determined earlier) into 8 equal $\frac{1}{2}\phi$ silt fractions, and 4 equal $\frac{1}{2}\phi$ clay fractions. This took the fine limit of all samples containing clay material to 10ϕ (0,98 m). In view of the subjective variables involved with the method, calculation of the textural parameters by means of Folk and Ward's (1957) and Folk's (1968) inclusive graphic measures was considered more appropriate than usage of the moment measures. Data reduction was accomplished with a computer programme written by R. Lefever (U.C.L.A., Los Angeles), and modified by G.J. Moir (U.C.T., Cape Town).

A number of tests were conducted on a single sample to assess the influence of the mud-proportioning procedure on the textural parameters. The various conditions examined were as follows:

1. The mud fraction omitted.
2. The total mud weight assigned to the 4,0-4,5 ϕ interval.
3. Silt and clay weights divided proportionately into 8 and 4 $\frac{1}{2}\phi$ units respectively (as done in this study).
4. $\frac{1}{2}\phi$ silt and clay weights derived from a hand-drawn, smoothed, frequency curve, but still maintaining the previously determined weights of the silt and clay fractions.

The results obtained are shown below:

Inclusive graphic measures	Method			
	1	2	3	4
Mean	2,630	3,662	5,663	5,492
Sorting	,803	,880	2,783	2,753
Skewness	,058	,735	,011	,124
Kurtosis	,925	,912	,632	,628

Although method 4 is probably closest to the truth, it still involved speculation and was prohibitively time consuming. The close similarity between these results and those of method 3, and particularly since the latter procedure was both simple and quick, it was decided to adopt it for general usage. The results obtained from this method are considered to be sufficiently accurate for the objectives of the study.

Appendix A.6 Faecal pellets

Disaggregation of faecal pellets was accomplished by oxidising the organic matter binding the mud particles together. This was accomplished using 30% H_2O_2 , gently heating the samples on a hot-water bath, and occasionally adding a single drop of octanol to break the surface tension of froth bubbles (Beams, pers. comm.). Before-and-after treatment weighings gave the raw data necessary for determining the weight percentage of faecal pellets in the $>63\mu m$ size fractions. A short computer programme was written to access the sediment size data kept on file at the U.C.T. Computer Centre in order to express the faecal pellets as weight percentages of the total samples.

The sediment lying adjacent to the seaward flank of the diatomaceous mud belt was problematical because of the presence of decomposed, organic-rich diatom remains. The results obtained from these samples were often ambiguous, and it was therefore decided to discard them in favour of an arbitrarily assigned value based on the Cruise Card estimates. When the faecal pellet content was reported as being 'abundant', a value of $<10\%$ was assigned (Appendix B.6), but reports of 'common' or 'present' were ignored because of the abundance of diatom/organic matter/sediment clots.

Since the method utilized here differed from that of other workers in the general area (Birch, 1975; Rogers, 1977), its precision was tested using three compositionally diverse samples, and the results are shown in the following table.

	Foraminiferal sand (Sample 3410)	Terrigenous sand (Sample 3889)	Faecal pellet sand (Sample 3721)
	9	15	65
	4	17	68
	11	20	62
	12	12	74
	14	15	70
$\bar{X}$	10,0	15,8	67,8
σ_x	3,8	3,0	4,6
RD	38,1	18,6	6,8

The results indicate that the precision of the method is roughly the same as the ultrasonic vibrating-bath method (Birch, op.cit; Rogers, op.cit.). Break-down of delicate foraminifera and other fragile components during wet-sieving is therefore equally severe in both procedures.

Appendix A.7 Calcium carbonate

Standard procedure at U.C.T. for carbonate determination of marine sediments is the gasometric technique of Hülsemann (1966), which has been favourably compared to atomic absorption, spectrophotometry, EDTA, and weight-loss methods by Siesser and Rogers (1971). The method makes use of the reactivity of CaCO_3 with acid (2N HCl), and the CO_2 evolved is measured at the ambient atmospheric and hydrostatic pressures and temperature:

i.e. The weight percentage $\text{CaCO}_3 =$

$$0.1603 \frac{\text{Vol. CO}_2 \text{ evolved (ml)} \times \text{Barom. press. (mm Hg)} - \text{H}_2\text{O vap. press. (mm Hg)}}{\text{Sample weight (g)} \times \text{Absolute temperature}}$$

The accuracy of the determinations was checked by running the samples in batches of 6, followed by an analysis of standard Analytical Reagent Grade CaCO_3 . If the latter result deviated by more than 2% of its stated purity, the sample determinations in the batch were adjusted accordingly. The precision of the method for diatomaceous sediment has been determined on four samples:

	3426	3754	3756	3950
	16,8	4,9	48,9	11,9
	15,8	3,7	47,1	10,9
	15,6	4,4	49,3	11,0
	18,1	5,4	48,8	11,5
	16,5	4,8	47,4	12,0
$\bar{X}$	16,6	4,6	48,3	11,5
σ_x	1,0	,6	1,0	,5
RD	5,9	13,7	2,1	4,6

It is evident that the reproducibility of CaCO_3 determinations on diatomaceous mud is quite good, except when the concentrations are very low. The mean coefficient of variation as determined on 42 non-diatomaceous marine and beach samples is 4,7% (Siesser and Rogers, 1971).

A computer programme was written to reduce the raw data (Bremner, 1972), and make correction for CO_2 liberated by francolite (carbonate-fluorapatite). The pelletal phosphorite, glauconitized pelletal phosphorite and concretionary phosphorite from the study area contain an average of 3,6, 3,9 and 4,9% CO_2 respectively (see Table 5.10).

Appendix A.8 Particle counting

A.8.1 Mollusca

Samples containing more than 50 individuals were counted, and those with less were simply noted for species presence (Tankard and Kilburn, pers.comm.). In the case of bivalvia, left and right valves of each species were counted separately, and the highest number was taken as the population of the species in the sample. Frequency percentages of the different species were calculated for the densely populated samples and the results are listed symbolically in Appendix B.8. This tabulation, consisting of 28 samples and 18 different species is a summary of the original listing which included 84 samples and 52 species. Summarizing involved sample inclusion if more than 50 individuals were present, and species inclusion if the number of individuals counted in all the samples exceeded 10.

A.8.2 Foraminifera, Radiolaria, Mollusca and Echinoidea

The seven most commonly occurring benthic foraminifera, one planktonic species, Radiolaria and Mollusca and echinoid fragments were counted as volume percentages in the $>63\mu\text{m}$ size fraction of 84 widely separated samples (Appendix B.9). One hundred or more grains were counted using a specially constructed plastic tray designed to fit a standard microscope stage. The bottom of the tray was roughened, to prevent rolling of grains after dispersal by sprinkling fine-grained quartz sand over a thin layer of Araldite. To afford a good background contrast to the white tests, the inside of the tray was painted ~~black~~. Use of this tray avoided the expense of having numerous thin-sections made and as can be seen from the precision count made on a sample containing most components (see below), the relative deviation of a 20% population density is about 10%. This order of precision is satisfactory for determining the population densities of the most commonly occurring shells since the relative deviations decrease significantly when they constitute more than 20% of the total assemblage.

Sample 3972 - Palgrave Point

	Mollusca	Echinoidea	TOTAL	Ammonia	Elphidium	Hyalinia	Uvigerina	Bulimina	Bolivina	Brizalina	Other	TOTAL	Orbulina	Other	TOTAL	Radiolaria	TOTAL
	53	1	54	8	4	1	5				4	22	3	21	24		24
	43	4	47	6	4		8	1		5	5	29		23	23	1	24
	49	3	52	5	3		7				6	21		24	24	3	27
	49	3	52	11	2		6	1		2	4	26		21	21	1	22
	52	-	52	8	4	1	6			2	6	27		19	19	2	21
$\bar{X}$	49,2	2,2	51,4	7,6	3,4	,4	6,4	,4		1,8	5,0	25,0	,6	21,6	22,2	1,4	23,6
σ_x	3,9	1,6	2,6	2,3	,9	,6	1,1	,6		2,1	1,0	3,4	1,3	2,0	2,2	1,1	2,3
RD	7,9	74,7	5,1	30,3	26,3	>100	17,8	>100		>100	20,0	13,6	>100	9,0	9,8	81,4	9,8

Appendix A.9 Organic matter

The titration technique of Morgans (1956) was used for determining C_{org} in the sediments. The samples were analysed in duplicate, except when the deviation about their mean exceeded 10%, and then triplicate or even quadruplicate runs were made. The method involves addition of excess oxidizing agent in an H_2SO_4 medium (10,5N $K_2Cr_2O_7$), and then back titrating to null point with Fe_2SO_4 . The reagents were regularly standardized after every batch of 20 duplicate analyses. The formula used by Morgans (op.cit.) is based on the premise that 1 ml N $K_2Cr_2O_7$ is equivalent to 3 mg C_{org} :

$$\text{Weight percentage } C_{org} = \frac{V_1 - V_2}{W} \times 0,003 \times 100$$

where V_1 = volume of N $K_2Cr_2O_7$ (10,5 ml)

V_2 = volume of N Fe_2SO_4 (ml)

W = sample weight

The accuracy of the method has been determined by Summerhayes (1972a), who used several mixtures of quartz and sucrose and found it to be accurate within $\pm 3\%$ at the 95% confidence level. However, the nature and state of oxidation of organic matter may vary considerably in different sedimentological environments, and various organic matter: organic carbon ratios, ranging between 1,6 and 1,9 (Emery, 1960), have been advocated in the past. A ratio of 1,8, as prescribed by Morgans (op.cit.), has been utilized here.

Indications are that surface sediment is usually in a higher state of oxidation than sediment from below (Emery, 1960; Niino et al., 1969) thus suggesting that the results obtained here by wet oxidation would differ from analyses made by dry combustion. However, Gaudette et al. (1974) have found for lacustrine and shallow marine sediments that the titration and LECO combustion methods agree very well (correlation coefficient = 0,989).

The precision of the titration method is quite good with a maximum relative deviation of less than 5%. In contrast to other analytical methods used in this study, the reproducibility of results deteriorates slightly with increasing abundance of C_{org} . This is probably a function of the reaction kinetics as indicated by a delayed colour change at the end of a titration with samples containing very large amounts of C_{org} .

	3426	3754	3756	3950
	13,7	7,5	11,7	9,1
	13,4	7,4	11,9	9,0
	13,4	7,8	11,7	9,5
	12,3	7,5	12,0	9,3
	14,0	7,6	11,8	9,1
	14,0	7,6	11,9	9,0
	13,7	7,6	12,3	9,1
	13,2	7,6	12,2	9,1
	14,0	7,7	10,9	8,9
	13,6	7,8	10,7	8,9
X	13,6	7,6	11,7	9,1
σ_x	,5	,1	,5	,2
RD	3,8	1,6	4,3	1,9

A short computer programme was written to reduce the raw data to weight percentages of C_{org} and organic matter (Bremner, 1973) in the samples. At the same time, various statistical parameters such as the mean percentage deviation of the duplicate analyses, and the standard deviation and precision of all the analyses were also determined.

Appendix A.10 Opal

Three principal methods exist for quantitatively determining the abundance of biogenous silica in marine sediments. One of them is a wet chemical technique used by Russian scientists (Bezrukov, 1955; Strakhov, 1957; and Ponomarev, 1961 in Lisitzen, 1972) and involves 'double extraction' of opal with a 5% Na_2CO_3 solution; another method involves the conversion of opal to cristobalite by heating, followed by X-ray diffraction and conventional peak height measurement (Goldberg, 1958; Calvert, 1966, 1974); and the third method employs the use of infrared spectroscopy (Chester and Elderfield, 1968).

The procedure used here is semiquantitative, and follows a technique developed by van Andel (1964) in his study of the Gulf of California. In view of the large number of samples recovered from the diatomaceous mud belt (153), the relative simplicity and rapidity of this technique received strong favour, but accuracy of the results was consequently forfeited. It involved point counting diatom frustules in the $>63\mu m$ fraction (see Flowchart in Fig.5.1), usually 100 particles, and proportioning this 'count percentage' to a 'weight percentage' of the total sediment. Calvert (1966) has pointed out that diatoms range in size from 10 to $200\mu m$, and by restricting counts to the $>63\mu m$ fraction, a bias is automatically introduced. However, comparison of his X-ray results from the Gulf of California with the counting results of van Andel (1964), led him to conclude that:

"The correlation between the amount of opal and the number of diatom frustules in the sand fraction is significant and the determination of diatoms by counting gives a reasonable measure of the relative amounts and

distribution of opal in the sediments."

However, Zhuze (1971) has found that the opal content of sediment usually diverges substantially from the total counts when the diatom assemblage is dominated by thin-walled species, but with thick-walled species, of which the $>63\mu\text{m}$ fraction is largely composed (see Section 5.3), the agreement is fairly good.

The reasoning involved with converting the sand fraction count percentages, to total sample weight percentages was as follows: Subtraction of the weight percentages of previously determined biogenic and authigenic components in the diatomaceous samples from 100% yielded a balance which consisted entirely of opal and terrigenous material:

$$\text{i.e., Balance} = 100,0 - \{(\text{CaCO}_3 + \text{organic matter}) + (\text{authigenic components})\} \\ = \{\text{wt.\% opal}\} + \{\text{wt.\% terrigenous material}\} \text{ in total sample.}$$

The ratio of the count % of opal and the wt.% insoluble residue (which had also been previously determined in the $>63\mu\text{m}$ fraction) was then tacitly assumed to remain constant when extrapolated to the total sample:

$$\text{i.e., } \frac{\text{Count \% opal } (>63\mu\text{m})}{\text{wt.\% insol.res. } (>63\mu\text{m})} = \frac{\text{wt.\% opal (tot.sample)}}{\text{wt.\% terrig.mat. (tot.sample)}}$$

The concentration of opal and terrigenous material in the diatomaceous muds were then obtained from the following relationships:

Wt. % opal in total sample

$$= \frac{\text{count \% opal } (>63\mu\text{m})}{\{\text{count \% opal } (>63\mu\text{m})\} + \{\text{wt.\% insol.res. } (>63\mu\text{m})\}} \times \frac{\text{Balance}}{1}$$

Wt. % terrigenous material in total sample

$$= \text{Balance} - \{\text{wt.\% opal in total sample}\}.$$

From the foregoing it can be seen that the accuracy of reported values in Appendix B.7, and the distribution of opal as shown in Figure 5.21, can only be regarded as a first approximation. Obviously the relationship equating the abundance of sand-size opal and sand-size terrigenous material to their respective concentrations in the total sample is a potentially highly misleading assumption, but the degree of error involved would be most severe with samples containing small amounts of opal. Precision of the counting and proportioning techniques have been determined on 4 diatomaceous mud samples, and the results are shown below.

3426		3754		3756		3950	
Counts	Opal	Counts	Opal	Counts	Opal	Counts	Opal
%	wt.%	%	wt.%	%	wt.%	%	wt.%
5	3	98	79	9	25	24	35
10	5	84	79	2	16	17	29
17	8	90	79	7	24	16	28
4	2	87	79	5	22	29	39
2	1	81	79	11	26	26	37
$\bar{X}$	7,6		88,0		6,8		22,6
σ_x	6,0		2,8		3,5		4,0
RD	79,3		73,0		51,4		17,6
			7,4				25,4
			0				14,5

It is apparent that the precision is directly proportional to the abundance of opal, and consequently, inversely proportional to the abundance of terrigenous diluent. Poor reproducibility with samples containing small amounts of opal is probably due to some extent to the unavoidable problem of individual frustules covering each other in the counting tray, and also to the difficulty in obtaining a random distribution in the tray. Counting problems occasionally arose with samples from the western edge of the diatomaceous mud belt, where discrete frustules were often replaced by a non-structured, jelly-like, slimy mass. These samples were classified as 'dirty', and an arbitrary value of 5% opal was simply assigned to them. Of significance, is that for each of the samples considered, the precision of the opal determination is always better than the diatom counts.

Appendix A.11 Calculation of some physical parameters of the diatomaceous mud belt

The length of the mud belt was determined by scaling its distance in n.miles, and converting this value to kms (1 n.mile = 1,852 km). Breadths were scaled in n.miles along 37 transverse sample lines, and similarly converted to kms. Thicknesses were obtained from 6 echograms across the mud belt where the irregular, sub-bottom, acoustic reflector was generally clearly evident beneath the transparent diatomaceous mud (Fig.3.5). Depth measurements were made at 1 n.mile intervals along each of the echograms the results of which are summarized in the following Table.

Table A.11.1 Average and maximum thicknesses of the diatomaceous mud belt along six transverse echograms (metres)

Line number		1	14	18	22	31	35
Location		Sylvia Hill	Swakopmund	Cape Cross	Ambrose Bay	Sand Table Hill	Mowe Point
Average	>5% opal	5,0	6,1	4,4	4,9	7,6	1,4
	>50% opal	5,9	7,9	5,8	6,1	10,3	-
Maximum		12	15	10	12	15	2

* For location of Line numbers, see Fig.3.3.

The depth of the eastern and western edges of the mud belt were determined from sample stations located closest to the deposit margins along 37 transverse sample lines. Where the edge of the deposit occurred between two sample stations, the depth was estimated by considering the depth at both of the stations. The overall mean depth of the entire mud belt was then calculated from:

$$1/37 \left[\sum_{n=1}^{37} ((\text{Eastern edge depth} + \text{western edge depth})/2) \right]$$

Areas were calculated in n.miles² using a polar planimeter, and converted to km² (0,29155335 n.miles² = km²).

The average concentration of opal was determined from the mean concentration of all samples containing more than 5% opal (142).

The density of both wet and dry sediment from the diatomaceous mud belt was determined by placing exactly 75 ml of mud into a narrow-necked flask, weighing, drying, and weighing again. Five samples for each of two sets were selected:

Set 1. Samples containing maximum opal values (84%) from around Pelican Point.

Set 2. Samples containing opal values as close as possible to the average opal content of the entire deposit (54,3%). They were chosen from both the eastern and western flanks of the mud belt, where terrigenous and carbonate dilution is respectively most significant.

It must be pointed out that these density measurements were made on sediment that had been sealed in plastic storage tubs for approximately 2 years.

The results are listed in the following Table.

Table A.11.2 Density of sediment from the diatomaceous mud belt

Set 1				Set 2			
Sample No.	Wet density	Dry density	Opal (%)	Sample No.	Wet density	Dry density	Opal (%)
3510	1,05	,18	85	3424	1,38	,68	54
3517	1,01	,15	84	3542	1,11	,87	55
3536	1,04	,17	83	3780	1,29	,76	55
3538	1,06	,21	82	3952	1,12	,78	52
3545	1,08	,18	86	4010	1,06	,92	56
Average	1,05	,18	84,0	Average	1,19	,80	54,4

Appendix A.12 P₂O₅ and K₂O

All P₂O₅ and K₂O analyses were performed by the Phosphate Development Corporation (FOSKOR), Phalaborwa, Transvaal, on subsamples of untreated sediment, as well as on mud fraction (<63µm) separates. The P₂O₅ determinations were made spectrophotometrically using the ammonium molybdate/vanadate method, and K₂O was analysed for by means of X-ray fluorescence spectrometry (XRF). Summerhayes (1972a) has established that the standard deviation of P₂O₅ determinations undertaken by FOSKOR are 0,5%, 0,4%, and 0,1% for P₂O₅ concentrations of 0,5%, 5,0% and 15% respectively, and the accuracies are roughly of the same order of magnitude. Birch (1975) has established the precision of their K₂O analyses to be approximately 5% at the 95% confidence level for all concentrations of K₂O.

Appendix A.13 Phosphorite and Glauconite

P₂O₅ determinations on the 'C' subsamples (see Fig.5.1) are a summation of the individual contributions from pelletal phosphorite (pP), glauconitized pelletal phosphorite (gpP) and concretionary phosphorite (cP). The K₂O results however, reflect not only the concentration of three glauconite (G) types, but of terrigenous mica and feldspar as well. Separation of the authigenic components was therefore desirable in order to be able to quantify their individual concentrations in the sediment.

Both G and gpP are magnetically susceptible to varying degrees, and consequently were separable from each other, and from the non-magnetic fraction of the samples. Since most of the authigenic minerals occur in the sand fraction of the sediment (Section 5.4), the mud was removed by wet-sieving (Fig.5.1), and the residue passed through a Franz Isodynamic Separator. The optimal instrument settings were found to be: pitch 25°, roll 15°, vibration setting 9, and amperage adjustment from 0,3 to 1,4 mA. The order of mineral extraction and the most commonly occurring contaminants in each of the concentrates were as follows:

- (i) Small, dark green/black glauconite; contaminated by very fine-grained quartz and mica; amperage setting 0,3 mA.
- (ii) Intermediate, dark green glauconite; contaminated by 'proto glauconite' foram infillings; amperage setting 0,5 mA.
- (iii) Large, yellowish-green glauconite; contaminated by foram infillings and iron-stained quartz; amperage setting 0,7 mA.
- (iv) Glauconitized pelletal phosphorite of variable colour and size; contaminated by iron-stained quartz and pelletal phosphorite; amperage setting 1,0 to 1,4 mA.

Before passing the sand fractions through the separator, diatom frustules were first point-counted to obtain the weight percentage of opal (see Fig.5.1 and Appen-

dix A.10). After the G and gpP had been isolated, 100 grains of both the magnetic and non-magnetic fractions were point-counted again to make correction for contamination in the authigenic mineral concentrates. This laborious procedure served to improve the results of samples with significant contamination, but point-counting different size-particles is, itself, not strictly valid. The small, dark green/black glauconites were found to be present in such small quantities, that it was decided not to retain them as separate concentrates. Mica was isolated from this glauconite by carefully decanting it from a beaker of water, and after drying, the glauconite was simply added to the concentrates of intermediate and large glauconite types when present. The G and gpP were thus expressible as weight percentages of the total samples.

It was not possible to separate the non-magnetic pP and the usually friable cP from the remaining sediment, and they are therefore reported together in Appendix B.7. However, the fact that they occur in different regions of the continental shelf allows them to be easily distinguished in Fig.5.23. To determine the pP + cP concentrations in the samples, the reported P_2O_5 values were converted to the mineral apatite and the separated gpP concentrations subtracted from it. This was done at an early stage in the analytical treatment of the samples using the reported value of 36% P_2O_5 in carbonate-fluorapatite (Deer et al., 1962). Later on, when the authigenic minerals were examined geochemically by microprobe and X-ray fluorescence, it was found that gpP had a P_2O_5 content of about 25%, pP about 28%, and cP about 33% (see Tables 8.1 and 8.2). This means that the pP and cP results reported in Appendix B.7 and illustrated in Fig.5.23 are too small by a constant factor of approximately 7%. Since this error is quite small and would only be of significance with samples very rich in either of the two components, it was decided not to recalculate them.

The distinctive location of particular glauconite types made description of their individual distributions possible and consequently, as with pP and cP, they are all shown together in a single diagram (Fig.5.25).

Reproducibility of the procedure for magnetically separating G and gpP from the sediment was checked using three samples with variable concentrations of the two components.

	<u>3440</u>		<u>3686</u>		<u>3897</u>	
	G	gpP	G	gpP	G	gpP
	1,1	15,2	5,7	28,9	20,4	4,8
	1,3	14,6	5,6	28,1	21,5	5,4
	,9	17,3	5,1	27,3	20,9	4,7
	1,1	16,1	6,3	28,3	19,6	5,6
	1,2	15,8	6,4	29,1	19,9	4,4
$\bar{X}$	1,1	15,8	5,8	28,3	20,5	5,0
σ_x	,2	1,0	,5	,7	,8	,5
RD	13,4	6,5	9,3	2,5	3,7	10,0

It is apparent that the method is particularly sensitive to the concentration of the components in the samples, and that a relative deviation of 15% could be expected to be a maximum for samples with low concentrations.

Appendix A.14 $\frac{1}{2}\phi$ sieve analysis of phosphorite and glauconite

Six sand samples, that were previously size fractionated into $\frac{1}{2}\phi$ intervals by drysieving (see Appendix A.5), were sent to FOSKOR for individual P_2O_5 and K_2O analysis (Fig.5.29). The samples chosen were all rich in one or more of the authigenic mineral components pP, gpP and G. Small amounts of mud-size sediment obtained after drysieving the samples were probably the result of disintegration of fragile sand-size components eg., foram tests, and for completeness, these fractions were submitted for analysis as well.

In calculating the weight percentages of phosphorite and glauconite in each of the size fractions, it was assumed that 32% P_2O_5 was equivalent to 100% phosphorite, and 8% K_2O was equivalent to 100% glauconite. The actual P_2O_5 contents of pP and gpP are slightly different (see Tables 8.1 and 8.2), but so small as to have negligibly affected the size of the histogram blocks. The weight percentage of non-authigenic components in each of the size fractions was then determined from $100\% - (\text{weight percentage phosphorite} + \text{weight percentage glauconite})$.

Appendix A.15 X-ray diffraction analysis of the authigenic minerals

A total of ten authigenic-mineral concentrates were X-rayed at the same time that the sediment clay fractions were being investigated for their mineralogy (Chapter 7). $CuK\alpha$ radiation was used in both investigations, and the instrument settings were identical (see Appendix A.28) except for the rate meter sensitivity (RM), the time constant (TM) and the goniometer speed (GS). In this study, these settings were: $RM = 4 \times 10^2$, $TC = 4$, $GS = 2^\circ 20/\text{minute}$. After concentrates of pP, gpP and G had been prepared, first with the use of bromoform, then with a Franz Isodynamic Separator, and finally by handpicking (the cP nodules had been washed free of diatomaceous mud), they were all crushed to -240 mesh, and mounted on glass slides using an eye-dropper. Two traces were made for each of the phosphorite samples, one to determine their CO_2 contents (see Appendix A.16) and the other for mineralogical identification purposes. Two mineralogical traces were made for the glauconite concentrates, one of them, as with the phosphorites, covered the range 3° to $57^\circ 2\theta$, and the other extended from 3° to $13^\circ 2\theta$ after heating to $550^\circ C$ for 1 hour. Five typical diffractograms of the various authigenic minerals are shown in Fig.5.30.

Appendix A.16 CO₂, C_{org} and F in the phosphorite minerals

The CO₂ content of the various phosphorite minerals was determined using two different methods (except for gpP) as a check on the results. The first of these involved gasometric analysis, as was used for determining CaCO₃ in the unconsolidated sediments (see Appendix A.7), and between one and four separate analyses were made on hand-picked phosphorite concentrates depending on the variability of results and the availability of material. The second method involved XRD peak-pair measurements as described by Le Geros et al. (1967) and Gulbrandsen (1970). Diffraction traces were made for the range 50,5° to 53,5° 2θ, and the angular difference between (004) and (410) reflections was measured independently by two different workers. The Δ2θ (004-410) values were then converted to weight percentages of CO₂ using the regression line presented by Gulbrandsen (op.cit.). Instrument settings were as before (see Appendix A.15) except for RM = 1 x 10², TC = 10, GS = ½° 2θ/minute.

C_{org} and F were determined on a different set of subsamples because of lack of material left over after CO₂ determinations. The pP and gpP in this set of subsamples were concentrated using bromoform only, since hand-picking proved to be very time consuming and tedious. The degree of contamination, mostly from quartz and foram tests, was kept below 1% however by point-counting. Concretions were once again washed to remove diatomaceous mud, and all the phosphorite concentrates were then crushed to -240 mesh.

C_{org} analyses were made in duplicate using the same method (Morgans, 1956) as was used for determining C_{org} in the unconsolidated sediments (see Appendix A.9). The fluorine content was determined by FOSKOR using an Orion Reserach Ionalyser Model 801, which was calibrated against NaF, and involved a fluoride specific ion electrode technique. Birch (1975) has found the precision of this method to be good, and obtained a relative deviation of 3,17% for replicate analyses.

Appendix A.17 Terrigenous sediments

The terrigenous fraction of the unconsolidated sediment was determined by a deductive evaluation process which involved subtraction of the sum of the weight percentages of all biogenic and authigenic components in the sediment from 100%. The value thus obtained was assumed to represent material derived entirely from terrigenous sources. For samples classified as belonging to the diatomaceous mud belt (>5% opal) the process was somewhat more complicated owing to the fact that opal abundances were calculated on the basis of point counts, and the weight percent terrigenous material was equated to the balance of the sediment minus the weight percent of opal (see Appendix A.10). Naturally, the errors incurred during each of the analytical operations performed in the determination of the biogenic and authigenic components would have been inherited by the terrigenous result, and the accuracy of results, as listed in Appendix B.7, are therefore estimated to be no better than about 10%.

Appendix A.18 Insoluble Residue (quartz)

Determination of the insoluble residue (quartz) in the sand fraction of the sediment samples was the last analytical operation performed. It involved treating them with 10% HCl and gradually increasing the strength of acid additions to 20% to remove all the carbonate. Because of the slow settling rate of diatom frustules, their removal from the sand was easily accomplished by careful decantation after each acid treatment. When all effervescence with acid had ceased, the remaining residue was washed twice with fresh water and allowed to dry in an oven at 40°C.

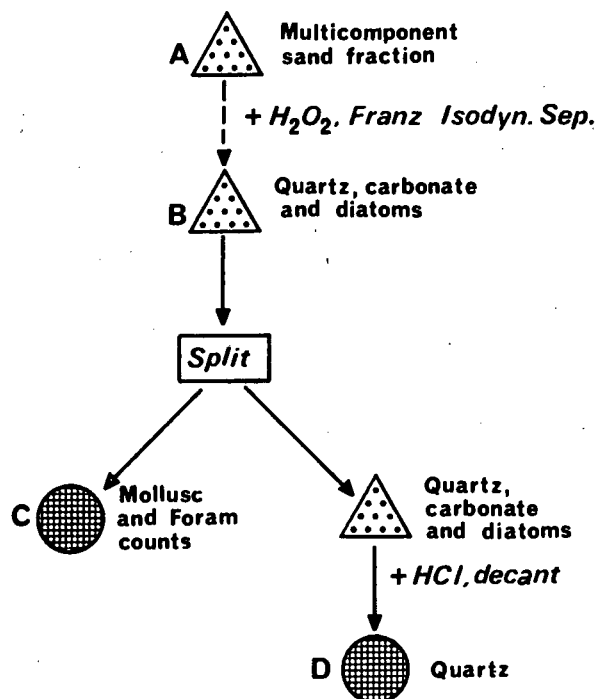
Treatment of samples with abundant pelletal phosphorite (pP) and mica differed slightly from the general procedure described above in order to concentrate these minerals for further study. The pP-containing samples were first treated with 25% CH₃COOH (Ireland, 1971) to remove the carbonate and then split into two fractions, one for pP study and the other for HCl treatment. The method used for separating mica from the residues is described in Appendix A.21.

The weight percentage insoluble residue in the sand fraction of samples containing no pP was derived from four sediment weighings (see flowchart summary, and Fig.5.1):

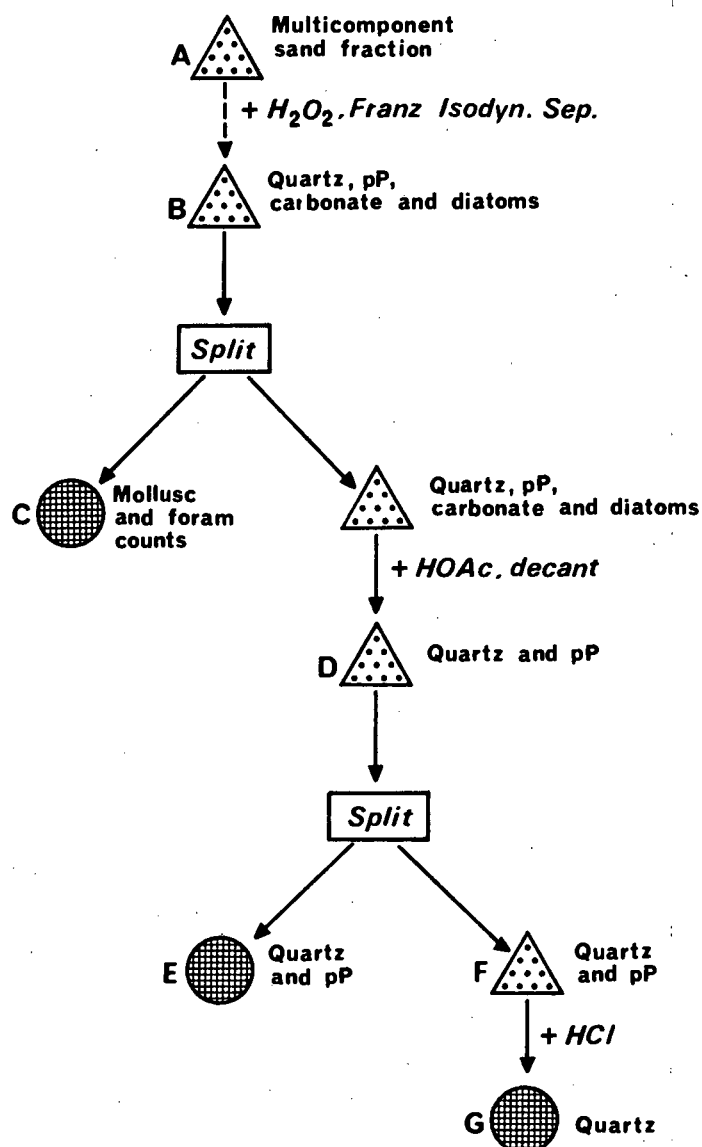
- A. The weight of multicomponent sand obtained after wet-sieving it from the other textural components.
- B. The weight of quartz-carbonate-diatom sand prior to splitting it into two fractions.
- C. The weight of the sand split isolated for counting Mollusca-foraminifera.
- D. The weight of insoluble residue left behind after HCl treatment of the other sand split.

FLOWCHART SUMMARIES

pP NOT PRESENT



pP PRESENT



A formula relating these four variables for computer reduction was derived as follows: The sand split weight from which the insoluble residue was derived = $B - C$, and the sand split fraction due to insoluble residue is therefore = $\frac{D}{B - C}$.

The sand split isolated for mollusc-foram counts contained insoluble residue in the same proportion and its weight is therefore = $\frac{CD}{B - C}$. The loss of this insoluble residue was therefore added to that obtained from the acid treated split thus giving a total weight of $D + \frac{CD}{B - C}$. Assuming that no loss of insoluble residue was incurred during faecal pellet and G-gpP removal, this total weight represents the insoluble residue contained in the sand after wet-sieving it from the other textural components. The weight percentage insoluble residue in the sand fraction is therefore:

$$= \frac{D + \frac{CD}{B - C}}{A} \times 100$$

$$= \frac{100BD}{A(B - C)}$$

For samples containing pP, the weighings A, B and C were used to determine the weight percentage insoluble residue, but D had to be determined (see flowchart summary). This was done using three additional sediment weighings:

- E. The weight of the sand split isolated for pP study.
- F. The weight of the sand split isolated for insoluble residue concentration.
- G. The weight of the insoluble residue left behind after HCl treatment.

The proportion of insoluble residue in the two sand splits = $\frac{G}{F}$, and its total weight in D therefore = $G + \frac{G}{F} E$. Substituting this into the function derived above, the weight percentage insoluble residue in the sand fraction then

$$= \frac{100[G(1 + \frac{E}{F})]}{A(B - C)}$$

Precision of the method is poor, due mainly to the inadvertent loss of terrigenous material during the many analytical operations performed on the sand fraction prior to concentrating the insoluble residue. Replicate analyses on four samples indicate that the sediment composition bears no influence on the precision of results, and that the relative deviation simply varies proportionately with the abundance of terrigenous material in the sand fractions.

	Foraminiferal sand	Faecal pellet sand	Terrigenous sand	Diatomaceous sand
	3410	3721	3889	3950
	4	1	45	5
	2	1	34	6
	6	-	37	5
	1	-	43	3
	-	1	45	5
$\bar{X}$	2,6	,6	40,8	4,8
σ_x	2,4	,6	5,0	1,1
RD	92,3	100,0	12,3	22,8

Appendix A.19 $\frac{1}{10} \phi$ size analysis of the insoluble residue

Size analysis of the small amounts of quartzose insoluble residue was achieved with a settling tube of 20 cms internal diameter, and a fall height of 200 cms. In principle, the system was activated from a power source, which linked through a strain gauge at the top of the tube to an amplifier and graphic recorder. As sediment settled onto the pan at the bottom of the tube, a cumulative weight curve, suitably pre-scaled to occupy most of the paper width in the recorder (25 cm), was traced for later measurements. After a batch of ten samples had been run, measurement of the records was made at 30 intervals between the 'starting time' and the plotted curve, and these raw data were reduced using a computer programme compiled by G.J. Moir (U.C.T., Cape Town). Statistical output included weight percentages expressed at $1/10 \phi$ intervals, and the four moment measures (Appendix B.14). Precision was established by Flemming (1976) using one of the writer's samples to calibrate the instrument, and the results obtained by him are shown below:

Sample 3193								
Fine sand	Very fine sand		Silt	Moment measures				
2,0 to 3,0 ϕ	3,0 to 3,5 ϕ	3,5 to 4,0 ϕ	4,0 to 4,5 ϕ	Mean	Sorting	Skewness	Kurtosis	
,1	41,3	50,3	8,3	3,59	,30	-,05	-1,11	
-	48,6	46,2	5,2	3,55	,28	,13	-1,10	
-	49,8	46,2	4,0	3,52	,26	,11	-,80	
,4	45,1	42,7	11,8	3,58	,31	,08	-1,16	
-	54,4	40,6	5,0	3,50	,27	,23	-,82	
$\bar{X}$	,1	47,8	45,2	6,9	3,55	,28	,10	-1,00
σ_x	,2	4,9	3,7	3,2	,04	,02	,19	,17
RD	173,2	10,3	8,2	46,6	1,08	7,41	90,55	17,33

Errors in the process are likely to occur from four contributory factors (Flemming, 1976): splitting of the sample, introduction of the sample to the tube, inhomogeneity of the tube water temperature, and incorrect measurement of the record. According to Flemming (op.cit.), a combination of all these errors, particularly with monomineralic samples such as were considered here, affect the true size distribution of the sample insignificantly.

Appendix A.20 Surface textures of quartz grains

A number of coarse sand-size quartz particles were hand-picked from the >63 μ m fraction of continental shelf samples, as well as from hinterland-dune and beach-foreshore samples, for photography using a scanning electron microscope. The grains were submitted to Mr. R.H.M. Cross of Rhodes University, Grahamstown, who under the direction of Mr. J. Rogers, and assistance from Miss L. Cadle, sought, and photographed diagnostic features on their surfaces. The grains were first coated with gold-palladium, and then mounted in a Japan Electron Optics Laboratory JSM-U3 scanning electron microscope. At least three photographs of each grain were taken: a general view of the whole grain (50-120x), a profile view of the edge (1000x), and finally, the surface detail (5000x).

Appendix A.21 Mica

Mica in the samples was first separated with the Franz Isodynamic Separator during G and gpP concentration, and subsequently purified by repeated decantation during concentration of the insoluble residues. Final beneficiation of the mica was accomplished by agitating dry mica concentrates on a large sheet of glossy paper at an angle of about 10°. This technique facilitated separation of fine-grained quartz with the mica flakes remaining 'stuck' to the paper. Because of the many operations performed in obtaining the mica concentrates, their extraction is not shown in Fig.5.1. The precision of the mica determinations listed in Appendix B.15 is probably of the order of 25%.

Appendix A.22 R-mode factor analysis (principal components procedure)

The factor analysis technique was introduced by Spearman in 1904, and principal component analysis, by Hotelling in 1933. Although both processes are essentially similar, the former describes interrelationships between sample variables, whereas the latter process emphasises the difference between sample variables. Good accounts of the two methods are given by Harbaugh and Merriam (1968), and by Le Maitre (1968) respectively. The computer programme used here, FACTOR 2, employs attributes of both techniques, and is one of the STATJOB series of programmes published by the Madison Academic Computing Center, University of Wisconsin.

The main advantage of this kind of analysis is that it reduces many complex component interrelationships to a few transformed, independent factors and furthermore, it quantifies the degree of association between the original variables. A limitation of the procedure is that subjective interpretation of the results is necessary, and a priori knowledge of the environment is therefore a distinct advantage. Another potentially misleading aspect involved with interpreting the results, is that although a particular component variable may be known to be highly concen-

trated in a particular environment, its association with other components there will not be indicated if it occurs elsewhere in high concentrations. Alternatively, a poorly concentrated component variable in a known environment may have a high degree of correlation with other components there, if its distribution is restricted essentially to this environment.

A number of different methods of portraying the association of variables and their factor loadings were tried (see Imbrie and Purd y, 1962; Harbaugh and Merriam, 1968), but diagrammatic representation of the rotated factor matrix using bar graphs was found to be the simplest and easiest to interpret (Reinson, 1975). The results are depicted in Fig. 5.37, where positive and negative loadings above 25% are shown using different symbolic patterns. Some of the statistical parameters relating to the variables and the factors have been included in the diagrams simply to aid in their interpretation.

Appendix A.23 The Sardinops cores

Twenty seven short gravity cores, averaging 35 cm in length and ranging between 10 and 91 cm, were inherited by the writer in an already sub-sampled and partially analysed state from Dr. C.P. Summerhayes. Each of the cores, when wet, had been split in half and sub-sampled into 5 cm sections, thus making a total of 193 sub-sections available for study. Storage over several years had resulted in their desiccation, and salt crusts were visible in many of the small plastic vials containing the sub-sections. Dr. Summerhayes cleaned them by scraping off the smeared outer 2 mm, and after examining them under a binocular microscope to broadly determine their textural and mineralogical properties, crushed and homogenised between 2 and 5 grams of each sub-section by hand in a porcelain pestle and mortar. He then analysed them for C_{org} using the wet oxidation method of Gross (1971), which he ascertained to be accurate to within $\pm 3\%$, but less reproducible than the Morgans (1956) method (Appendix A.9). Analyses were generally made in duplicate, but when results differed by more than 10%, additional determinations were made.

The writer analysed the Sardinops sub-sections for $CaCO_3$ by means of gasometry, and also submitted the material to FOSKOR for P_2O_5 and K_2O analysis. The method for determining $CaCO_3$ has been described in Appendix A.7, and the techniques used by FOSKOR for determining P_2O_5 and K_2O are discussed in Appendix A.12. The results of all these investigations are listed in Appendix B.16.

Appendix A.24 Collection, storage and dialysis of clay samples

Siegel and Pierce (1973) have recently obtained evidence that the type of sampling device used to recover sediment from the sea floor may have a significant effect on the composition of the clay mineral assemblage. In particular, they observed that the results obtained from grab and Phleger (gravity core) samples deviated by the widest margin, but were unable to offer any completely satisfactory explanations for the apparent differences. Samples used in the present study were recovered by means of the same two pieces of equipment (Fig.1.1), and the introduction of errors from this source may therefore have occurred. Regarding contamination of the sediment with trace elements contained in the sampling devices, Birch (1975), using for reference a corer constructed entirely from PVC, has ascertained that the elements Zn, Mn and Ni can, in extreme cases, be influenced up to 10% of their actual concentrations.

After collection, the samples were stored in air-tight plastic containers in an unfrozen state. Birch (1975) has examined the likelihood of trace element loss from the sediment by sorption onto the container walls using the metals Fe, Mn, Cu, Ni, Pb and Zn as tracers. He found that over a period of two months, no significant differences were detected between the element concentrations of frozen and unfrozen samples, but as an added precaution, all sub-samples used in the present study were collected by making top-to-bottom sections through the sediment in the central part of the containers.

The sub-samples, each consisting of approximately 50 g of wet sediment, were dialysed for 24 hours to remove interstitial salt (Fig.5.1), and for this purpose, commercially available dialysis tubing was used. The sediment was fed into approximately 0.5 m of the tubing with the aid of a wide-necked plastic funnel and a plastic push rod, and the knotted tubes were then suspended in a large vessel containing distilled water. Birch (1975) has made a study of the rate of loss of common sea-water salts through dialysis, and found that the elements Na, Mg, Ca and K in the interstitial water were effectively removed after five to six hours of dialysis, and more significantly, that elements adsorbed onto the surfaces of the sediment particles were not affected by the process.

Appendix A.25 Separation of clay-size sediment

Clay fractions were isolated from the dialysed sediment samples by a process of repeated settling and siphoning. After agitating the samples into suspension with distilled water, the $>2\mu\text{m}$ sediment fraction was allowed to settle to a depth defined by Stokes' theory as a function of time and the ambient temperature. To ensure that only the upper part of the suspension containing the $<2\mu\text{m}$ sediment was drawn off, a J-shaped siphon tube was constructed to fit a graduated adjustable

rack, and this allowed rapid lowering of the siphon tip to the correct depth below the surface. The entire process was repeated up to ten times with samples containing abundant clay-size material, the end-point being indicated when the upper part of the suspension turned clear. Nevertheless, since no dispersant such as Calgon could be used because of the geochemical work planned, it is possible that some of the clay may have been lost during the separation procedure due to flocculation.

Concentration of the clay material from the large volumes of water siphoned off (2 to 4 litres) was initially accomplished by allowing it to settle over a 2 to 3 week period, and then decanting off the clear supernatant liquid. Final concentration was then made using a high-speed centrifuge. At this stage, the clay-fraction concentrates were homogenised and then split into two parts, one for use in the X-ray diffraction analysis, and the other for atomic absorption analysis.

Appendix A.26 Pre-treatment of clay-size sediment for X-ray diffraction analysis

Calcium carbonate was dissolved from the clay-size material using an unbuffered solution of 25% CH_3COOH and, following this, the organic matter was oxidized with 30% H_2O_2 . Amorphous Fe and Si were not removed because from a trial run made on five compositionally different samples, extraction of the iron (Mehra and Jackson, 1960) was found to have negligible effect on the diffractograms, and after opal removal (Hashimoto and Jackson, 1960) there was no clay material left in the diatomaceous samples to work on. The clays were then saturated with Mg by gently agitating them in a solution of 1N MgCl_2 for 4 hours using a mechanical shaker.

To obtain samples with a preferred orientation parallel to (001), an eye-dropper was used to sediment the clay onto glass slides, which were then dried fairly rapidly at 50°C to prevent differential settling (Stokke and Carson, 1973). Two slides were prepared for each sample. One was used for diffracting first the untreated clay and then again after heating at 550°C for one hour, and the other slide was used for diffracting the clay after it had been glycolated. Several attempts to glycolate the clays by conventional fuming techniques proved unsatisfactory, and eventually, ethylene glycol was simply painted over the sedimented clay surface with a very fine camel-hair brush.

Appendix A.27 Semi-quantitative estimation of the clay mineralogy by X-ray diffraction

Clay mineral identifications were based on the characteristic basal reflections, and their abundances were estimated by weighting the integrated peak areas after the method of Johns et al. (1954).

Montmorillonite was recognized by its $14\text{\AA}$ basal spacing which expands to $17\text{\AA}$ on glycolation, and collapses to $10\text{\AA}$ after heating to 550°C . The peak intensity

of the clay mineral was estimated by counting the number of squares on the recorder chart beneath the $17\text{\AA}$ glycolated peak.

Illite was identified by its $10\text{\AA}$ and $2,3\text{\AA}$ peaks, which remained unaffected after glycolation and heating, and its intensity was estimated by multiplying the number of squares beneath the $10\text{\AA}$ glycolated peak by 4.

A clay mineral with $14\text{\AA}$ basal spacing, which collapsed to $10\text{\AA}$ on heating to 550°C , but showed no expansion on glycolation, was attributed to vermiculite. Lack of information regarding the form factor function of this clay mineral prevented calculation of its intensity value, and as a result, its abundance was simply expressed as a ratio in terms of illite, i.e., the $14\text{\AA}$ glycolated peak count/ $10\text{\AA}$ glycolated peak count (Appendix B.17).

The $7\text{\AA}$ glycolated peak corresponds to the basal (001) reflection of kaolinite as well as to the second-order (002) chlorite and vermiculite reflections. An attempt to resolve the $3,5\text{\AA}$ peak resulting from the second and fourth order basal reflections of kaolinite and chlorite/vermiculite respectively (Biscaye, 1974) proved unsuccessful, and consequently, a chemical test for the presence of chlorite was resorted to. Seven samples that previously had been 'slow scanned' over the $3,5\text{\AA}$ peak area were treated with warm ($\pm 50^{\circ}\text{C}$) 6N HCl for 16 hours, and subsequently X-rayed again (Schultz, 1964). Persistence of the $7\text{\AA}$ peak after this treatment, and virtual disappearance of the $14\text{\AA}$ peak after heating to 550°C was taken to indicate that chlorite was present in only trace amounts. Furthermore, since the second order basal reflection of vermiculite has very weak intensity (Griffin, 1971), the reported values of kaolinite + chlorite + vermiculite at $7\text{\AA}$ is probably largely due to the abundance of kaolinite.

Samples from the diatomaceous mud belt south of Ambrose Bay were found to contain negligible terrigenous clay material due to heavy dilution from diatom frustules. It was therefore arbitrarily decided that a counting score of 50 squares for the sum of relevant basal reflections on the recorder chart, provided a convenient cut-off value below which estimates of mineral proportions were considered to be tenuous. Eight samples were affected in this way, and although trace quantities of illite were always clearly apparent, the clay-mineral proportions in these samples were not determined.

Crystallinity of the montmorillonite was not measurable from the ratio of the low angle valley depth to the $17\text{\AA}$ peak height (Biscaye, 1964) because imperfect goniometer alignment resulted in an abnormally low background on the low angle side of the peak. Instead, the half peak-width/peak-height ratio of the $17\text{\AA}$ montmorillonite peak was used as a measure of its crystallinity. All these results are listed together in Appendix B.17.

Pierce and Siegel (1969) have shown that semi-quantitative estimates of the clay mineralogy are generally inaccurate (i.e., methods not utilizing internal

standards), although the particular technique used may be highly precise. They found that most of the error introduced arose from slide preparation and the method of calculation. In the present study, no tests of accuracy were undertaken, but replicate determinations of the clay mineral composition were made on 3 different samples from the glass-slide preparation stage. The results are shown in the following table:

River silt HOANIB			Diatomaceous mud 3811			Upper slope mud 3704			
17Å	10Å	7Å	17Å	10Å	7Å	17Å	10Å	7Å	
18	71	11	9	83	8	30	47	23	
16	72	12	12	80	8	29	47	24	
16	73	11	14	81	5	29	49	22	
19	70	11	8	81	11	33	46	21	
15	72	13	10	81	9	32	45	23	
$\bar{X}$	16,8	71,6	11,6	10,6	81,2	8,2	30,6	46,8	22,6
σ_x	1,6	1,1	0,9	2,4	1,1	2,2	1,8	1,5	1,1
RD	9,5'	1,5	7,8	22,6	1,4	26,8	5,9	3,2	4,9

Precision of the X-ray results is strongly dependent on the sediment composition due to the presence in the diatomaceous clay samples of opaline Si, and in the terrigenous clay samples, of amorphous Fe. The diffraction peaks of samples from the diatomaceous mud belt were particularly broad and poorly-defined, but as mentioned above, the abundance of terrigenous clay material in these samples is very low.

Appendix A.28 Instrument settings for the X-ray diffractometer

X-ray diffraction traces of the clay samples were obtained using a Philips PW 1540 X-ray diffractometer fitted with a proportional counter. Ni-filtered CuK_{α} radiation was used, and the instrument settings were as follows: Kv/mA = 48/20, proportional counter = 1500 volts; rate meter sensitivity = 1×10^3 to 4×10^3 c.p.s; time constant = 1, slits = $1^\circ/0,1^\circ/1^\circ$, and attenuation = 2.

Untreated slides were scanned from 3° to $30^\circ 2\theta$, and the heated and glycolated slides from 3° to $13^\circ 2\theta$ at $2^\circ 2\theta$ /minute. Seven untreated slides were also 'slow scanned' at $\frac{1}{2}^\circ 2\theta$ /minute in an attempt to resolve the chlorite-kaolinite peak at $3,5\text{\AA}$ (Biscaye, 1964).

Appendix A.29 Pre-treatment of clay-size sediment for atomic absorption analysis

The method employed for dissolving clay mineral sample-splits for geochemical study was developed by Dr. M.J. Orren and Dr. J. Rogers (pers.comm.) to accommodate marine clays rich in organic matter.

Exactly 0,250g of crushed sample was initially treated with 4ml 65% HNO_3 and 1ml 70% HClO_4 in a 50ml pyrex beaker (conc. HNO_3 dissolves Pt if chloride is present, so Pt crucibles could not be used at this stage). Fuming of the contents of the beaker on a hot plate until the remaining residue appeared to be only slightly damp resulted in complete dissolution of the CaCO_3 and organic matter. It was then transferred, with the aid of a rubber 'polliceman' and a minimum of double distilled water, to a Pt crucible. Treatment with 5ml 40% HF and 5ml 70% HClO_4 , and evaporation on a hot plate to dampness for a second time resulted in volatilization of silica as white fumes of silicon fluoride. After cooling, the residue was re-dissolved with 5ml 0,5N HCl, transferred to a 50ml volumetric flask, and diluted to the mark with double-distilled water. Duplicate solutions were prepared for each of the samples, and a single blank was made to accompany every batch of five solutions.

Appendix A.30 Clay geochemistry by atomic absorption

Before rigorous analysis of the clay samples for a particular element, the approximate concentration range was determined using one of the duplicate sample solutions, and two or three prepared standard solutions. Three standard solutions of suitable concentration were then prepared accurately from stock solution, and, for those elements requiring a buffer during analysis, a 1% KCl or 1% CsCl solution was made up as required (Appendix B.19). Aspiration of the sample solutions, together with the buffer solutions, was accomplished through use of a T-piece constructed out of plastic capillary tubing and Teflon, and between 3 and 5 absorbance readings were made on each of the solutions.

The sequence followed for analysing the samples, standards and blanks was as follows: 3 standard solutions - 5 sample solutions and 1 blank - 5 sample solutions and 1 blank - 3 standard solutions - etc. This procedure allowed control of the instrument drift by plotting new absorbance vs. ppm working curves for each group of 10 sample solutions. After deducting the blank from the sample absorbance readings, the latter were then multiplied by the dilution factor (200) to give the concentration of the element in solutions. Each duplicate pair of analyses was then averaged to give the final (uncorrected) concentration of the element in the sample.

This part of the geochemical analysis was carried out with the assistance of Dr. M.J. Orren of the Geochemistry Dept., U.C.T.

Appendix A.31 Accuracy of the atomic absorption method

The accuracy of trace and major element determinations on geological samples by atomic absorption is a function of the concentration of these elements in the aspirated solutions (Govett and Whitehead, 1973). At low concentrations, enhancement due to background absorption is the main interference, whereas at high concentrations, particularly of the majors, suppression of the results due to matrix effects is the predominant interference. To overcome these problems, six international standards were analysed for the same elements that were determined in the clay samples except Cd, for which no reported values existed. These analyses were carried out one year after the clay samples had been studied, but the methods and instrument settings used were identical. The standard material was kindly provided by Mr. J.P. Willis of the Geochemistry Dept., U.C.T., who also gave considerable advice during the course of the investigation.

It is recognized that the standards, NIM-G (granite), NIM-N (norite), NIM-S (syenite), AGV-1 (andesite), BCR-1 (basalt) and W-1 (diabase) diverge widely from the average composition of the marine sediments, and this sometimes resulted in the clay values lying outside the range of the standard values. Another potential source of error may have arisen from the recommended standard values, being only best estimates of a whole range of reported values that usually disagree by a factor of two or three, but sometimes by as much as ten or more. However, despite these problems, it is felt that there is merit in using international standards for checking the analytical accuracy, particularly for highly concentrated elements such as the majors, where matrix effects may cause significant changes in the results. Furthermore, the standards are now sufficiently well known that any variation in their recommended concentrations is likely to fall within the margin of error of the atomic absorption method.

For each of the elements studied (except Cd), a best-fitting linear regression curve was determined for the analytical results obtained from the international standard materials using the Biomedical computer program BMD05R. Graphical presentation of these curves is shown in Fig. A.31 together with their equations, and the range of element concentrations in the clay samples after correction. The intercepts of the linear regression curves on the Y-axes, together with their slopes, were then used to adjust the determined clay values for each of the elements studied. In general, the best fitting least squares regression lines show enhancement relative to the theoretical 45° lines for the trace elements, and suppression for the major elements. The elements showing least deviation between the two lines are Cu, Ni, Sr, Fe and Mn. The final results listed in Appendix B.18 have all (except for Cd) been corrected using these curves.

Appendix B.20 is a listing of the recommended standard values (Flanagan, 1973;

CORRECTION CURVES FOR GEOCHEMICAL ANALYSIS OF CLAY SAMPLES BY ATOMIC ABSORPTION SPECTROPHOTOMETRY

International Standards

- NIM-G
- NIM-N
- NIM-S
- AGV-1
- BCR-1
- W-1

() Corrected element concentration range of the clay samples

--- Theoretical 45° line (1:1 correspondence)
 — Best fitting, linear regression curves drawn through the uncorrected standard analytical values (equations below plots)

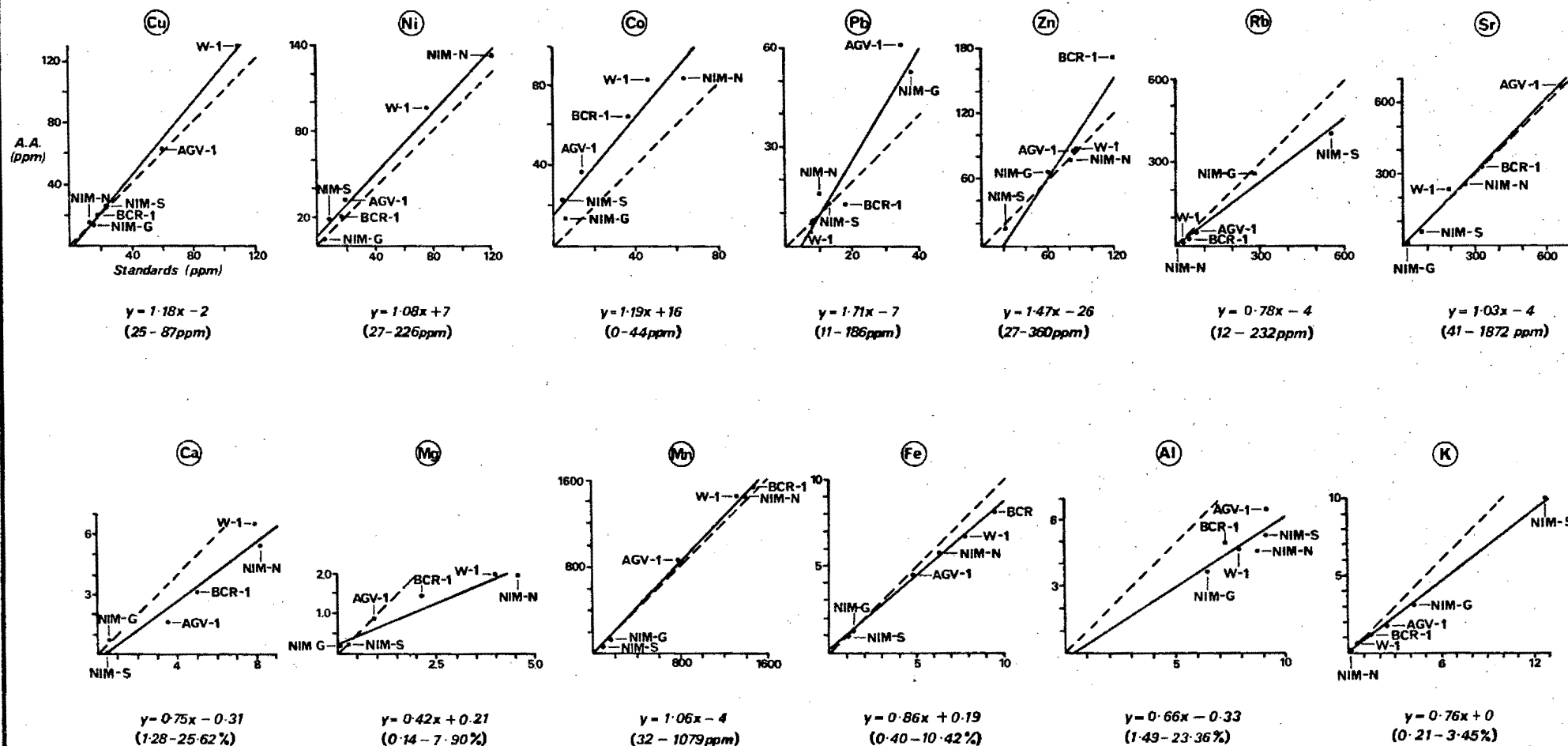


Figure A.31

Abbey, 1975; Internal U.C.T. Standards) compared with the corrected values obtained from this study, and the percentage error between them. It is apparent that agreement is generally quite good and the largest errors tend to occur, as may be expected, in the standards with lowest elemental concentrations (Ahrens, 1957).

Amongst the trace elements, Ni, Pb, Co, and Rb show the worst results (largest average percentage error), and Ca and Mg are the worst amongst the majors. Some of the reasons for the relatively poor accuracies obtained for these elements probably are (M.J. Orren, pers.comm.):

- Ni - the lowest elemental concentrations biased the average percentage error, otherwise agreement between the recommended and calculated values is fairly good.
- Pb - the erratic nature of the analysed results suggest contamination, and with the low concentrations of the aspirated solutions (200 x dilution factor), atmospheric contamination may be quite severe.
- Co - in most cases the calculated values exceed the recommended values, and, due to the abundance of iron in the standards, it is possible that the weak iron spectral line at 240,7 nm, which is not resolved from the Co analytical line, may have been responsible for enhancement of the cobalt results.
- Rb - the lowest elemental concentrations also caused bias of the average percentage error, and the value calculated for NIM-G has probably been affected by contamination.
- Ca, Al and Mg - these three elements were the only majors analysed using the N_2O flame. Nitrous oxide, because of its different density to air, aspirates at a different rate. All three of the elements have consequently suffered from matrix effects, but in the case of Al, this is not evident in the average percentage error because its concentration in the standards is consistently high.

Appendix A.32 Precision of the atomic absorption method

One year after the clay samples had been investigated mineralogically and geochemically, four diatomaceous mud samples, which were previously used for determining the precision of some of the sedimentological methods (samples 3426, 3754, 3756 and 3950), were used in a replicate study of the geochemical technique. This investigation was carried out in conjunction with the accuracy test of the method (Appendix A.31).

Birch (1975) has found that no significant element loss occurs when samples are stored in air-tight plastic containers over a two-month period (Appendix A.24), however, lower results were obtained in the replicate analyses of sample 3756 for all the elements studied excepting Ni (Appendix B.21) thus indicating that at least some loss was incurred during the storage period of one year. This reproducibility

test is therefore not strictly valid due to the time gap between the two investigations. Also, since the test involved the entire procedure from the subsampling stage to the final result, the possibility existed that slightly different materials may have been examined which adds to the general uncertainty of the results. In spite of these problems however, the percentage deviation between the two sets of results is, in most cases, quite small, thus suggesting that the combined effect of these error sources is probably within the limit of error of the method.

The results of the precision tests are shown in Appendix B.21, from which it is apparent that deviations for any particular sample are generally of the same order of magnitude as the deviations exhibited by the elements. This is interpreted as meaning that, apart from the 'built in' inaccuracies described above, the errors introduced during sample preparation and during the instrumental procedure are roughly the same.

Appendix A.33 Element partition between different sediment size fractions

Most geochemical studies on marine sediments have been conducted on the bulk sediment samples e.g., Calvert and Price (1971b), Summerhayes (1972a), Jones (1973), Reinson (1975), but recently, a few investigations have been confined to the clay fractions of the sediment so that the mineralogy and geochemistry of the same textural material could be compared e.g., Wright (1974a, 1974b), Parker (1974). Since adsorption, precipitation and co-precipitation (metallic coatings), complexing with organic molecules, and incorporation in crystal lattices are important factors controlling element concentrations in the coarser sediment fractions (Gibbs, 1973), it was decided to examine the levels of element enrichment in the gravel/sand, silt and clay fractions of four texturally diverse samples from the diatomaceous mud belt. Partition studies on the chemical aspects of element associations such as oxides, carbonates and organic matter, have been undertaken by Hirst and Nichols (1958), Chester and Hughes (1967), and Birch (1975).

The concentration of 14 elements analysed for in the partition study are shown in Appendix B.21 from where it appears that a good many elements show no particular preference for any of the sediment size fractions e.g., Zn, Mg, Fe, K and Rb. This diversified presence may be a result of Zn occurring in copepod exoskeletons and in association with organic matter, whereas the other elements are common constituents of terrigenous minerals of all sizes. Cu and Ni are most concentrated in the clay fractions of the four samples, thus suggesting their association with organic matter in the diatomaceous mud. The highest concentrations of Mn and Al occur in the silt fractions of the samples, possibly reflecting hydrogenous coatings on diatom frustules, and the remaining elements, Ca, Sr, Cd and Pb are all best represented in the gravel/sand fractions of the samples. Ca and Sr are ex-

plainable in terms of foraminifera in the western flank of the diatomaceous mud belt, Cd is probably incorporated in the opaline frustules of robust diatom species, and Pb may be present as discrete grains of lead sulphide.

The abundance of the elements in each of the sediment size fractions has been calculated from their weight percentages and their respective element concentrations. For example, sample 3426 contains 64 ppm Cu in the gravel/sand fraction (Appendix B.21), and this fraction constitutes 57,8% of the total sample (Appendix B.7); the abundance of Cu in this sediment size fraction is therefore = $(64 \times 57,8)/100$, which = 37% (Appendix B.22).

The frequency of maximum element concentrations in each of the sediment size fractions is shown graphically in Fig. A.33 together with the frequency of maximum element abundances and the weight percentages of the sediment size fractions. From these histograms, it would seem that in determining the relative abundances of the elements in each of the sediment size fractions, the weight percentages of the size fractions play a much more significant role than the concentration of the elements in the size fractions. In fact, there appears to be a rough inverse relationship between the concentration of the elements in the size fractions and the abundance of the elements in the size fractions, and the latter show close similarity with the weight percentages of the size fractions. For example, in sample 3426 the greatest number of elements are most concentrated in the clay fraction of the sample (9 elements, see Fig.A.33), however, the least number of elements are most abundant in this fraction (no elements, see Fig.A.33). In other words, the sediment size fraction constituting the smallest part of the bulk sample (the lowest weight percentage) is likely to contain the greatest number of elements in the most concentrated state, and the smallest number of elements in the most abundant state. The reason for this is not properly understood, but it seems to indicate that for any particular size fraction in a sample, if it is large the elements will be poorly concentrated, and if it is small the elements will be highly concentrated.

Considering the abundances of individual elements in the various sediment size fractions (Appendix B.22), none of them occur most abundantly in more than two of the four samples in either the silt or clay size fractions, but a good many of them occur most abundantly in three or all the samples in the gravel/sand fraction viz., Ni, Pb, Cd, Ca, Sr, Mg and Fe. This is due to the great number of most abundant elements occurring in the gravel/sand fractions of samples 3426 and 3756 (Fig.A.33), the insignificance of the silt-size fraction in all four samples and only one sample, 3754, containing the greatest number of most abundant elements in the clay fraction.

In summary, element partitioning between different sediment size fractions of four diatomaceous samples indicate that for the 14 elements examined:

- The concentration of elements in any particular size fraction is usually inversely related to the weight percentage of the size fraction.

FREQUENCY OF MAXIMUM ELEMENT CONCENTRATIONS AND ABUNDANCES IN THREE SEDIMENT SIZE FRACTIONS

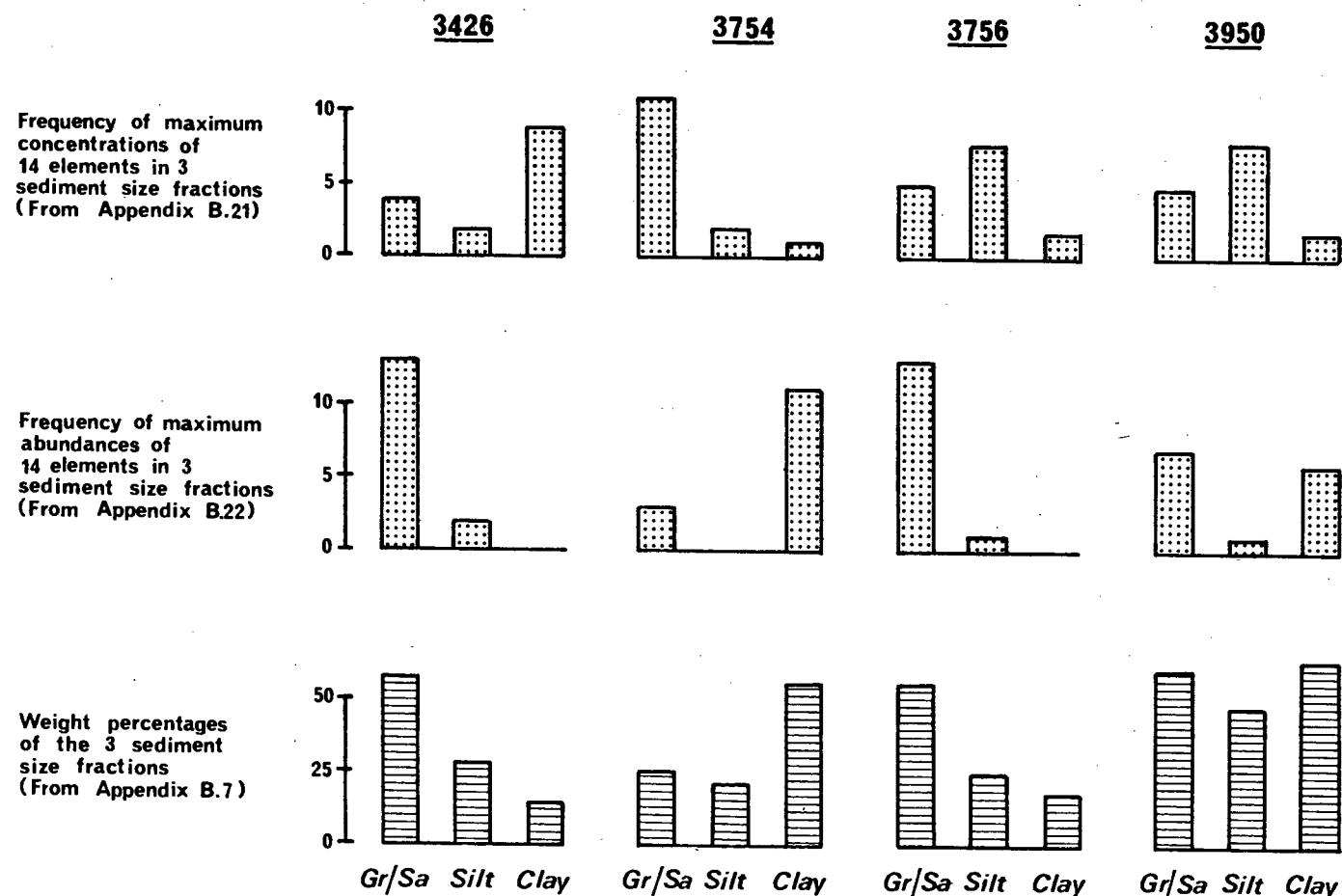


Figure A.33

- The abundance of elements in any particular size fraction is usually directly proportional to the weight percentage of the size fraction.
- The silt fraction, although it may have the greatest number of most concentrated elements, never has the greatest number of most abundant elements.

These observations may be the result of dilution factors as they influence the elements in each of the size fractions e.g., sand-size diatom frustules diluting Cu- and Ni-rich organic matter, clay-size organic matter diluting Ca- and Sr-rich foraminiferal tests, etc. It would thus appear that restriction of the geochemical study (Chapter 7) to the clay fraction of the sediments alone was not justified due to the great variation in composition of the sediments. With sediments of purely terrigenous origin however, it may well be advantageous, particularly since the geochemistry and mineralogy of the same size fraction would then be comparable.

Appendix A.34 Preparation of authigenic minerals for geochemical study

Concretionary phosphorite (cP) was washed with double-distilled water to remove loose bits of adhering diatomaceous sediment. Glauconite (G) and glauconitized pelletal phosphorite (gpP), because of their magnetic susceptibilities (Appendix A.13), were isolated from the bulk of the sediment with the aid of a Franz Isodynamic Separator. The pelletal phosphorite (pP), together with some of the gpP, were initially concentrated using bromoform, and subsequently isolated on the Franz.

Only with the pP and gpP did purification present problems, both from an inter-mineral point of view, and from extraneous material. The contamination was kept below 1% however, by manually separating the two minerals through hand-picking and point-counting. Nevertheless, three pP and three gpP samples still showed abnormal major and trace element concentrations after analysis by XRF, and these results were consequently discarded. It has been reported (Willis, pers.comm.) that Br separations may cause interference in the determination of Rb because the spectral lines of the two elements are very close together, and trace quantities of Br tend to adhere on the phosphorite particles even after washing with alcohol. The low Rb concentrations found in pP and gpP, however, suggest that possible enhancement from this source is negligible.

After purification of the authigenic minerals, a small portion was retained for electron microprobe study and the remainder was crushed to -240 mesh in an automatic agate grinder for 40 minutes. This material was then prepared into fusion discs and briquettes as set out in Appendix A.35.

Appendix A.35 Analysis of authigenic minerals by X-ray fluorescence

A.35.1 Major Elements

The elements Si, Al, Fe, Mg, Ca, K, P, Mn and Ti were determined on glass discs prepared by fusion of 0.28g of crushed sample (weighed to 5th decimal place) with lithium borate flux, according to the method of Norrish and Hutton (1969). Most of the samples were analysed in duplicate but because of lack of material in some of them, a few had to be done singly (Appendix B.23). H_2O^- was obtained by measuring the weight loss of the samples after heating to $110^\circ C$ for 8 hours. The determination of loss on ignition (L.O.I.) was complicated by the presence of fluorine in the phosphorite samples because on liberation, it combined with structurally bonded water to form HF which attacked silica crucibles and the walls of the drying oven. To overcome this, the phosphorite samples were first heated in Pt crucibles over a bunsen burner to drive off the volatiles ($950^\circ C$ for $\frac{1}{2}$ an hour), and subsequently were transferred to Si crucibles and heated in an oven at $1000^\circ C$ for 12 hours.

Analysis of the samples was accomplished using international and departmental standards and blanks provided by the Dept. of Geochemistry, U.C.T., on a Philips PW 1220 semi-automatic spectrometer according to the methods described by Willis et al. (1971). The raw data were reduced using departmental computer programs which calculated working curves from the standard materials, and made correction for such factors as dead time, spectral line interferences and matrix effects. The instrument settings used on the spectrometer are given in Appendix B.25, and the major element concentration of standards used in the analyses are given in Appendix B.26.

A.35.2 Trace elements

The elements Nb, Zr, Y, Sr, Rb, Ba, Co, Cr, V, Zn, Cu, Ni and S were determined using bakelite/boric acid-backed briquettes, which were made from 0.40g of crushed sample and compressed in a die at 10 tons/inch². All the samples were analysed singleton and the results are shown in Appendix B.24. Mass absorption coefficients were determined from the Mo Compton peak for Rb K α radiation for calculation of Nb, Zr, Y, Sr, Rb, Zn, Cu and Ni, and mass absorption coefficients using Birks (1963) values were calculated from major element data for the determination of Co, Cr, V, S and Ba. As with the major element analyses, international and departmental standards and blanks were used, and several departmental computer programs were utilized for reducing the raw data. All analyses except Ba were made on a Philips PW 1220 spectrometer, the latter being done on a Philips PW 1540. The instrument settings used on the spectrometer are given in Appendix B.25, and the trace element concentrations of standard materials used are shown in Appendix B.27.

Appendix A.36 Analysis of authigenic minerals by electron microprobe

The elements Si, Al, Fe, Mg, Ca, Na, K, P and S were determined on a Cambridge Microscan V microprobe using specially prepared glass-slide mounts of the sample material. Granular materials were sprinkled onto warm araldite, and thin sections of rock phosphorite and concretionary phosphorite were cut from the samples. These specimens were then polished on both sides, mounted onto graduated slides for area location, polished using 0,25µm diamond paste, and finally, were coated with a layer of carbon ($\pm 500\text{\AA}$) in order to make them electrically conductive while under the electron beam.

During quantitative spot analysis of the samples, the elements K and Na were determined first because of their tendency to volatilize under the electron beam. To minimize this problem even further, a defocussed beam of 10-20µm was employed which has been found experimentally (Rickard, pers.comm., Birch, 1975) to cause measurable loss of the alkali elements during the counting time employed (20 seconds). The K α lines were measured using an electron beam setting of 15 Kv, and the beam current at the surface of the specimen was $0,5 \times 10^{-7}$ amps. as determined from a Faraday Cage; this was kept constant throughout the analyses. Standard materials used during the analytical work are listed together with their element concentrations in Appendix B.28, and the analyzing crystals employed were: RAP for Si, Al, Mg and Na, QUARTZ for Fe, Ca and K, and PET for P and S.

The nominal element concentrations were obtained from the raw data using a computer program called PRDAT and matrix corrections were then calculated with a second program called ABFAN (Boyd et al., 1968) to give the final corrected compositions of the samples.

Appendix A.37 Advantages and disadvantages of X-ray fluorescence and electron microprobe methods of analysis

The main advantage of XRF over the EMP method of analysis is that it determines the chemical composition of the bulk sample rather than that of a small area (10-20µm) of a single particle, since the latter may differ substantially from the average chemical composition of the sample. The main disadvantage of the XRF method for analysing specific minerals of a sedimentary assemblage, is the difficulty with which uncontaminated concentrates of the material can be prepared for analysis.

The principle advantage of the EMP method is the ability to focus the electron beam on specific regions of a mineral particle and thus detect compositional changes occurring within it e.g., the glauconitized pelletal phosphorite. The disadvantage as mentioned above, is the likelihood of focussing the electron beam onto a silt size quartz, pyrite, or other relatively large particle within the matrix of the

grain. To overcome this problem, it is necessary to analyse, not only a large number of spots within the same grain, but also a large number of grains from the same sample.

As a consequence of the disadvantages inherent in the two methods, the results obtained from both investigations have been included in tables constructed to show the major element compositions of the authigenic minerals (Tables 8.2, 8.3 and 8.4). This also facilitated comparison with results obtained by other workers who used one or the other of the two methods.

Appendix A.38 Overlap between geochemical studies on the clay fraction of the sediment (Chapter 7), and on the authigenic minerals (Chapter 8)

A brief account is given here on the extent of overlap between the two geochemical investigations undertaken in this study, one on the authigenic minerals, and the other on the clay fraction of the sediments. Lack of sample correspondence between atomic absorption (AA) and X-ray fluorescence (XRF) studies was due to the absence of authigenic minerals in most samples selected for the sediment study. Similarly, lack of sample correspondence between the XRF and electron microprobe (EMP) studies was due to insufficient authigenic material existing for both of the investigations. Lack of element correspondence between the three geochemical methods was a result of non-availability of hollow cathode lamps for the AA spectrophotometer, and depended on the nature of the XRF and EMP runs set up by the Dept. of Geochemistry for analysis of their own samples.

Table A.38.1 Sample and element overlaps between geochemical studies on the clay-size sediment, and on the authigenic minerals

AA - XRF		XRF - EMP	
Samples	Elements	Samples	Elements
3773(cP)	Al	3773(cP)	Si
3784(cP)	Fe	3784(cP)	Al
3411(pP)	Mg	4031(cP)	Fe
3877(G)	Ca	3411(pP)	Mg
	K	3906(gpP)	Ca
	Co	3914(gpP)	Na
	Cu	3941(gpP)	K
	Mn	3677(G)	P
	Ni	3877(G)	S
	Rb	4037(G)	
	Sr		
	Zn		

The availability of elements in ambient clay-size sediment, particularly the traces, would be expected to influence the levels of element enrichment in the authigenic minerals. Consequently, the following table has been compiled to show

the element concentrations of both components using the four samples that overlapped between the two studies.

Table A.38.2 Element concentrations in the authigenic minerals and the ambient clay-size sediment

Sample No.	3773 and 3784		3411		3877	
Component	Clay ¹	cP	Clay ²	pP	Clay ³	G
Si	ND	-	ND	2,60	ND	22,53
Al*	2,64	-	15,0	,59	7,36	2,74
Fe*	,79	,02	5,68	2,28	7,12	17,20
Mg*	,81	,45	4,24	,50	4,07	2,58
Ca*	4,27	34,67	3,49	33,18	2,48	,25
Na	ND	,68	ND	,43	ND	,03
K*	,41	-	3,39	,35	3,45	6,23
P	ND	14,30	ND	12,46	ND	,09
S	ND	,77	ND	2,97	ND	,04
Ba	ND	79	ND	43	ND	6
Cd	45	ND	2	ND	-	ND
Co*	-	<5	18	9	11	<10
Cu*	50	5	44	23	46	6
Cr	ND	13	ND	218	ND	473
Mn*	51	18	215	45	225	220
Ni*	108	6	82	75	86	6
Nb	ND	43	ND	<3	ND	<3
Pb	13	ND	48	ND	61	ND
Rb*	29	<3	188	8	126	202
Sr*	162	2355	149	2250	145	14
Ti	ND	40	ND	495	ND	2090
Y	ND	7	ND	220	ND	7
V	ND	18	ND	43	ND	333
Zn*	130	73	114	29	99	30
Zr	ND	<3	ND	26	ND	43

1 = diatomaceous mud, 2 = stiff pre-Holocene mud, 3 = glauconitic sand

* = elements determined in both AA and XRF studies

ND = not determined, - = not detected, <n = <(lower limit of detection)

Major elements in %, trace elements in ppm

Five major and seven trace elements are common to both studies. With regard to the trace elements, the relationship between the element abundances in the authigenic minerals and the ambient sediment can be summarised as follows (using element abundance ratios of Nicholls (1967), see Tables 8.5 and 8.6):

cP is enriched in Sr, equivalent in Co, Cu and Ni, and impoverished in Mn and Rb.

pP is enriched in Sr, equivalent in Co, Cu and Ni, and impoverished in Mn, Rb and Zn.

G is enriched in no elements, equivalent in Mn and Rb, and impoverished in Ni, Sr and Zn.

APPENDIX BResults

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Appendix B.1 Sample locations

Station number	Sample type	Lat. deg. min.	Long. deg. min.	Depth (metres)	Dist. from shore (n.miles)	Station number	Sample type	Lat. deg. min.	Long. deg. min.	Depth (metres)	Dist. from shore (n.miles)
CRUISE 273											
3407	SGC	24 46,0	13 4,0	1310	85	3441	G	24 16,0	14 10,0	135	19
3408	SGC	24 46,0	13 14,0	932	77	3442	G	24 15,8	14 21,2	69	9
3409	SGC	24 46,0	13 24,0	635	67	3443	G	24 15,8	14 23,5	76	7
3410	SGC	24 43,0	13 34,0	413	58	3444	G	24 15,8	14 25,6	68	5
3411	SGC	24 43,0	13 45,0	283	48	3445	G	24 16,0	14 27,4	38	3
3412	D	24 43,0	13 48,0	270	45	3446	G	24 16,0	14 29,8	18	1
3413	G	24 43,0	13 59,0	159	35	3447	G	24 5,5	14 26,3	23	1
3414	G	24 36,0	14 8,0	154	25	3448	G, LGC	24 6,0	14 24,2	52	3
3415	G	24 36,0	14 18,0	125	16	3449	G	24 6,0	14 21,9	73	5
3416	G	24 36,0	14 27,4	45	8	3450	G	24 6,0	14 19,8	88	7
3417	G	24 36,2	14 29,4	34	6	3451	G	24 6,0	14 17,6	109	10
3418	G	24 36,5	14 31,2	21	5	3452	G	24 6,0	14 12,1	124	14
3419	G	24 36,0	14 33,2	18	3	3453	SGC	24 5,7	14 5,3	165	20
3421	G	24 26,0	14 33,8	23	2	3454	SGC	24 5,8	13 55,8	232	29
3422	G	24 26,0	14 31,6	28	4	3455	SGC	24 5,6	13 44,8	270	40
3423	G	24 26,0	14 29,2	32	6	3456	SGC	24 6,3	13 34,4	285	50
3424	G	24 26,0	14 26,8	51	8	3457	SGC	24 6,0	13 24,0	304	57
3425	G	24 26,0	14 24,6	78	10	3458	SGC	24 6,0	13 12,0	725	69
3426	G	24 26,0	14 13,8	130	19	3459	SGC	24 6,0	12 57,0	1403	83
3427	G	24 26,0	14 3,1	160	28	3460	SGC	23 57,5	12 51,0	1287	88
3428	SGC	24 26,0	13 52,2	283	38	3461	SGC	23 57,5	13 1,0	850	79
3429	SGC	24 27,0	13 41,2	345	48	3462	SGC	23 57,5	13 11,5	430	70
3430	SGC	24 26,2	13 30,0	352	57	3463	SGC	23 57,5	13 22,5	300	60
3431	SGC	24 25,0	13 21,0	609	65	3464	SGC	23 56,0	13 33,8	271	50
3432	SGC	24 26,0	13 9,0	1048	75	3465	SGC	23 56,8	13 43,4	248	41
3433	SGC	24 26,0	12 59,0	1446	84	3466	SGC	23 55,8	13 54,4	220	31
3434	SGC	24 15,5	12 58,0	1423	83	3467	G	23 55,8	14 6,4	161	19
3435	SGC	24 15,5	13 9,0	992	74	3468	G	23 56,0	14 19,2	90	8
3436	SGC	24 17,0	13 19,5	635	64	3469	G	23 56,0	14 21,3	79	6
3437	SGC	24 18,0	13 28,5	330	57	3470	G	23 56,0	14 23,4	68	4
3438	SGC	24 16,6	13 40,8	308	45	3471	G	23 56,0	14 25,6	46	3
3439	SGC	24 15,8	13 52,4	270	34	3472	G	23 55,8	14 27,8	38	1
3440	G	24 15,8	14 2,4	186	25	3473	G	23 45,9	14 28,6	20	1

Appendix B.1 (continued)

Station number	Sample type	Lat. deg. min.	Long. deg. min.	Depth (metres)	Dist. from shore (n.miles)	Station number	Sample type	Lat. deg. min.	Long. deg. min.	Depth (metres)	Dist. from shore (n.miles)
CRUISE 273 cont.											
3474	G	23 45,9	14 26,6	38	3	3508	G	23 26,2	13 55,9	163	28
3475	G	23 46,0	14 24,4	54	5	3509	G	22 53,7	14 29,5	15	2
3476	G, LGC	23 45,9	14 22,4	72	6	3510	G	22 53,1	14 28,8	16	3
3477	G	23 45,8	14 20,2	86	9	3511	G	22 52,4	14 28,0	21	4
3478	G	23 46,2	14 9,2	147	19	3512	G	22 51,5	14 27,0	35	5
3479	G	23 46,0	13 58,6	185	29	3513	G	22 56,5	14 23,4	40	1
3480	G	23 46,0	13 48,0	202	39	3514	G	22 56,0	14 21,4	58	3
3481	SGC	23 46,0	13 37,0	232	49	3515	G	22 56,2	14 19,5	76	5
3482	SGC	23 46,0	13 26,0	272	59	3516	G	22 56,2	14 16,8	91	7
3483	SGC	23 46,0	13 14,0	326	69	3517	G, LGC	22 56,5	14 14,8	100	10
3484	SGC	23 46,0	13 1,0	651	82	3518	G	22 56,4	14 4,2	125	19
3485	SGC	23 46,0	12 48,0	1170	93	3519	G	22 56,0	13 53,3	138	29
3486	SGC	23 46,0	12 35,0	1755	104	3520	G	22 55,6	13 42,8	142	39
3487	SGC	23 36,0	12 33,0	1570	105	3521	SGC	22 56,0	13 31,4	218	49
3488	SGC	23 36,0	12 44,0	1228	95	3522	SGC	22 56,0	13 20,7	344	59
3489	SGC	23 36,0	12 55,0	840	86	3523	SGC	22 55,7	13 9,8	295	69
3490	SGC	23 37,0	13 6,0	510	75	3524	SGC	22 56,0	12 58,0	475	80
3491	SGC	23 37,5	13 15,7	333	67	3525	SGC	22 56,0	12 48,0	850	90
3492	SGC	23 36,6	13 27,5	265	55	3526	SGC	22 56,0	12 35,0	1409	102
3493	SGC	23 36,0	13 38,3	223	46	3527	SGC	23 6,0	12 34,0	1460	102
3494	G	23 36,4	13 48,8	175	37	3528	SGC	23 6,0	12 44,5	1077	93
3495	G	23 36,3	13 59,8	164	26	3529	SGC	23 5,5	12 55,5	720	82
3496	G	23 35,7	14 10,2	140	17	3530	SGC	23 6,0	13 6,7	600	72
3497	G	23 35,4	14 19,6	89	9	3531	SGC	23 6,5	13 17,5	365	62
3498	G	23 35,6	14 21,4	78	7	3532	G	23 6,0	13 28,4	268	52
3499	G	23 35,8	14 23,8	58	5	3533	G	23 6,4	13 40,0	153	42
3500	G	23 36,0	14 25,0	42	4	3534	G	23 6,1	13 51,7	146	30
3501	G	23 36,0	14 28,0	22	2	3535	G	23 6,5	14 2,8	132	20
3502	G	23 26,0	14 24,0	45	2	3536	G	23 6,2	14 14,5	102	9
3503	G	23 26,1	14 22,2	68	3	3537	G	23 6,2	14 16,8	98	8
3504	G	23 27,3	14 19,5	82	6	3538	G	23 6,1	14 18,8	80	6
3505	G	23 26,6	14 18,0	93	8	3539	G	23 6,1	14 21,0	60	3
3506	G	23 26,2	14 16,0	103	9	3540	G	23 6,1	14 24,2	38	1
3507	G	23 26,2	14 4,6	142	20	3541	G	23 16,0	14 26,8	22	2

Appendix B.1 (continued)

Station number	Sample type	Lat. deg. min.	Long. deg. min.	Depth (metres)	Dist. from shore (n.miles)	Station number	Sample type	Lat. deg. min.	Long. deg. min.	Depth (metres)	Dist. from shore (n.miles)
CRUISE 273 cont.						CRUISE 279					
3542	G	23 16,0	14 24,7	39	4	3655	SGC	17 23,5	11 2,0	1514	42
3543	G	23 15,8	14 22,5	60	5	3656	SGC	17 23,5	11 13,0	871	30
3544	G	23 15,9	14 20,4	77	7	3657	G	17 23,5	11 23,0	328	21
3545	G	23 16,0	14 18,3	88	9	3658	G	17 23,5	11 34,0	138	10
3546	G,LGC	23 16,4	14 7,0	127	19	3659	G	17 23,5	11 38,0	91	6
3547	G	23 16,3	13 56,0	151	29	3660	G	17 15,6	11 39,9	67	5
3548	G	23 15,7	13 46,0	160	38	3661	G	17 15,6	11 37,7	82	7
3549	G	23 16,2	13 34,8	186	48	3662	G	17 15,6	11 35,6	97	9
3550	G	23 16,0	13 24,5	302	58	3663	G	17 15,6	11 33,6	110	11
3551	G	23 15,8	13 13,4	386	67	3664	G	17 15,6	11 23,2	198	21
3552	G	23 15,9	13 2,6	584	77	3665	SGC	17 15,6	11 12,8	700	31
3553	SGC	23 16,6	12 47,6	1003	91	3666	SGC	17 15,5	11 3,5	1485	39
3554	SGC	23 26,3	12 49,6	1017	89	3667	SGC	17 56,3	11 7,3	1670	39
3555	SGC	23 26,6	13 1,8	590	78	3668	SGC	17 56,3	11 17,8	828	28
3556	SGC	23 26,0	13 13,0	379	67	3669	SGC	17 56,3	11 28,2	220	30
3557	G	23 26,0	13 23,8	278	58	3670	G	17 56,3	11 32,5	185	15
3558	G	23 25,9	13 34,4	197	48	3671	G	17 56,3	11 35,6	155	12
3559	G	23 25,8	13 45,4	162	38	3672	G	17 56,3	11 37,7	128	10
3560	SGC	24 34,0	13 13,0	1060	76	3673	G	17 56,3	11 40,0	121	8
3561	SGC	24 34,8	13 25,0	655	64	3674	G	17 56,3	11 41,7	108	7
3562	SGC	24 36,4	13 35,0	391	56	3675	G	18 10,0	11 45,0	91	7
3563	SGC	24 35,9	13 46,5	321	46	3676	G	18 10,0	11 42,8	113	9
3564	SGC	24 35,9	13 57,5	207	35	3677	G	18 10,0	11 40,6	128	10
3565	D	24 36,5	13 58,5	206	34	3678	G	18 10,0	11 39,7	133	12
3566	G	24 46,2	14 13,3	149	24	3679	G	18 10,0	11 29,2	278	22
3567	G	24 46,0	14 24,4	104	16	3680	SGC	18 10,0	11 18,7	919	30
3568	G	24 25,8	14 35,0	43	8	3681	SGC	18 10,0	11 11,2	1610	37
3569	G	24 45,9	14 37,6	38	6	3682	SGC	18 35,0	11 9,0	1510	48
3570	G	24 46,0	14 39,4	38	5	3683	SGC	18 35,0	11 19,6	991	40
3571	G	24 46,2	14 41,4	28	3	3684	SGC	18 35,0	11 30,0	1935	30
3572	G	24 48,8	14 43,4	19	3	3685	G	18 35,8	11 40,9	219	20
						3686	G	18 36,5	11 51,6	192	12

Appendix B.1 (continued)

Station number	Sample type	Lat. deg. min.	Long. deg. min.	Depth (metres)	Dist. from shore (n.miles)	Station number	Sample type	Lat. deg. min.	Long. deg. min.	Depth (metres)	Dist. from shore (n.miles)
CRUISE 279 cont.											
3687	G	18 36,6	11 53,8	175	10	3719	G	19 34,0	12 22,8	140	21
3688	G	18 36,8	11 56,0	167	8	3720	G	19 34,0	12 11,0	237	32
3689	G	18 36,9	11 58,3	138	7	3721	G	19 34,0	11 59,8	301	42
3690	G	18 54,0	12 19,7	95	4	3722	G	19 34,0	11 48,5	340	51
3691	G	18 53,2	12 16,8	100	6	3723	SGC	19 34,0	11 37,1	397	60
3692	G	18 53,1	12 15,2	108	8	3724	SGC	19 33,0	11 24,0	492	70
3693	G	18 52,0	12 13,2	116	9	3725	SGC	19 33,0	11 13,8	802	78
3694	G	18 50,9	12 2,8	193	15	3726	SGC	19 33,0	11 3,5	1060	84
3695	G	18 49,8	11 52,2	270	22	3727	G	22 52,8	14 23,8	50	3
3696	G	18 48,6	11 42,2	280	27	CRUISE 283					
3697	SGC	18 47,3	11 31,7	375	33	3736	G	24 55,4	14 45,3	38	2
3698	SGC	18 46,2	11 21,3	703	42	3737	G	24 55,4	14 43,0	52	4
3699	SGC	18 44,7	11 11,0	1210	50	3738	G	24 54,8	14 41,5	61	6
3700	SGC	18 55,0	10 43,0	1455	80	3739	G	24 54,8	14 39,0	76	8
3701	SGC	19 19,0	10 31,2	1292	100	3740	G	24 54,8	14 37,4	83	9
3702	SGC	19 21,0	10 42,0	1211	92	3741	G	24 55,0	14 26,4	112	20
3703	SGC	19 21,5	10 52,8	1222	84	3742	G	24 55,2	14 15,7	152	28
3704	SGC	19 22,0	11 3,6	941	72	3743	G	24 54,7	14 5,1	163	35
3705	SGC	19 22,0	11 14,0	675	69	3744	G	24 54,5	13 53,6	182	45
3706	SGC	19 22,0	11 24,8	462	64	3745	SGC	24 55,0	13 43,0	360	55
3707	G	19 22,0	11 35,8	345	55	3746	SGC	24 55,0	13 31,0	673	64
3708	G	19 22,0	11 46,2	305	47	3747	SGC	24 55,0	13 21,0	1050	73
3709	G	19 22,0	11 56,8	258	37	3748	SGC	24 56,0	13 6,0	1500	85
3710	G	19 22,0	12 7,2	181	30	3749	G	22 35,0	14 27,0	22	3
3711	G	19 22,0	12 17,8	128	21	3750	G	22 35,0	14 25,0	30	5
3712	G	19 21,4	12 30,8	98	10	3751	G	22 35,5	14 23,5	39	6
3713	G	19 21,4	12 33,0	85	9	3752	G	22 35,0	14 22,0	53	8
3714	G	19 21,0	12 34,7	75	7	3753	G	22 35,5	14 20,5	63	9
3715	G	19 34,0	12 41,0	88	7	3754	G	22 34,9	14 8,9	99	19
3716	G	19 34,0	12 39,0	98	8	3755	G	22 35,0	13 58,0	122	28
3717	G	19 34,0	12 37,0	105	10	3756	G	22 35,2	13 47,0	128	37
3718	G	19 34,0	12 34,8	115	11						

Appendix B.1 (continued)

Station number	Sample type	Lat. deg. min.	Long. deg. min.	Depth (metres)	Dist. from shore (n.miles)	Station number	Sample type	Lat. deg. min.	Long. deg. min.	Depth (metres)	Dist. sh (n.mi)
CRUISE 283 cont.											
3757	G	22 35,0	13 36,6	134	46	3790	SGC	21 54,0	12 37,0	550	7
3758	G	22 35,0	13 26,0	238	54	3791	SGC	21 54,0	12 26,0	880	7
3759	G	22 35,0	13 15,5	271	62	3792	SGC	21 54,0	12 15,0	1408	8
3760	G	22 35,0	13 3,0	301	70	3793	SGC	21 35,0	12 2,0	1460	9
3761	SGC	22 35,0	12 53,5	351	76	3794	SGC	21 35,0	12 13,0	1252	8
3762	SGC	22 35,5	12 42,0	1048	85	3795	SGC	21 35,0	12 23,0	980	7
3763	SGC	22 35,0	12 31,0	1509	95	3796	SGC	21 37,0	12 33,0	625	6
3764	SGC	22 15,0	12 20,5	1462	95	3797	SGC	21 36,0	12 42,0	360	5
3765	SGC	22 15,0	12 30,0	1080	85	3798	SGC	21 36,0	12 53,0	298	4
3766	SGC	22 16,0	12 41,0	698	68	3799	SGC	21 36,0	13 3,0	232	4
3767	SGC	22 16,0	12 51,0	370	68	3800	G	21 35,0	13 14,0	147	3
3768	G	22 15,0	13 3,0	280	58	3801	G	21 35,0	13 26,8	120	2
3769	G	22 15,0	13 14,0	223	49	3802	G	21 35,5	13 39,7	90	1
3770	G	22 15,0	13 27,0	169	40	3803	G	21 34,8	13 41,7	82	
3771	G	22 15,0	13 37,4	130	34	3804	G	21 34,8	13 43,9	65	
3772	G	22 15,0	13 48,0	115	26	3805	G	21 34,9	13 45,8	54	
3773	G	22 15,0	13 58,8	96	17	3806	G	21 34,7	13 48,1	35	
3774	G	22 15,3	14 8,8	61	10	3807	G	21 15,0	13 36,6	29	
3775	G	22 15,0	14 11,6	49	7	3808	G	21 14,8	13 34,0	48	
3776	G	22 15,3	14 13,5	42	6	3809	G	21 14,5	13 32,0	66	
3777	G	22 15,1	14 15,8	28	4	3810	G	21 15,0	13 30,0	73	
3778	G	22 14,9	14 18,3	20	2	3811	G	21 14,5	13 28,0	87	
3779	G	21 55,0	14 2,5	24	3	3812	G	21 15,0	13 17,2	129	1
3780	G	21 55,0	14 ,0	30	4	3813	G	21 14,8	13 7,0	139	2
3781	G	21 55,0	13 58,0	40	5	3814	G	21 15,0	12 56,2	263	3
3782	G	21 54,5	13 56,0	51	7	3815	G	21 15,5	12 45,5	332	4
3783	G	21 55,0	13 53,4	66	8	3816	G	21 15,0	12 34,5	390	5
3784	G	21 55,0	13 43,0	106	16	3817	G	21 15,0	12 24,0	683	6
3785	G	21 55,0	13 32,5	130	25	3818	SGC	21 15,0	12 12,0	940	7
3786	G	21 55,0	13 21,5	160	35	3819	SGC	21 16,0	12 2,0	1166	8
3787	G	21 55,0	13 10,0	186	45	3820	SGC	21 16,0	11 48,0	1502	9
3788	SGC	21 54,0	12 59,0	303	54	3821	SGC	20 55,0	11 37,5	1525	9
3789	SGC	21 54,0	12 49,0	325	62	3822	SGC	20 55,0	11 47,5	1260	8

Appendix B.1 (continued)

Station number	Sample type	Lat. deg. min.	Long. deg. min.	Depth (metres)	Dist. from shore (n.miles)	Station number	Sample type	Lat. deg. min.	Long. deg. min.	Depth (metres)	Dist. from shore (n.miles)
CRUISE 283 cont.						3857	SGC	20 14,5	12 10,0	295	50
3823	SGC	20 55,0	11 59,0	980	78	3858	SGC	20 15,2	12 21,2	264	41
3824	SGC	20 56,0	12 10,0	720	67	3859	G	20 14,4	12 30,9	210	32
3825	SGC	20 56,0	12 20,0	541	59	3860	G	20 16,3	12 41,9	130	24
3826	SGC	20 56,0	12 28,0	382	52	3861	G	20 14,0	12 50,0	117	17
3827	SGC	20 55,0	12 40,0	344	42	3862	G	19 55,0	12 38,5	122	18
3828	SGC	20 55,5	12 53,0	252	29	3863	G	19 55,0	12 26,0	150	28
3829	G	20 55,0	13 2,2	140	21	3864	G	19 57,0	12 19,4	196	34
3830	G	20 55,0	13 14,5	106	11	3865	G	19 57,2	12 8,6	253	43
3831	G	20 55,0	13 16,6	96	9	3866	SGC	19 55,0	11 54,8	348	54
3832	G	20 55,0	13 18,8	83	7	3867	SGC	19 55,5	11 44,0	440	63
3833	G	20 55,0	13 21,0	66	5	3868	SGC	19 55,0	11 33,0	614	73
3834	G	20 55,6	13 22,8	43	3	3869	SGC	19 55,0	11 22,0	825	83
3835	G	20 34,7	13 15,2	42	3	3870	SGC	19 55,0	11 12,0	1026	92
3836	G	20 34,5	13 12,8	65	5	3871	SGC	19 55,0	11 1,0	1230	101
3837	G	20 35,0	13 11,1	81	7	3872	SGC	19 55,0	10 51,0	1244	108
3838	G	20 35,0	13 8,8	93	8	3873	SGC	19 56,0	10 32,7	1385	121
3839	G	20 35,0	13 6,2	105	10	3874	SGC	19 44,0	10 26,0	1353	119
3840	G	20 34,8	12 56,5	133	19	3875	SGC	19 34,0	10 30,0	1328	110
3841	G	20 35,0	12 45,5	205	29	3876	SGC	17 4,0	11 3,5	1036	40
3842	G	20 34,0	12 35,0	289	38	3877	G	17 4,0	11 13,5	447	30
3843	SGC	20 35,0	12 24,4	310	48	3878	G	17 4,0	11 42,0	30	3
3844	SGC	20 35,0	12 13,5	339	57	3879	G	17 4,0	11 40,0	58	5
3845	SGC	20 35,5	12 5,0	566	64	3880	G	17 4,0	11 38,0	74	7
3846	SGC	20 35,0	11 52,0	810	74	3881	G	17 4,0	11 36,0	91	9
3847	SGC	20 35,0	11 41,0	1065	84	3882	G	17 4,0	11 34,0	103	11
3848	SGC	20 35,0	11 30,0	1222	94	3883	G	17 4,0	11 24,0	140	20
3849	SGC	20 35,0	11 6,0	1500	116	3884	SGC	17 34,0	11 7,0	1502	35
3850	SGC	20 15,0	10 34,0	1433	133	3885	SGC	17 34,0	11 17,0	776	25
3851	SGC	20 14,0	10 55,0	1472	114	3886	G	17 34,0	11 27,0	222	16
3852	SGC	20 15,0	11 16,5	1072	97	3887	G	17 32,0	11 30,0	167	13
3853	SGC	20 15,0	11 27,5	979	87	3888	G	17 32,0	11 32,0	154	11
3584	SGC	20 15,0	11 37,5	831	78	3889	G	17 32,0	11 34,0	130	10
3855	SGC	20 15,2	11 48,5	601	70	3890	G	17 32,0	11 36,0	115	7
3856	SGC	20 15,0	11 59,0	369	60						

Appendix B.1 (continued)

Station number	Sample type	Lat. deg. min.	Long. deg. min.	Depth (metres)	Dist. from shore (n.miles)	Station number	Sample type	Lat. deg. min.	Long. deg. min.	Depth (metres)	Dist. from shore (n.miles)
CRUISE 283 cont.											
3891	G	17 32,0	11 38,5	104	6	3924	SGC	19 10,0	11 38,0	332	45
3892	G	17 32,0	11 41,0	65	3	3925	SGC	19 10,4	11 47,7	290	40
3893	G	17 45,0	11 43,0	63	2	3926	SGC	19 11,5	11 59,0	236	30
3894	G	17 45,0	11 41,0	93	5	3927	G	19 12,6	12 10,6	139	22
3895	G	17 45,0	11 38,0	115	7	3928	G	19 14,2	12 28,2	94	9
3896	G	17 45,0	11 35,7	125	9	3930	G	19 14,4	12 30,4	74	7
3897	G	17 45,0	11 33,0	0	11	3931	G	19 14,5	12 32,4	66	6
3898	G	17 45,0	11 22,5	251	21	3932	G	19 14,7	12 34,1	56	5
3899	SGC	17 45,0	11 12,0	1050	32	3933	G	19 15,0	12 35,8	36	2
3900	SGC	18 23,0	11 10,0	1520	41	3934	G	19 44,0	12 50,0	47	2
3901	SGC	18 23,0	11 20,0	620	32	3935	G	19 44,0	12 48,0	69	5
3902	SGC	18 23,0	11 30,0	249	25	3936	G	19 44,0	12 46,0	82	6
3903	G	18 24,0	11 39,0	169	19	3937	G	19 44,0	12 44,0	93	8
3904	G	18 24,0	11 44,0	150	14	3938	G	19 44,0	12 42,0	100	9
3905	G	18 24,0	11 46,0	130	12	3939	G	19 43,2	12 33,0	130	17
3906	G	18 24,0	11 48,0	128	10	3940	G	19 43,6	12 20,5	184	28
3907	G	18 24,0	11 50,0	112	9	3941	G	19 44,0	12 9,8	264	37
3908	G	18 24,0	11 52,0	98	7	3942	G	19 44,0	11 59,3	325	46
3909	G	19 1,2	11 26,4	45	2	3943	SGC	19 44,0	11 49,0	373	54
3910	G	19 ,6	12 23,9	73	5	3944	SGC	20 7,0	11 53,0	378	62
3911	G	19 ,7	12 21,6	90	6	3945	SGC	20 7,0	12 3,0	310	53
3912	G	19 ,3	12 18,9	95	9	3946	SGC	20 7,0	12 12,2	263	46
3913	G	19 ,4	12 17,3	105	10	3947	G	20 7,0	12 22,2	218	37
3914	G	18 59,7	11 7,0	135	18	3948	G	20 6,7	12 33,6	150	27
3915	SGC	19 ,0	11 57,0	233	25	3949	G	20 7,0	12 43,8	122	18
3916	SGC	18 57,0	11 43,0	305	33	3950	G	19 55,0	12 47,0	100	11
3917	SGC	18 56,0	11 32,0	285	39	3951	G	19 55,0	12 49,4	92	9
3918	SGC	18 55,0	11 19,0	468	48	3952	G	19 55,0	12 51,6	82	7
3919	SGC	18 54,0	10 58,0	1100	66	3953	G	19 55,0	12 53,6	67	5
3920	SGC	19 8,0	10 52,0	1223	77	3954	G	19 55,0	12 55,8	45	3
3921	SGC	19 8,2	11 10,0	738	63	3955	G	20 7,0	12 54,7	96	10
3922	SGC	19 9,0	11 18,0	528	57	3956	G	20 6,8	12 56,4	83	7
3923	SGC	19 9,4	11 30,0	368	49	3957	G	20 6,6	12 58,4	77	5

Appendix B.1 (continued)

Station number	Sample type	Lat. deg. min.	Long. deg. min.	Depth (metres)	Dist. from shore (n.miles)	Station number	Sample type	Lat. deg. min.	Long. deg. min.	Depth (metres)	Dist. from shore (n.miles)
CRUISE 283 cont.											
3958	G	20 7,0	13 4	63	4	3991	G	21 7,2	13 11,0	125	20
3959	G	20 7,0	13 3,0	45	3	3992	G	21 7,0	13 0	210	28
3960	G	20 15,2	13 4,0	97	8	3993	G	21 6,7	12 49,4	320	36
3961	G	20 15,2	13 2,0	90	9	3994	SGC	21 7,2	12 39,0	380	45
3962	G	20 15,2	13 0	77	10	3995	SGC	21 27,0	12 43,0	344	52
3963	G	20 15,2	12 58,0	51	12	3996	SGC	21 25,0	12 53,5	285	42
3964	G	20 15,2	12 56,0	45	14	3997	G	21 25,5	13 4,5	163	33
3965	G	20 27,0	13 11,0	58	3	3998	G	21 25,0	13 16,0	132	24
3966	G	20 27,0	13 8,8	76	5	3999	G	21 25,0	13 26,6	110	16
3967	G	20 27,0	13 6,7	95	7	4000	G	21 25,0	13 35,2	89	9
3968	G	20 27,0	13 4,4	105	8	4001	G	21 25,0	13 37,3	80	8
3969	G	20 27,0	13 2,2	112	11	4002	G	21 25,0	13 39,5	65	6
3970	G	20 27,0	12 51,8	138	21	4003	G	21 25,0	13 41,5	46	5
3971	D	20 26,0	12 44,0	140	28	4004	G	21 25,0	13 44,0	30	3
3972	G	20 26,0	12 41,0	200	31	4005	G	21 45,0	13 53,9	29	3
3973	G	20 27,0	12 30,4	279	39	4006	G	21 45,0	13 51,8	44	5
3974	SGC	20 27,0	12 20,4	303	46	4007	G	21 45,0	13 49,5	63	7
3975	SGC	20 27,0	12 10,2	325	55	4008	G	21 45,2	13 47,4	75	9
3976	SGC	20 48,0	12 30,0	337	47	4009	G	21 45,3	13 44,8	86	11
3977	SGC	20 48,4	12 39,7	332	39	4010	G	21 45,0	13 34,5	118	18
3978	SGC	20 48,0	12 50,3	250	30	4011	G	21 45,3	13 23,0	145	29
3979	D	20 48,0	12 54,0	160	26	4012	G	21 44,8	13 12,8	164	38
3980	G	20 48,0	13 2,0	137	20	4013	SGC	21 45,2	13 1,2	270	47
3981	G	20 48,1	13 11,5	110	11	4014	SGC	21 45,0	12 51,8	311	55
3982	G	20 48,4	13 13,4	95	9	4015	SGC	22 5,0	12 56,0	325	60
3983	G	20 48,4	13 15,7	93	7	4016	G	22 5,0	13 7,0	244	50
3984	G	20 48,0	13 17,9	75	5	4017	G	22 5,4	13 18,0	183	41
3985	G	20 48,2	13 20,0	48	3	4018	G	22 4,6	13 28,6	154	33
3986	G	21 7,0	13 20,2	38	2	4019	G	22 4,0	13 39,6	125	24
3987	G	21 7,0	13 28,2	63	5	4020	G	22 5,0	13 49,6	102	18
3988	G	21 7,0	13 26,0	82	6	4021	G	22 5,0	14 8	68	10
3989	G	21 6,4	13 23,5	100	9	4022	G	22 5,0	14 2,9	58	9
3990	G	21 6,3	13 21,0	93	11	4023	G	22 5,0	14 5,0	48	7

Appendix B.1 (continued)

Station number	Sample type	Lat. deg. min.	Long. deg. min.	Depth (metres)	Dist. from shore (n.miles)	Station number	Sample type	Lat. deg. min.	Long. deg. min.	Depth (metres)	Dist. from shore (n.miles)
CRUISE 283 cont.						CRUISE 300 cont.					
4024	G	22 5,0	14 7,2	38	5	4678	D	24 17,0	13 52,0	252	34
4025	G	22 5,0	14 9,2	29	4	4679	D	24 6,0	13 56,0	220	29
4026	G	22 25,0	14 22,4	32	4	4680	D	23 55,0	13 54,0	210	31
4027	G	22 25,1	14 20,2	23	6	4681	D	23 46,0	13 58,0	180	29
4028	G	22 25,0	14 17,9	44	7	4682	D	23 36,0	14 ,0	158	26
4029	G	22 25,0	14 16,0	54	10	4683	D	23 16,2	13 56,0	150	29
4030	G	22 25,0	14 13,8	63	12	4684	D	23 16,4	14 23,0	56	6
4031	G	22 25,4	14 2,6	103	21	4685	D	23 16,2	14 26,6	25	3
4032	G	22 25,2	13 52,5	121	27	4686	D	22 45,0	14 28,0	32	3
4033	G	22 25,5	13 41,6	129	37	4687	D	22 35,0	14 27,0	25	2
4034	G	22 25,0	13 30,0	172	46	4688	D	22 35,0	14 22,6	45	7
4035	G	22 25,0	13 20,0	235	52	4689	D	22 25,0	14 20,0	32	6
4036	G	22 25,0	13 9,0	265	59	4690	D	22 15,2	14 17,8	18	4
4037	SGC	22 25,0	12 48,0	450	75	4691	D	22 15,0	14 13,8	32	5
4038	SGC	22 45,0	12 41,0	1153	97	4692	D	22 50,0	14 7,7	33	5
4039	SGC	22 43,0	13 0,0	308	80	4693	D	21 55,0	14 2,0	25	2
4040	SGC	22 45,0	13 13,0	320	69	4694	D	21 45,0	13 53,7	40	2
4041	SGC	22 43,0	13 25,0	308	57	4695	D	21 35,0	13 48,0	36	4
4042	G	22 45,0	13 35,4	140	48	4696	D	21 25,0	13 41,8	42	5
4043	G	22 44,7	13 47,0	132	36	4697	D	21 15,0	13 35,0	49	5
4044	G	22 45,0	13 57,4	125	28	4698	D	21 7,0	13 31,5	20	2
4045	G	22 45,0	14 8,5	110	19	4699	D	20 54,1	13 22,5	50	35
4046	G	22 45,1	14 18,8	77	12	4700	D	20 47,9	13 20,2	40	3
4047	LGC	22 45,2	14 21,6	69	9	4701	D	20 34,0	13 13,0	53	3
4048	G	22 45,0	14 23,7	56	7	4702	D	20 34,0	13 12,6	69	5
4049	G	22 44,5	14 26,5	43	5	4703	D	20 34,0	13 10,5	88	7
4050	G	22 45,0	14 28,0	35	3	4704	D	20 33,5	13 7,0	104	9
4051	G	24 55,0	13 43,0	352	61	4705	D	20 27,0	13 2,2	109	11
CRUISE 300						4706	D	20 26,8	13 4,2	85	9
4675	D	24 44,0	13 59,0	152	35	4707	D	20 27,0	13 6,7	78	7
4676	D	24 36,0	13 57,0	163	35	4708	D	20 27,0	13 8,9	70	5
4677	D	24 26,0	13 52,0	250	37	4709	D	20 27,0	13 11,0	60	3
						4710	D	20 23,7	13 9,2	52	6

Appendix B.1 (continued)

Station number	Sample type	Lat. deg. min.	Long. deg. min.	Depth (metres)	Dist. from shore (n.miles)	Station number	Sample type	Lat. deg. min.	Long. deg. min.	Depth (metres)	Dist. from shore (n.miles)
RUISE 300 cont.						4743	D	17 17,0	11 22,0	250	22
711	D	20 15,0	13 4,0	51	7	4744	D	17 34,0	11 28,0	167	16
712	D	20 15,0	13 2,0	77	9	4745	D	17 56,3	11 30,0	206	18
713	D	20 15,0	13 ,0	90	10	4746	D	18 15,2	11 53,2	22	2
714	D	20 15,0	12 58,0	102	12	4747	D	18 22,0	11 39,0	149	18
715	D	20 15,0	12 56,0	100	13	4748	D	18 23,0	11 30,0	251	25
716	D	20 6,0	13 2,0	40	3	4749	D	18 49,0	11 41,5	265	27
717	D	19 55,0	12 55,0	51	3	4750	D	18 49,0	12 3,0	120	13
718	D	19 44,0	12 50,0	50	3	4751	D	19 13,0	12 10,0	180	22
719	D	19 35,0	12 42,0	80	6	4752	D	19 11,0	11 48,0	310	40
720	D	19 22,0	12 31,0	102	10	4753	D	19 34,0	12 ,0	290	41
721	D	19 15,0	12 32,0	70	5	4754	G,D	19 34,0	12 23,0	132	21
722	D	19 15,0	12 28,0	98	10	4755	D	19 56,0	12 26,0	152	28
723	D	19 ,0	12 19,8	90	2	4756	D	19 56,0	12 10,0	260	42
724	D	18 52,7	12 21,4	50	3	4757	D	20 13,0	12 8,0	288	51
725	D	18 52,0	12 12,0	90	10	4758	D	20 11,0	12 31,0	210	31
726	D	18 37,0	11 58,4	97	8	4759	D	20 11,0	12 50,0	125	15
727	D	18 36,0	11 52,0	138	11	4760	D	20 26,0	12 51,0	186	22
728	D	18 35,7	11 48,8	140	14	4761	D	20 27,0	12 45,0	160	28
729	D	18 26,0	11 44,0	150	16	4762	D	20 36,0	12 45,3	200	29
730	D	18 26,0	11 47,8	105	12	4763	D	20 36,1	12 57,0	130	19
731	D	18 26,0	11 51,0	68	9	4764	D	20 48,0	12 50,0	238	30
732	D	18 14,6	11 53,0	28	3	4765	D	20 48,0	13 1,0	175	20
733	D	18 10,0	11 44,5	95	6	4766	LGC	21 7,0	13 23,8	90	9
734	D	18 10,2	11 39,7	130	11	4767	D	21 7,0	13 ,0	200	28
735	D	17 55,0	11 41,0	95	8	4768	D	21 7,0	12 38,0	360	46
736	D	17 44,0	11 39,0	111	6	4769	D	21 20,0	12 42,0	343	50
737	D	17 32,0	11 36,6	114	8	4770	D	21 20,0	13 6,0	155	29
738	D	17 32,0	11 32,0	144	12	4771	D	21 26,0	13 3,0	200	35
739	D	17 24,0	11 38,0	98	6	4772	D	21 54,0	12 49,0	322	62
740	D	17 15,0	11 40,0	80	6	4773	D	21 54,0	13 10,0	193	44
741	D	17 4,0	11 42,0	48	4	4774	LGC	21 55,0	13 31,0	130	25
742	D	17 4,0	11 34,0	106	11	4775	D	22 14,0	13 17,5	211	45

Appendix B.1 (continued)

Station number	Sample type	Lat. deg. min.	Long. deg. min.	Depth (metres)	Dist.from shore (n.miles)	Station number	Sample type	Lat. deg. min.	Long. deg. min.	Depth (metres)	Dist.from shore (n.miles)
RUISE 300 cont.											
776	D	22 35,0	13 25,0	233	55	4808	D	23 36,0	13 38,0	199	46
777	D	22 35,0	13 8,0	300	67	4809	D	23 16,4	13 34,4	185	48
778	LGC	22 35,0	12 16,0	2095	106	4810	LGC	23 6,0	13 57,0	145	26
779	D	22 56,0	13 9,0	291	70						
780	D	23 16,0	13 13,0	385	67						
781	D	22 57,6	13 31,3	190	50						
782	LGC	22 35,0	14 14,0	80	14						
783	D	23 26,0	14 24,0	61	2						
784	D	23 36,0	14 22,0	70	7						
785	D	23 36,0	14 27,0	30	3						
786	D	23 45,0	14 27,0	32	3						
787	D	23 57,0	14 25,6	50	2						
788	D	23 57,4	14 22,0	75	6						
789	D	24 7,8	14 25,0	55	3						
790	D	24 17,0	14 27,0	61	4						
791	D	24 17,0	14 24,0	72	7						
792	D	24 27,0	14 25,2	85	10						
793	D	24 27,0	14 30,0	60	6						
794	D	24 35,0	14 27,0	44	8						
795	D	24 35,0	14 21,0	77	13						
796	D	24 46,6	14 35,0	50	8						
797	D	24 46,0	14 40,0	35	6						
798	D	24 56,0	14 43,0	60	5						
799	D	24 55,0	14 5,0	162	35						
800	D	24 55,0	13 42,0	280	54						
801	D	24 37,0	13 35,0	393	56						
802	D	24 19,0	13 27,0	330	58						
803	D	23 54,0	13 32,0	269	51						
804	LGC	24 9,0	12 40,0	2090	99						
805	LGC	16 70,2	40 40,1	2480	91						
806	D	23 38,5	13 15,0	327	67						
807	G	23 46,0	13 47,0	216	40						

Appendix B.2 Mass transport velocities at various depths for three different wave states

Average waves		Storm waves			
		Local		Distant	
d	U_m	d	U_m	d	U_m
10	35,8	10	202,9	70	27,7
15	17,9	15	101,2	75	24,9
20	9,7	20	54,8	80	22,4
30	3,0	30	16,9	90	18,4
40	,9	40	5,1	100	15,3
50	,3	50	1,5	125	9,8
				150	6,4
				200	2,8
				250	1,2
				300	,5
				350	,2

d = depths (metres)

U_m = mass transport velocities (cms/sec).

Appendix B.3 Location and age of stiff muds from the outer margin

Sample No.	Location		Depth (metres)	Age ⁺
	Latitude	Longitude		
Northern Stiff Mud Province				
3655*	17° 23,5'	11° 2,0'	1514	Middle Miocene
3665*	17° 15,6'	11° 12,8'	700	Middle Miocene to Pliocene
3667	17° 56,3'	11° 17,3'	1670	Quaternary
3668	17° 56,3'	11° 17,8'	828	Quaternary
3681	18° 10,0'	11° 11,2'	1610	Quaternary
3698	18° 46,2'	11° 21,3'	703	Quaternary
3886*	17° 34,0'	11° 27,0'	222	Quaternary
3990	18° 23,0'	11° 10,0'	1520	Quaternary
3901	18° 23,0'	11° 20,0'	620	Quaternary
3921	19° 18,2'	11° 10,0'	738	Quaternary
Southern Stiff Mud Province				
3409	24° 46,0'	13° 24,0'	635	Quaternary
3411*	24° 43,0'	13° 45,0'	283	Middle Miocene to Pliocene
3431*	24° 25,0'	13° 21,0'	609	Middle Miocene to Pliocene
3555*	23° 26,6'	13° 1,8'	590	Pliocene
3564*	24° 35,9'	13° 57,5'	207	Quaternary

+ Dated by W.G. Siesser using calcareous nannofossils.

* Examined for their clay mineralogy and geochemistry (see Chapter 7).

Appendix B.4 Terrestrial rocks from the continental shelf

Sample Number	Classification	P ₂ O ₅	K ₂ O	Sample Number	Classification	P ₂ O ₅	K ₂ O
<u>Metasediments</u>				4709F	Rhyolite	,26	4,50
4688A	Metaquartzite	,21	4,63	G	Rhyolite	,27	4,72
4689A	Biotite-rich arkose	,11	1,71	4710A	Rhyolite	,38	4,86
4691B	Metaquartzite	,16	,01	B	Rhyolite	,32	4,16
4692A	Biotite schist	,28	1,79	4711A	Anderite	,27	4,74
D	Metaquartzite	,18	6,11	B	Rhyolite	,33	4,66
4701B	Biotite schist	,18	1,94	C	Rhyolite	,20	4,25
4704	Metaquartzite	-	-	D	Rhyolite	,30	4,31
4724D	Metaquartzite	,13	2,93	E	Rhyolite	,29	3,62
E	Metaquartzite	,13	,66	F	Rhyolite	,52	4,19
F	Metaquartzite	,15	5,76	4714B	Diorite	,48	4,81
4732B	Quartz mudstone	,26	3,74	4724A	Rhyolite	,30	4,41
<u>Vein quartz</u>				B	Granite	,29	4,44
4688B	Milky quartz	,43	,03	C	Rhyolite	,28	5,59
4701A	Milky quartz	,36	,03				
4724G	Milky quartz	,13	,12				
<u>Igneous rocks</u>							
3710A	Olivine tholeiite	,12	,88				
4687A	Pegmatitic granite	,21	10,02				
D	Andesite	,36	1,74				
F	Quartz gabbro	,42	4,95				
4688C	Gabbro	,19	,94				
4689B	Pegmatitic granite	-	-				
4702B	Diorite	,37	3,97				
4703B	Pegmatitic granite	,06	7,47				
4706A	Rhyolite	,41	6,32				
B	Rhyolite	,33	4,87				
4709A	Andesite	,25	5,60				
B	Rhyolite	,33	4,74				
C	Rhyolite	2,27	4,53				
D	Andesite	,25	3,96				
E	Rhyolite	,33	4,50				

Appendix B.5 Classification of consolidated rocks from the inner shelf

Sample No.	Depth (metres)	Handspecimen colour (Geol.Soc.Amer.Rock Color Chart, 1963)	Angularity	Classification
3710A	181	-	-	Olivine tholeiite
B			-	Phospholut: phos mudst
3784	106	01 gry 5 Y 3/2	A	Bd v.f.s calcaren: qtz lime wkst
3967	95	Dy yel 5 Y 6/4	R	Calcaren: lime wkst
4687A	25			Pegmatitic granite
B		M lt gry N6	R	Bd f.s calcaren: qtz lime wkst
C		Lt gry N 7	A	Calcilut: lime mudst
D				Andesite
E		M lt gry N 6	R	V.f.s calcaren: qtz lime wkst
F				Quartz gabbro
G		V lt gry N 8	R	F.s calcaren: qtz lime pkst
4688A	45			Metaquartzite
B				Vein quartz
C				Gabbro
4689A	32			Biotite-rich arkose
B				Pegmatitic granite
4691A	32	M lt gry N 6	R	M.s calcaren: qtz lime pkst
B				Metaquartzite
4692A	33			Biotite schist
B		Dy yel 5 Y 6/4	A	C.g.s calcirud: qtz lime pkst
C		M dk gry N 4	R	C.g.s calcirud: qtz fels lime pkst
D				Metaquartzite
4701A	53			Vein quartz
B				Biotite schist
C		V lt gry N 8	A	Bd c.g.s calcirud: moll lime grust
4702A	69	Gry yel 5 Y 8/4	R	C.g.s calcirud: pels qutz fels rock lime pkst
B				Diorite
4703A	88	M lt gry N 6	A	Bd c.g.s calcaren: peb qtz lime pkst
B				Pegmatitic granite
4704	104			Metaquartzite
4705	109	01 gry 5 Y 3/2	A	Calcilute: lime mudst
4706A	85			Rhyolite
B				Rhyolite
C		Lt gry N 7	A	Calcilut: peb lime mudst
4709A	60			Andesite
B				Rhyolite
C				Rhyolite
D				Andesite
E				Rhyolite
F				Rhyolite
G				Rhyolite
4710A	52			Rhyolite
B				Rhyolite
C		Lt gry N 7	R	V.f.s calcaren: qtz lime wkst
4711A	51			Andesite
B				Rhyolite
C				Rhyolite
D				Rhyolite
E				Rhyolite
F				Rhyolite
G		Gry yel 5 Y 8/4	R	Calcilut: lime mudst
4714A	102	Dy yel grn 5 G Y 5/2	A	V.f.s calcaren: peb qtz glauc lime wkst
B				Diorite
C		V lt gry N 8	A	Calcilute: peb lime mudst

Appendix B.5 (continued)

Sample No.	Depth (metres)	Handspecimen colour (Geol.Soc.Amer.Rock Color Chart, 1963)	Angularity	Classification
4722	98	M gry N 5	A	Bd m.s calcaren: peb lime wkst
4723	90	M gry N 5	A	Bd m.s calcaren: lime wkst
4724A	50			Rhyolite
B				Granite
C				Rhyolite
D				Metaquartzite
E				Metaquartzite
F				Metaquartzite
G				Vein quartz
4727A	138	Lt ol gry 5 Y 5/2	A	Lamination -v.f.s calcaren: qtz lime wkst/v.f.s phospholut: qtz pell phos wkst
B		Lt ol gry 5 Y 5/2	A	Cast - v.f.s phosaren: qtz phos wkst
C		Mod ol brn 5 Y 4/4	A	Bone - phosaren: phos wkst
D		Ol gry 5 Y 3/2	A	Bone - phosaren: phos wkst
4729	150	-	-	Phosaren: phos wkst
4732A	28	Dy yel 5 Y 6/4	A	C.g.s calcirud: peb qtz lime pkst
B				Qtz mudst
4737A	114	Ol gry 5 Y 3/2	A	Bd calcilut: lime mudst
B		M gry N 5	A	F.s calcilut: qtz glauc lime wkst
4739	98	-	-	Calcilut: lime mudst
4742	106	Ol gry 5 Y 3/2	A	Bd calcilut: lime mudst
4744A	167	Lt ol gry 5 Y 5/2	A	Bd calcilut: lime mudst
B		Gry ol 10 Y 4/2	A	Bd calcilut: lime mudst
C		Ol gry 5 Y 3/2	A	Cast - phospholut: phos mudst
D		Mod brn 5 Y R 4/4	A	Bone - f.s phosaren: qtz phos wkst
4729	150	-	-	Phosaren: phos wkst
4732A	28	Dy yel 5 Y 6/4	A	C.g.s calcirud: peb qtz lime pkst
B				Qtz mudst
4737A	114	Ol gry 5 Y 3/2	A	Bd calcilut: lime mudst
B		M gry N 5	A	F.s calcilut: qtz glauc lime wkst
4739	98	-	-	Calcilut: lime mudst
4742	106	Ol gry 5 Y 3/2	A	Bd calcilut: lime mudst
4744A	167	Lt ol gry 5 Y 5/2	A	Bd calcilut: lime mudst
B		Gry ol 10 Y 4/2	A	Bd calcilut: lime mudst
C		Ol gry 5 Y 3/2	A	Cast - phospholut: phos mudst
D		Mod brn 5 Y R 4/4	A	Bone - f.s phosaren: qtz phos wkst
E		Yel gry 5 Y 7/2	R	Calcilut: lime mudst
4745A	206	Lt ol gry 5 Y 5/2	A	Bd calcilut: lime mudst
B		Ol gry 5 Y 3/2	A	Bone/mud - phospholut: phos mudst/f.s phosaren: qtz phos pkst
4758A	210	Lt ol gry 5 Y 5/2	A	Bd f.s calcaren: qtz lime wkst
B		Lt ol gry 5 Y 5/2	A	Bd f.s calcaren: qtz lime wkst
C		Lt ol gry 5 Y 5/2	A	Bd f.s calcaren: qtz lime wkst
4760A	186	Yel gry 5 Y 7/2	A	Calcilut: lime mudst
B		Lt ol gry 5 Y 5/2	A	Bd f.s calcaren: qtz lime pkst
C		Ol gry 5 Y 3/2	A	Bd c.g calcaren: qtz fels lime pkst
4761A	160	Gm yel 5 Y 8/4	R	Phospholut: phos lime mudst
B		Ol gry 5 Y 3/2	A	Bd limst - calcilut: lime mudst/m.s calcaren: qtz lime wkst
C		Lt ol gry 5 Y 5/2	R	M.s calcaren: qtz lime pkst
D		Lt ol gry 5 Y 5/2	R	M.s calcaren: qtz lime pkst
4798A	60	Lt ol gry 5 Y 5/2	A	Calcilut: lime must
B		Lt ol gry 5 Y 5/2	A	Bd calcilut: lime mudst

Appendix B.5 (continued)

Sample No.	Depth (metres)	Handspecimen colour (Geol. Soc. Amer. Rock Color Chart, 1963)	Angularity	Classification
A5409	310	Mod brn 5 YR 4/4	A	Bone - phospholut: phos mudst
A5515A	216	Dy yel 5 Y 6/4	A	Calcilut: lime mudst
B		01 gry 5 Y 3/2	A	Bd calcilut: lime mudst

Note: Angular(A) implies that the sample was broken off the sea floor, or else has suffered little transport from its place of origin.

Rounded(R) implies definite transport from its place of origin.

A	- angular	Phos	- phosphate
Bd	- bored	Phosaren	- phosarenite
Brn	- brown	Phospholut	- phospholutite
C	- coarse	Phosphorud	- phosphorudite
Calcaren	- calcarenite	Pkst	- packstone
Calcilut	- calcilutite	Qtz	- quartz/quartzose
Calcirud	- calcirudite	Tr	- trace
Dy	- dusky	R	- rounded
Dk	- dark	Rock	- rocky
F	- fine	S	- sand
Fels	- feldspar/feldspathic	V	- very
G	- grain	Wkst	- wackestone
Glauc	- glauconite/glauconitic	Yel	- yellow/yellowish
Grn	- green/greenish		
Grnst	- grainstone		
Gry	- grey/greyish		
Limest	- limestone		
Lt	- light		
Mudst	- mudstone		
M	- medium		
Mod	- moderate		
Moll	- mollusca		
01	- olive		
Peb	- pebbly		

Appendix B.6 Percentage composition of marine sedimentary rocks from the continental shelf

Sample No.	CARBONATE GRAINS					NON-CARBONATE GRAINS						INTERGRANULAR FABRIC						%	%		
	Molluscs	Echinoderm	Benthic forams	Planktonic forams	TOTAL	Terrigenous			Phosphorite		Glauconite	Pyrite	TOTAL	Pseudospar	Microspar	Micrite	Collophane			Diallage	TOTAL
						Quartz	Feldspar	Rock	Pellets	Fragments											
Lime mudstones																					
3967						5	Tr	1		1	2	Tr		9	30	61			91	5,08	1,38
4687						Tr					1			1	20	79			99	3,22	,65
4705						1					1	Tr	1	3	40	57			97	2,58	,74
4711G						1			Tr	3				4	96				96	,16	,47
4737A				Tr	Tr	3	Tr	Tr				Tr	2	5	25	70			75	3,64	,59
4739						1					Tr		1	2		98			98	-	-
4742						Tr							Tr	Tr	20	80			100	4,01	,53
4744A				Tr	Tr	1					Tr	Tr	1	2	40	58			98	5,50	,65
B						Tr								Tr	40	53	7		100	6,91	,61
E						Tr								Tr	10	90			100	,76	1,13
4745A						2				Tr	1	Tr	3		20	77			97	1,15	,60
4760A						3	Tr	Tr				Tr	1	4	10	86			96	,88	,96
4761B/						5				Tr	Tr	1	6		5	89			94	3,34	,73
4798A				Tr	1	1						1	1		40	58			98	,39	,14
B						Tr				1	1	Tr	2		30	68			98	7,26	,12
A5515A															50	50			100	,22	,55
B				Tr	Tr	3				Tr	Tr	Tr	3		40	57			97	18,84	1,03
Quartzose lime wackestones																					
3784				1	Tr	1				1	Tr	Tr	Tr	16	30	53			83	6,96	,87
4687B						25	1	Tr			1	Tr		27	5	63	5		73	6,42	,94
E						15	Tr	Tr			Tr	Tr		15	10	75			85	7,47	,97
4710C						10	1	1			2			14	20	5	7		86	,38	,58
4727A/				1	1	20	1	Tr			3	Tr	Tr	24		75			75	9,72	,93
4758A				Tr	Tr	Tr	20	2	Tr		1	Tr	1	24	10	63	3		76	3,86	,83
B				Tr	Tr	Tr	20	2	Tr		1	Tr	1	24	10	63	3		76	5,20	,72
C				Tr	Tr	Tr	20	2	Tr		1	Tr	1	24	10	63	3		76	6,84	1,02
4761B/						40	2			2	Tr	Tr		44	50	6			56	3,34	,73
Quartzose lime packstones																					
4687G						40	1	1		Tr				42	5	53			58	6,38	1,10
4691						65	2			1				68	25	7			32	1,15	1,54
4760B						45	1	1		1	Tr	Tr		48	20	32			52	3,04	1,11
4761C						50	1	1		Tr		Tr		52	25	23			48	1,23	1,07
D						50	1	1		Tr		Tr		52	25	23			48	1,06	1,11

Appendix B.6 (continued)

Sample No.	CARBONATE GRAINS					NON-CARBONATE GRAINS						INTERGRANULAR FABRIC						% P_2O_5	% K_2O			
	Molluscs	Echinoderm	Benthic Forams	Planktonic Forams	TOTAL	Terrigenous			Phosphorite		Glauconite	Pyrite	TOTAL	Pseudospar	Microspar	Micrite	Collophane			Diagenesis	TOTAL	
						Quartz	Feldspar	Rock	Pellets	Fragments												
<u>Mollusc lime grainstone</u>																						
4701C/	100				100															6,90	,36	
<u>Pebbly quartzose lime mudstones</u>																						
4706C						5					5	10	85	5			90		2,27	1,15		
4714C						5					5	10	85	5			90		1,21	1,07		
<u>Pebbly quartzose lime wackestones</u>																						
4722	Tr				Tr	15	Tr	Tr	Tr	1		Tr	16	60	24		84		5,07	,81		
4723	Tr				Tr	15	Tr	Tr	Tr	1		Tr	16	60	24		84		-	-		
4714A						16					10	26	60	14			74		1,14	1,75		
4737B						10	1	254		Tr	10	21	75	4			79		,51	,94		
<u>Pebbly quartzose lime packstones</u>																						
4692B	1				1	55	9	2				66		34			34		3,53	3,00		
C						50	10	5				65	35				35		,72	2,08		
4702A						40	20	13				73		27			27		,10	2,69		
4703A						35	1	Tr		Tr	1	37	30	33			63		,25	,79		
4706C						35	15	5			Tr	55	45				45		3,32	1,05		
4732A						75	3	2				80		18	2		20		,28	2,29		
<u>Phosphorite (mollusc casts)</u>																						
4727B						15	1	Tr		1	Tr	2	19		81		81		20,16	,67		
4744C						1					Tr	2	3		97		97		12,72	,61		
<u>Phosphorite (bones)</u>																						
4727C						7	1	Tr		2	1	5	16		40	44	84		26,40	,35		
D						7	1	Tr		2	1	5	16		60	24	84		24,24	,75		
4744D						16	1	Tr		2	1	4	24		38	38	76		12,62	,34		
4745B/						5						5			20	75	95		12,91	,18		
A5409		Tr			Tr	1				2	Tr	Tr	3		60	37	97		27,16	,27		
<u>Phosphorite (lamellar)</u>																						
4727A/	TR				Tr	20	Tr	Tr		10		3	33		67		67		9,72	,93		

Appendix B.6 (continued)

Sample No.	CARBONATE GRAINS					NON-CARBONATE GRAINS							INTERGRANULAR FABRIC						P 2 O 5	K 2 O	
	Molluscs	Echinoderm	Benthic Forams	Planktonic Forams	TOTAL	Terrigenous			Phosph- orite		Glauconite	Pyrite	TOTAL	Pseudospar	Microspar	Micrite	Collophane	Diallage			TOTAL
						Quartz	Feldspar	Rock	Pellets	Fragments											
Phosphorite (rocks)																					
3710B	Tr Tr Tr Tr					5	Tr		2	Tr	Tr	1	8				92		92	-	-
4729						5	Tr		5	1	7		18			2	80		82	26,66	,62
4745B/						50		1			5		56				44		44	12,91	,18
4761A						Tr							Tr			40	60		100	19,62	,23
4701C/						5							5				95		95	6,90	,36

Appendix B.7 Sediment texture and composition (weight percentages)

SAMPLE NUMBER	TEXTURE					COMPOSITION						INSOL. RESIDUE	
						Biogenic			Authigenic			Terrig- enous	(Quartz) in >63μ fraction
	Gravel	Sand	Silt	Clay	Faecal pellets	CaCO ₃ (apatite- free)	Organic matter	Amorph. Si	pP+cP*	gpP*	G*		
Cruise 273													
3407	-	24,8	46,5	28,7	6	59,4	6,6	-*	2,7	-	-	31,3	-
3408	-	27,0	52,9	20,1	5	47,0	9,8	-	1,2	-	-	42,0	2
3409	-	4,0	49,8	46,2	1	ND*	14,5	-	ND	-	,8	ND	5
3410	,1	67,0	24,9	8,0	9	40,3	5,7	-	18,9	-	8,0	27,1	2
3411	4,8	51,7	26,8	16,7	2	21,7	7,0	-	51,3	1,8	,9	17,3	2
3412	9,8	65,5	22,2	2,5	2	ND	ND	-	ND	1,1	-	ND	2
3413	7,9	79,2	2,0	10,9	5	22,1	3,8	Tr*	43,9	,9	,6	28,7	7
3414	7,2	75,9	5,8	11,1	<10	27,1	13,1	4	20,5	1,1	1,2	33,0	3
3415	6,0	79,0	6,8	8,2	<10	10,2	12,4	3	17,4	,7	,5	55,8	45
3416	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
3417	-	97,9	,2	1,9	ND	,1	,3	5	1,2	-	Tr	93,4	78
3418	-	98,6	,2	1,2	15	1,1	,3	-	1,5	-	Tr	97,1	88
3419	53,0	46,3	-	,7	-	5,8	,2	-	,4	-	Tr	93,6	94
3420	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
3421	-	99,0	,6	,4	-	,8	,3	-	,6	-	Tr	98,3	97
3422	-	98,3	,2	1,5	ND	,6	ND	Tr	,8	-	Tr	ND	97
3423	-	86,8	4,0	9,2	ND	1,5	1,1	25	,9	-	Tr	71,5	95
3424	,1	72,5	13,4	14,0	ND	2,2	6,1	54	3,7	-	-	34,0	62
3425	1,7	67,9	9,4	21,0	ND	3,8	7,1	56	3,0	-	-	30,1	54
3426	1,0	56,8	28,0	14,2	<10	15,8	24,6	3	7,8	-	Tr	48,8	5
3427	16,7	59,2	3,7	20,4	<10	45,0	2,7	Tr	8,7	-	2,6	41,0	19
3428	10,7	72,6	10,4	6,2	5	20,9	5,4	-	40,7	5,2	,1	27,7	3
3429	3,5	67,5	16,3	12,7	5	44,4	6,1	-	19,7	2,7	,3	26,8	1
3430	-	60,8	32,2	7,0	8	74,0	5,6	-	12,1	,4	,3	7,6	1
3431	,6	65,0	20,4	14,0	30	54,8	9,7	-	5,2	-	7,5	22,8	7
3432	-	28,4	45,3	26,3	4	60,3	7,1	-	,8	-	Tr	31,8	-
3433	-	6,4	50,5	43,1	4	72,6	5,0	-	,7	-	-	21,7	-
3434	-	8,1	50,6	41,3	1	76,5	5,7	-	,4	-	-	17,4	-
3435	-	27,4	45,9	26,7	1	84,3	7,1	-	1,4	-	Tr	7,2	1

Appendix B.7 (continued)

SAMPLE NUMBER	TEXTURE					COMPOSITION							INSOL. RESIDUE
	Gravel	Sand	Silt	Clay	Faecal pellets	Biogenic			Authigenic			Terrig- enous	(Quartz) in >63μ fraction
						CaCO ₃ (apatite- free)	Organic matter	Amorph. Si	pP+cP	gpP	G		
Cruise 273 cont.													
3436	-	45,0	31,4	23,6	5	64,9	6,2	-	2,1	-	,6	26,2	1
3437	,1	54,0	29,6	16,3	12	ND	6,9	-	ND	1,2	,1	ND	1
3438	5,1	77,1	10,0	7,8	8	29,4	5,1	-	18,3	7,4	,2	39,6	1
3439	14,3	83,9	1,6	,2	3	37,4	5,3	-	31,5	3,5	,3	22,0	1
3440	-	96,8	2,3	,9	<10	6,0	7,4	Tr	20,0	15,2	1,1	50,3	28
3441	8,0	51,1	28,5	12,4	ND	16,5	19,2	55	8,8	-	Tr	,5	-
3442	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
3443	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
3444	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
3445	1,1	48,7	33,9	16,3	ND	3,5	11,1	23	5,6	-	Tr	76,8	22
3446	-	95,9	,9	3,2	ND	,9	,6	5	,8	-	Tr	92,7	96
3447	-	88,3	7,5	4,2	ND	1,5	2,3	5	1,2	-	Tr	90,0	91
3448	-	40,9	27,5	31,6	ND	7,0	16,4	62	2,6	-	-	12,0	19
3449	,1	52,6	26,7	20,6	ND	4,4	10,0	32	2,7	-	Tr	50,9	65
3450	,2	46,3	12,7	40,8	ND	6,9	9,2	34	2,7	-	Tr	47,2	69
3451	-	24,4	13,2	62,4	ND	9,9	12,7	64	2,4	-	-	11,0	16
3452	6,6	80,0	5,9	7,4	<10	15,5	10,2	2	34,2	,2	,6	37,3	6
3453	ND	ND	ND	ND	19	60,0	4,8	-	25,4	,4	,4	9,0	ND
3454	9,7	82,7	1,4	6,2	2	23,3	5,4	-	49,8	1,7	Tr	19,8	1
3455	13,5	75,3	4,5	6,7	4	50,1	4,7	-	22,1	4,6	Tr	18,5	2
3456	4,6	75,3	9,8	10,3	9	66,7	5,7	-	17,1	5,1	Tr	5,4	-
3457	1,0	69,0	21,4	8,6	7	76,7	4,4	-	2,9	3,8	Tr	12,2	-
3458	-	31,6	42,4	26,0	5	60,5	6,8	-	2,2	-	-	30,5	3
3459	-	18,2	46,3	35,5	3	75,4	5,9	-	1,2	-	-	17,5	-
3460	-	27,3	47,1	25,6	4	71,9	6,1	-	,9	-	-	21,1	-
3461	-	35,6	51,3	13,1	6	71,1	7,3	-	,8	-	Tr	20,8	2
3462	,4	71,5	19,7	8,4	10	66,4	4,7	-	3,0	-	,4	25,5	5
3463	2,7	77,8	12,6	6,9	17	ND	5,6	-	ND	5,1	Tr	ND	1
3464	ND	ND	ND	ND	ND	ND	3,4	-	ND	ND	ND	ND	ND
3465	19,5	77,0	,4	3,1	19	77,8	5,9	-	-	12,0	-	4,3	1

Appendix B.7 (continued)

SAMPLE NUMBER	TEXTURE					COMPOSITION							INSOL. RESIDUE
	Gravel	Sand	Silt	Clay	Faecal pellets	Biogenic			Authigenic			Terrig- enous	(Quartz) in >63μ fraction
						CaCO ₃ (apatite- free)	Organic matter	Amorph. Si	pP+cP	gpP	G		
Cruise 273 cont.													
3466	15,5	51,6	28,1	4,8	ND	69,2	4,9	-	<11,8	ND	ND	ND	
3467	26,9	63,1	2,9	7,1	15	65,7	6,9	-	11,0	1,2	,1	15,1	ND
3468	-	53,5	11,8	34,7	ND	6,5	10,3	61	9,7	-	Tr	13,5	2
3469	,3	54,0	16,7	29,0	ND	8,9	10,7	47	9,6	-	Tr	23,8	20
3470	,1	77,8	7,0	15,1	ND	3,2	5,7	48	13,2	-	Tr	29,9	46
3471	-	86,4	10,4	3,2	ND	1,8	4,6	8	8,1	-	Tr	77,5	55
3472	-	49,4	37,5	13,1	ND	5,1	12,6	22	2,7	-	Tr	57,6	30
3473	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	76
3474	-	94,4	3,7	1,9	ND	,4	3,6	51	17,8	-	Tr	27,2	ND
3475	,3	38,1	27,5	34,1	ND	ND	10,1	69	ND	-	-	ND	51
3476	,2	52,5	10,5	36,8	ND	,8	7,7	63	15,7	-	Tr	12,8	11
3477	,1	27,9	19,8	52,2	ND	5,4	8,8	55	13,9	-	Tr	16,9	20
3478	27,0	62,0	5,7	5,3	ND	61,2	7,3	2	18,3	1,2	,1	9,9	26
3479	9,3	81,4	5,4	3,9	15	70,1	6,0	-	15,7	3,7	Tr	4,5	3
3480	3,3	88,9	3,1	4,7	15	67,4	6,1	-	7,0	11,3	Tr	8,2	3
3481	ND	ND	ND	ND	ND	81,3	2,6	-	< 6,3	ND	ND	ND	1
3482	,4	83,6	8,1	7,9	33	61,6	7,8	-	1,4	1,3	Tr	27,9	ND
3483	-	71,4	15,2	13,4	6	79,9	5,4	-	2,0	-	,1	12,6	-
3484	-	41,4	38,6	16,0	5	68,8	6,0	-	1,7	-	,3	23,2	1
3485	-	34,6	34,0	31,4	5	65,4	7,1	-	,9	-	-	26,6	5
3486	,1	16,4	38,8	44,7	2	80,6	4,3	-	1,1	-	-	14,0	-
3487	-	18,3	40,9	40,8	3	77,9	5,0	-	,6	-	-	16,5	-
3488	-	33,6	42,1	24,3	5	ND	6,8	-	ND	-	-	ND	-
3489	-	36,0	39,2	24,8	8	76,6	6,6	-	1,2	-	,1	15,5	-
3490	,1	62,5	27,7	9,7	8	47,3	5,5	-	12,4	-	2,5	32,3	2
3491	1,0	69,8	17,6	11,6	5	58,4	5,6	-	2,1	1,2	Tr	32,7	14
3492	,5	87,9	3,6	8,0	22	76,7	6,4	-	-	8,0	-	8,9	1
3493	11,3	77,1	3,1	8,5	14	64,0	6,8	-	2,9	10,1	-	16,2	-
3494	6,3	85,8	1,6	6,3	14	73,7	6,6	-	7,2	-	Tr	12,5	-
3495	8,5	76,0	5,0	10,5	<10	46,6	8,5	Tr	10,8	-	Tr	34,1	1
3496	,3	30,9	20,4	48,4	<10	17,0	19,9	42	2,9	-	Tr	18,2	3

Appendix B.7 (continued)

SAMPLE NUMBER	TEXTURE					COMPOSITION							INSOL. RESIDUE
						Biogenic			Authigenic			Terrig- enous	(Quartz) in >63μ fraction
	Gravel	Sand	Silt	Clay	Faecal pellets	CaCO ₃ (apatite- free)	Organic Matter	Amorph. Si	pP+cP	gpP	G		
Cruise 273 cont.													
3497	-	36,7	26,2	37,1	ND	8,9	12,7	33	13,1	-	Tr	32,3	
3498	,2	35,4	28,7	35,7	ND	4,2	11,1	60	2,7	-	Tr	22,0	22
3499	,1	74,6	18,0	7,3	ND	1,3	4,9	44	10,6	-	Tr	39,2	26
3500	,1	90,2	3,5	6,2	ND	,4	3,7	11	11,6	-	Tr	73,3	63
3501	,4	84,7	8,7	6,2	3	1,6	2,3	-	1,6	-	1,5	93,0	72
3502	-	81,6	12,7	5,7	ND	1,3	4,7	28	4,1	-	Tr	61,9	87
3503	,4	77,1	10,4	12,1	ND	2,4	6,0	59	5,6	-	Tr	27,0	55
3504	,2	49,7	18,4	31,7	ND	4,3	8,6	60	6,1	-	Tr	20,0	41
3505	,2	23,8	22,9	53,1	ND	5,6	10,9	63	2,0	-	Tr	18,5	30
3506	,2	28,7	20,8	50,3	ND	5,6	10,4	61	14,2	-	Tr	8,8	26
3507	1,2	52,3	23,5	23,0	<10	37,7	20,7	3	3,0	-	Tr	35,6	14
3508	5,7	69,5	12,0	12,8	<10	39,2	13,7	Tr	2,9	-	Tr	44,2	2
3509	,5	35,0	25,6	38,9	ND	2,4	10,5	84	1,9	-	Tr	1,2	3
3510	-	3,0	41,0	56,0	ND	2,5	9,8	85	1,5	-	Tr	1,2	2
3511	-	5,5	38,0	56,5	ND	3,4	11,1	67	1,7	-	Tr	16,8	1
3512	-	10,5	53,7	35,8	ND	3,8	12,1	82	1,6	-	-	,5	23
3513	-	19,2	50,6	30,2	ND	3,0	14,4	80	1,9	-	-	,7	1
3514	-	19,3	48,6	32,1	ND	4,6	15,5	77	2,1	-	-	,8	-
3515	-	15,2	70,5	14,3	ND	2,4	14,8	80	2,1	-	-	,7	-
3516	-	,3	36,0	63,7	ND	4,0	15,8	78	2,0	-	-	,2	-
3517	-	10,5	25,3	64,2	ND	4,9	9,7	84	1,0	-	-	,4	-
3518	-	14,2	23,3	62,5	ND	5,7	13,0	79	1,4	-	-	,9	1
3519	,3	61,1	20,8	17,8	<10	18,3	16,2	62	2,2	-	Tr	1,3	-
3520	4,3	89,2	2,6	3,9	18	33,5	7,6	-	48,5	,3	-	10,1	-
3521	5,2	68,8	13,5	12,5	ND	76,4	7,6	-	<4,5	ND	ND	ND	1
3522	2,4	76,4	12,7	8,5	6	83,1	4,2	-	5,7	5,0	,1	1,9	ND
3523	,4	69,2	20,0	10,4	7	7,13	5,9	-	1,0	-	,3	21,5	1
3524	,7	72,3	14,4	12,6	5	70,5	3,9	-	2,6	-	1,9	21,1	2
3525	-	37,1	37,8	25,1	8	68,7	6,1	-	,7	-	-	24,5	8
3526	-	9,8	47,5	42,7	1	80,2	5,4	-	,6	-	-	13,8	3
3527	-	22,0	38,2	39,8	5	74,3	5,2	-	,4	-	-	20,1	-

Appendix B.7 (continued)

SAMPLE NUMBER	TEXTURE					COMPOSITION							INSOL. RESIDUE
						Biogenic			Authigenic			Terrig- enous	(Quartz) in >63μ fraction
	Gravel	Sand	Silt	Clay	Faecal pellets	CaCO ₃ (apatite- free)	Organic matter	Amorph. Si	pP+cP	gpP	G		
Cruise 273 cont.													
3528	-	32,8	42,6	24,6	8	80,3	6,7	-	,6	-	-	12,4	-
3529	-	17,9	58,9	23,2	ND	68,2	6,7	-	,9	-	-	24,2	ND
3530	,2	69,8	18,2	11,8	7	80,2	4,4	-	1,1	-	1,1	13,2	5
3531	,3	53,6	26,0	20,1	10	70,3	6,6	-	-	5,5	Tr	17,6	1
3532	-	84,9	7,0	8,1	34	64,3	10,0	-	3,8	4,5	-	17,4	1
3533	11,3	85,1	2,4	1,2	17	68,0	5,3	-	6,5	-	Tr	20,2	2
3534	4,4	79,3	16,0	,3	<10	65,2	13,7	Tr	3,9	-	Tr	17,2	1
3535	-	38,9	15,3	45,8	ND	9,1	14,1	74	2,1	-	-	,7	-
3536	-	10,6	24,3	65,1	ND	4,8	10,2	83	1,6	-	-	,4	1
3537	-	9,8	34,0	56,2	ND	1,7	13,8	82	1,6	-	-	,9	1
3538	-	25,3	25,1	49,6	ND	ND	15,1	82	ND	-	-	ND	-
3539	-	24,0	44,9	31,1	ND	2,3	13,3	72	2,4	-	-	10,0	14
3540	-	25,3	42,8	31,9	ND	5,7	11,2	75	1,9	-	-	6,2	8
3541	,2	97,9	-	1,9	-	,4	-	-	,6	-	Tr	99,0	97
3542	10,2	59,4	17,4	13,0	ND	3,2	5,7	55	3,1	-	Tr	33,0	55
3543	-	42,7	37,8	19,5	ND	ND	6,3	63	ND	-	-	ND	38
3544	-	24,0	22,7	53,3	ND	2,4	8,1	71	4,1	-	-	14,4	20
3545	-	3,3	34,9	61,8	ND	3,1	9,1	86	1,5	-	-	,3	-
3546	-	3,2	19,0	77,8	ND	6,1	12,4	80	1,4	-	-	,1	-
3547	1,2	70,6	13,6	14,6	ND	26,8	17,8	52	1,8	-	Tr	1,6	-
3548	10,8	60,2	13,4	15,6	20	70,5	8,7	-	3,2	-	Tr	17,6	1
3549	2,3	83,4	5,1	9,2	23	52,7	8,2	-	12,2	4,1	-	22,8	-
3550	-	73,0	11,9	15,1	19	64,3	6,6	-	2,6	4,4	-	22,1	1
3551	-	47,7	33,9	18,4	18	66,8	8,6	-	3,4	,8	Tr	20,4	1
3552	-	27,4	42,5	30,1	5	35,8	6,6	-	4,6	-	2,5	50,5	5
3553	-	12,0	55,9	32,1	3	66,8	8,7	-	1,1	-	-	23,4	-
3554	-	11,1	45,3	43,6	3	66,9	7,3	-	1,0	-	-	24,8	-
3555	-	43,0	31,2	25,8	6	74,7	6,5	-	5,6	-	1,5	11,7	5
3556	,1	55,4	24,3	20,2	7	54,4	6,7	-	,1	3,8	Tr	35,0	1
3557	-	52,8	38,1	9,1	19	67,9	9,1	-	3,2	3,1	-	16,7	-
3558	1,2	88,1	3,2	7,5	20	52,4	8,8	-	10,7	11,8	-	16,3	-

Appendix B.7 (continued)

SAMPLE NUMBER	TEXTURE					COMPOSITION							INSOL. RESIDUE
	Gravel	Sand	Silt	Clay	Faecal pellets	Biogenic			Authigenic			Terrig- enous	(Quartz) in >63μ fraction
						CaCO ₃ (apatite- free)	Organic matter	Amorph. Si	pP+cP	gpP	G		
Cruise 273 cont.													
3559	13,4	76,1	4,9	5,6	15	77,9	6,8	-	6,4	-	Tr	8,9	1
3560	-	16,2	55,1	28,7	5	67,3	8,6	-	1,9	-	Tr	22,2	-
3561	-	22,2	50,2	27,6	6	56,5	7,4	-	1,0	-	,3	34,8	1
3562	-	53,7	30,6	15,7	9	59,5	6,2	-	1,0	5,9	1,2	26,2	4
3563	13,3	76,7	1,7	8,3	1	27,3	5,7	-	44,4	4,2	,5	17,9	1
3564	19,3	66,0	7,5	7,2	ND	ND	15,7	Tr	ND	ND	ND	ND	-
3565	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
3566	-	60,5	17,7	21,8	<10	22,3	21,6	34	5,7	-	Tr	16,4	1
3567	1,9	58,1	18,6	21,4	ND	11,2	13,4	56	12,2	-	Tr	7,2	13
3568	2,0	98,0	-	-	ND	2,1	,8	-	,3	-	-	96,8	97
3569	-	97,0	,2	2,8	ND	2,2	,6	Tr	,6	-	-	96,6	96
3570	-	100,0	-	-	ND	,8	,3	-	,3	-	-	98,6	98
3571	-	87,8	1,2	11,0	ND	1,3	,5	Tr	,5	-	-	97,7	100
3572	-	100,0	-	-	6	1,4	,1	-	,4	-	-	98,1	92
Cruise 279													
3655	,5	10,7	29,5	59,3	4	25,3	1,9	-	,3	-	3,1	69,4	20
3656	-	45,2	33,3	21,5	6	9,2	3,1	-	,9	-	1,1	85,7	68
3657	-	35,4	11,9	12,7	4	14,7	3,8	-	2,9	-	17,8	60,8	37
3658	,2	77,9	12,4	9,5	20	2,5	2,2	-	5,9	-	13,0	76,4	58
3659	1,4	47,4	30,7	20,5	ND	6,1	4,3	4	1,2	-	Tr	84,4	49
3660	,3	53,2	28,6	17,9	20	3,9	3,7	-	1,3	-	Tr	91,1	55
3661	-	41,4	40,7	17,9	ND	7,0	4,6	8	1,1	-	Tr	79,3	41
3662	,6	43,2	42,1	14,1	ND	6,5	4,1	8	1,1	-	Tr	80,3	45
3663	,1	62,3	27,2	10,4	14	4,1	2,5	-	2,4	-	18,0	73,0	47
3664	,1	77,6	14,0	8,3	6	16,9	2,5	-	2,9	-	45,6	32,1	14
3665	-	55,4	32,6	12,0	5	6,6	2,5	-	1,2	-	2,0	87,7	64
3666	-	31,8	47,0	21,2	6	9,1	3,4	-	,9	-	2,4	84,2	53
3667	-	11,5	57,0	31,5	ND	16,5	6,2	- Tr	,7	-	Tr	76,6	13
3668	,1	25,7	48,8	25,4	ND	8,4	3,1	-	<1,1	ND	ND	ND	ND
3669	-	74,0	6,2	19,8	ND	19,8	3,3	-	<7,3	ND	ND	ND	ND

Appendix B.7 (continued)

SAMPLE NUMBER	TEXTURE					COMPOSITION							INSOL. RESIDUE
	Gravel	Sand	Silt	Clay	Faecal pellets	Biogenic			Authigenic			Terrig- enous	(Quartz) in >63 μ fraction
						CaCO ₃ (apatite- free)	Organic matter	Amorph. Si	pP+cP	gpP	G		
Cruise 279 cont.													
3670	-	77,0	12,6	10,4	27	5,1	4,9	-	9,7	-	14,8	65,5	31
3671	-	86,5	6,6	6,9	7	1,0	2,2	-	6,3	-	66,7	23,8	12
3672	-	87,7	6,0	6,3	4	,5	1,3	-	5,9	-	72,8	19,5	10
3673	-	82,0	8,2	9,8	9	5,3	2,4	-	3,8	-	41,8	46,7	38
3674	1,0	69,6	14,3	15,1	13	3,4	3,7	-	2,2	-	11,9	78,8	61
3675	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
3676	-	87,3	6,4	6,3	6	1,2	1,7	-	1,3	-	1,9	93,9	87
3677	-	87,0	6,7	6,3	5	,4	1,4	-	1,3	-	30,8	66,1	59
3678	-	86,4	6,6	7,0	6	,4	1,5	-	1,2	-	6,2	90,7	84
3679	-	69,5	19,6	10,9	12	3,9	2,9	-	6,2	-	13,9	73,1	55
3680	-	28,7	52,9	18,4	11	12,7	4,1	-	1,1	-	Tr	82,1	43
3681	-	10,1	60,6	29,3	5	17,6	5,5	-	1,3	-	Tr	75,6	26
3682	-	22,9	47,3	29,8	7	23,0	5,7	-	,7	-	Tr	70,6	22
3683	-	31,1	40,0	28,9	10	10,8	5,7	-	1,1	-	Tr	82,4	21
3684	,2	53,3	18,9	27,6	ND	ND	3,7	-	ND	ND	ND	ND	ND
3685	-	84,8	9,4	5,8	21	8,2	3,3	-	7,2	-	10,8	70,5	51
3686	1,6	90,9	3,2	4,3	16	4,0	3,7	-	8,2	28,9	5,7	49,5	23
3687	25,6	62,6	4,8	7,0	10	35,7	3,0	-	6,2	16,0	2,4	36,7	20
3688	2,8	88,3	2,7	6,2	7	19,5	2,9	-	-	34,6	3,5	39,5	23
3689	14,9	73,6	7,0	4,5	7	14,2	2,4	-	4,5	-	1,7	77,2	52
3690	,3	89,6	5,0	5,1	ND	,8	1,4	Tr	2,4	-	Tr	95,4	91
3691	-	91,0	3,5	5,5	6	,5	1,6	-	1,6	-	Tr	96,3	74
3692	-	89,9	4,5	5,6	5	,3	1,5	-	1,6	-	Tr	96,6	91
3693	,2	91,0	4,8	4,2	3	1,2	1,8	-	4,5	-	1,1	91,4	86
3694	3,1	85,0	4,4	7,5	11	4,1	3,2	-	3,5	,7	,3	88,2	74
3695	-	89,8	3,4	6,8	40	30,9	6,3	-	,7	1,2	1,2	59,7	26
3696	,1	85,9	7,3	6,7	33	56,7	5,4	-	2,0	-	4,7	31,2	10
3697	,8	62,5	21,0	15,7	9	48,7	4,7	-	1,2	-	1,7	43,7	15
3698	-	12,5	59,9	27,6	6	27,5	8,2	-	,8	-	Tr	63,5	7
3699	-	67,1	21,5	11,4	28	36,6	6,1	-	,8	-	Tr	56,5	5

Appendix B.7 (continued)

SAMPLE NUMBER	TEXTURE					COMPOSITION							INSOL. RESIDUE
						Biogenic			Authigenic			Terrig- enous	(Quartz) in >63μ fraction
	Gravel	Sand	Silt	Clay	Faecal pellets	CaCO ₃ (apatite- free)	Organic matter	Amorph. Si	pP+cP	gpP	G		
Cruise 279 cont.													
3700	-	23,0	49,5	27,5	5	56,7	4,9	-	,5	-	-	37,9	2
3701	-	31,7	41,3	27,0	7	66,3	4,5	-	,4	-	-	28,8	1
3702	-	30,6	40,7	28,7	8	58,0	6,0	-	1,3	-	-	34,7	2
3703	-	27,6	43,4	29,0	10	51,0	6,7	-	,8	-	-	41,5	2
3704	-	19,2	52,9	27,9	5	52,0	6,6	-	,6	-	-	40,8	1
3705	-	26,0	53,5	20,5	8	51,5	7,0	-	,7	-	-	40,8	2
3706	,6	62,1	22,9	14,4	8	63,4	4,6	-	,6	-	-	31,4	3
3707	-	67,4	21,4	11,2	34	56,3	8,0	-	,7	-	-	35,0	-
3708	-	76,5	12,7	10,8	52	47,0	10,5	-	,8	-	-	41,7	1
3709	3,4	77,8	10,1	8,7	23	37,8	7,2	-	-	20,1	1,9	33,0	12
3710	39,8	49,9	4,5	5,8	10	47,2	3,2	-	4,3	5,9	,5	38,9	27
3711	,5	91,3	3,0	5,2	3	1,6	2,4	-	10,0	-	2,9	83,1	83
3712	,1	49,0	20,8	30,1	<10	9,8	13,4	Tr	3,1	-	Tr	73,7	38
3713	,3	83,6	6,8	9,3	<10	1,5	4,3	Tr	2,1	-	Tr	92,1	86
3714	-	86,1	5,6	8,3	ND	1,0	2,9	Tr	1,7	-	Tr	94,4	92
3715	-	81,2	7,3	11,5	ND	2,4	5,0	Tr	2,1	-	Tr	90,5	83
3716	-	64,3	14,1	21,6	ND	8,9	11,2	Tr	2,1	-	Tr	77,8	57
3717	1,0	40,1	23,8	35,1	<10	18,4	17,5	Tr	2,1	-	Tr	62,0	3
3718	-	38,5	27,4	34,1	<10	29,9	18,5	Tr	1,6	-	Tr	50,0	3
3719	14,4	80,0	2,2	3,4	6	56,2	3,1	-	13,1	13,6	1,0	13,0	28
3720	12,9	74,5	6,7	5,9	27	46,2	11,9	-	-	18,7	,7	22,5	8
3721	,7	87,2	4,5	7,6	65	52,4	12,5	-	2,0	-	,4	32,7	-
3722	-	77,7	10,6	11,7	31	64,1	8,0	-	1,0	-	,5	26,4	-
3723	-	72,4	17,7	9,9	16	73,2	5,4	-	,6	-	-	20,8	-
3724	-	40,7	39,9	19,4	8	56,6	6,4	-	,8	-	-	36,2	-
3725	-	23,0	53,0	24,0	6	53,7	7,1	-	,5	-	-	38,7	2
3726	-	24,7	45,7	29,6	6	55,6	6,3	-	,4	-	-	37,7	2
3727	,1	29,1	27,6	43,2	ND	4,3	10,5	81	1,1	-	-	3,1	4
Cruise 283													
3736	5,7	66,3	21,3	6,7	ND	2,2	2,9	Tr	1,7	-	Tr	93,2	96

Appendix B.7 (continued)

SAMPLE NUMBER	TEXTURE					COMPOSITION							INSOL. RESIDUE
	Gravel	Sand	Silt	Clay	Faecal pellets	Biogenic			Authigenic			Terrig- enous	(Quartz) in >63μ fraction
						CaCO ₃ (apatite- free)	Organic matter	Amorph. Si	pP+cP	gpP	G		
Cruise 283 cont.													
3737	,7	54,9	35,3	9,1	ND	3,3	5,2	Tr	4,3	-	5,1	82,1	
3738	1,7	77,9	8,0	12,4	ND	4,3	4,4	Tr	8,9	-	5,7	76,7	67
3739	3,4	50,5	19,3	26,8	ND	9,2	7,2	8	6,6	-	4,3	64,7	64
3740	1,2	60,6	14,6	23,6	ND	7,3	10,4	7	8,6	-	5,0	61,7	41
3741	1,2	62,8	18,3	17,7	<10	16,8	21,0	15	10,4	-	Tr	36,8	44
3742	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	3
3743	54,6	41,3	-	4,1	5	19,5	2,0	-	31,9	3,1	,3	43,2	ND
3744	57,0	34,3	3,7	5,0	7	53,5	3,2	-	2,0	20,8	,8	19,7	1
3745	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	7
3746	-	17,5	59,0	23,5	8	60,0	10,9	-	3,5	-	1,6	24,0	ND
3747	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	4
3748	-	16,5	45,4	38,1	4	73,9	6,0	-	1,1	-	-	19,0	ND
3749	-	75,6	22,1	2,3	ND	1,0	,2	15	,8	-	-	83,0	-
3750	-	37,9	42,4	19,7	ND	1,0	4,8	29	1,0	-	-	64,2	58
3751	13,3	85,6	-	1,1	-	1,3	,8	-	,4	-	-	97,5	62
3752	9,0	89,3	,3	1,4	1	,3	,5	-	1,6	-	-	97,6	99
3753	1,0	55,0	17,0	27,0	ND	2,0	5,7	85	7,0	-	-	,3	96
3754	-	25,1	18,7	56,2	ND	4,8	13,6	79	1,1	-	-	3,0	-
3755	-	25,6	22,1	52,3	ND	6,1	14,7	73	5,3	-	-	,9	3
3756	8,4	46,7	26,5	18,4	ND	48,7	21,1	22	<1,6	Tr	Tr	8,2	1
3757	ND	ND	ND	ND	ND	83,9	3,1	-	<,8	ND	ND	ND	-
3758	1,1	89,2	4,2	5,5	23	70,4	6,0	-	,2	4,6	-	18,8	ND
3759	-	82,4	11,3	6,3	31	73,9	6,9	-	-	3,7	-	15,5	1
3760	-	73,8	18,2	8,0	22	68,5	5,6	-	-	1,7	Tr	24,2	-
3761	-	62,6	23,2	14,2	6	76,9	4,7	-	,8	-	,6	17,0	-
3762	-	18,1	44,0	37,9	7	66,3	7,4	-	,6	-	-	25,7	2
3763	-	18,6	28,6	52,8	5	69,0	5,2	-	,8	-	-	25,0	-
3764	-	18,2	39,0	42,8	4	64,5	5,0	-	,4	-	-	30,1	-
3765	-	3,5	65,2	31,3	1	64,9	7,6	-	,6	-	-	26,9	-
3766	-	47,6	35,1	17,3	3	51,0	5,2	-	,7	-	24,1	19,0	2

Appendix B.7 (continued)

SAMPLE NUMBER	TEXTURE					COMPOSITION						INSOL. RESIDUE	
						Biogenic			Authigenic			Terrig- enous	(Quartz) in >63μ fraction
	Gravel	Sand	Silt	Clay	Faecal pellets	CaCO ₃ (apatite- free)	Organic matter	Amorph. Si	pP+cP	gpP	G		
Cruise 283 cont.													
3767	-	44,0	35,2	20,8	2	77,0	4,3	-	,8	-	,5	17,4	2
3768	-	90,1	3,5	6,4	41	75,7	6,4	-	,4	2,5	,1	14,9	1
3769	27,3	62,1	4,6	6,0	17	82,9	3,8	-	3,5	,9	Tr	8,9	1
3770	13,0	76,5	5,4	5,1	<10	81,1	7,4	Tr	,5	-	Tr	11,0	1
3771	1,8	25,7	43,8	28,7	ND	57,0	16,3	Tr	1,7	-	Tr	25,0	-
3772	11,7	14,7	20,2	53,4	ND	15,8	17,2	12	5,0	-	Tr	50,0	3
3773	,2	17,4	27,8	54,6	ND	7,0	10,2	80	2,1	-	-	,7	1
3774	3,2	47,4	20,1	29,3	ND	3,5	5,4	85	2,2	-	-	3,9	4
3775	-	30,5	31,7	37,8	ND	1,8	10,5	79	2,1	-	-	6,6	9
3776	30,7	68,4	-	,9	-	,7	,2	-	1,5	-	-	97,6	98
3777	-	49,6	49,7	,7	2	1,5	1,4	-	1,3	-	-	95,8	85
3778	-	43,3	50,6	6,1	3	1,5	1,8	-	,8	-	-	95,9	72
3779	-	29,7	60,7	9,6	15	1,7	4,9	-	1,4	-	-	92,0	33
3780	-	48,6	46,3	5,1	ND	1,0	1,8	55	1,1	-	-	41,1	21
3781	-	51,6	27,1	21,3	ND	3,5	6,0	88	,8	-	-	1,7	3
3782	-	44,9	29,8	25,3	ND	2,0	8,4	86	,8	-	-	2,8	3
3783	-	38,7	27,9	33,4	ND	2,7	8,8	78	5,4	-	-	5,1	6
3784	7,8	14,6	13,6	64,0	ND	3,7	11,3	50	3,1	-	-	31,9	3
3785	19,5	47,4	18,4	4,7	<10	48,7	14,1	Tr	3,8	-	Tr	33,4	2
3786	5,1	86,7	,4	7,8	17	83,5	4,3	-	2,9	,3	Tr	9,0	-
3787	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
3788	ND	ND	ND	ND	ND	ND	ND	-	<3,0	ND	ND	ND	ND
3789	-	44,1	38,6	17,3	18	71,6	6,3	-	2,0	-	-	20,1	1
3790	,5	53,1	26,8	19,6	8	71,5	4,5	-	,9	-	4,7	18,4	3
3791	-	25,9	45,3	28,8	9	65,1	7,6	-	,7	-	-	26,6	1
3792	-	14,7	42,4	42,9	4	68,6	5,6	-	,3	-	-	25,5	-
3793	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
3794	-	14,1	43,5	42,4	5	63,7	6,9	-	,6	-	-	28,8	-
3795	-	16,2	48,6	35,2	8	62,1	8,0	-	,5	-	-	29,4	1
3796	-	25,7	47,6	26,7	10	63,7	7,3	-	,6	-	-	28,4	5

Appendix B.7 (continued)

SAMPLE NUMBER	TEXTURE					COMPOSITION							INSOL. RESIDUE
						Biogenic			Authigenic			Terrig- enous	(Quartz) in >63μ fraction
	Gravel	Sand	Silt	Clay	Faecal pellets	CaCO ₃ (apatite- free)	Organic matter	Amorph. Si	pP+cP	gpP	G		
Cruise 283 cont.													
3797	,3	50,9	30,3	18,5	10	72,8	5,4	-	,5	-	-	21,3	4
3798	1,4	74,6	10,7	13,3	43	66,1	8,9	-	,7	-	-	24,3	3
3799	38,5	47,2	7,6	6,7	11	83,7	3,5	-	,8	-	Tr	12,0	4
3800	9,3	82,7	3,8	4,2	19	77,9	5,9	-	1,1	-	Tr	15,1	4
3801	2,9	78,6	11,5	7,0	<10	25,8	9,8	Tr	26,0	8,4	Tr	30,0	10
3802	4,7	29,0	12,4	53,9	ND	3,3	20,1	70	4,8	-	-	1,8	2
3803	1,7	34,5	25,1	38,7	ND	4,1	11,9	75	7,1	-	-	1,9	3
3804	-	41,1	29,6	29,3	ND	1,7	11,7	84	2,1	-	-	,5	1
3805	-	31,7	47,1	21,2	ND	1,1	6,4	81	1,6	-	Tr	9,9	9
3806	-	65,7	29,0	5,3	ND	1,5	2,6	60	1,4	-	Tr	34,5	41
3807	-	91,4	6,6	2,0	9	1,0	,7	-	1,4	-	Tr	96,9	85
3808	-	1,9	51,2	46,9	ND	10,0	2,8	7	,6	-	Tr	79,6	11
3809	-	6,2	42,3	51,5	ND	12,1	4,8	10	2,9	-	Tr	70,2	34
3810	,5	35,6	36,3	27,6	ND	2,0	6,4	73	3,7	-	-	14,9	20
3811	-	19,6	29,5	50,9	ND	4,3	9,5	84	1,4	-	-	,8	1
3812	7,6	85,7	3,9	2,8	ND	19,8	5,3	Tr	2,9	1,1	Tr	70,9	68
3813	,2	89,4	8,5	1,9	7	11,6	1,5	-	,6	-	Tr	86,3	81
3814	1,1	89,8	3,8	5,3	35	60,0	8,0	-	,8	-	Tr	31,2	6
3815	,1	78,9	12,6	8,4	36	67,1	7,5	-	,6	-	Tr	24,8	5
3816	-	60,2	25,0	14,8	13	72,0	5,9	-	,5	-	Tr	21,6	7
3817	-	22,9	51,8	25,3	10	60,4	7,8	-	,4	-	-	31,4	2
3818	-	18,1	52,1	29,8	10	62,2	8,7	-	,5	-	-	28,6	1
3819	-	22,5	44,9	32,6	9	63,7	7,0	-	,3	-	-	29,0	-
3820	-	20,8	36,5	42,7	5	73,5	4,0	-	,3	-	-	22,2	-
3821	-	16,0	42,7	41,3	5	71,1	4,3	-	,3	-	-	24,3	1
3822	-	19,9	41,6	38,5	6	67,8	5,7	-	,4	-	-	26,1	-
3823	-	26,0	40,1	33,9	9	61,1	7,6	-	,4	-	-	30,9	-
3824	-	17,5	50,1	32,4	10	57,8	8,8	-	,6	-	-	32,8	-
3825	-	32,7	46,9	20,4	11	66,3	,4	-	,6	-	-	32,7	1
3826	,9	53,6	30,7	14,8	11	75,0	,3	-	,4	-	TR	24,3	2

Appendix B.7 (continued)

SAMPLE NUMBER	TEXTURE					COMPOSITION							INSOL. RESIDUE
						Biogenic			Authigenic			Terrig- enous	(Quartz) in >63 μ fraction
	Gravel	Sand	Silt	Clay	Faecal pellets	CaCO ₃ (apatite- free)	Organic matter	Amorph. Si	pP+cP	gpP	G		
Cruise 283 cont.													
3827	6,3	68,6	14,4	10,7	16	70,8	5,8	-	,5	-	Tr	22,9	10
3828	9,4	63,7	12,5	14,4	29	43,4	4,1	-	1,2	-	Tr	51,3	25
3829	15,4	78,1	1,5	5,0	6	17,7	2,3	-	,9	-	Tr	79,1	85
3830	-	20,8	38,9	40,3	ND	6,8	16,2	74	1,6	-	-	1,4	2
3831	1,8	33,3	30,2	34,7	ND	3,9	10,1	76	2,1	-	-	7,9	11
3832	-	45,6	30,4	24,0	ND	2,1	9,0	41	4,1	-	-	43,8	53
3833	-	13,8	60,5	25,7	ND	1,4	11,0	61	1,6	-	-	25,0	11
3834	-	49,5	43,9	6,6	ND	2,2	3,3	10	1,3	-	-	83,2	26
3835	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
3836	,3	83,1	11,2	5,4	ND	1,4	2,7	4	2,0	-	Tr	89,9	91
3837	11,0	81,1	3,2	4,7	ND	3,3	1,6	Tr	4,8	-	Tr	90,3	86
3838	3,4	82,0	6,4	8,2	ND	6,0	2,9	Tr	2,8	-	Tr	88,3	87
3839	3,3	48,9	20,3	27,5	13	28,1	8,8	-	2,1	-	Tr	61,0	66
3840	1,1	95,4	1,6	1,9	3	3,3	1,4	-	,6	-	Tr	94,7	95
3841	6,2	87,8	2,5	3,5	13	77,6	4,8	-	< ,5	ND	ND	ND	3
3842	,2	73,8	14,6	11,4	39	55,8	10,7	-	,9	-	Tr	32,6	4
3843	,7	51,0	30,3	18,0	11	69,1	6,5	-	,3	1,4	Tr	22,7	3
3844	,1	51,9	28,9	19,1	4	76,7	5,3	-	,4	-	-	17,6	1
3845	-	32,5	48,7	18,8	9	67,0	6,8	-	,5	-	-	25,7	1
3846	-	29,8	41,7	28,5	11	62,0	7,5	-	,5	-	-	30,0	-
3847	-	24,6	45,0	30,4	13	61,7	7,5	-	,4	-	-	30,4	1
3848	-	25,0	41,4	33,6	5	67,1	5,1	-	,3	-	-	27,5	-
3849	-	19,2	47,7	33,1	5	74,9	4,1	-	,4	-	-	20,6	-
3850	-	49,1	24,2	26,7	3	83,4	1,7	-	2,7	-	-	12,2	-
3851	-	34,8	31,4	33,8	3	78,4	2,7	-	,2	-	-	18,7	1
3852	-	29,0	44,7	26,3	9	79,9	6,4	-	,5	-	-	13,2	1
3853	-	22,5	53,4	24,1	10	60,1	7,3	-	,4	-	-	32,2	1
3854	-	20,9	55,2	23,9	8	61,6	7,0	-	,3	-	-	31,1	1
3855	-	36,0	41,2	22,8	7	63,6	7,0	-	,5	-	-	28,9	1
3856	,4	60,5	24,7	14,4	14	72,5	5,7	-	,4	-	Tr	21,4	1

Appendix B.7 (continued)

SAMPLE NUMBER	TEXTURE					COMPOSITION						INSOL. RESIDUE	
	Gravel	Sand	Silt	Clay	Faecal pellets	Biogenic			Authigenic			Terrig- enous	(Quartz) in >63μ fraction
						CaCO ₃ (apatite- free)	Organic matter	Amorph. Si	pP+cP	gpP	G		
Cruise 283 cont.													
3857	1,3	66,7	10,7	21,3	28	64,1	8,6	-	-	3,8	Tr	23,5	2
3858	ND	ND	ND	ND	28	57,5	10,5	-	2,9	3,8	Tr	25,3	1
3859	16,3	75,6	4,3	3,8	15	75,2	4,9	-	-	1,8	Tr	18,1	3
3860	40,6	57,0	,7	1,7	8	55,1	1,8	-	1,8	-	Tr	41,3	57
3861	1,3	83,4	7,4	7,9	10	6,1	4,3	-	1,2	-	Tr	88,4	86
3862	,3	3,6	62,7	33,4	ND	21,9	17,5	Tr	1,4	-	Tr	59,2	20
3863	53,2	38,9	3,8	4,1	11	75,7	3,2	-	1,9	-	Tr	19,2	24
3864	27,8	49,2	18,2	4,8	12	75,7	4,5	-	-	2,8	Tr	17,0	7
3865	1,0	76,1	13,2	9,7	25	63,9	8,8	-	-	8,0	-	19,3	2
3866	-	63,8	23,5	12,7	18	69,7	6,7	-	,4	-	-	23,2	-
3867	-	58,8	26,1	15,1	9	73,5	3,8	-	,6	-	-	22,1	-
3868	-	33,1	44,4	22,5	10	61,7	5,8	-	,5	-	-	32,0	-
3869	-	3,4	66,2	30,4	1	59,2	7,2	-	,4	-	-	33,2	-
3870	-	7,6	59,5	32,9	2	58,0	6,4	-	,4	-	-	35,2	1
3871	-	10,9	55,9	33,2	2	68,3	5,9	-	,4	-	-	25,4	1
3872	-	26,4	43,3	30,3	2	74,6	3,9	-	,3	-	-	21,2	-
3873	-	37,1	32,9	30,0	3	82,0	2,5	-	,3	-	-	15,2	-
3874	-	39,5	30,0	30,5	3	79,9	2,7	-	,3	-	-	17,1	-
3875	-	34,5	37,6	27,9	4	73,3	4,3	-	,5	-	-	21,9	-
3876	-	32,5	50,8	16,7	10	8,4	2,6	-	,8	-	Tr	88,2	62
3877	-	94,9	2,1	3,0	4	,6	2,7	-	1,3	-	92,0	3,4	2
3878	,2	98,0	,5	1,3	1	2,5	1,3	-	,8	-	Tr	95,4	95
3879	,2	60,7	29,7	9,4	36	6,4	2,9	-	1,1	-	Tr	89,6	37
3880	1,2	36,0	53,8	9,0	<10	4,9	4,1	Tr	1,0	-	Tr	90,0	14
3881	-	27,3	60,3	12,4	<10	5,7	5,1	Tr	-	2,5	4,5	82,2	34
3882	1,3	32,1	56,1	10,5	24	6,7	4,0	-	1,2	-	Tr	88,1	8
3883	1,2	75,8	17,4	5,6	20	11,1	1,7	-	3,6	-	18,8	64,8	42
3884	-	10,4	58,5	31,1	ND	17,3	4,1	Tr	,8	-	Tr	77,8	22
3885	-	24,1	52,0	23,9	9	13,7	3,6	-	1,1	-	1,8	79,8	45
3886	,6	84,2	9,4	5,8	14	17,4	2,4	-	6,6	-	15,0	58,6	38

Appendix B.7 (continued)

SAMPLE NUMBER	TEXTURE					COMPOSITION						INSOL. RESIDUE	
						Biogenic			Authigenic			Terrig- enous	(Quartz) in >63μ fraction
	Gravel	Sand	Silt	Clay	Faecal pellets	CaCO ₃ (apatite- free)	Organic matter	Amorph. Si	pP+cP	gpP	G		
Cruise 283 cont.													
3887	-	84,3	11,5	4,2	15	1,7	2,7	-	5,9	5,9	18,9	64,9	33
3888	,8	75,5	15,8	7,9	12	2,5	3,0	-	<18,9	ND	ND	ND	8
3889	1,1	72,6	17,1	9,2	15	4,0	3,1	-	3,0	2,3	19,7	67,9	39
3890	11,7	58,9	18,0	11,4	15	13,1	3,3	-	19,4	1,1	18,8	44,3	23
3891	2,3	48,3	33,0	16,4	<10	ND	3,5	Tr	-	-	1,9	ND	54
3892	,5	75,1	17,2	7,2	13	3,0	2,3	-	1,3	-	Tr	93,4	79
3893	,2	54,7	32,3	12,8	ND	3,7	3,3	4	1,7	-	Tr	87,3	78
3894	,5	75,2	15,1	9,2	ND	2,8	3,0	4	1,5	-	Tr	88,7	74
3895	,8	73,5	13,5	12,2	11	2,1	2,6	-	2,6	,2	7,8	84,7	54
3896	-	86,9	6,2	6,9	8	1,1	2,4	-	4,2	1,6	53,8	36,9	15
3897	1,0	80,4	9,8	8,8	9	2,0	2,8	-	6,0	4,8	20,4	64,0	38
3898	,2	82,0	11,8	6,0	13	23,3	3,6	-	4,8	-	15,3	53,0	34
3899	-	35,6	42,6	21,8	9	9,4	3,0	-	1,1	-	2,5	84,0	59
3900	,3	10,2	48,2	41,3	ND	20,7	8,3	Tr	,8	-	2,2	68,0	7
3901	-	37,9	45,0	17,1	8	19,4	3,7	-	1,1	-	3,4	72,4	54
3902	10,6	72,0	9,5	7,9	9	10,9	2,4	-	9,5	-	4,8	72,4	61
3903	,5	88,8	5,0	5,7	9	3,7	4,0	-	10,2	21,5	9,3	51,3	25
3904	,5	84,6	9,4	5,5	6	7,9	1,9	-	3,3	2,5	1,1	83,3	75
3905	,5	88,8	6,1	4,6	5	1,6	2,0	-	5,1	2,8	,3	88,2	82
3906	1,5	89,8	4,6	4,1	6	1,4	2,3	-	7,9	4,7	,6	83,1	74
3907	-	89,7	5,9	4,4	6	,9	1,8	-	1,8	-	Tr	95,5	91
3908	-	87,8	7,4	4,8	6	,7	2,3	-	1,6	-	-	95,4	90
3909	,3	57,8	34,7	7,2	ND	3,3	3,3	31	,9	-	-	61,5	79
3910	,6	76,6	12,7	10,1	ND	1,1	3,1	12	1,7	-	-	82,1	90
3911	1,6	83,9	8,2	6,3	ND	1,4	2,9	Tr	2,0	-	-	93,7	90
3912	,4	89,3	4,9	5,4	ND	,9	2,1	Tr	2,1	-	-	94,9	92
3913	-	89,5	6,0	4,5	ND	,6	1,6	Tr	1,2	-	-	96,6	94
3914	1,3	90,4	4,1	4,2	7	3,7	2,9	-	10,9	10,8	1,0	70,7	57
3915	34,2	52,7	5,7	7,4	10	18,5	2,7	-	23,5	14,1	-	41,2	46
3916	,1	81,6	11,8	6,5	43	49,3	8,1	-	1,3	-	1,2	40,1	8

Appendix B.7 (continued)

SAMPLE NUMBER	TEXTURE					COMPOSITION							INSOL. RESIDUE
	Gravel	Sand	Silt	Clay	Faecal pellets	Biogenic			Authigenic			Terrig- enous	(Quartz) in >63μ fraction
						CaCO ₃ (apatite- free)	Organic matter	Amorph. Si	pP+cP	gpP	G		
Cruise 283 cont.													
3917	,4	71,6	18,0	10,0	11	65,3	4,8	-	1,3	-	2,9	25,7	3
3918	,1	60,3	22,6	17,0	8	58,1	3,6	-	1,3	-	1,4	35,6	6
3919	-	14,4	51,8	33,8	5	42,4	6,2	-	,6	-	-	50,8	2
3920	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
3921	-	24,2	45,7	30,1	7	64,0	6,6	-	,6	-	-	28,8	1
3922	1,3	49,6	29,6	19,5	8	52,1	4,9	-	,6	-	1,7	40,7	4
3923	-	68,1	20,9	11,0	35	50,9	7,0	-	,5	-	Tr	41,6	1
3924	,5	54,9	27,6	17,0	22	61,6	6,4	-	,4	-	Tr	31,6	2
3925	16,8	67,3	8,1	7,8	47	50,3	9,1	-	,4	-	1,2	39,0	4
3926	28,4	48,1	11,0	12,5	7	43,2	3,0	-	6,5	10,7	,7	35,9	18
3927	14,6	74,8	4,7	5,9	8	26,6	2,7	-	4,4	,7	,6	65,0	72
3928	,2	73,4	16,3	10,1	ND	3,8	6,0	Tr	2,6	,6	,4	86,6	81
3929	,4	64,8	20,7	14,1	ND	6,0	8,6	4	1,7	-	Tr	79,7	74
3930	-	92,3	2,6	5,1	ND	1,0	3,5	4	1,7	-	Tr	89,8	93
3931	4,4	82,6	2,7	10,3	ND	2,1	2,4	4	1,3	-	Tr	90,2	93
3932	-	74,7	15,6	9,7	ND	2,3	4,7	15	1,4	-	Tr	76,6	85
3933	,4	98,1	,4	1,1	ND	,4	,3	-	,8	-	Tr	98,5	98
3934	,1	35,2	48,2	16,5	ND	,5	6,0	25	1,7	-	-	66,8	40
3935	-	28,2	50,5	21,3	ND	2,6	8,2	39	2,2	-	-	48,0	19
3936	-	24,0	1,9	74,1	ND	4,2	10,9	61	3,8	-	-	20,1	29
3937	,6	41,6	26,8	31,0	<10	10,7	11,9	4	3,1	-	-	70,3	48
3938	5,9	35,5	29,5	29,1	<10	20,4	10,9	Tr	2,2	-	-	66,5	9
3939	2,6	64,8	17,5	15,1	<10	6,4	9,7	Tr	,6	,6	1,0	81,7	61
3940	12,0	78,8	2,2	7,0	19	48,3	5,1	-	-	14,2	-	32,4	18
3941	,2	79,9	8,9	11,0	26	52,4	7,3	-	-	11,3	,4	28,6	2
3942	-	79,2	12,4	8,4	49	57,8	9,7	-	,8	-	-	31,7	-
3943	-	61,3	26,4	12,3	18	70,2	6,5	-	,6	-	-	22,7	-
3944	,1	61,1	26,1	12,7	24	69,0	7,5	-	,5	-	-	23,0	-
3945	,2	78,7	12,8	8,3	37	64,7	8,5	-	,7	-	-	26,1	1
3946	25,0	60,2	8,3	6,5	36	67,7	6,8	-	-	9,8	,3	15,4	2

Appendix B.7 (continued)

SAMPLE NUMBER	TEXTURE					COMPOSITION							INSOL. RESIDUE
	Gravel	Sand	Silt	Clay	Faecal pellets	Biogenic			Authigenic			Terrig- enous	(Quartz) in >63μ fraction
						CaCO ₃ (apatite- free)	Organic matter	Amorph. Si	pP+cP	gpP	G		
Cruise 283 cont.													
3947	31,8	63,2	,5	4,5	18	78,8	4,4	-	-	9,1	-	7,7	4
3948	21,7	68,4	3,1	6,8	10	43,7	3,5	-	2,6	-	Tr	50,2	56
3949	,9	86,6	5,4	7,1	6	4,9	3,4	-	2,8	-	Tr	88,9	100
3950	-	36,8	24,6	38,6	ND	11,7	16,4	36	1,5	-	-	34,4	5
3951	2,6	38,2	22,9	36,3	ND	11,1	14,6	33	2,4	-	-	38,9	7
3952	11,1	48,5	18,9	21,5	ND	13,3	6,7	52	5,4	-	-	22,6	44
3953	2,4	67,4	12,9	17,3	ND	4,3	3,5	57	3,8	-	-	31,4	56
3954	-	53,1	33,2	13,7	ND	1,9	5,4	38	1,0	-	-	53,7	56
3955	8,1	38,3	24,5	29,1	ND	22,5	,4	21	1,9	-	-	54,2	13
3956	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
3957	2,0	32,2	28,9	36,9	ND	6,9	10,0	59	5,3	-	-	18,8	33
3958	-	45,7	22,6	31,7	ND	2,1	9,7	63	1,0	-	-	24,2	34
3959	-	49,7	36,9	13,4	ND	2,0	5,4	25	1,4	-	-	66,2	46
3960	,9	83,0	5,3	10,8	ND	3,1	3,1	4	1,1	-	Tr	88,7	90
3961	3,0	24,8	23,4	48,8	ND	12,1	10,0	60	2,0	-	-	15,9	27
3962	2,6	79,6	7,5	10,2	ND	2,5	3,8	4	5,2	-	Tr	84,5	81
3963	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
3964	-	55,7	34,2	10,1	ND	2,6	3,1	20	1,5	-	-	72,8	60
3965	,4	86,0	4,7	8,9	ND	2,0	2,9	4	1,6	-	Tr	89,5	91
3966	,5	87,9	3,7	7,9	ND	1,4	3,0	4	1,8	-	Tr	89,8	90
3967	22,3	58,8	16,8	2,1	ND	63,6	,2	4	1,7	-	Tr	30,5	15
3968	9,1	75,0	6,7	9,2	13	19,2	4,7	-	1,6	-	Tr	74,5	77
3969	8,0	77,7	9,8	4,5	5	17,0	2,5	-	,8	-	Tr	79,7	89
3970	,2	96,3	2,2	1,3	4	2,8	1,6	-	,7	-	Tr	94,9	93
3971	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
3972	2,7	90,0	,5	6,8	14	74,6	4,8	-	,9	-	Tr	19,7	5
3973	-	83,1	4,4	12,5	53	52,7	11,3	-	-	6,2	-	29,8	3
3974	,2	78,9	12,6	8,3	44	64,3	8,3	-	,2	2,6	-	24,6	1
3975	,6	59,5	26,9	13,0	16	74,4	6,2	-	,4	-	-	19,0	1
3976	,2	63,9	26,9	9,0	18	ND	5,3	-	,5	-	Tr	ND	1

Appendix B.7 (continued)

SAMPLE NUMBER	TEXTURE					COMPOSITION						INSOL. RESIDUE	
	Gravel	Sand	Silt	Clay	Faecal pellets	Biogenic			Authigenic			Terrig- enous	(Quartz) in >63μ fraction
						CaCO ₃ (apatite- free)	Organic matter	Amorph. Si	pP+cP	GpP	G		
Cruise 283 cont.													
3977	-	74,3	14,9	10,8	30	67,3	5,6	-	,6	-	Tr	26,5	4
3978	ND	ND	ND	ND	ND	ND	ND	-	< ,9	ND	ND	ND	ND
3979	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
3980	-	93,8	2,0	4,2	4	1,5	2,0	-	,6	-	-	95,9	95
3981	20,3	73,8	5,8	,1	11	24,7	4,4	-	1,5	-	Tr	69,4	76
3982	3,0	42,1	18,9	36,0	ND	17,4	12,1	16	1,8	-	Tr	52,7	43
3983	,1	33,7	23,9	42,3	ND	5,8	12,4	76	1,3	-	-	4,5	6
3984	1,0	36,2	36,9	25,9	ND	3,3	9,9	81	1,6	-	-	4,2	6
3985	-	33,3	54,4	12,3	ND	2,3	6,1	55	1,6	-	-	35,0	6
3986	-	86,3	9,9	3,8	5	1,1	1,6	-	1,1	-	-	96,2	87
3987	-	39,1	35,5	25,4	ND	1,5	10,4	71	4,7	-	-	12,4	10
3988	,8	33,5	29,8	35,9	ND	1,6	14,9	69	3,1	-	-	11,4	14
3989	-	37,0	27,8	35,2	ND	3,6	17,2	74	2,7	-	-	2,5	29
3990	,3	35,3	23,7	40,7	ND	7,5	16,7	70	2,5	-	-	3,3	4
3991	46,1	51,4	,5	2,0	7	57,7	1,5	-	,5	-	-	40,3	69
3992	38,5	57,6	,1	3,8	7	53,6	2,0	-	,5	-	-	43,9	5
3993	1,0	81,3	9,4	8,3	49	58,1	10,3	-	,7	-	-	30,9	6
3994	4,5	52,0	27,8	15,7	12	70,4	5,9	-	,4	-	-	23,3	6
3995	,7	61,6	25,9	11,8	11	72,3	4,6	-	,6	-	-	22,5	5
3996	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
3997	5,5	91,7	,2	2,6	11	79,4	2,8	-	,5	-	Tr	17,3	8
3998	16,8	72,5	4,9	5,8	12	41,9	3,8	-	1,6	-	Tr	52,7	58
3999	-	38,6	31,3	30,1	<10	31,0	18,7	13	1,7	-	-	35,6	2
4000	1,3	39,0	17,2	42,5	ND	1,9	12,1	83	1,6	-	-	1,4	2
4001	-	55,2	17,8	27,0	ND	1,4	9,1	85	2,7	-	-	1,8	2
4002	,1	31,0	39,0	29,9	ND	1,4	10,1	86	1,3	-	-	1,2	2
4003	,5	79,7	16,7	3,1	ND	,7	3,7	28	10,3	-	-	57,3	46
4004	-	82,1	16,1	1,8	ND	,7	1,2	18	1,8	-	-	78,3	16
4005	,4	91,9	,1	7,6	ND	1,2	,4	7	1,5	-	-	89,9	26
4006	-	47,9	41,6	10,5	ND	1,5	5,3	79	2,1	-	-	12,1	13

Appendix B.7 (continued)

SAMPLE NUMBER	TEXTURE					COMPOSITION							INSOL. RESIDUE
						Biogenic			Authigenic			Terrig- enous	(Quartz) in >63μ fraction
	Gravel	Sand	Silt	Clay	Faecal pellets	CaCO ₃ (apatite- free)	Organic matter	Amorph. Si	pP+cP	gpP	G		
Cruise 283 cont.													
4007	,7	58,4	19,4	21,5	ND	,8	9,8	81	6,3	-	-	2,1	3
4008	1,7	57,3	12,0	29,0	ND	2,4	15,5	75	4,8	-	-	2,3	4
4009	,2	53,3	16,0	30,5	ND	5,5	10,7	80	3,5	-	-	,3	1
4010	,3	52,9	18,2	28,6	ND	15,5	16,2	56	3,4	-	-	8,9	-
4011	19,2	70,8	8,8	1,2	20	74,8	6,6	-	5,1	-	Tr	13,5	1
4012	11,9	86,4	,3	1,4	12	90,1	3,1	-	,5	-	Tr	6,3	1
4013	-	93,3	3,4	3,3	37	68,5	8,1	-	,5	3,2	,3	19,4	2
4014	,5	77,9	14,9	6,7	33	72,8	6,6	-	,2	,7	,1	19,6	2
4015	4,8	73,0	14,1	8,1	33	79,1	5,0	-	1,4	,7	,1	13,7	2
4016	ND	ND	ND	ND	ND	ND	ND	-	<12,4	ND	ND	ND	ND
4017	-	95,1	,8	4,1	27	81,7	5,9	-	,7	-	Tr	11,7	1
4018	34,4	62,5	,3	2,8	15	91,2	3,4	-	1,0	-	Tr	4,4	1
4019	,8	52,4	36,1	10,7	ND	36,9	23,9	34	2,3	-	-	2,9	-
4020	-	34,5	15,6	49,9	ND	3,5	16,0	78	1,8	-	-	,7	1
4021	1,1	48,1	18,5	32,3	ND	1,6	8,4	74	14,7	-	-	1,3	2
4022	-	52,1	23,3	24,6	ND	1,3	7,9	85	4,6	-	-	1,2	1
4023	-	63,8	26,4	9,8	ND	14,0	5,9	76	1,8	-	-	2,3	3
4024	-	38,3	44,5	17,2	ND	3,4	11,3	50	2,8	-	-	32,5	9
4025	36,6	63,4	-	-	-	,6	,1	-	,5	-	-	98,8	98
4026	,1	99,9	-	-	-	,3	,1	-	,4	-	Tr	99,2	99
4027	-	100,0	-	-	1	,5	,3	-	1,9	-	Tr	97,3	96
4028	4,0	72,8	18,8	4,4	ND	1,8	6,6	6	38,6	-	-	47,0	19
4029	-	53,9	40,2	5,9	ND	2,2	5,7	87	2,1	-	-	3,0	3
4030	-	52,4	11,5	29,1	ND	1,1	9,3	86	3,2	-	-	,4	1
4031	-	32,2	11,5	56,3	ND	2,7	12,6	82	1,8	-	-	,9	-
4032	-	37,0	14,9	48,1	ND	9,1	14,7	75	1,2	-	-	-	-
4033	5,8	60,8	19,6	13,8	ND	57,0	18,5	Tr	1,5	-	Tr	23,0	-
4034	46,3	51,0	,3	2,4	7	96,6	1,8	-	,3	-	Tr	1,3	-
4035	6,8	88,5	-	4,7	23	74,8	4,6	-	4,9	4,4	-	11,3	1
4036	,3	80,1	13,8	5,8	34	77,9	7,2	-	-	3,6	-	11,3	-

Appendix B.7 (continued)

SAMPLE NUMBER	TEXTURE					COMPOSITION							INSOL. RESIDUE
	Gravel	Sand	Silt	Clay	Faecal pellets	Biogenic			Authigenic			Terrig- enous	(Quartz) in >63μ fraction
						CaCO ₃ (apatite- free)	Organic matter	Amorph. Si	pP+cP	gpP	G		
Cruise 283 cont.													
4037	,6	30,3	21,2	47,9	6	26,2	3,1	-	2,2	-	12,8	55,7	3
4038	-	28,8	43,9	27,3	13	89,5	5,6	-	,5	-	-	4,4	-
4039	-	55,5	35,6	8,9	21	78,6	5,6	-	,7	-	-	15,1	1
4040	1,7	70,7	19,5	8,1	11	85,2	4,2	-	4,8	2,9	,2	2,7	1
4041	1,6	80,4	12,8	5,2	26	77,1	6,1	-	-	3,8	-	13,0	1
4042	4,8	93,1	1,6	,5	18	83,4	5,3	-	1,7	-	Tr	9,6	4
4043	12,0	68,5	16,3	3,2	ND	67,1	10,9	Tr	2,5	-	Tr	19,5	1
4044	-	49,3	24,9	25,8	ND	23,2	23,7	43	2,7	-	-	7,4	-
4045	-	20,4	17,6	62,0	ND	4,6	13,5	79	1,3	-	-	1,6	1
4046	2,3	38,3	36,4	23,0	ND	2,4	8,7	81	4,4	-	-	3,5	4
4047	,3	19,7	15,5	64,5	ND	3,1	8,4	80	1,1	-	-	7,4	5
4048	-	9,2	52,8	38,0	ND	1,7	8,6	82	,8	-	-	6,9	-
4049	-	1,3	78,3	20,4	ND	2,9	6,8	10	,8	-	-	79,5	2
4050	-	1,4	74,4	24,2	ND	6,2	5,2	44	,7	-	-	43,9	12
4051	,3	87,4	6,7	5,6	8	28,0	5,8	-	25,9	12,3	1,3	26,7	2

* pP+cP = pelletal phosphorite + concretionary phosphorite

gpP = glauconitized pelletal phosphorite

G = glauconite

- = component not present

ND = not determined because of insufficient sample. In addition, Faecal pellets were not determined within the diatomaceous muds.

Tr = trace quantities

Appendix B.8 Summary of the percentage frequency of Mollusca from grab and dredge samples

	MOME 3927 POINT	3940	3756D	3947	3961 PALGR. POINT	3841	3839	3838	3881	3982	3812	3998	3800	CAPE 4011 CROSS	WALVIS 3533 BAY	SANDWICH 4682D HARBOUR	4681D	3478	4680D	3467	4679D	3452	4678D	4677D	3427	4676D	3412	SYLVIA 3413 HILL
DEPTH(metres)	139	184	260	218	90	205	105	93	110	95	129	132	147	145	153	158	180	147	210	161	220	124	252	250	160	163	270	159
CaCO ₃ (weight %)	26,6	48,3		78,8	12,1	77,6	28,1	6,0	5,7	17,4	19,8	41,9	4,9	74,8	68,0			61,2				15,5			45,0	-	22,1	
GRAVEL(weight %)	14,6	12,0		31,8	3,0	6,2	3,3	3,4	-	3,0	7,6	16,8	1,2	19,2	11,3			27,0				6,6			16,7	9,8	7,9	
MUD(weight %)	10,6	9,3	22,9	5,0	72,1	6,0	47,8	14,6	6,0	55,0	6,8	10,7	8,0	10,0	3,6	15,6	9,3	11,0		10,0	7,6	13,4	1,8	16,6	24,2	14,7	-	12,9
BIVALVIA																												
<i>Aequipecten cf. commulata</i>	*			Tr							*	*		Tr													*	
<i>Cardium asiaticum</i>		*									*	Tr			*			Tr										*
<i>Carditella similis</i>	**			**	*				*			*			*	*		*			*	*		*	*	*	*	*
<i>Dosinia lupinus</i> Δ	*	*		*	*	*	*	*	*		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
<i>Limopsis chuni</i>					*	*	*	*	*		*	*	*	*	Tr	**	**	*	*	*	**	*	*	*	**	**	*	**
<i>Lucinoma capensis</i> Δ	Tr	*	**	*	*	*	**	**	**	**	**	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
<i>Nucula nucleus</i>	*	*		*	Tr				*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
<i>Nuculana bicuspadata</i>	*			*	*		*		*	*	*	*	*	*	*	*	*	*	*	*	Tr	*	*	Tr	*	*	Tr	
<i>Ostrea</i> sp.		*	*	Tr					*				*				*	*	*	*	*	*	*	*	*	*	*	
<i>Solenia binghami</i>												Tr		Tr		Tr	*				*	*	*	Tr	*	**	*	
<i>Tellinomya trigona</i>				*					*	*	*	*	*	*	*	*	*	*	*	*	Tr	*	*	*	*	*	*	
<i>Tellina gilchristi</i> Δ	*	*		*	*	*			*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	
<i>Thracia cf. convexa</i>												Tr	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	
<i>Timoclea ovata</i>				*	*		*		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	
<i>Venerupis senegalensis</i>								*		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	
GASTROPODA																												
<i>Nassarius analogicus</i> Δ	*	*			*	*	*	*	*	*	*	Tr	Tr	Tr			*	*	*	*	*	*	*	*	*	*	*	
<i>Turritella declevis</i>																*	*	*	*	*	*	*	*	*	*	*	*	
<i>Volutocorbis abyssicola</i>	Tr	*	*								*	Tr				Tr	*	*	*	*	*	*	*	Tr	*	*	Tr	
- = absent component, or not determined because of insufficient sample Tr = trace																												

- = absent component, or not determined because of insufficient sample
 Tr = trace (<1%)
 * = present (1 - 49,9%)
 ** = abundant (>50%)
 Δ = the distribution and concentration of these species are shown in Figure 5.17

Appendix B.9 Volume percentage of foraminifera and other biogenic grains in the >63 μ m fraction of samples

Sample Number	PLANKTON															CaCO ₃ (weight %)		
	Foraminifera												Radiolaria		TOTAL			
	BENTHONIC										PLANKTONIC							
	<u>Ammonia beccarii</u>	<u>Elphidium cf. advenum</u>	<u>Hyalinea balthica</u>	<u>Uvigerina sp.</u>	<u>Bulimina marginata</u>	<u>Bolivina sp.</u>	<u>Brizalina spathulatus</u>	Other	TOTAL	<u>Orbulina universa</u>	Other	TOTAL						
Mollusca	Echinoidea	TOTAL																
3409	11	5	16				2			7	14	23	11	46	57	4	61	32,4
3411	95		95											5	5		5	28,4
3413	95													5	5		5	27,7
3426	7		7						42	51		93						16,8
3434		1	1					1	1		3	5	12	73	85	9	94	76,6
3438	4	3	7		2	3	5	2		8	25	45	3	44	47	1	48	32,6
3452	95		95											5	5		5	19,8
3454	95		95											5	5		5	29,7
3455	47		47	3	3	3	1	2		4	7	23	2	25	27	2	29	53,4
3457	3		3		1	7	2	1		1	13	25	1	61	62	1	63	77,5
3479	53		53	3	4	2	1			6	7	23		25	25		25	72,5
3486													14	83	97	3	100	80,8
3489										3	2	5	14	77	91	4	95	76,8
3494	68	3	71		1	1				1	9	12		19	19		19	74,6
3496									54	29		83		15	15	1	16	17,3
3508	28	3	31	6	11				12	15	7	51	2	16	18		18	39,6
3520	66	2	68	8			1		1	2	3	15		17	17		17	39,6
3523	15	1	16	1	20		1	1		7	11	41	1	41	42	1	43	71,4
3526		1	1							1	2	3	13	76	89	7	96	80,2
3549	22		22	1		2	4			3	5	15	3	60	63		63	54,7
3552								1		2	4	7	8	83	91	2	93	36,4
3556	19		19	1		4				11	7	23	4	54	58		58	54,9
3562	1	2	3					1			7	8	2	79	81		81	60,4
3655										3	39	42		52	52	6	58	25,3
3657	4		4	7	4			2		76	4	93		3	3		3	15,0
3667		3	3				6		3		10	19	4	59	63	13	76	16,6
3683								2	2	13	9	26	2	61	63	11	74	11,0
3696		1	1	1	1	1	4	2		4	6	19	8	72	80		80	56,9
3699	3	1	4				1				8	9	7	59	66	21	87	36,7
3700								1		5	3	9	7	79	86	5	91	56,8
3703								1			4	5	16	67	83	12	95	51,1
3706	47		47							10	2	12		41	41		41	63,5
3707				2			2		1	6	5	16	3	71	74		74	56,4
3709	22		22	4	1		9			4	5	23	10	45	55		55	39,2
3712										54	26	81	6	13	19		19	10,2
3716	5		5							55	16	75	8	11	19	1	20	9,2
3717	10		10							57	12	69	10	10	20	1	21	18,6
3719	87		87							1	3	4	1	6	7		7	59,9
3723	11		11							12	5	17	1	71	72		72	73,2
3748								3			4	7	1	87	88	5	93	74,0
3756	10	1	11						37	19	2	58		31	31		31	48,9

Appendix B.9 (continued)

Sample Number												PLANKTONIC			Radiolaria	TOTAL	CaCO ₃ (weight %)	
	Foraminifera																	
	BENTHONIC											PLANKTONIC						
	<u>Ammonia beccarii</u>	<u>Elphidium cf. advenum</u>	<u>Hyalinea balthica</u>	<u>Uvigerina sp.</u>	<u>Bulimina marginata</u>	<u>Bolivina sp.</u>	<u>Brizalina spathulatus</u>	Other	TOTAL	<u>Orbulina universa</u>	Other	TOTAL						
Mollusca	Echinoidea	TOTAL																
3759	6		6	5	1	4	4	1		16	18	49		47	47	47	74,3	
3762		2	2					6			3	9	11	75	86	3	89	66,4
3771	4		4						21	26	5	52	5	39	44		44	57,2
3784	1	1	2						22	12	1	35	1	60	61	2	63	4,0
3786	48		48	2	1		3			2	7	15	5	33	38		38	83,9
3790								6		7	1	14		85	85	1	86	71,6
3796							1	2		2	2	7	8	84	92	1	93	63,8
3815	5		5	2			6			12	11	31	2	62	64		64	67,1
3821										1	4	5	25	66	91	4	95	71,1
3827	12		12	2	2	3	2			25	7	41	1	46	47		47	70,9
3839	16		16						59	9		68	3	13	16		16	28,3
3843					1	3	2			12	6	24	1	75	76		76	69,3
3847											1	1	36	50	86	13	99	61,8
3850											3	3	16	80	96	1	97	83,8
3851						1						1	12	83	95	4	99	78,4
3852											1	1	30	58	88	11	99	80,0
3855										2	6	8	1	90	91	1	92	63,7
3861	12	1	13						24	8	3	35	21	31	52		52	6,3
3863	47		47	5					3	8	2	18	5	30	35		35	75,9
3867										23	2	35		74	74	1	75	73,5
3872							1	1			2	4	11	82	93	3	96	74,6
3875													20	76	96	4	100	73,4
3886		4	4	18	22	5	14			11	3	73		23	23		23	18,2
3898	4		4	17	6	7	3	1		21	5	60		36	36		36	23,9
3900							1		21	56	4	82		2	2	16	8	20,8
3917	1		1	7		3	1			19	3	33		66	66		66	65,4
3921		1	1	1					1	8	2	12		86	86	1	87	64,1
3927	24		24	4					1	6	6	17		59	59		59	27,3
3938	5		5						49	14	1	64	4	27	31		31	20,7
3941				1			2			3	2	8	3	89	92		92	53,6
3948	50	2	52	5	4		1	1	4	8	2	25	4	19	23		23	44,0
3950	2		2						71	12		83	1	14	15		15	11,9
3972	53	1	54	8	4	1	5				4	22	3	21	24		24	74,7
3975	5	1	6			4	4			12	2	22	2	70	72		72	74,5
3977	1	1	2	2	3	6	5			16	1	33	1	64	65		65	67,4
3998	43		43	6	3		2		4	14		29	5	23	28		28	42,1
4010	48	1	49	3	4	3	1		2	1	4	18	7	26	33		33	1,7
4014	10		10	2		3	3	5			7	20	3	51	54		54	73,0
4018	55		55	2			3		1	2	2	10	6	28	34	1	35	91,4
4037				1		3	2	4		16	3	29	6	64	70	1	71	26,5
4039	2		2		3		1			7	7	18	1	79	80		80	78,7
4042	30		30	1	1		3		1	2	3	11		59	59		59	83,6
4051		2	2	4	1	3	3			2	7	20		78	78		78	32,8

Appendix B.10 The order* of abundance of common planktonic foraminifera from the upper slope

	Walvis Ridge Terrace <u>3703</u>	Cape Cross <u>3796</u>	Sylvia Hill <u>3748</u>
<u>SUBANTARCTIC SPECIES</u>			
<u>Globigerina quinqueloba</u>	2	2	2
<u>Globigerina bulloides</u>	3	3-4	3-4
<u>Globorotalia scitula</u>			5
<u>TRANSITIONAL SPECIES</u>			
<u>Globorotalia inflata</u>	1	1	1
<u>SUBTROPICAL SPECIES</u>			
<u>Globigerinoides ruber</u>	8		8
<u>Globorotalia truncatulinoides</u>		6	6
<u>Globoquadrina dutertrei</u>	5	3-4	3-4
<u>Orbulina universa</u>	4	5	7
<u>Orbulina bilobata</u>	7		
<u>TROPICAL SPECIES</u>			
<u>Globigerinoides sacculifer</u>	6		

* 1 = most abundant, 8 = least abundant

The abundance of common diatom species from the continental margin south of Walvis Bay

	Diatomaceous mud belt					Outer shelf		Upper slope		
	Walvis Bay	Sandwich Harbour	Conception Bay	Meob Bay	Meob Bay	Sandwich Harbour	Meob Bay	Walvis Bay	Conception Bay	Meob Bay
Sample number	3514	3500	3445	3571	3566	3559	3563	3528	3458	3407
Depth (metres)	58	42	38	28	149	162	321	1077	725	1310
Amorphous silica (weight percentage)	77	11	23	Tr	34	-	-	-	-	-
<u>Actinocyclus ehrenbergii</u>	**	*	*	*	*		*	*	*	*
<u>Actinoptychus splendeus</u>				*						
- <u>undulatus</u>	*	*	*	*						
<u>Arachnoidiscus ehrenbergi</u>	*			*						
<u>Biddulphia longicouris</u>				*						
<u>Chaetoceros constrictus</u>				*				*		
- <u>didymus</u>	*	*		**						
- <u>lorenzianus</u>	*									
- <u>subsecundus</u>	*									
<u>Coscinodiscus centralis</u>	**	*	*	*	*	*		*	*	*
- <u>gigas v. praetexta</u>	**	*		*	*	*	*	*		*
- <u>janischi</u>		*								
- <u>stellaris</u>	*									
<u>Fragilaria karstenii</u>	**	*	*	**	*		*	*	*	*
<u>Paralia sulcata</u>	*		*							
<u>Pleurosigma</u> sp.	*	*								
<u>Thalassiosira decipiens</u>	*		*	*						
<u>Triceratium balearisum</u> f. <u>biquadrata</u>	*									
- <u>favus</u>	*									

* Present (<+50%)
 ** Abundant (>+50%) visual estimates

Appendix B.12 The CO₂ content of phosphorites

Sample No.	Gasometry			X-ray diffraction					MEAN	
	Determinations			Mean	Determinations					Mean
Pelletal phosphorite (pP)										
3411	3,3	2,8	3,3	3,13	3,3	3,4	2,8	2,7	3,05	3,09
3522	3,0	2,9		2,95	3,6	5,2	3,7	4,5	4,25	3,82
3558	3,8			3,80	4,2	3,9	4,0	5,2	4,33	4,22
3563	3,0	2,9		2,95	3,1	3,1	3,6	2,6	3,10	3,22
3719	3,1	2,8		2,95	3,6	3,9	3,6	3,6	3,68	3,43
3904	3,1	3,2		3,15	3,0	3,4	4,0	3,6	3,50	3,38
3914	4,4	3,7	3,4 4,0	3,88	3,3	4,5	3,3	4,0	3,78	3,83
Averages				3,3					3,7	3,6
Glauconitized pelletal phosphorite (gpP)										
3906					3,7	5,0	3,6	4,3	4,15	
3914					3,9	5,3	4,0	4,8	4,50	
3915					3,9	4,6	3,3	2,6	3,60	
3941					3,1	3,4	3,9	4,5	3,73	
4051					3,3	3,4	3,6	3,6	3,48	
Averages									3,9	3,9
Concretionary phosphorite (cP)										
3773	5,4	5,4		5,40	5,4	4,8	5,5	6,1	5,45	5,43
3784	4,7	4,9		4,80	4,9	5,0	5,5	5,9	5,33	5,15
3802	4,4	3,8	5,0, 3,8	4,25	4,3	3,4	3,1	3,7	3,63	3,94
4031	4,0	4,0		4,00	4,8	5,6	5,3	5,5	5,30	4,87
Averages				4,6					4,9	4,9

Appendix B.13 The C_{org} and F content of phosphorites

Pelletal phosphorite (pP)			Glauconitized pelletal phosphorite (gpP)				Concretionary phosphorite (cP)		
Sample No.	C _{org}	F	Sample No.	Colour	C _{org}	F	Sample No.	C _{org}	F
3410	2,21	3,02	3493	Moderate brown 5 YR 4/4	1,50	2,39	3773	1,24	3,32
3411	2,84	3,20	3558	Moderate brown 5 YR 4/4	1,57	2,48	3784	1,38	3,10
3428	2,81	3,22	3688	Moderate yellowish brown 10 YR 5/4	2,26	2,28			
3429	2,91	3,26	3710	Moderate yellowish brown 10 YR 5/4	1,72	1,60			
3439	2,67	3,22	3719	Dark yellowish brown 10 YR 4/2	2,10	2,65			
3454	2,66	3,15	3720	Light olive grey 5 Y 5/2	1,59	2,04			
3455	2,71	3,25	3881	Light olive grey 5 Y 5/2	,87	2,76			
3456	2,29	3,37	3903	Light olive brown 5 Y 5/6	,51	2,84			
3463	2,50	3,29	3904	Moderate brown 5 YR 4/4	,75	2,24			
3493	2,59	3,31	3914	Dark yellowish orange 10 YR 6/6	,60	2,82			
3494	2,37	3,38	3915	Moderate brown 5 YR 4/4	1,18	2,67			
3563	2,82	3,30	3926	Moderate brown 5 YR 4/4	2,00	2,67			
Averages					1,4	2,5		1,3	3,2

Appendix B.14 Weight percentages and statistical parameters of the insoluble residue (quartz)

Sample Number	V.C. to m. sand -1,0 to 2,0φ	F. sand 2,0 to 3,0φ	V.F. sand		Silt 4,0 to 5,0φ	Moment measures			
			3,0 to 3,5φ	3,5 to 4,0φ		Mean (φ)	Sorting (φ)	Skewness	Kurtosi
3409	25,5	17,4	56,7	-	-	2,70	,89	-,44	-,61
3411	-	-	74,6	25,4	-	3,45	,16	,49	,27
3413	3,0	37,9	37,1	12,0	-	3,07	,43	-1,10	10,53
3415	45,4	23,5	23,1	8,0	-	2,17	1,04	-,03	-1,67
3417	-	79,9	18,6	1,5	-	2,80	,25	,47	1,40
3419	81,2	18,5	,3	-	-	1,54	,51	,16	-,57
3423	-	62,0	35,2	2,8	-	2,96	,23	,36	-,02
3426	-	-	27,9	44,7	17,4	3,69	,29	,11	-,99
3427	-	-	84,3	15,7	-	3,29	,20	,32	-,43
3438	-	28,5	38,4	33,1	-	3,20	,49	-,36	-,68
3440	-	32,1	59,4	8,5	-	3,15	,26	-,12	,72
3445	-	26,4	46,5	19,3	7,8	3,30	,39	,37	-,44
3452	24,8	11,7	43,7	15,8	4,0	2,80	,92	-,38	-,74
3454	-	18,7	71,6	9,7	-	3,16	,18	,45	,19
3455	-	11,5	70,3	18,2	-	3,30	,26	,25	,04
3462	-	-	39,0	46,7	14,3	3,63	,30	,12	-,92
3467	-	45,3	41,2	13,5	-	3,11	,28	,43	-,26
3470	-	45,9	50,2	3,9	-	3,07	,20	,36	-,36
3474	,3	65,6	29,7	4,4	-	2,95	,26	,29	1,40
3479	-	17,8	30,1	41,7	10,4	3,48	,42	-,15	-1,19
3489	-	8,3	27,9	63,8	-	3,51	,28	-,69	2,00
3490	-	3,5	35,9	39,2	21,4	3,66	,39	,06	-,80
3494	-	66,3	23,7	10,0	-	2,78	,46	,27	-1,23
3502	-	-	56,0	44,0	-	3,48	,23	,15	-1,06
3508	-	8,4	34,9	43,3	13,4	3,55	,35	-,02	-,68
3520	-	16,3	29,8	53,9	-	3,48	,34	-,17	-1,20
3523	-	-	35,0	59,8	5,2	3,62	,20	,29	-,73
3524	-	-	29,0	48,5	22,4	3,72	,33	,06	-1,02
3539	-	,3	52,5	32,6	14,6	3,57	,29	,34	-,59
3552	-	-	36,5	47,4	16,1	3,65	,24	,30	-,85
3556	-	42,5	24,0	33,5	-	3,25	,37	,14	-1,53
3562	11,7	6,3	31,3	33,3	17,4	3,32	,82	-,73	1,34
3567	-	51,0	31,2	17,7	-	3,00	,41	,03	-,42
3568	96,5	2,6	,9	-	-	,93	,41	1,51	11,70
3655	6,2	5,1	60,0	27,8	,9	3,29	,55	-1,10	5,09
3657	-	4,8	55,0	38,4	1,8	3,42	,29	,12	-,92
3659	-	-	45,9	45,2	8,9	3,58	,29	,26	-,68
3661	-	-	43,3	45,5	11,2	3,60	,30	,19	-,86
3663	2,6	7,4	55,5	29,3	5,2	3,34	,47	-,92	7,23
3665	-	-	34,1	55,3	10,5	3,65	,28	,11	-,75
3667	-	3,9	14,1	42,7	39,3	3,84	,41	-,39	,28
3670	2,1	11,0	42,2	40,8	3,9	3,40	,45	-,71	3,40
3674	-	1,6	76,1	22,3	-	3,33	,22	,31	-,44
3678	-	4,3	80,2	15,5	-	3,27	,20	,26	-,59
3679	-	20,0	61,0	19,0	-	3,24	,26	,10	-,21
3683	-	-	39,7	42,3	18,0	3,65	,35	,16	-,89
3686	6,3	13,2	49,3	27,7	3,5	3,20	,58	-,76	2,89
3692	-	6,6	56,5	31,6	5,3	3,41	,33	,21	-,31
3694	-	4,5	64,8	29,9	1,8	3,37	,30	-,03	,64
3696	-	-	60,4	34,9	4,7	3,45	,29	,27	-,64

Sample Number	V.C. to m. sand -1,0 to 2,0φ	F. sand 2,0 to 3,0φ	V.F. sand		Silt 4,0 to 5,0φ	Moment measures			
			3,0 to 3,5φ	3,5 to 4,0φ		Mean (φ)	Sorting (φ)	Skewness	Kurtosis
3700	-	20,3	26,1	53,6	-	3,45	,42	-,28	-,98
3703	-	-	-	72,6	27,4	3,85	,30	,52	-,67
3706	-	1,3	27,1	52,6	19,0	3,69	,30	-,04	-,58
3709	,9	13,2	47,2	36,6	2,1	3,34	,44	-,50	1,42
3712	-	4,6	66,4	29,0	-	3,34	,29	-,61	3,82
3716	-	13,1	65,0	21,4	,5	3,28	,27	,28	-,31
3719	1,7	38,5	45,6	11,5	2,7	3,12	,39	-,13	2,80
3738	14,8	29,6	40,7	14,9	-	2,82	,89	-,84	1,84
3744	-	5,4	63,0	27,7	3,9	3,37	,32	,25	-,32
3754	31,3	28,2	11,3	29,2	-	2,44	1,22	-,40	-,73
3759	-	12,0	45,6	40,1	,3	3,42	,33	-,01	-1,11
3783	-	27,3	8,1	65,6	-	3,44	,47	-,39	-1,06
3790	-	-	27,9	72,1	-	3,65	,16	,12	-1,18
3796	-	1,9	25,8	36,9	35,4	3,80	,40	-,07	-,95
3810	-	12,0	54,7	26,0	7,3	3,38	,38	,18	-,37
3815	-	-	65,2	34,8	-	3,45	,17	,27	-,74
3827	-	7,1	81,3	11,6	-	3,24	,19	,25	-,58
3829	-	62,3	33,4	4,3	-	2,98	,24	,64	1,71
3831	3,5	8,9	30,9	39,0	17,7	3,49	,57	-,70	2,77
3832	,1	35,0	44,7	14,7	5,5	3,21	,36	,37	,13
3837	77,3	19,8	2,5	,4	-	1,65	,61	,02	,70
3839	-	7,8	58,4	33,8	-	3,38	,29	,01	-,41
3843	-	-	68,0	32,0	-	3,41	,20	,01	-,61
3861	12,0	69,9	12,9	5,2	-	2,51	,51	,35	-,04
3863	-	37,7	51,0	11,3	-	3,13	,26	,21	-,65
3872	9,3	79,9	5,8	5,0	-	2,40	,44	,69	1,66
3876	-	-	35,1	60,1	4,8	3,61	,24	,04	-,87
3877	-	25,5	39,9	26,0	8,6	3,31	,51	-,14	-,88
3879	-	-	48,1	45,0	6,9	3,56	,28	,21	-,80
3881	,4	23,3	49,3	27,2	-	3,24	,40	-,34	,23
3884	-	-	17,2	63,7	19,2	3,75	,23	,17	-1,06
3886	-	19,1	52,8	23,6	4,5	3,31	,34	,35	-,63
3888	-	-	13,1	65,7	21,2	3,75	,24	,29	-,91
3891	-	4,6	58,7	32,7	4,0	3,40	,31	,24	-,86
3895	-	4,5	66,4	25,6	3,5	3,38	,29	,36	,01
3896	,5	27,8	47,0	20,1	4,0	3,18	,48	-,25	,48
3898	-	21,0	46,5	25,6	6,9	3,35	,39	,31	-,46
3900	-	5,1	18,7	76,2	-	3,57	,24	-,59	,82
3902	-	24,0	50,8	24,9	,2	3,27	,31	,22	-,75
3907	-	25,0	49,8	22,1	3,1	3,27	,33	,37	-,42
3910	1,0	29,5	48,5	19,2	1,8	3,18	,42	-,23	,66
3914	9,3	15,3	45,5	27,8	2,1	3,16	,65	-,77	2,23
3917	-	-	37,1	58,8	4,1	3,59	,17	,54	,85
3927	,2	26,9	60,7	12,2	-	3,17	,27	,35	1,96
3931	42,6	44,3	9,6	3,5	-	2,13	,74	-,04	-,28
3938	-	-	71,7	28,3	-	3,36	,23	,12	-,93
3941	-	7,6	29,7	43,5	19,2	3,62	,41	-,11	-,31
3948	,3	27,7	51,8	18,9	1,3	3,22	,32	,18	,60
3950	-	29,7	33,3	37,0	-	3,25	,46	-,23	-1,10
3952	-	13,8	53,1	28,9	4,2	3,36	,34	,23	-,67
3957	5,8	37,3	33,3	17,7	4,9	3,06	,64	-,76	4,22
3962	,2	27,6	59,9	12,3	-	3,16	,29	-,18	1,80
3965	-	24,1	52,8	21,0	2,1	3,27	,30	,29	-,31
3966	-	28,8	49,3	18,1	3,9	3,24	,37	,15	,42
3968	33,5	33,7	19,8	13,0	-	2,44	,98	-,27	-,67
3969	63,4	23,5	9,2	3,9	-	1,88	,81	,15	-,22

Appendix B.14 (continued)

Sample Number	V.C. to m. sand	F. sand	V.F. sand		Silt	Moment measures			
	-1,0 to 2,0 ϕ	2,0 to 3,0 ϕ	3,0 to 3,5 ϕ	3,5 to 4,0 ϕ	4,0 to 4,0 ϕ	Mean (ϕ)	Sorting (ϕ)	Skewness	Kurtosis
3970	3,2	73,6	23,0	,2	-	2,76	,33	-,26	1,21
3972	-	43,1	46,8	10,1	-	3,09	,29	,34	,85
3975	-	1,7	38,5	59,8	-	3,52	,30	-,19	-1,26
3977	-	-	87,2	12,8	-	3,31	,16	,47	,34
3980	-	77,0	18,1	4,9	-	2,80	,35	,53	,94
3984	-	-	43,0	34,4	22,6	3,60	,40	,04	-1,38
3987	-	-	16,4	61,1	22,5	3,78	,24	,12	-1,08
3991	47,3	48,7	4,0	-	-	2,01	,57	-,08	-,39
3998	7,4	80,3	9,1	3,2	-	2,52	,42	,31	,55
4003	-	7,2	46,3	35,9	10,6	3,51	,38	,14	-,45
4011	21,9	24,9	17,3	35,9	-	2,85	,92	-,30	-,91
4014	-	-	64,5	34,4	1,1	3,49	,19	,46	,13
4015	-	-	64,2	35,8	-	3,46	,19	,26	-,64
4028	37,2	31,7	14,0	11,1	7,0	2,23	1,30	-,14	-1,19
4037	2,8	10,9	14,0	69,7	2,6	3,49	,49	-,91	2,79
4042	-	5,5	75,8	18,7	-	3,29	,22	,14	-,29
4051	-	5,9	78,9	15,3	-	3,27	,25	,48	,80

- = not present

Note: the 4th moment (Kurtosis) as defined in the computer program differs from the conventional sedimentological definition. Equation of the Kurtosis values listed above with Friedman's (1962) verbal classification is as follows: Very platykurtic = -3,0 to -0,9, platykurtic = -0,9 to -0,3, mesokurtic = -0,3 to 0,3, leptokurtic = 0,3 to 1,5, very leptokurtic = 1,5 to 6,0, extremely leptokurtic = >6,0.

Appendix B.15 Weight percentage mica in selected samples

Sample Number	Nearest geographic location	Depth (metres)	Dist. from shore (n.miles)	Weight percentage in	
				sand fraction	total sample
3749	Swakopmund	22	3	42	32
3778	Swakopmund	20	2	29	13
3805	Cape Cross	54	6	27	8
3806	Cape Cross	35	4	18	12
3834	Ambrose Bay	43	3	81	40
3959	Sand Table Hill	45	3	37	18
3964	Palgrave Point	45	14	18	10
3985	Palgrave Point	48	3	93	31
3986	Ambrose Bay	38	2	8	7
Averages		39	5	39	19

Appendix B.16 Location and composition of Sardinops cores

Core Sec- tion	Lat. Deg.Min.	Long. Deg.Min.	Depth (metres)	Length (cm)	CaCO ₃ (apatite- free)	Corg	P ₂ O ₅	K ₂ O
24 Diatomaceous Mud (Group)								
a	23 01	14 19	80	20	1,9	7,8	,8	1,2
b					2,2	7,1	,8	,9
c					1,3	7,7	,8	1,0
d					,2	9,8	,9	1,3
25 Diatomaceous Mud (Group)								
a	22 55	14 13	104	33	ND	5,0	ND	ND
b					2,1	4,4	,3	,8
c					6,5	5,0	,4	,6
d					2,7	4,5	,3	,5
e					2,7	4,2	,4	,5
f					3,0	5,7	,3	,6
g					3,3	6,8	,5	,6
26 Diatomaceous Mud (Group)								
a	22 55	14 02	129	39	2,6	7,7	,8	,6
b					2,8	7,2	,4	,5
c					8,9	6,1	,6	,5
d					19,2	10,9	,8	,6
e					6,8	10,8	,7	,6
f					3,8	9,5	,6	,6
g					1,4	9,7	1,1	,6
h					6,3	5,9	,4	,5
27 Diatomaceous Mud (Group)								
a	22 49	13 59	130	40	ND	10,4	,3	ND
b					1,6	10,1	,5	,6
c					13,2	6,8	,8	,5
d					23,3	11,3	1,3	,6
e					23,0	14,6	1,0	,8
f					12,2	12,2	,6	,7
g					11,9	13,8	,6	,7
h					14,2	11,6	,8	,6
28 Diatomaceous Mud (Group)								
a	22 49	14 12	106	91	ND	5,5	,2	ND
b					1,9	5,5	,5	,5
c					2,0	7,1	,5	,6
d					1,2	6,8	,7	1,1
e					1,8	6,6	,4	,6
f					4,1	6,7	,5	,6
g					1,9	5,8	,7	,8
h					2,5	3,0	,3	,9
i					1,3	6,8	,4	,6
j					2,3	5,4	,4	,5
k					3,5	5,1	,4	,6
l					2,3	5,9	,4	,6
m					2,5	6,3	,5	,6
n					1,6	6,9	,5	,5
o					4,6	4,9	,3	,7
p					5,6	4,4	,3	,4
r					6,5	4,9	,3	,3
s					9,9	4,4	,3	,3

Appendix B.16 (continued)

Core Sec- tion	Lat. Deg.Min.	Long. Deg.Min.	Depth (metres)	Length (cm)	CaCO ₃ (apatite- free)	Corg	P ₂ O ₅	K ₂ O
29 Diatomaceous Mud (Group)								
a	22 46	14 17	75	65	2,9	4,0	,4	ND
b					,1	4,3	,2	,6
c					2,7	3,9	,4	,7
d					1,3	3,9	,5	,6
e					1,7	4,7	,6	,6
f					,6	ND	,5	,6
g					1,5	4,5	,4	1,0
h					1,5	2,7	,7	,8
i					,7	3,3	,3	,6
j					,8	3,2	,6	,7
k					,4	4,0	,4	,7
l					1,4	5,6	,6	,7
m					,1	5,5	,8	,7
30 Diatomaceous Mud (Group)								
a	22 44	14 12	95	37	ND	ND	ND	ND
b					3,2	5,7	,3	ND
c					2,0	6,8	,7	ND
d					1,1	6,7	,5	ND
e					1,3	6,9	,5	1,0
f					2,3	6,0	,4	,7
g					2,1	5,6	,4	,6
31 Diatomaceous Mud (Group)								
a	22 44	14 02	121	43	3,3	6,9	,4	,4
b					3,0	6,0	,2	,6
c					7,4	6,7	,5	ND
d					2,1	9,2	,9	ND
e					1,7	12,5	,6	ND
f					4,4	9,7	,5	,7
g					4,7	8,3	,5	,6
h					4,2	7,4	,5	,6
i					5,2	5,6	,4	,5
32 Diatomaceous Mud (Group)								
a	22 37	14 12	95	53	ND	6,5	1,7	ND
b					ND	7,7	1,7	1,0
c					,2	5,8	2,2	,7
d					1,6	6,5	1,8	,9
e					1,6	4,0	,6	,8
f					,5	6,4	2,6	,7
g					1,6	5,8	,9	,5
h					2,0	4,8	,2	,7
i					2,8	4,9	,4	,7
j					1,2	4,3	5,2	,7
k					1,4	3,5	12,1	,3
33 Diatomaceous Mud (Online)								
a	22 51	14 16	93	63	3,3	5,2	,3	,6
b					3,8	5,9	,4	,6
c					ND	4,0	1,3	,7
d					,7	4,4	,5	,6
e					1,6	7,1	,4	,5
f					1,6	6,2	,5	,6
g					2,4	4,8	,9	,6

Appendix B.16 (continued)

Core Sec- tion	Lat. Deg.Min.	Long. Deg.Min.	Depth (metres)	Length (cm)	CaCO ₃ (apatite- free)	Corg	P ₂ O ₅	K ₂ O
h					2,8	5,2	,3	,5
i					2,3	4,8	,3	ND
j					1,6	3,9	,8	,5
k					3,3	4,6	,2	,5
l					4,5	4,9	,4	,5
m					3,0	5,2	,2	,5
34 Diatomaceous Mud (Online)								
a	22 51	13 55	135	33	28,7	16,6	,8	1,0
b					33,1	12,3	,8	,5
c					35,3	12,3	,6	,7
d					33,6	12,9	,8	,8
e					33,4	12,0	,6	,8
f					34,4	13,8	,8	ND
g					42,4	15,4	,6	ND
35 Shelly Phos. foram sand (Online)								
a	22 51	13 33	157	10	73,4	3,3	1,1	,2
b					77,1	2,7	1,0	,2
36 Foram sand (Online)								
a	22 51	13 02	311	25	75,9	2,2	,4	,4
b					74,4	2,9	,4	,4
c					50,0	2,5	,5	,5
d					74,4	2,3	,4	,5
e					50,0	2,5	,5	,5
37 Diatomaceous mud with phos. laminations (Online)								
a	23 56	14 28	99	20	16,9	9,7	3,7	,9
b					18,1	11,5	3,2	1,0
c					17,2	11,9	1,8	1,0
d					16,1	10,6	1,4	1,0
38 Phos. foram sand (Online)								
a	23 56	13 58	210	25	51,5	3,7	13,9	,5
b					51,5	1,9	10,9	,3
c					50,4	1,6	10,3	,5
d					29,7	1,4	18,9	,5
e					31,3	1,4	21,3	,5
39 Phos. foram sand (Online)								
a	23 56	13 29	265	35	64,6	3,1	3,8	,4
b					64,5	2,9	5,0	,4
c					62,6	3,0	5,4	,4
d					70,2	4,1	4,4	,4
e					41,5	3,2	5,2	,4
f					64,8	2,3	5,4	,4
g					60,6	1,8	6,9	,4
40 Phos. faecal pellet foram sand (Online)								
a	23 23	13 35	194	21	55,2	5,1	7,7	,5
b					53,1	4,8	8,4	,5
c					52,2	4,5	7,5	,3
d					70,7	1,8	5,8	,2

Appendix B.16 (continued)

Core Sec- tion	Lat. Deg.Min.	Long. Deg.Min.	Depth (metres)	Length (cm)	CaCO ₃ (apatite- free)	Corg	P ₂ O ₅	K ₂ O
41 Phos. foram sand/diatomaceous mud (Online)								
a	23 23	13 57	146	37	11,8	2,3	22,0	,4
b					23,1	7,9	17,7	,4
c					1,1	7,5	,4	1,5
d					1,0	7,3	,5	1,1
e					,8	8,1	,4	1,4
f					1,0	8,3	,6	1,1
g					,9	6,5	,4	1,2
h					,7	6,2	,7	1,1
42 Diatomaceous mud (Online)								
a	23 23	14 18	110	45	5,0	6,7	,4	,7
b					4,0	7,1	,4	,7
c					3,3	5,5	,4	,7
d					5,4	5,9	,4	,5
e					4,6	5,9	,3	,5
f					5,0	5,9	,4	,5
g					9,1	5,5	,3	,5
h					5,5	5,5	,4	,5
i					4,3	5,7	,5	,6
43 Diatomaceous mud (Online)								
a	21 47	13 47	83	32	1,0	8,9	3,6	,6
b					3,9	7,0	3,0	,7
c					3,6	8,1	2,2	,7
d					3,1	6,1	1,5	,8
e					3,7	5,4	,7	,8
f					3,7	5,6	1,2	,9
g					4,5	6,9	,7	,6
44 Faecal pellet foram sand (Online)								
a	21 47	13 04	274	12	45,5	5,9	,7	,7
b					62,7	5,5	,6	,7
c					62,3	5,5	,7	,6
45 Micaceous diatom mud (Online)								
a	21 10	13 26	84	33	7,7	9,2	1,5	1,0
b					6,4	9,3	1,0	1,0
c					5,7	8,0	,8	1,1
d					5,4	7,5	,8	1,2
e					8,0	7,9	,6	1,0
f					4,8	7,2	,5	1,1
g					5,9	6,5	,5	1,0
46 Shelly quartzose foram sand (Online)								
a	21 10	13 05	137	10	62,9	2,7	,3	ND
b					69,7	2,0	,3	,6
47 Foram sand (Online)								
a	21 10	12 45	357	39	70,3	3,4	,3	,6
b					63,6	4,4	,3	,7
c					58,2	4,2	,3	,7
d					65,8	3,6	,3	,8
e					64,1	3,6	,3	,7
f					67,7	3,8	,3	,7
g					70,8	2,4	,3	,8
h					67,7	2,6	,3	,7

Appendix B.16 (continued)

Core Sec- tion	Lat. Deg.Min.	Long. Deg.Min.	Depth (metres)	Length (cm)	CaCO ₃ (apatite- free)	Corg	P ₂ O ₅	K ₂ O
48 Faecal pellet foram sand (Online)								
a	22 15	13 16	194	10	74,5	4,4	,8	,3
b					73,8	4,1	,8	,3
49 Diatomaceous quartzose silt (Online)								
a	22 15	13 36	121	38	21,8	12,8	,6	,6
b					30,0	14,0	,8	,5
c					23,1	12,5	,7	,6
d					42,3	12,7	,8	,6
e					29,7	14,0	,6	,7
f					33,1	14,0	,9	,7
g					40,4	15,4	1,2	,6
h					35,8	13,4	1,0	,7
50 Diatomaceous mud (Online)								
a	22 15	13 59	84	28	3,1	6,5	,9	ND
b					3,0	6,5	,5	,8
c					5,5	5,8	,5	ND
d					4,0	5,4	,9	,6
e					4,4	4,7	1,1	,7
f					4,8	4,8	,5	,7

ND = insufficient material available for analysis

Each of the subsections from "a" onwards measure 5cms in length, except for the last, which is usually less than 5cms

Appendix B.17 Mineralogy of the sediment clay fraction (<2µm)

Sample No.	Environment and material	Total counts	Percentages			14Å/10Å ratio	Crystallinity of 17Å peak
			17Å	10Å	7Å		
Kunene	River silt	489	59	9	32	,17	,07
Hoarib	" "	667	18	71	11	,24	,11
Ugab	" "	384	9	80	11	,10	,25
Swakop	" "	1,284	4	87	9	,03	,27
3661	Inner shelf	637	31	50	19	,27	,13
3674	Kunene mud	569	34	52	14	,38	,21
3881	" "	60	13	73	13	,33	,50
3891	" "	648	30	54	16	,27	,16
3426	Inner shelf	54	9	82	9	,50	,40
3451	diatomace-	<50	-	Tr	-	-	-
3496	ous mud	<50	-	Tr	-	-	-
3517	"	<50	-	Tr	-	-	-
3546	"	<50	-	Tr	-	-	-
3567	"	<50	-	Tr	-	-	-
3712	"	153	11	73	16	,33	,22
3717	"	341	12	79	9	,33	,30
3754	"	<50	-	Tr	-	-	-
3756	"	162	-	91	9	1,00	,43
3773	"	<50	-	Tr	-	-	-
3784	"	<50	-	Tr	-	-	-
3802	"	50	9	87	4	,75	,50
3811	"	121	9	83	8	,38	,50
3831	"	130	9	86	5	,27	,57
3839	"	108	7	85	7	,40	,36
3910	"	348	28	66	6	,39	,36
3950	"	77	13	78	9	,67	,28
3961	"	73	18	77	5	,60	,33
3413	Mid shelf	268	-	94	6	1,18	,25
3494	sand	250	-	91	9	,79	,21
3687	"	381	33	55	12	,38	,18
3694	"	704	31	59	10	,29	,21
3710	"	651	24	65	11	,54	,18
3759	"	652	-	87	13	,78	,15
3800	"	448	-	87	13	,82	,21
3841	"	429	9	78	13	,45	,21
3877	"	549	35	47	19	,39	,12
3409	Upper slope	346	36	43	21	,83	,26
3704	mud	429	30	47	23	,56	,17
3762	"	291	14	62	24	,69	,17
3845	"	481	12	67	21	,41	,29
3884	"	459	30	48	22	,36	,17
3411	Outer margin	780	28	60	12	,30	,15
3431	stiff muds	215	16	74	9	,21	,20
3555	"	406	28	63	9	,29	,23
3564	"	484	19	70	11	,23	,20
3655	"	442	71	20	9	,76	,10
3665	"	553	43	41	16	,45	,07
3886	"	457	35	46	18	,35	,12
14-16	Upper slope	427	13	75	12	,09	,21
44-46	piston core	363	15	75	10	,14	,23
75-77	No.2	459	29	59	12	,20	,10

Tr = trace amounts

- = not detected

Appendix B.18 Trace and major element composition of the sediment clay fraction (<2µm)

Sample No.	Environment	Cu*	Ni*	Pb*	Zn*	Co*	Cd*	Rb*	Sr*	Ca	Mg	Mn*	Fe	Al	K
Kunene	River	25	48	186	104	20	3	154	72	10,2	1,76	458	6,14	23,4	1,36
Hoanib	Silt	57	45	34	266	37	Tr	153	132	5,45	7,90	831	7,97	10,0	2,54
Ugab	"	39	51	73	360	40	6	177	182	3,57	5,88	956	10,2	13,0	3,37
Swakop	"	83	64	45	242	44	Tr	232	99	2,61	5,74	1,080	10,4	18,4	3,24
3661	Inner	36	70	24	89	15	4	127	136	3,88	5,02	280	8,97	13,2	1,39
3674	shelf	28	59	28	91	7	3	116	130	3,18	4,93	187	8,14	10,2	1,78
3881	kunene	36	63	20	83	Tr	34	76	82	2,09	1,91	132	3,18	5,60	1,10
3891	mud	31	59	18	74	12	4	110	137	4,51	4,26	202	5,96	9,86	1,57
3426	Inner	68	128	40	171	Tr	44	39	431	9,70	1,55	91	1,92	3,61	,31
3451	shelf	38	38	Tr	60	-	38	Tr	91	1,95	,55	45	,78	1,63	,21
3496	diatom.	32	49	27	47	-	17	25	227	5,13	,69	38	,85	2,04	,39
3517	mud	29	52	24	62	-	33	23	41	2,66	,43	45	,85	2,63	,37
3546	"	25	27	Tr	27	-	21	Tr	44	1,28	,14	32	,40	1,49	,24
3567	"	51	68	25	96	-	55	36	201	4,89	,64	54	1,16	2,94	,44
3712	"	37	58	24	73	6	14	79	201	4,39	2,45	144	3,09	6,20	1,28
3717	"	40	78	31	83	6	20	82	239	6,38	2,22	145	3,01	6,40	1,23
3754	"	25	36	17	76	-	17	Tr	86	1,32	,57	37	,66	1,60	,34
3756	"	87	226	41	256	11	56	33	1,080	23,0	1,55	60	1,50	3,91	,63
3773	"	44	126	Tr	164	-	60	28	153	3,78	,98	47	,96	3,03	,50
3784	"	55	89	25	95	-	29	30	171	4,75	,64	54	,61	2,24	,31
3802	"	53	66	28	76	-	30	30	70	1,43	1,02	74	1,00	3,03	,34
3811	"	32	46	20	49	-	34	65	81	1,89	1,50	118	2,19	4,57	,97
3831	"	51	56	26	58	Tr	26	91	78	2,00	2,07	156	2,96	6,53	1,36
3839	"	49	85	Tr	101	5	23	85	267	7,04	2,36	132	2,92	5,07	1,28
3910	"	37	65	Tr	83	7	13	134	137	5,72	3,91	206	4,65	8,03	1,83
3950	"	39	52	Tr	68	-	19	59	153	5,21	2,05	103	2,72	4,64	,90
3961	"	28	58	21	140	-	20	61	222	6,68	1,60	110	2,19	4,63	,84
3413	Mid	58	118	31	207	Tr	15	34	670	19,0	1,45	126	1,48	3,61	,71
3494	shelf	58	129	21	137	13	10	25	1,060	25,0	1,14	49	,83	1,99	,21
3687	sand	38	76	35	69	Tr	Tr	105	291	7,71	3,24	182	4,89	8,56	1,78
3694	"	38	64	54	66	Tr	8	110	225	5,93	3,12	224	4,92	9,95	1,94
3710	"	43	88	29	57	10	8	88	542	14,3	2,67	146	3,78	5,59	1,31

Appendix B.18 (continued)

Sample No.	Environment	Cu*	Ni*	Pb*	Zn*	Co*	Cd*	Rb*	Sr*	Ca	Mg	Mn*	Fe	Al	K
3710	Mid shelf sand "	43	88	29	57	10	8	88	542	14,3	2,67	146	3,78	5,59	1,31
3759		60	123	36	85	21	9	51	1,240	25,6	1,38	74	1,52	4,16	,60
3800		49	112	44	79	7	10	33	768	21,0	1,02	57	1,04	2,22	,29
3841		55	117	49	79	Tr	8	66	628	17,7	2,64	123	3,15	5,32	1,44
3877		46	86	61	99	11	-	126	145	2,48	4,07	225	7,12	7,36	3,45
3409	Upper slope mud "	49	72	29	119	10	3	76	188	5,20	4,21	164	8,34	9,35	1,11
3704		51	93	26	122	15	5	76	592	13,9	3,43	136	4,86	7,72	1,20
3762		58	126	32	87	28	4	54	1,870	29,6	3,79	88	2,62	6,69	1,15
3845		69	123	29	159	15	5	77	729	19,0	2,72	132	4,37	7,25	1,16
3884		54	79	28	121	13	Tr	101	320	8,65	4,43	171	7,69	10,4	1,58
3411	Outer margin stiff muds "	44	82	48	114	18	Tr	188	149	3,49	4,24	215	5,68	15,0	3,39
3431		47	70	54	110	7	4	232	216	7,04	4,07	232	5,45	15,5	1,28
3555		63	114	24	167	13	4	148	414	9,70	3,95	194	4,94	11,1	2,77
3564		59	128	19	114	Tr	38	121	172	3,03	3,02	209	5,46	15,5	1,88
3655		44	84	42	184	28	4	165	382	9,70	4,36	208	7,05	13,7	2,82
3665		29	56	28	146	11	Tr	132	355	8,37	4,76	214	7,41	8,87	2,11
3886		39	83	38	125	11	4	141	171	6,38	4,29	223	6,14	12,1	1,83
14-16	Upper slope piston core No.2	56	104	32	87	21	6	54	1,090	25,6	2,12	125	2,48	5,64	1,26
44-46		55	108	65	118	21	8	46	1,030	28,3	1,88	131	2,52	7,39	1,05
75-77		57	100	35	110	15	4	59	1,030	23,0	2,00	56	2,13	5,16	,97
Lower limit of determination		9	7	16	2	5	3	20	30	0,06	0,02	6	0,03	0,05	0,006

* These elements reported in ppm, the others in %.

- = Not detected.

Tr = Present, but concentration below the limit of determination.

Note: The lower limit of determination (sensitivity), which is the concentration which will generate a signal of 1% absorbtion or 0,0044 Absorbance Units (Anonymous, ., 1971), was determined by proportioning the average absorbance value of the least concentrated aqueous standard solution, to 0,0044 A.U., and then multiplying this concentration (ppm) by the dilution factor (200).

Appendix B.19 Instrument settings for the atomic absorption spectrophotometer
Varian Techtron Model A.A.6.

Element	Wave length (nm)	Slit width (nm)	Lamp current (mA)	Fuel	Flow rate (Litres/min.)	Oxidant	Flow rate (Litres/min.)
Cu	324,7	0,5	3	Acetylene	2	Air	11
Ni	232,0	0,2	3	Acetylene	2	Air	11
Pb	217,0	0,1	5	Acetylene	2	Air	11
Zn	213,9	0,5	5	Acetylene	2	Air	11
Co	240,7	0,1	5	Acetylene	2	Air	11
Cd	228,8	0,5	3	Acetylene	2	Air	11
Rb*	780,0	0,2	15	Acetylene	2	Air	11
Sr*	460,7	0,5	10	Acetylene	5	N ₂ O	9
Ca*	422,7	0,2	10	Acetylene	5	N ₂ O	9
Mg*	285,2	0,2	3	Acetylene	5	N ₂ O	9
Mn	279,5	0,2	5	Acetylene	2	Air	11
Fe	248,3	0,2	5	Acetylene	2	Air	11
Al*	309,3	0,5	5	Acetylene	5	N ₂ O	9
K*	404,4	1,0	5	Acetylene	2	Air	11

* A 1% KCl ionisation buffer was used, except for K, where 1% CsCl was used.

Appendix B.20 Standard and calculated elemental concentrations of six international standards using atomic absorption spectrophotometer

B.20.1 Trace elements (ppm)

Int. Std.	Cu			Ni			Pb			Zn			Co			Rb			Sr			Mn		
	Std.	Calc.	err.	Std.	Calc.	err.	Std.	Calc.	err.	Std.	Calc.	err.	Std.	Calc.	err.	Std.	Calc.	err.	Std.	Calc.	err.	Std.	Calc.	err.
NIM-G	15	14	6,67	4*	2	50,0	38	35	7,89	60	63	4,76	6	-		274	335	22,2	13	10	23,1	155	132	14,8
NIM-N	13	15	15,4	121*	117	3,31	10	14	40,0	80	70	12,5	65	57	12,3	9	5	44,4	254	250	1,57	1390	1360	2,37
NIM-S	23	24	4,35	8	11	37,5	13	12	7,69	21	28	33,3	4	6	50,0	550	522	5,09	76	54	29,0	77	74	3,96
AGV-1	60	55	8,33	19	23	21,1	35	40	14,3	84	77	8,33	14	17	21,4	67	61	8,96	657	653	,609	744	816	5,43
BCR-1	18	19	5,56	16	13	18,8	18	12	33,3	120	134	11,7	38	40	5,26	47	33	29,8	330	322	2,42	1470	1440	2,04
W-1	110	112	1,82	76	82	7,89	8	9	12,5	86	78	9,30	47	56	19,2	21	12	42,9	190	229	17,0	1320	1360	3,42
Average % error	7,02			23,1			19,3			13,3			34,7			25,6			12,3			5,3		

B.20.2 Major elements (%)

Int. Std.	Ca			Mg			Fe			Al			K		
	Std.	Calc.	err.	Std.	Calc.	err.	Std.	Calc.	err.	Std.	Calc.	err.	Std.	Calc.	err.
NIM-G	5503	1,36	148,	30302	,046	53,6	1,3709	1,26	7,87	6,4196	6,12	4,78	4,8140	3,98	17,4
NIM-N	8,1975	7,63	6,97	4,5600	3,98	12,8	6,2600	6,52	4,13	8,7164	7,68	11,9	,2075	,255	22,8
NIM-S	,4860	,407	16,1	,2895	,023	92,2	1,0072	,862	14,4	9,0816	8,61	5,23	12,7843	12,9	,671
AGV-1	3,5735	2,53	29,2	,9349	1,29	37,6	4,7842	5,10	6,63	9,1133	10,5	14,8	2,4323	2,25	7,52
BCR-1	4,9885	4,60	7,78	2,1051	2,99	42,0	9,4564	9,26	2,08	7,2399	8,06	11,3	1,3947	1,47	5,48
W-1	7,8473	9,11	16,1	3,9990	4,14	3,61	7,7708	7,65	1,62	7,8697	7,68	2,45	,5313	,713	34,1
Average % error	37,3			40,3			6,1			8,4			14,7		

* U.C.T. values. All other trace element values from Flanagan (1973), except Mn, which is from Abbey (1975).

All major element values from Abbey (1975)

$$\% \text{ error} = \frac{|\text{Std.} - \text{Calc.}|}{\text{Std.}} \times 100, \text{ Average } \% \text{ error} = \frac{\Sigma \% \text{ error}}{6}$$

Appendix B.21 Trace and major element concentrations of different sediment size fractions, and percentage deviations between two separate clay-fraction determinations

	3426					3754					3756					3950					Average P.D.
	Gr/Sa	Silt	Clay	Old Clay	P.D.	Gr/Sa	Silt	Clay	Old Clay	P.D.	Gr/Sa	Silt	Clay	Old Clay	P.D.	Gr/Sa	Silt	Clay	Old Clay	P.D.	
Cu*	64	51	84	68	10,5	44	40	46	25	29,6	64	58	71	87	10,1	50	57	66	39	25,7	19,0
Ni*	115	87	129	128	,389	99	74	51	36	22,2	122	117	319	226	17,1	78	86	64	52	10,3	12,5
Pb*	22	16	21	40	31,2	12	12	6	17	47,8	32	21	19	27	17,4	14	22	10	13	13,0	27,4
Zn*	79	38	139	171	10,3	69	64	42	76	9,32	57	105	76	256	54,2	56	67	73	68	3,55	19,4
Co*	1	4	1	1	0	-	-	-	-	-	16	16	7	11	22,2	1	-	-	-	-	11,1
Cd*	92	39	46	44	2,22	99	60	30	17	27,7	55	34	27	56	34,9	50	39	22	19	7,32	18,0
Rb*	20	15	38	39	1,30	25	20	15	15	0	10	25	17	33	32,0	51	61	54	59	4,42	9,43
Sr*	892	444	402	431	3,48	223	116	102	86	8,51	998	861	743	1079	18,4	588	427	215	153	16,9	11,8
Ca	21,42	10,97	8,77	9,70	5,04	7,17	1,52	,89	1,32	19,5	21,1	23,6	17,3	23,0	14,0	11,02	5,29	3,78	5,21	15,9	13,6
Mg	,91	,67	1,17	1,55	14,0	,79	,69	,45	,57	11,8	1,19	,62	,93	1,55	25,0	1,26	1,26	1,12	2,05	29,3	20,0
Mn*	72	93	93	91	1,09	89	78	52	37	16,9	59	83	55	60	4,35	137	183	133	104	12,2	8,39
Fe	1,16	1,20	1,44	1,92	14,3	1,45	1,12	,69	,66	2,22	,63	,78	,64	1,50	40,2	2,29	2,60	1,78	2,72	20,9	19,4
Al	2,77	3,50	3,91	3,61	4,00	1,47	1,89	1,15	,60	31,4	2,24	3,21	2,36	3,91	24,7	4,46	5,73	5,35	4,64	7,11	16,8
K	,58	,67	,91	,31	49,2	,56	,55	,46	,34	15,0	,37	,60	,55	,63	6,78	,99	1,39	1,03	,90	6,74	19,4

* concentrations in ppm, otherwise in %.

- = present in trace amounts

Old clay = original value determined 1 year previously, see Table

Percentage deviation (P.D.) = $\left[\frac{x_1 - x_2}{\frac{x_1 + x_2}{2}} \right] \times 100$, where x_1 = present clay value and x_2 = old clay value

Average P.D. = EPD/4.

Appendix B.22 Trace and major element abundances in different sediment size fractions, and percentage deviations between total and bulk element abundances

Size fractions (Z)**	3426					3754					3756					3950					Average P.D.				
	Gr/Sa	Silt	Clay	Total	Bulk	P.D.	Gr/Sa	Silt	Clay	Total	Bulk	P.D.	Gr/Sa	Silt	Clay	Total	Bulk	P.D.	Gr/Sa	Silt		Clay	Total	Bulk	P.D.
	57,8	28,0	14,2				25,1	18,7	56,2				55,1	26,5	18,4				36,8	24,6	38,6				
Cu*	37	14	12	63	74	8,03	11	7	26	44	35	11,4	35	15	13	63	60	2,44	18	14	25	57	51	5,56	6,86
Ni*	66	24	18	108	133	10,4	25	14	29	68	59	7,09	67	31	59	157	121	13,0	29	21	25	75	76	,66	7,77
Pb*	13	4	3	20	12	25,0	3	2	3	8	9	5,88	18	6	4	28	25	5,66	5	5	4	14	9	21,7	14,6
Zn*	46	11	20	77	73	2,67	17	12	24	53	44	9,28	31	28	14	73	77	2,67	21	16	28	65	56	7,44	5,52
Co*	1	1	-	2	4	33,3	-	-	-	-	-	-	9	4	2	15	14	3,45	-	-	-	-	-	-	18,4
Cd*	53	11	6	70	77	4,76	25	11	17	53	43	10,4	30	9	5	44	43	1,15	18	10	8	36	37	1,37	4,43
Rb*	12	4	5	21	28	14,3	6	4	8	18	20	5,26	6	7	3	16	25	22,0	19	15	21	55	59	3,51	11,3
Sr*	516	124	57	697	811	7,56	56	22	57	135	140	1,82	550	228	137	915	786	7,58	216	105	83	404	332	9,78	6,69
Ca	12,4	3,07	1,25	16,7	20,3	9,63	1,80	,28	,50	2,58	3,11	9,31	11,6	6,25	3,19	21,1	22,1	2,41	4,06	1,30	1,46	6,82	6,30	3,96	6,33
Mg	53	,19	,17	,89	1,26	17,2	,20	,13	,25	,58	1,31	38,6	,66	,16	,17	,99	1,28	12,8	,46	,31	,43	1,20	1,88	22,1	22,7
Mn*	5	26	13	44	80	29,0	22	15	29	66	63	2,33	33	22	10	65	77	8,45	50	45	51	146	158	3,95	10,9
Fe	,67	,34	,20	1,21	1,24	1,22	,36	,21	,39	,96	,82	7,87	,35	,21	,12	,68	,74	4,23	,84	,64	,69	2,17	2,16	,23	3,39
Al	1,60	,93	,56	3,14	2,47	11,9	,37	,35	,65	1,37	2,47	28,7	1,23	,85	,43	2,51	2,71	3,83	1,64	1,41	2,07	5,12	5,18	,53	11,3
K	,34	,19	,13	,66	,73	5,04	,14	,10	,26	,50	,54	3,85	,20	,16	,10	,46	,66	17,9	,36	,34	,40	1,10	1,16	2,65	7,35

* concentrations in ppm, otherwise in %.

** from Table

- = present in trace amounts.

Percentage deviation (P.D.) = $\left[\frac{x_1 - x_2}{\frac{x_1 + x_2}{2}} \right] \times 100$, where x_1 = total, and x_2 = bulk

Average P.D. = EPD/4.

Appendix B.23 Major element geochemistry of phosphorites⁺ and glauconite from analysis by XRF (%)

	Pelletal phosphorite (pP)					Glauconitized pelletal phosphorite (gpP)					Concretionary phosphorite (cP)				Glauconite (G)			
	3411	3439	3454	3558*	Average	3719	3906	3914	3941*	Average	3773	3784*	4031*	Average	3677	3877	4037*	Average
SiO ₂	5,56	5,31	4,74	4,26	4,97	8,76	7,16	8,27	8,86	8,06	-	-	-	-	49,07	48,20	47,98	48,42
Al ₂ O ₃ **	1,10	1,14	1,18	1,06	1,12	1,92	1,37	1,68	1,74	1,66	-	-	-	-	5,31	5,17	6,28	5,59
Fe ₂ O ₃	3,25	2,53	2,36	2,05	2,55	6,54	7,31	6,25	6,91	6,70	,02	,04	,03	,03	25,27	24,59	23,19	24,35
MgO	,83	,84	,80	,83	,83	1,06	,79	1,03	,87	,96	,79	,73	,86	,79	4,40	4,27	4,19	4,29
CaO	46,43	46,28	47,72	47,28	46,93	38,68	37,38	40,12	39,74	38,73	48,69	48,15	48,24	48,36	,56	,34	,87	,59
Na ₂ O	,57	,51	,51	,41	,50	,35	,36	,31	,07	,34	,91	,96	,98	,95	,01	,04	,01	,02
K ₂ O	,42	,41	,39	,29	,38	,68	,62	,49	,75	,60	-	-	-	-	7,96	7,50	8,69	8,05
P ₂ O ₅	28,54	27,84	28,56	27,22	28,04	24,24	25,54	25,96	26,39	25,25	33,06	32,16	32,64	32,62	,19	,17	,29	,22
S	2,97	2,35	2,04	1,88	2,31	1,99	2,19	1,83	1,34	2,00	,76	,79	,82	,79	,06	,04	,08	,06
F	3,20	3,22	3,15	3,25 [@]	3,21	2,65	2,45 [@]	2,82	2,45 [@]	2,64	3,32	3,10	3,21 [@]	3,21	,14	,12	,13 [@]	,13
L.O.I.	10,36	10,63	10,33	11,98	10,83	12,11	14,06	11,99	10,90	14,77	13,39	13,34	14,31	13,68	5,55	6,09	6,59	6,08
H ₂ O ⁻	1,28	1,17	,96	1,37	1,20	1,95	2,01	2,29	2,70	2,08	2,72	2,34	2,53	2,53	2,14	2,74	2,20	2,36
SUB TOTAL	104,51	102,23	102,74	101,88	102,87	100,93	101,24	103,04	102,72	103,79	103,66	101,61	103,62	102,96	100,66	99,27	100,50	100,16
O=S	1,49	1,18	1,02	,94	1,16	1,00	1,10	,92	,67	,92	,38	,40	,41	,40	,03	,02	,04	,03
O=F	1,34	1,35	1,32	1,37	1,35	1,11	1,03	1,18	1,03	1,09	1,39	1,30	1,35	1,35	,06	,05	,05	,05
TOTAL	101,68	99,70	100,40	99,57	100,36	98,82	99,11	100,94	101,02	101,78	101,89	99,91	101,86	101,21	100,57	99,20	100,41	100,08
CO ₂	3,09	3,57 [@]	3,57 [@]	4,22	3,61	3,89 [@]	4,15	4,50	3,73	4,07	5,43	5,15	4,87	5,15	-	-	-	-
Corg	2,84	2,67	2,66	2,62 [@]	2,70	2,10	1,39 [@]	,60	1,39 [@]	1,37	1,24	1,38	1,31 [@]	1,31	-	-	-	,32
CaO/P ₂ O ₅	1,63	1,66	1,67	1,74	1,68	1,60	1,46	1,55	2,42	1,76	1,47	1,50	1,48	1,48	2,95	2,00	3,00	2,65
F/P ₂ O ₅	,112	,116	,110	,119	,114	,109	,096	,109	,149	,116	,100	,096	,098	,098	,737	,706	,448	

Samples were analysed in duplicate on Norrish Fusion Discs, except * which were analysed singleton because of lack of material for two discs

+ Only selected pP and gpP are listed here because of significant sample contamination in some samples (see Appendix A.34).

**Total iron reported as Fe₂O₃.

@ = Insufficient material, therefore average values used (see Appendices B.12 and B.13).

S analysed as trace element using briquettes.

CO₂, Corg and F analyses (see Appendix A.16).

Appendix B.24 Trace element geochemistry of phosphorites and glauconite from analysis by XRF (ppm)

	Pelletal phosphorite (pP)					Glauconitized pelletal phosphorite (gpP)					Concretionary phosphorite (cP)				Glauconite (G)			
	3411	3439	3454	3558	Average	3719	3906	3914	3941	Average	3773	3784	4031	Average	3677	3877	4037	Average
Nb	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3*	<3	<3	<3
Zr	26	44	28	17	29	31	31	37	11	28	<3	<3	<3	<3	43	33	55	44
Y	220	206	187	212	206	348	315	267	204	284	6	8	7	7	7	8	14	10
Sr	2250	2270	2270	2260	2260	1850	1630	1860	1160	1630	2410	2300	2330	2350	14	18	23	18
Rb	8	8	8	5	7	20	23	16	22	20	<3	<3	<3	<3	202	167	185	185
Ba	43	66	100	55	66	64	57	77	48	62	83	74	80	79	6	12	17	12
Co	9	<7	<7	<6	<10	11	<8	<8	9	<12	<5	<5	<5	<5	<10	<10	<10	<10
Cr	218	195	183	182	195	382	299	310	210	300	15	10	18	14	473	776	894	714
V	43	38	40	38	40	75	79	66	49	67	24	12	23	20	222	160	159	180
Zn	29	26	27	24	27	41	44	56	43	46	66	79	108	84	30	31	30	30
Cu	23	28	24	38	28	45	25	37	86	48	<2	9	2	4	6	<2	3	4
Ni	75	63	60	43	60	97	33	71	117	80	6	6	8	7	6	3	18	9
Ti**	495	520	455	380	463	1420	590	945	600	890	30	50	50	43	2090	965	870	1310
Mn**	45	20	25	30	30	160	75	85	40	90	35	-	-	12	220	95	90	135

Samples were analysed singleton on briquettes

* Results below the lower limit of detection. These L.L.D. values were incorporated in "average" determinations

** Ti, Mn analysed as major elements, and % values converted to ppm

Appendix B.25

Instrument settings and conditions for the X-ray fluorescence spectrometers

Element	Tube	Kv/ma	Crystal	Collimator	Detector	Discrim.	2 θ ^o	Counting time(secs)
<u>Philips P.W. 1220</u>								
Fe	W	55/36	LiF ₂₂₀	Fine	Flow.	Ext.	85,64	10
Mn	W	55/36	LiF ₂₂₀	Fine	Flow.	Ext.	95,12	40
Ti	Cr	55/36	LiF ₂₀₀	Coarse	Flow.	Ext.	86,29	10
Ca	Cr	55/36	LiF ₂₀₀	Fine	Flow.	Ext.	113,14	10
K	Cr	55/36	LiF ₂₀₀	Coarse	Flow.	Ext.	136,83	20
Si	Cr	55/36	P.E.T.	Coarse	Flow.	Ext.	109,06	100
Al	Cr	55/36	P.E.T.	Coarse	Flow.	Ext.	144,98	100
Mg	Cr	55/36	T.L.A.P.	Fine	Flow.	140/145/1	45,07	200
P	Cr	55/36	P.E.T.	Coarse	Flow.	380/220/1	89,47	100
Na	Cr	55/36	T.L.A.P.	Coarse	Flow.	070/170/1	54,06	200
Nb	W	70/28	LiF ₂₂₀	Fine	Scint.	300/400/1	30,36	200
Zr	W	70/28	LiF ₂₂₀	Fine	Scint.	300/400/1	32,04	100
Y	W	70/28	LiF ₂₂₀	Fine	Scint.	300/400/1	33,82	100
Sr	W	70/28	LiF ₂₂₀	Fine	Scint.	300/400/1	35,79	100
Rb	W	70/28	LiF ₂₂₀	Fine	Scint.	300/400/1	37,92	100
Co	W	60/32	LiF ₂₂₀	Fine	Flow.	Ext.	77,94	200
Cr	W	60/32	LiF ₂₂₀	Fine	Flow.	Ext.	107,18	200
V	W	60/32	LiF ₂₂₀	Fine	Flow.	Ext.	123,28	200
Zn	Au	60/32	LiF ₂₂₀	Fine	Flow./scint.	240/440/1	60,67	200
Cu	Au	60/32	LiF ₂₂₀	Fine	Flow./scint.	240/440/1	65,65	200
Ni	Au	60/32	LiF ₂₂₀	Fine	Flow./scint.	240/440/1	71,38	200
S	Cr	55/36	Ge	Coarse	Flow.	Ext.	110,88	100
<u>Philips P.W. 1540</u>								
Ba	Cr	50/20	LiF ₂₂₀	Fine	Flow.	040/500/1	154,46	(3 x 100)

Appendix B.26 Major element concentration of standards used in X-ray fluorescence study (%)

Standard	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	MnO	TiO ₂	Loss*
GH	75,79	12,62	1,36	,05	,66	3,81	4,78	,01	,05	,08	,83
W-1	52,60	14,90	11,12	6,62	10,92	2,15	,64	,14	,17	1,08	,62
S-1	59,58	9,30	8,30	4,06	10,10	3,38	2,65	,22	,40	,48	,96
M-38	59,79	18,39	7,24	3,35	,73	1,75	5,12	,30	,11	,85	2,26
KL-11	51,54	16,01	10,88	6,69	10,97	2,19	,64	,19	,17	,89	,35
PG-11	73,35	13,76	1,94	,28	1,17	3,10	5,49	,07	,04	,22	,30
OK-272	61-16	16,34	6,59	1,04	2,35	5,25	5,03	,27	,24	1,04	,21
GSP-1	67,38	15,25	4,33	,96	2,02	2,80	5,53	,28	,04	,66	1,04
AGV-1	59,08	17,06	6,79	1,52	4,97	4,24	2,89	,49	,10	1,05	,91
BCR-1	54,50	13,61	13,40	3,46	6,92	3,27	1,70	,36	,18	2,20	,85
PCC-1	41,88	,73	8,23	43,22	,49	,05	-	,02	,12	,02	4,95
DTS-1	40,50	,24	8,64	49,80	,15	,05	-	-	,11	,01	,55
MRG-1	39,09	8,49	17,87	13,51	15,03	,62	,17	,16	,18	3,77	1,32
LBM-39	41,27	-	5,70	52,54	-	-	-	-	,05	-	,62
NIM-P	51,15	4,20	12,70	25,25	2,69	,36	,09	,02	,22	,20	,38
Fe-Ca	-	-	20,00	-	80,00	-	-	-	-	-	-
SiTi ₅	95,00	-	-	-	-	-	-	-	-	5,00	-
SiMn ₁₀	90,00	-	-	-	-	-	-	-	10,00	-	-
SiFe ₁₀	90,00	-	10,00	-	-	-	-	-	-	-	-
SiCa ₁₀	90,00	-	-	-	5,60	-	-	-	-	-	4,40
CAP-14	71,04	,76	,56	,22	14,18	-	,04	9,73	-	,02	3,00
CAP-21	57,17	1,24	,85	,37	21,39	-	,06	14,76	,01	,04	4,33
CAP-29	41,76	1,55	1,10	,48	27,81	-	,08	19,10	,01	,05	5,36
CAP-43	13,95	2,41	1,69	,78	43,12	-	,12	29,43	,02	,08	7,57
CAP-47	6,96	1,16	3,41	,42	47,50	-	,12	32,43	,03	,06	6,71
Average absolute error	,399	,100	,056	,167	,053	,036	,027	,074	,005	,009	
Average percentage error	,768	3,858	1,242	19,891	3,865	1,417	23,501	2,885	5,931	8,133	

* Loss on ignition at 950°C

- Not present, or not utilized

Appendix B.27 Trace element concentration of standards used in X-ray fluorescence study (ppm)

Standard	Nb	Zr	Y	Sr	Rb	Ba	Co	Cr	V	Zn	Cu	Ni	S
S-1	-	-	-	-	-	300,0	-	-	-	-	-	-	-
M-38	18,4	191,0	37,3	76,3	204,0	819,0	25,0	96,0	125,0	118,0	37,1	46,3	-
KL-11	5,2	95,0	21,5	200,0	13,4	208,0	50,8	271,0	233,0	78,5	86,0	67,1	-
PG-11	15,0	206,0	23,8	128,0	240,0	601,0	,4	17,8	8,6	30,8	1,2	1,7	-
OK-272	84,2	178,0	27,5	107,0	85,4	2854,0	2,0	153,0	11,5	80,4	2,1	850,0	-
AGV-1	-	-	-	-	-	1190,0	-	-	-	-	-	-	-
BCR-1	-	-	-	-	-	700,0	-	-	-	-	-	-	-
Allende	-	-	-	-	-	-	-	-	-	-	-	-	20700,0
GB48/65/10	-	-	-	-	-	-	-	-	-	-	-	-	2500,0
Av.% error	3,90	1,39	3,28	1,72	2,79	,88	78,76	3,35	14,76	2,77	1,45	2,46	5,510

- Not utilized

Appendix B.28 Major element concentration of standards used in electron microprobe study (%)

Standard	Si	Al	Fe	Mg	Ca	Na	K	P	S
Kakanui hornblende	18,87	7,89	8,49	7,72	7,36	1,93	1,70	-	-
Orthoclase	30,10	9,83	,02	-	-	,85	12,39	-	-
Apatite	-	-	-	-	40,50	-	-	18,60	-
Barite	-	-	-	-	-	-	-	-	13,74

- Not utilized

Appendix B.29 Major element geochemistry of phosphorites and glauconite from unconsolidated sediment and bedrock⁺ (electron microprobe) (%)

Sample No.	Unconsolidated sediment															
	Pelletal phosphorite (pP)						Glauconitized pelletal phosphorite (gpP)									
	3411	3563	3719	3904	3914	Average	3906		3914		3941		4051		Average	
No. of spot analyses	4	6	10	3	6	29	Nucleus	Rim	Nucleus	Rim	Nucleus	Rim	Nucleus	Rim	Nucleus	Rim
	4	6	10	3	6	29	9	11	3	6	9	14	3	4	24	35
SiO ₂	2,56	3,44	4,00	2,75	2,70	3,09	3,03	4,59	2,29	3,47	4,09	4,06	6,56	6,84	3,99	4,74
Al ₂ O ₃	,93	1,94	1,13	,62	,87	1,10	,70	,91	,82	1,04	1,23	1,25	2,24	,96	1,25	1,04
FeO*	1,68	4,72	6,22	8,68	4,76	5,21	10,48	8,04	6,02	5,87	3,82	5,34	3,60	4,03	5,98	5,82
MgO	,93	,97	,82	,83	,94	,90	,45	,69	,66	,73	,70	,64	,81	1,13	,66	,80
CaO	47,74	44,35	44,06	43,35	46,07	45,11	36,73	34,32	40,78	36,39	45,98	41,17	43,40	43,50	41,72	38,85
Na ₂ O	1,01	1,26	1,16	,97	1,03	1,09	,75	,64	,65	,49	,68	,42	,88	,84	,74	,60
K ₂ O	,23	,49	,35	,42	,30	,36	,49	,58	,27	,26	,23	,34	,59	,75	,40	,48
P ₂ O ₅	29,28	23,84	28,59	27,28	28,78	27,55	26,09	25,36	29,07	26,45	28,53	19,12	28,28	28,28	27,99	24,80
S	2,18	7,76	5,08	7,32	4,76	5,42	3,32	2,02	2,06	1,00	2,05	1,17	3,26	2,01	2,67	1,55
TOTAL	86,54	88,77	91,41	92,22	90,21	89,83	82,04	77,15	82,62	75,70	87,31	73,51	89,62	88,34	85,40	78,68

Light olive brown 5 Y 5/6 Dark yellowish orange 10 YR 6/6 Moderate brown 5 YR 4/4 Dark yellowish brown 10 YR 4/2

Sample No.	Unconsolidated sediment								Bedrock ⁺							
	Concretionary phosphorite (cP)				Glauconite (G)				Pelletal phosphorite(pP)				Glauconite(G)			
	3773	3784	4031	Average	3677	3877	4037	Average	3232	4729	4744	Average	3232	4729	4744	Average
No. of spot analyses	1	2	5	8	5	6	2	13	4	6	6	14	2	2	2	6
SiO ₂	-	,05	,16	,07	51,37	51,55	51,25	51,39	4,84	3,72	1,85	3,30	50,97	49,60	50,55	50,25
Al ₂ O ₃	,02	,02	,04	,03	5,39	5,21	6,93	5,84	1,24	1,30	,32	,93	5,13	3,24	5,33	4,45
FeO*	-	-	,01	-	21,05	23,50	20,69	21,75	6,96	6,99	10,96	8,48	22,34	23,98	22,39	23,01
MgO	1,37	1,36	1,54	1,42	4,84	4,83	4,52	4,73	,99	,83	,65	,80	4,78	5,29	4,72	4,96
CaO	52,23	54,20	48,41	51,61	,28	,22	,07	,19	42,56	44,02	42,97	43,26	,26	,30	,10	,21
Na ₂ O	,87	,55	,94	,79	,02	,04	,02	,03	1,02	1,05	1,10	1,06	,03	,04	,04	,06
K ₂ O	,05	,04	,03	,04	8,04	8,53	8,84	8,47	,48	,35	,23	,34	8,48	8,29	9,30	8,73
P ₂ O ₅	34,34	34,84	32,11	33,76	,15	,12	,10	,13	24,12	24,24	26,47	25,05	,08	,17	,10	,12
S	,66	,66	,60	,64	,03	,04	,04	,09	6,12	6,75	10,94	8,16	,08	,05	,06	,06
TOTAL	89,54	92,72	83,84	88,36	91,17	94,05	92,46	92,62	88,33	89,25	95,49	91,38	92,15	90,96	92,59	91,85

* Total iron reported as FeO. Glauconite contains Fe₂O₃, ∴ should multiply by 1.1113.
+ Pelletal phosphorite and glauconite in granular fabric of phosphorite rocks (see Chapter 4)