MESOZOIC GEOLOGY OF THE AGULHAS BANK, SOUTH AFRICA

by

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ABSTRACT

This thesis is concerned with the Mesozoic geological history of the Agulhas Bank on the continental shelf off the south coast of South Africa. It incorporates the results of oil exploration activities in the area since 1967: this involved the drilling of 17 boreholes (43 000m) and the recording of about 24 000 line km of seismic reflection profiles.

A structural investigation was facilitated by regional mapping of two key seismic reflectors; these are acoustic basement (horizon D at the base of the Mesozoic) and a prominent reflector and unconformable horizon (horizon C), within the Lower Cretaceous. An additional two horizons were mapped over part of the Agulhas Bank; they are horizons A (base of the Upper Cretaceous) and 11 (within the Upper Cretaceous). These reflector horizons were tied to stratigraphic control points in the boreholes.

A stratigraphic framework was erected and correlations were established by means of a study of borehole cuttings samples, cores and sidewall cores and a variety of wireline logs. The existing Mesozoic litho-stratigraphic framework was supplemented by defining reference stratotypes for the Swartkops and Sundays River Formations. Subsurface stratotypes are defined for two new units; they are termed the Infanta and Alphard Formations. A subsurface reference stratotype for the Alexandria Formation is presented. A chronostratigraphic framework and correlations, which became available through a study of microfauna and microflora, were integrated with structural and lithostratigraphic information. As a consequence four litho-tectonic units are recognised; their evolution is discussed also in terms of varying rates of sediment accumulation.

The Mesozoic geologic history of the Agulhas Bank is discussed in reference to the plate tectonic theory.

INTRODUCTION

LOCATION OF STUDY AREA

The study area is located on the Agulhas Bank, which constitutes the continental shelf off the south coast of the Republic of South Africa (fig. 1). It straddles latitude 35^{o} south between longitudes 20^{o} and 27^{o} east in the Indian Ocean and comprises an area of about 85 000 km ^{2} between the coastline and the 200 m isobath at the shelf break.

The Agulhas Bank lies to the south of the Cape mountain ranges, which extend between Cape Town and Port Alfred and are made up for the most part of intensely folded Ordovician-Lower Carboniferous sediments of the Cape System, forming an arcuate belt, convex northwards, in which isolated remnant Cretaceous basis are preserved (du Toit, 1954). Farther north the lowermost stratigraphic units of the Upper Carboniferous-Jurassic Karoo sediments follow conformably on the Cape sediments and dip north wards regionally. Seaward of the Agulhas Bank there is a relatively wide continental slope, a poorly developed rise and the following morphological features can be recognised.

The Transkei Basin;
Agulhas Plateau;
Agulhas Basin and the
Cape Rise, with an associated chain of seamounts trending north-east.

The area described lies in the horse latitudes during the southern hemisphere summer (December to February), when light variable winds and low rainfall prevail. During winter (June - August) there is an equatorial shift of the prevailing westerlies so that the study area is influenced by these winds and by migratory storms, which often introduce polar maritime air and are responsible for rainy conditions. The climate is modified by the south-westward-flowing, warm Agulhas current. Four climatic zones can be recognised in the coastal belt of the southern Cape Province; these are (Köppen classification in brackets):

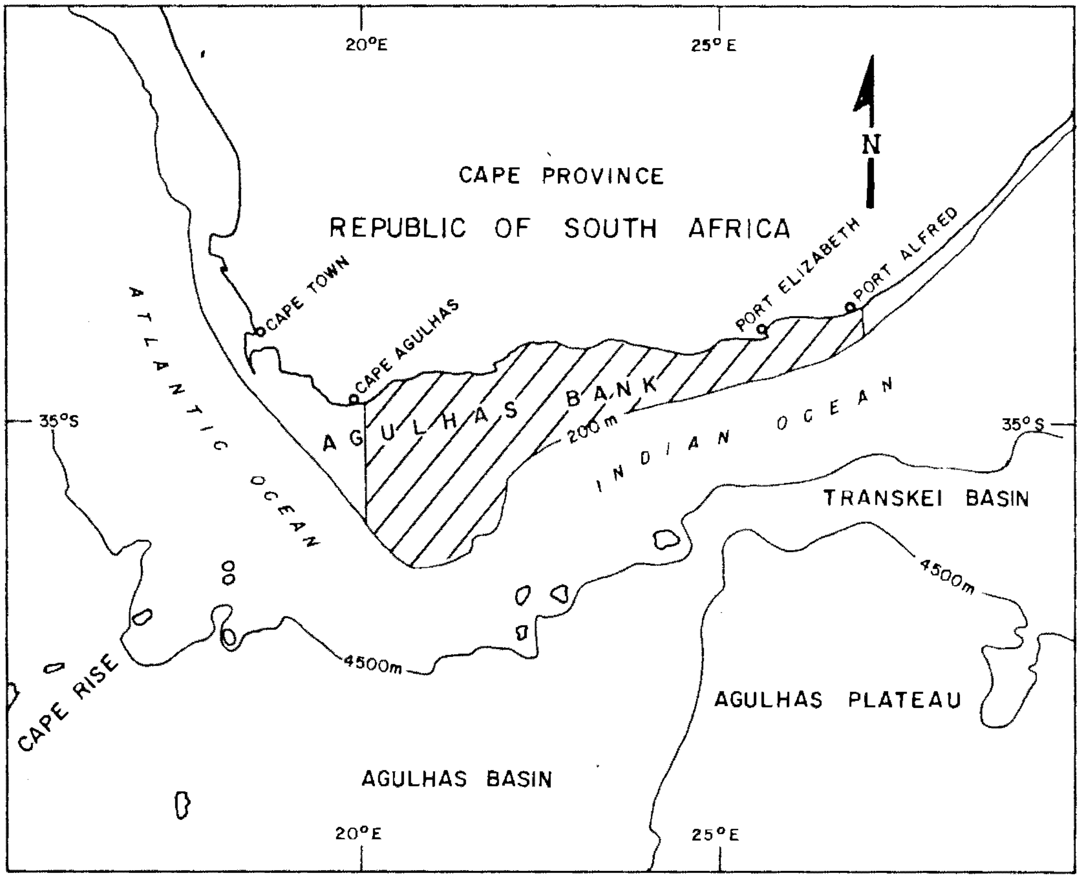

FIGURE 1. Location of the study area (cross-hatched) on the Agulhas Bank, South Africa.

South-western Cape winter rainfall area, with a mediterranean climate (CS);
Southern Cape coastal belt, with rain during all seasons (Cf);
South-eastern coastal belt, which is a warm temperature region with a summer rainfall maximum (Cfw); and the
Southern Karoo which is mainly desert (BW and BSK).

The most important streams are, in order of volume of discharge and drainage area, the Breede, Gouritz, Gamtoos and Sundays Rivers.

With the exception of the Breede River they have all breached the Cape mountain ranges and drain a large part of the interior of the Cape Province south of the Great Escarpment.

SCOPE OF STUDY

This study is concerned with structural, stratigraphic and certain sedimentological aspects of the Mesozoic sediments on the Agulhas Bank and represents an effort to unravel the post-Paleozoic geological history of the area. The information that was available for synthesis by the writer stems from active oil exploration activities since 1967. During that year the Southern Oil Exploration Corporation (Soekor) was granted prospecting rights over the area in terms of the Mining Rights Act (Act No. 20 of 1967); it entered into lease agreements with a number of international oil companies, who were obliged to submit to Soekor all uninterpreted data gathered in their concessions.

The study is confined to the Mesozoic sequence for various reasons. The underlying Cape Supergroup (Paleozoic) and older rocks are regarded as basement for oil exploration purposes by virtue of their metamorphic state (Rowsell and de Swardt, 1974). Boreholes were generally stopped a short distance below the base of the Mesozoic sediments; this boundary also constitutes acoustic basement on seismic reflection profiles. In conformance with good oil-field practice the surface casing in boreholes is generally placed within -300 m of the ocean floor; this precludes the possibility of gathering any data on sediments at stratigraphic levels above about the lowermost Tertiary.

The structural /4...

The structural information was gleaned largely from routine interpretations which were done by Soekor's geophysicists in close consultation with the writer. About 24 221 line km of seismic reflection profiles had become available through intermittent surveys by a number of different contractors for various concession-holders up to the end of 1974. Initially interpretations of these were aimed at mapping acoustic basement and a prominent reflector horizon within the overlying sedimentary succession. These two horizons, and all the others mapped subsequently, were tied to stratigraphic control points established by the writer in the 17 boreholes (<u>table I</u> and fig. 2) which have been drilled to date. These boreholes provided a stratigraphic framework for the Mesozoic sediments based on the integration of seismic reflection data with the following studies.

(a) Mega- and microscopic studies of washed -8 to +160 mesh size cuttings samples below the intermediate casing; these samples were composited over intervals ranging between 10 and 30 m depending on drilling penetration rates.

(b) Interpretation of a variety of wireline logs. These logs were recorded on a routine basis in the boreholes to facilitate stratigraphic, structural, reservoir and reservoir-fluid studies; they were all recorded by the Schlumberger Company on behalf of the operating companies.

(c) Studies of conventional and sidewall cores; these cores were cut intermittently to supplement the studies outlined above.

(d) Synthesis of selected paleontological results which were obtained from a variety of sources, e.g. a Paleolab (Geneva) report for the G(a) A/1 borehole, Robertson Research International reports on 13 boreholes and internal reports by Soekor micropaleontologists (Mc Lachlan, de Klasz, Brenner, MacMillan, Pieterse and Scott) on all 17 boreholes.

TABLE 1

STATISTICAL SUMMARY : BOREHOLES ON THE AGULHAS BANK

	CO-ORDINATES		Water Depth (m)	Kelly	T.D. in Metres		Spud	Drilling Completed	Drilling days to T.D.	Operator
	S	E		m ASL	B. Kelly	B.S.L.				
G(a)-A/1	34°33' 08,17"	23°43' 14,67"	117,30	9,4	2202	2192,6	27.10.68	15. 3.69	88	Superior Oil
G(a)-A/2	34°34' 24,90"	23°45' 37,50"	115,80	28,0	3037	3009,0	13.12.69	23. 2.70	71	Superior Oil
G(a)-A/3	34°33' 47,37"	23°46' 17,95"	117,30	26,8	2475	2448,2	17. 3.70	23. 4.70	36	Superior Oil
G(a)-B/1	34°23' 02,75"	23°47' 45,92"	122,50	26,8	3648	3621,5	11. 5.70	31. 7.70	92	Superior Oil
F-1	35°00' 04,17"	22°14' 33,99"	109,40	28,0	2918	2890,2	14. 8.70	28. 9.70	44	Placid Oil
MB-A/1	34°13' 52,89"	22°11' 54,09"	60,30	26,8	1300	1273,2	27.10.70	16.11.70	21	Soekor/Rand Mines
PB-A/1	34°09' 39,913"	23°20' 12,126"	80,50	25,9	1810	1784,6	24.11.70	12.12.70	19	Soekor/Rand Mines
G(a)-C/1	34°43' 02,71"	23°02' 56,92"	115,50	26,8	1689	1662,2	15.10.70	31.10.70	16	Placid/Superior
G(b)-Gemsbok/1	34°29' 03"	24°14' 36"	121,90	29,4	3968	3938,6	12.11.70	3. 2.71	85	Total
E-1	34°39' 46,175"	21°15' 06,132"	76,35	33,5	2792	2758,5	14.12.72	20. 1.73	38	Chevron
D-A/1	35°05' 30,871"	20°55' 07,984"	87,00	33,5	2591	2557,5	4. 2.73	24. 3.73	48	Soekor
F-B/1	34°24' 22,003"	22°48' 40,378"	100,60	33,5	1052	1018,5	11. 4.73	20. 4.73	9	Aquitaine
F-D/1	34°51' 23,998"	22°56" 39,352"	130,76	34,1	1955	1920,9	3. 5.73	18. 5.73	15	Aquitaine
E-B/1	34°44' 12,006"	21°10' 00,973"	75,00	33,5	1963	1929,5	5. 6.73	27. 6.73	22	Soekor
F-E/1	34°55' 30,271"	22°22' 03,224"	114,00	33,5	2442	2408,5	11. 7.73	10. 8.73	30	Soekor
H(b)-Hartebeest/1	34°16' 38,479"	25°55' 19,664"	117,34	33,5	2450	2416,5	29. 8.73	30. 9.73	30	Soekor
G(b)-Springbok/1	34°37' 06,391"	24°17' 09,522"	124,70	33,5	2454	2420,5	14.10.73	9.11.73	26	Soekor
Total						40201,5			690	

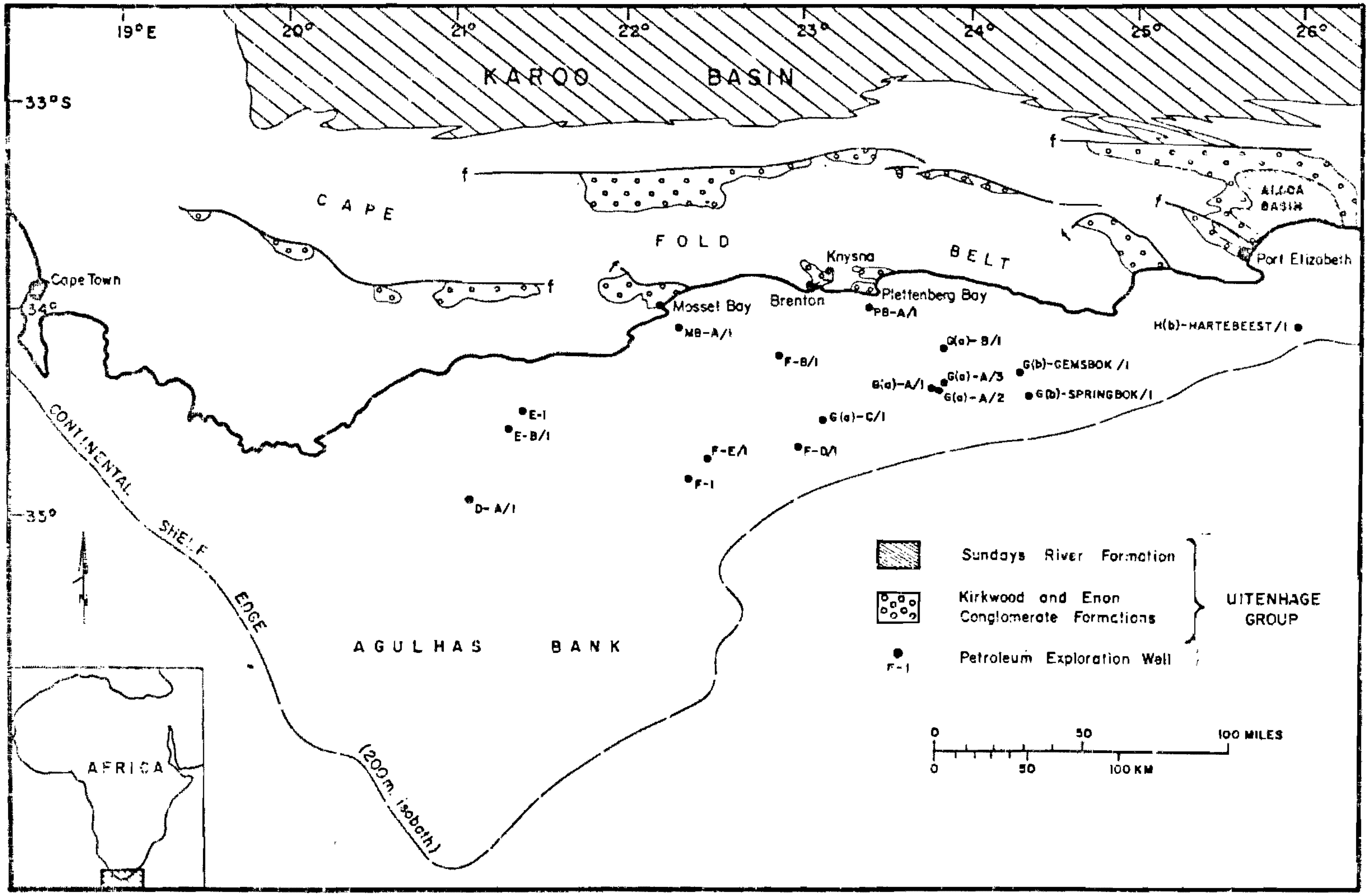

FIGURE 2 : Location of boreholes on the Agulhas Bank.

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A lithostratigraphic framework and correlation was established by the writer for the Mesozoic sediments in the Agulhas Bank by supplementing, where necessary, the stratotypes of the Uitenhage Group in the Algoa Basin (Winter, 1973). This work, and the incorporation of available chronostratigraphic information based on paleontologic studies, was done in conformance with the South African Code of Stratigraphy. The stratigraphic studies were carried out as part of the duties delegated by the South African Committee for Stratigraphy to the Cretaceous-Jurassic Working Group of which the writer was convenor since its inception in 1971. The structural, stratigraphic and paleontological data provided material for selected sedimentological studies, with particular emphasis on depositional processes and environments within the framework of the structural evolution of the Agulhas Bank. It was found that the Mesozoic geological history of the Agulhas Bank is consistent with the concept of plate tectonics.

PREVIOUS WORK

Geophysical-geological surveys have been carried out over the Agulhas Bank for more than three decades, and commenced with pendulum measurements (Vening Meinesz, 1941). It was not until the 1960s that surface ship gravity measurements were made (Graham and Hales, 1965); these indicated a probable depth of nearly 30 km to the mantle, the presence of a steep landward gradient of the M-discontinuity under the slope, and a structurally complex 5-km sediment layer which thins seawards of the Agulhas Bank. A seismic refraction profile measured at 35°18' south, 21°31' east (Green and Hales, 1966) revealed the presence of possible Cretaceous sediments to a depth of nearly 2,5 km. Refraction work by Ludwig et al (1968) showed variable thicknesses of sediment, possibly Cretaceous or younger in age, resting in structural depressions on Cape and underlying rocks with high sonic velocities.

Detailed sea-floor mapping started in 1967 with the establishment of the Marine Geology Unit by the South African National Committee for Oceanographic Research (SANCOR) at the University of Cape Town; since then this unit has been actively engaged, amongst others, in bathymetric, sea-floor-sampling and shallow seismic reflection surveys of the

continental /8...

continental shelf and upper slope.

Bathymetric maps or profiles have been produced by Dingle (1970), Dingle et al (1971), Birch and Rogers (1973), Scrutton (1973) and Simpson (1966, 1968, 1970). These show that the continental shelf widens from Cape Agulhas to a maximum of 240 km at about 21° east, then narrows markedly to 37 km off Cape Recife. The shelf break ranges in depth from 120 to 180 m. The only prominent topographic features on the Agulhas Bank are the Alphard Rise and a number of east-west-trending ridges in the vicinity of Cape St. Francis. In general three morphological zones can be recognised seawards of the shoreline:

a narrow near-shore rocky platform;
a gently sloping shelf; and
a steeper slope, with a poorly developed rise.

Geological maps of the Agulhas Bank (Dingle, 1970) indicate the presence of both Lower and Upper Cretaceous sediments close inshore and along the eroded shelf-break, a thin cover of Tertiary volcanics on the Alphard Rise (Dingle and Gentle, 1972), and the prominent south-east-trending Agulhas arch, where Senonian beds rest directly on Devonian-Silurian sediments of the Cape System. Leyden et al (1971) confirm that the Agulhas arch is made up of shallow basement with high seismic velocities and further demonstrate the presence along the shelf-edge of 3 to 4 km of sediment which shows increasing velocities with depth. They suggest that a considerable part of this succession may be rapidly deposited terrigenous and marine sediments of Cretaceous-Tertiary age, and speculate as to whether the Cretaceous Algoa basin extends onto the continental shelf. Towards the north-east of the Agulhas arch, along longitude 20°49' east, a thick, block-faulted succession was shown to be present by Spence (1970), who correlates the sediments to the Uitenhage Series on the basis of interval velocities. The same profile was used by Hales and Nation (1972) for crustal studies which revealed the depth of the M-discontinuity beneath the Agulhas arch to be 32 km.

Dingle (1971 a) provided further evidence in favour of a Cretaceous dating, based on studies of ostracods from the Algoa Basin, for sediments on the Agulhas Bank. In the same year (Dingle, 1971 b) he portrayed the Tertiary history and referred to, amongst others, a marine transgression during the Upper Cretaceous. A Jurassic dating of the Brenton marine beds (Dingle and Klinger, 1972) near Knysna was shown to have significance in terms of the break-up of Gondwanaland (Dingle and Klinger, 1971), as did the location of a marginal fracture zone (Francheteau and Le Pichon, 1972), with which is associated the Agulhas marginal fracture ridge (Talwani and Eldholm, 1973; Scrutton and du Plessis, 1973). Also of significance was the observation that the Agulhas Bank lies in a marginal smooth magnetic zone. (Mascle and Philips, 1972).

The term Agulhas basin was coined by Simpson and Dingle (1973) in referring to the Mesozoic and younger sediments on the Agulhas Bank. It is also referred to as the St. Francis Basin (Emery et al, 1975) and the Outeniqua basin (Dingle and Scrutton, 1974). This basin, as defined, lies between the Agulhas and Recife arches and is sub-divided by smaller block-faulted buried ridges (Dingle, 1973 a) which correspond to promontories on the coastline and projections of anticlinorial axes in the Cape fold belt. The sedimentary basin lies shoreward of the Agulhas marginal fracture ridge, which acted as a sediment dam (Scrutton and du Plessis, 1973) until the late Cretaceous. The earliest post-Paleozoic sediments in the Outeniqua basin accumulated in intermontane valleys during the Jurassic, but well after the formation of the Cape fold belt in the mid-Triassic (Dingle, 1973 b). During the intervening period South Africa was subjected to intense erosion (peneplanation), producing what King (1951) called the "Gondwana surface". The climate at this time was thought to have been dry (Bigarella, 1970); desert conditions are postulated for the interior throughout Jurassic time.

The Agulhas Bank features prominently in compilations of regional oceanography by Siesser et al (1974) and Emery et al (1974). The latter show free-air gravity anomalies over ridges which are associated with the Agulhas fracture zone and over the continental slope.

It was /10...

It was proposed that the boundary between oceanic and continental crust resulted from transcurrent movement along this fracture zone while rift faults developed in the late Jurassic. Emery et al (1974) postulate a major hiatus in the mid-Cretaceous; this was followed by a late Cretaceous transgression and a regression accompanied by folding at the end of the Cretaceous.

A summary of the geology of the isolated Cretaceous outcrops in the Cape fold belt is provided by, amongst others, Haughton (1928), Haughton et al (1937 a, 1937 b), du Preez (1944), du Toit (1954), Rigassi and Dixon (1970), Engelbrecht et al (1962) and Lock et al (in press). These studies reveal the presence of isolated, fault-bounded, asymmetric basins that developed parallel to the tectonic grain of the Cape fold belt; the basins were filled with substantial thicknesses of non-marine, coarse clastics in the Worcester, Robertson, Swellendam, Riversdale, Oudtshoorn, Mossel Bay, Gamtoos and Baviaanskloof areas. The age of the faults on land associated with Mesozoic rifting has long been under discussion. Haughton (1969), du Toit (1954) and Truswell (1970) conclude that large vertical movements took place in the mid-Cretaceous (post-Neocomian), while Dingle (1973 b) suggests a pre-Coniacian age for these intermittent tectonic events. King (1951, p. 246) assigns a mid-Jurassic to earliest Cretaceous time for rifting of Gondwanaland. Nearly 1 900 m of marine Lower Cretaceous Sundays River sediments are known to occur in the Algoa Basin, where the stratotypes of the Uitenhage Group are defined and named in accordance with the South African Stratigraphic Code (Winter, 1973, du Toit et al in press). The Algoa Basin was considered to be a more complex basin controlled by more than one bounding fault. Du Toit (1954) pointed to the significence of sedimentary dips into the controlling fault as indicative of sedimentation concurrent with movement.

STRUCTURE

METHODS OF STUDY

The principal source of structural information are seismic reflection profiles, and dipmeter data recorded in the majority of the boreholes. About 24 000 line km of seismic reflection profiles have been intermittently acquired over the Agulhas Bank between 1967 and 1974. These surveys were recorded and processed by a variety of contractors such as Compagne Général de Geophysique (C.G.G.), Geophysical Services Incorporated (G.S.I.), Ray Geophysical, United Geophysical, Seismic Engineering, Gulfrex, Mobil and Shell.

Digital recording of most seismic data made possible high-speed electronic computing and efficient attenuation of multiple reflectors by deconvolution techniques. Overall data enhancement by high-multiplicity shooting and stacking has effected immense quality improvement in seismic data in recent years. One of the earlier problems encountered during the recording of seismic reflection profiles on the Agulhas Bank was the hard sea bottom, which set up standing seismic waves resulting in destructive ringing (reverberation). This resulted locally in poor penetration and concomitant difficulties in detecting deep-seated horizons. The problem was overcome, to a large extent by sophisticated filtering techniques and deconvolution.

In the geophysical files at Soekor there is documentation of the rapid evolution of the seismic reflection method since 1967. The main stages were:

(i) analogue automatic volume control recording, floating cable;
(ii) analogue programme-gain recording, common depth-point cover;
(iii) digital recording, streamer cable, non-dynamite source;
(iv) binary gain 48-fold recording; and
(v) Maxipulse, 48 channel, 2-mile streamer cable, acceleration cancelling hydrophones in tapered arrays.

The /12...

The interpretation of seismic reflection profiles was done on a routine basis in Soekor's geophysical section by Messrs. Wardle, Wood and Crous in close consultation with the author. The following reflector horizons were mapped throughout the study area:

Horizon D : acoustic basement, approximate base of Mesozoic sediments (pl.1)
Horizon C : Lower Cretaceous reflector, locally in unconformity surface (pl.2)
Horizon A : approximate base of Upper Cretaceous (pl.3)
Horizon 11 : wireline-log marker horizon in the Upper Cretaceous near base of Santonian (pl.4).

These horizons were tied into control points in boreholes using velocity functions computed from velocity surveys in 14 of the boreholes. As a rough guide the following relationship may be used for the conversion of depth and sonic travel time on the Agulhas Bank:

$$y = 88{,}46 + 0{,}38\,x$$

where y = one-way travel time in milliseconds
and x = depth in metres below sea level.

This relationship was arrived at through a least-squares regression analysis by the writer of 96 pairs of data points from 10 borehole velocity analyses which yielded a line of best fit with a correlation coefficient of 0,98.

Supplementary structural information was obtained from the interpretation of dipmeter results. The surveys and processing were done by the Schlumberger Company in 15 boreholes. The dipmeter is a four-pad device, which records four resistivity curves continuously down the borehole; these curves are digitised and automatically correlated, and corrections are applied for borehole deviation, hole size, sonde position and magnetic deviation. The results are presented by Schlumberger in such a way that they shown the structural attitude of sediments at the borehole site. The interpretation of dipmeter results was done by the writer in accordance with principles described by Schlumberger (1970).

REGIONAL /13...

REGIONAL STRUCTURAL ASPECTS

Agulhas Bank

The two-way time-contour map of horizon D (pl. 1) bears witness to the presence of a large number of steeply dipping normal faults at the approximate base of the Mesozoic sediments; these faults generally trend west-north-west close inshore, where they are roughly parallel to the tectonic grain of the Cape fold belt. On the eastern part of the Agulhas Bank the faults swing in an arcuate manner to a southerly direction near the 200-m isobath. These horst-and-graben faults give rise to the observed relief at acoustic basement level and contribute substantially towards the recognition of the following principal Mesozoic structural elements (from west to east):

Agulhas arch
Bredasdorp basin
Infanta arch (St. Blaize arch according to Dingle, 1973 b)
Pletmos basin
St. Francis arch
Gamtoos basin
Recife arch
Algoa basin

Horizon C is a prominent reflector within the Lower Cretaceous and has a general shallow seaward dip interrupted by broad anticlines, synclines and a limited number of normal faults. The relief on this horizon is a subdued replica of the structure on horizon D, so that the orientation and position of the principal structural features on horizon C are reflections of those listed above. It is impossible to trace this horizon over the Recife arch into the Algoa basin and for this reason a strongly unconformable horizon at the base of the Companian in the H(b)-Hartebeest/1 borehole termed "top of layer 3", has been mapped in this area.

A seismic reflector near the base of the Upper Cretaceous, termed

"horizon A" /14...

"horizon A", (pl. 3) strikes roughly north 80° east and dips approximately 3° seawards. This regional slope is interrupted by the following:

(a) A distinct swing of the contours to the north-west along the northern flank of the Agulhas arch onto which it onlaps;

(b) A number of broad south-east-plunging anticlines. The most prominent of these is superimposed on the arcuate Infanta arch, where it is affected by faults. Another plunging anticline is present about 50 km south-west of the Infanta arch; it is superimposed on an anticline at basement level which branches off from the Infanta arch;

(c) Relatively minor faulting in the area about 100 km south-east of Plettenberg Bay; and

(d) A prominent fault about 50 km south-east of Cape Infanta.

Mapping of horizon A is not possible in the nearshore belt, where it is too shallow for identification on reflection profiles. It cannot be traced across the St. Francis arch and it has consequently not been mapped in the Gamtoos basin and farther eastwards.

Horison 11 occurs within the Upper Cretaceous, strikes roughly N 80° E, and has a monotonous regional seaward dip of about 2° (pl. 4); this regional attitude is interrupted by the same anticlinal features as those observed on horizon A, but their amplitude is considerably subdued at this higher stratigraphic level. Horizon 11 is so shallow that it can be identified on seismic reflection profiles only over the central part of the study area.

The results of refraction work, which had been recorded independently by a number of different investigators, are in general agreement with those of Soekor's seismic reflection mapping. The following table lists those refraction profiles which provide corroboration for the principal Mesozoic structural features described above:

Feature /15...

Feature	Green & Hales (1966)	Ludwig et al, (1968)	Leyden et al, (1971)	Spence (1970)
Agulhas arch			profile 224	profile 4
Bredasdorp basin	profile 4		profiles 225, 226, 227	
Infanta arch			profiles 228, 229	
Pletmos basin		profiles 151, 152 W	profile 230	
St. Francis arch		profiles 152 E, 153		
Gamtoos basin			profile 231	
Algoa basin			profile 232	

The lowermost refracting horizons (or velocity interfaces) on a number of these refraction profiles generally show a close correspondence to either seismic horizon C or horizon D.

Cape Fold Belt

The arcuate Cape fold belt, concave southwards, reflects an orogeny with vergence, overfolding and thrusting directed outwards (de Swardt et al, 1974; Newton, 1975). The most consistent structural element over most of the belt is a strong axial plane cleavage or foliation, which marks the regional plane of orogenic transport. It disrupts authigenic minerals of the lower greenschist facies of metamorphism, indicating that the Bokkeveld sediments, at least, were deeply buried and partially reconstituted before the main folding took place (de Swardt and Rowsell, 1974) during the Triassic (Dingle, 1973 b). The rocks that are involved in this folding are sediments of the Silurian-Lower Carboniferous Cape System and possibly also of the older Klipheuwel and Malmesbury successions; the latter is intruded by Cape granites dated at about 600 m.y. The Karoo sequence was involved in the Cape orogeny at least up to the lower part of the Beaufort sediments.

The repetitive outcrops of the Cape sediments are essentially expressions of a number of anticlinoria and synclinoria. Thrust faults with a moderately steep southerly dip are known to occur in the Baviaanskloof area (Theron, 1969) and are suspected to be also present farther south, along

the /16...

the long narrow synclines occupied by Bokkeveld sediments. As far westwards as George the folding was very intense - even the George granite apparently acquired a strong east-west foliation (de Swardt et al, 1974).

Where the fold belt crosses the Langeberg between Worcester and Swellendam only weak folding is apparent and the basal Table Mountain Sandstone is often undeformed. South of the Worcester fault the folding is more intense and takes the form of fairly tight, chevron-type folds superimposed on earlier west-north-west trending broad synclines and anticlines. A number of faults are shown on the 1970 edition of the geological map of South Africa, in the Bredasdorp area; they are parallel to the Cape folding in this area (King, 1951, p. 313).

It is remarkable to what extent the directions of Mesozoic rift faulting parallel the tectonic grain of the Cape fold belt in the eastern and central parts of the study area. However, it is extremely unlikely that a genetic relationship exists, since erosion down to Cape sediments in the greenschist facies of metamorphism intervened between the Cape orogeny and the Mesozoic rift faulting. In the western part of the study area the Mesozoic structural grain cuts across the southwesterly trend of the Cape folds.

Agulhas Marginal Fracture Zone

The Agulhas fracture zone, with which is associated a fracture ridge (Scrutton and du Plessis, 1973) and a linear positive magnetic anomaly (Simpson, 1968), is responsible for the juxtaposition of continental and oceanic crust along the South African eastern and southern margin. It is located on a small circle disposed 68° away from the Early Cretaceous spreading pole (Franchetau and Le Pichon, 1972) and is responsible for the straightness and narrowness of the continental margin along the east coast (Simpson and Dingle, 1973). The fracture ridge is considered to have acted as a Mesozoic sediment trap (Scrutton and du Plessis, 1973).

The Agulhas fracture zone strikes N 50° E and truncates the Agulhas

arch /17...

arch (Scrutton and du Plessis op cit, fig. 3). It is equated with the Falkland fracture zone (Le Pichon and Hayes, 1971). Emery et al (1975) and Dingle and Scrutton (1974) consider this fracture zone to have played a significant part in the breakup of west Gondwanaland during the Mesozoic by dextral transcurrent movement. This wrench fault can be regarded as a fundamental fault (de Sitter, 1959, p. 175) or a megashear (Carey, 1958); it is a first-order structure having a significant component of lateral movement, i.e. it is a strike-slip fault whose horizontal displacement exceeds the thickness of the crust.

PRINCIPAL MESOZOIC STRUCTURAL ELEMENTS

The following is a discussion of the principal Mesozoic structural features defined by the four seismic reflection horizons that have been mapped.

Agulhas Arch

This broad, essentially linear arch at the level of horizon D plunges south-east away from Cape Agulhas (pl. 1); it has a broad, flat crest and is asymmetric in cross-section with a steeper north-eastern flank. If the 500-millisecond basement contour line is taken as defining the limits of the arch, it widens from 25 km near the coastline to more than 80 km near the 200-m isobath.

The crest of the arch is bald in respect of sediments between horizons D and C, because the latter onlaps onto horizon D along a line sub-parallel to the 400-millesecond depth contour (fig. 3). Horizon C is too shallow along the flanks of the Agulhas Arch to be accurately mapped and the exact location of its onlap onto horizon D cannot be established. It is possible that this onlap occurs close to the 400-millisecond contour on horizon C all along the north-eastern flank of the Agulhas arch. Horizons A and 11 could not be identified over the crest of the arch; they are suspected to onlap onto horizon C in an overstepping fashion along the flanks of the arch in view of the presence of Senonian sediments that have been dredged along this flank (Dingle, 1970).

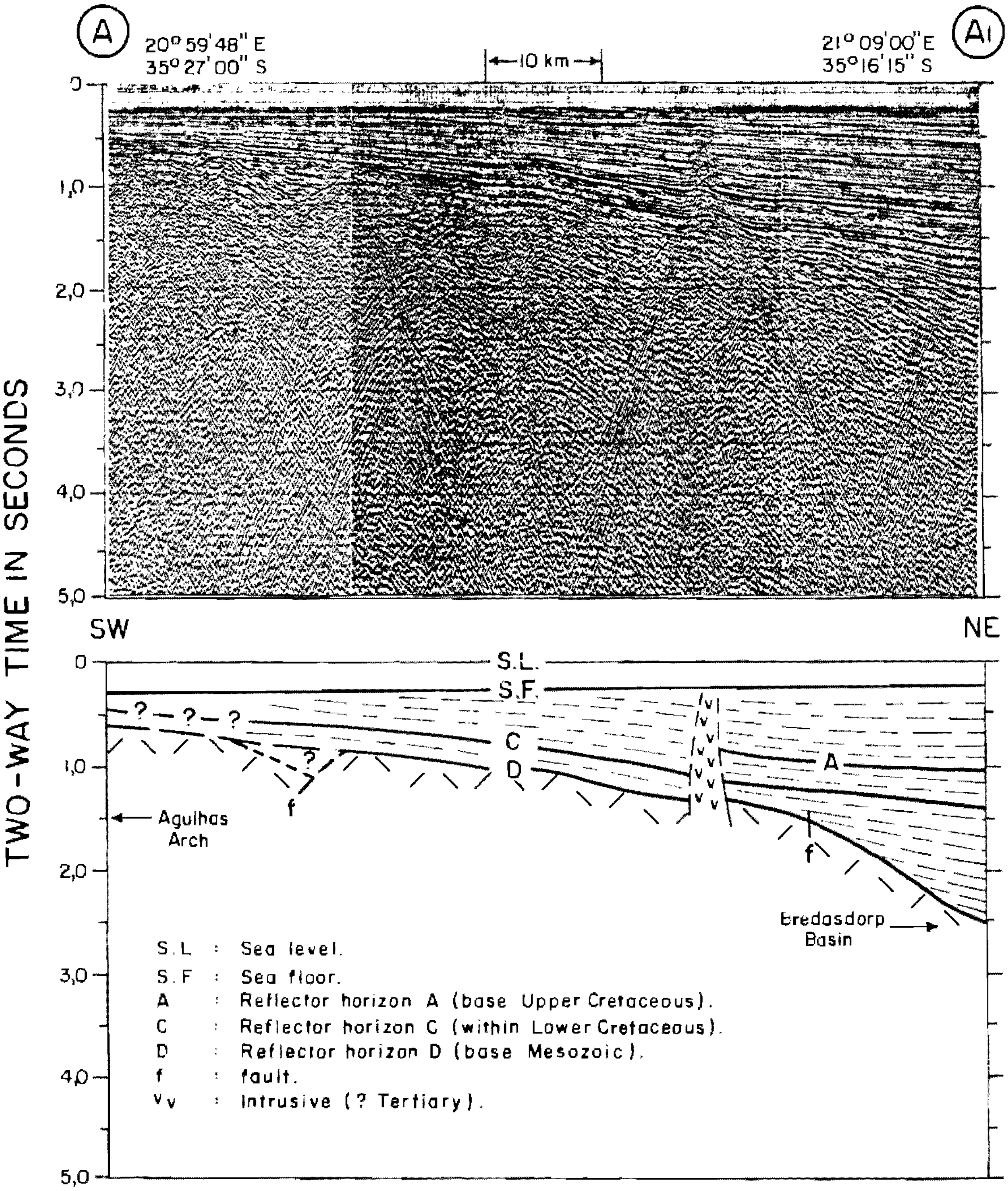

FIG. 3 NE - SW SEISMIC REFLECTION PROFILE ACROSS THE NORTH-EASTERN FLANK OF THE AGULHAS ARCH SHOWING LOWER CRETACEOUS SEDIMENTS ONLAPPING BASEMENT. LINE OF PROFILE IS SHOWN ON PLATES 1 AND 2.

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Seismic reflection evidence indicates onlaps onto the north-eastern flank and a generally thin cover of sediments favours the early existence of positive relief over the Agulhas arch. The flatness of the crest could be a feature inherited from the Gondwana landscape or be due to erosion at times of emergence. Cape sediments have been dredged from the crest close inshore (Dingle, 1970). The nature of the north-eastern flank of the Agulhas arch remains problematical, particularly in respect of the role played by faulting. The present evidence favours a faulted hinge axis to account for this steeply dipping flank (fig. 3).

The core of the Agulhas arch may be represented on land by north-west-trending outliers of Cape granite and Malmesbury metasediments in the area between Paarl and St. Helena Bay (Scrutton and Dingle, 1974), while the north-eastern flank may be continued by the fault-dissected anticlinal feature formed by T.M.S. quartzite between Cape Agulhas and Somerset West. In a seaward direction the Agulhas arch is known to persist to the Agulhas marginal fracture zone, by which it is presumably truncated at a position about 150 km south-east of Cape Agulhas (Scrutton and du Plessis, 1975).

Bredasdorp Basin

The Bredasdorp basin is named after the town of that name not far from the coast. It is a broad, essentially undulating, steep-sided structural depression, some 120 km wide at the level of horizon D (pl. 1 and fig. 4). Its long axis trends south-east, parallel to the flanking arches. A number of roughly ovate depressions are observed on horizon D, in the central part of this basin; these depressions attain depths of more than three seconds (two-way time) locally. At its north-western extremity, near the coastline, the basin splays with the development of a number of south-east plunging ridges. The most prominent one of these can be projected landwards to Struispunt, is bald in respect of horizon C and is flanked on the south-west by a down-to-the-south normal fault with a displacement of about one second on horizon D. This fault persists upwards and displaces horizon C, and laterally for about 30 km to the south-east. There is no obvious fault onshore to which this one can

be correlated /22...

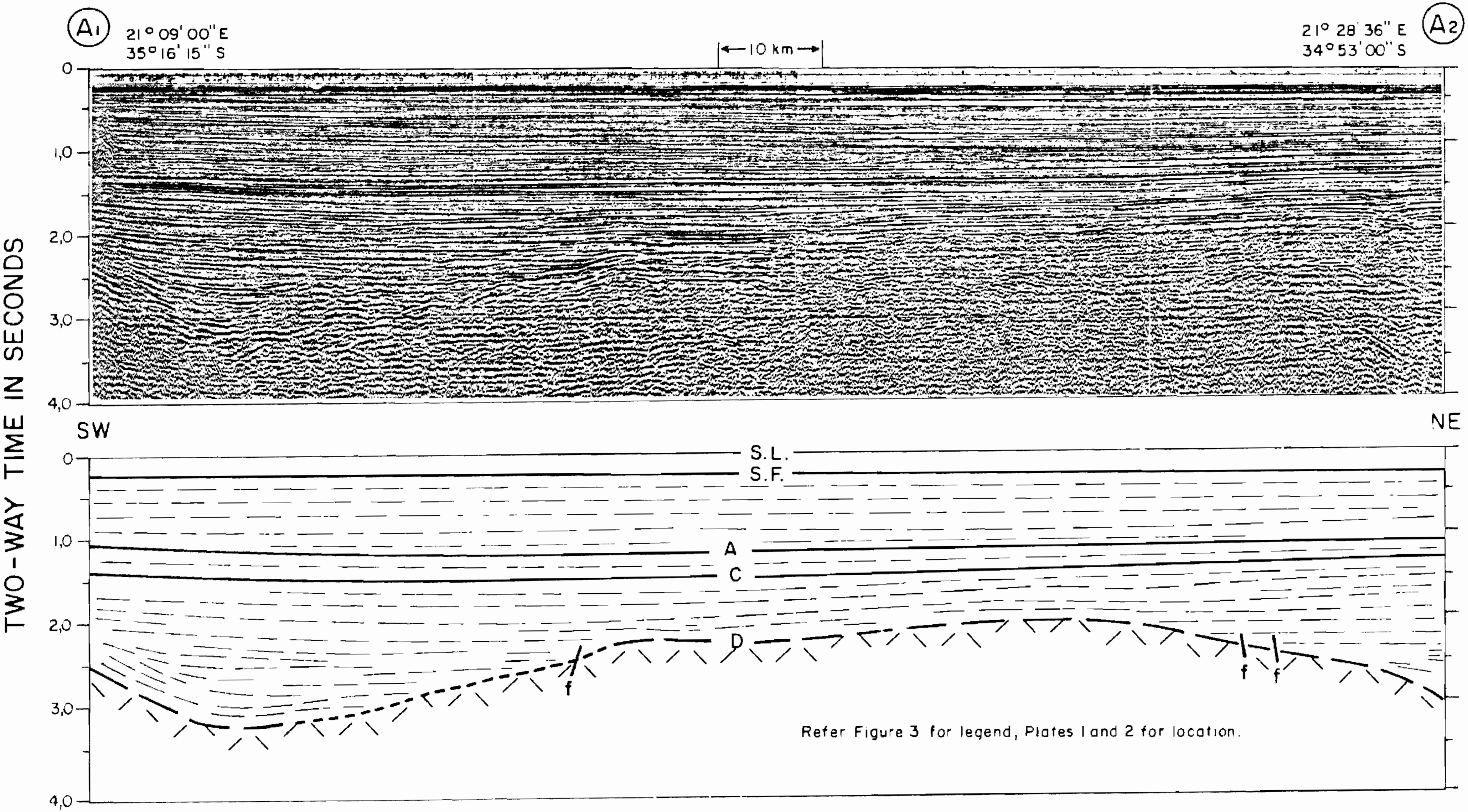
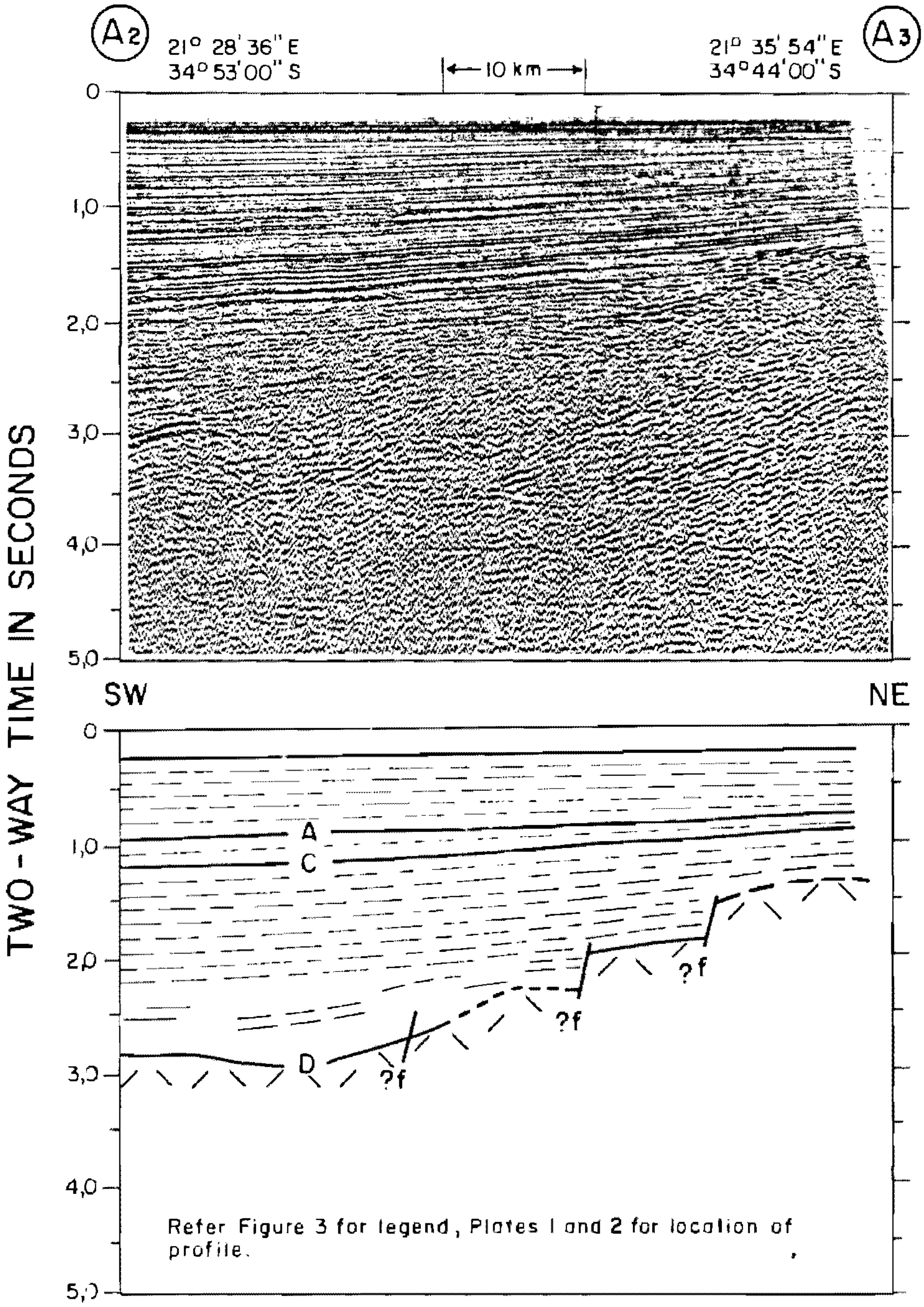


FIG. 4 NE - SW SEISMIC REFLECTION PROFILE ACROSS THE BREDASDORP BASIN.



Refer Figure 3 for legend, Plates 1 and 2 for location of profile.

FIG. 5 NE - SW SEISMIC REFLECTION PROFILE ACROSS THE STEEP (? FAULTED) NORTHEASTERN FLANK OF THE BREDASDORP BASIN be correlated, unless it is continued en echelon by the one a few kilometers north of Elim which brings the Nama and Bokkeveld into juxtaposition (Geol. Map S.A., 1970 Ed). An intrusive is located on the crest of this feature about 45 km south of Cape Infanta; it is presumably equivalent in age to the 58 m.y. old intrusives which occur on the Alphard Banks (Dingle and Gentle, 1972).

A prominent horst, about 40 km south-east of Cape Infanta on which the E-B/1 borehole was drilled, narrows abruptly in a north-westerly direction and is flanked on both sides by faults with about two seconds displacement; the southerly one has an arcuate trace on horizon D.

The northern flank of the Bredasdorp basin is a remarkably straight, faulted warp axis, judging by the closely spaced contours striking south-east out of St. Sebastian Bay (Cape Infanta)(fig. 5). The three ovate deeps referred to above are within 25 km of this flank.

At its seaward end, near the 200-m isobath, the basin shallows by way of a number of isolated, ovate highs which are suspected to be fault-induced. They are bald in respect of horizon C. To the south-west of these, along the northern flank of the Agulhas arch, an east-west fault pattern is associated with an eastward plunging anticline. This is a splay off the Agulhas arch along latitude 35°40'S and is evident on both horizons C and D. Collectively these features terminate the south-easterly plunge of the Bredasdorp basin.

A broad, flat trough on horizon C trends roughly south-east; its axis plunges in the same direction in conformance with the structure on horizon D. Numerous pluglike intrusives penetrate horizon C in the vicinity of and north-west of the D-A/1 borehole on the Alphard Banks. These intrusives have been dated as early Tertiary (Dingle and Gentle, 1972). An arcuate fault trace is interpreted to be present close to the E-B/1 borehole, where a closed contour is indicated. From this position a persistent east-west strike is observed, and the northern margin of the Bredasdorp basin on horizon C cannot be accurately defined.

The Bredasdorp /23...

The Bredasdorp basin is not detectable on higher structural-stratigraphic levels such as on horizons A and 11.

It should be borne in mind that on most reflection profiles in the Bredasdorp basin, acoustic basement is not a characteristic or prominent reflector horizon. This may be due to the camouflaging effect of multiple reflections or reverberation.

Infanta Arch

The Infanta arch is named after a cape on the coast and is roughly equivalent to the St. Blaize arch (Dingle, 1973 b). At the level of horizon D it is a broad, sloping bench, which extends in an arcuate manner from the coastline at Still Bay to the intersection of the 200-m isobath and longitude 23° E about 85 km south of Plettenberg Bay. A subsidiary south-east-plunging anticline splits off about 85 km south of Mossel Bay to constitute the north-eastern flank of the Bredasdorp basin. The main arch is affected if not controlled by many steeply dipping normal faults parallel to the crest of the arch. Towards the east the northern flank of the arch is defined by a down-to-the-north fault, which peters out towards the nort-west, while some 30 km south of Mossel Bay this flank is defined by another large, discontinuous east-west fault (1,5 seconds of displacement). A saddle-like depression occurs along the crest of the arch between these two downthrow faults, while a subsidiary eastward-plunging basin, some three seconds deep, is located about 100 km south-east of Mossel Bay between the Infanta arch and the northern flank of the Bredasdorp basin.

The Infanta arch can also be recognised on horizon C. However, the crest is bald in respect of this horizon over two fairly large areas, which are separated by the saddle-like depression referred to above. The Infanta arch is undoubtedly an early positive feature judging by the onlapping relationship of horizon C. Between the Infanta arch and the northern flank of the Bredasdorp basin a south-eastward-plunging syncline is present on horizon C. The anticlines on horizons A and 11 are subdued replicas of the structure at lower levels.

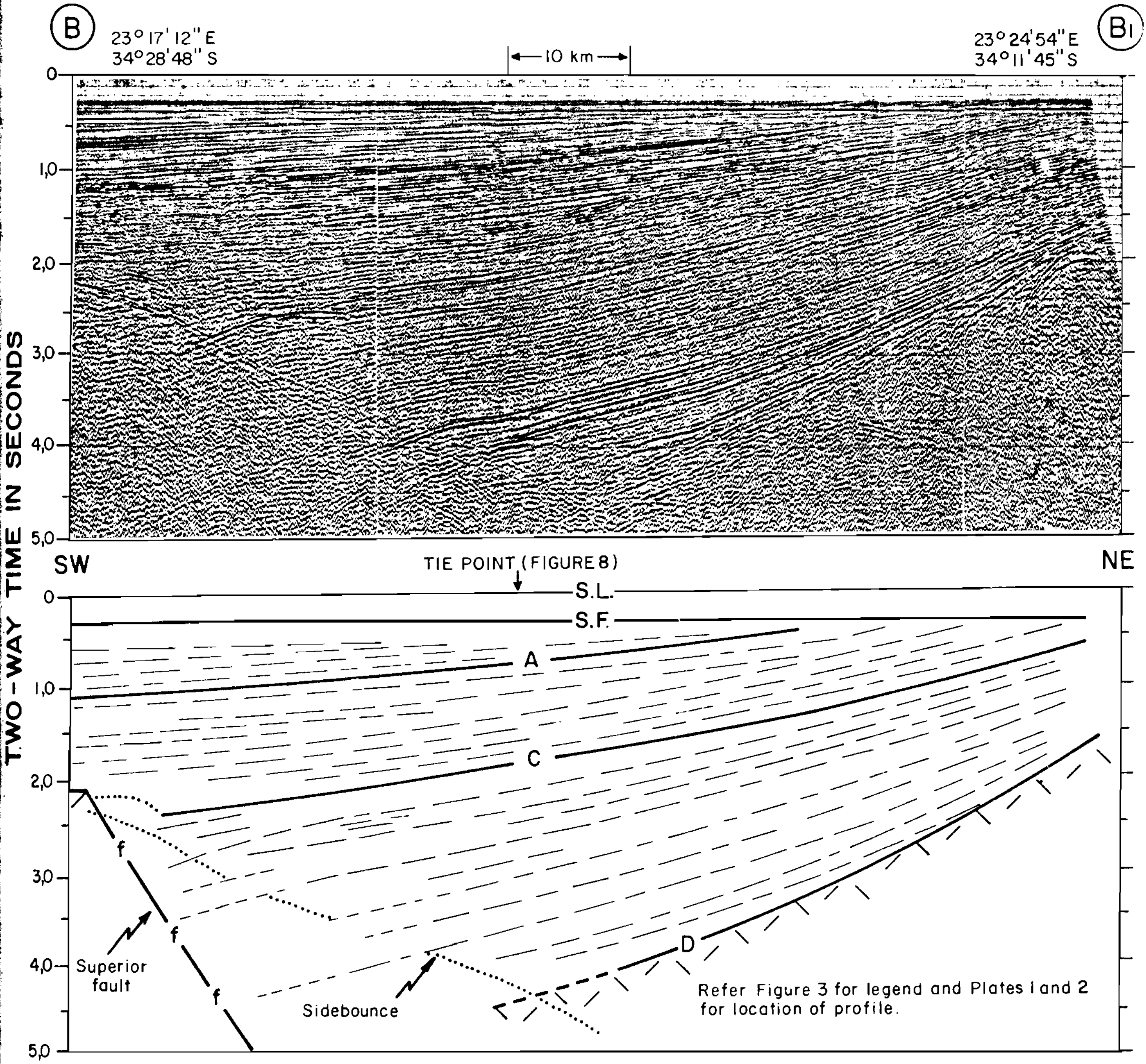
Pletmos Basin /24...

Pletmos Basin

The Pletmos basin derives its composite name from the coastal towns of Plettenberg Bay and Mossel Bay. It is defined as the 40-km to 50-km wide structural depression on horizon D between the Infanta arch and a large down-to-the-south fault south-east of Plettenberg Bay. This structure, referred to henceforth as the Plettenberg fault, has a displacement of almost five seconds on horizon D. It appears to persist westwards to near Plettenberg Bay, but has not been detected further west. This may be due to lack of seismic reflection coverage or the fault may go over into a relatively steep southerly slope, particularly in the area due south of Plettenberg Bay (fig. 6). In view of this, the Cretaceous outcrops in the Mossel Bay and Plettenberg Bay areas can be regarded as part of the structurally complex Pletmos basin. The Plettenberg fault is apparently shown in *en echelon* arrangement with one to the south of the George granite.

A south-east-trending normal fault - called the Superior fault - with a down-to-the-north displacement of over three seconds is present approximately in the middle of the Pletmos basin (fig. 6); it attains its maximum throw some 40 km south of Plettenberg Bay and fades out about 30 km to the east and 50 km to the west of this point. At its western end the fault splays and appears to be in *en echelon* relationship to the fault which marks the northern flank of the Infanta arch. Towards the east the fault also splays, and a major component continues in *en echelon* fashion some 15 km north of the termination of the Superior fault. In conformance with the opposite directions of dip on basement level towards the half-grabens associated with the Superior and Plettenberg faults, respectively, an anticlinal feature strikes south-east out of Plettenberg Bay. Between the Superior fault and the Infanta arch there is a subsidiary half-graben which plunges south-east.

As is the case on horizon D, horizon C is displaced by the arcuate Plettenberg fault. The Superior fault persists upward in the succession and displaces horizon C, but only by a small amount. A south-east-plunging syncline is defined by horizon C between the



Refer Figure 3 for legend and Plates I and 2 for location of profile.

FIG. 6 NE - SW SEISMIC REFLECTION PROFILE THROUGH THE PLETMOS BASIN NORTH OF THE SUPERIOR FAULT SHOWING THE RELATIVELY STEEP NORTHERN FLANK THE LOWER CRETACEOUS - UPPER JURASSIC INTERVAL BETWEEN HORIZONS C AND D THICKENS TOWARDS THE SUPERIOR FAULT AND ONLAPS BASEMENT TO THE NORTHEAST. REFER TO FIGURE 8 FOR TRANSVERSE PROFILE.

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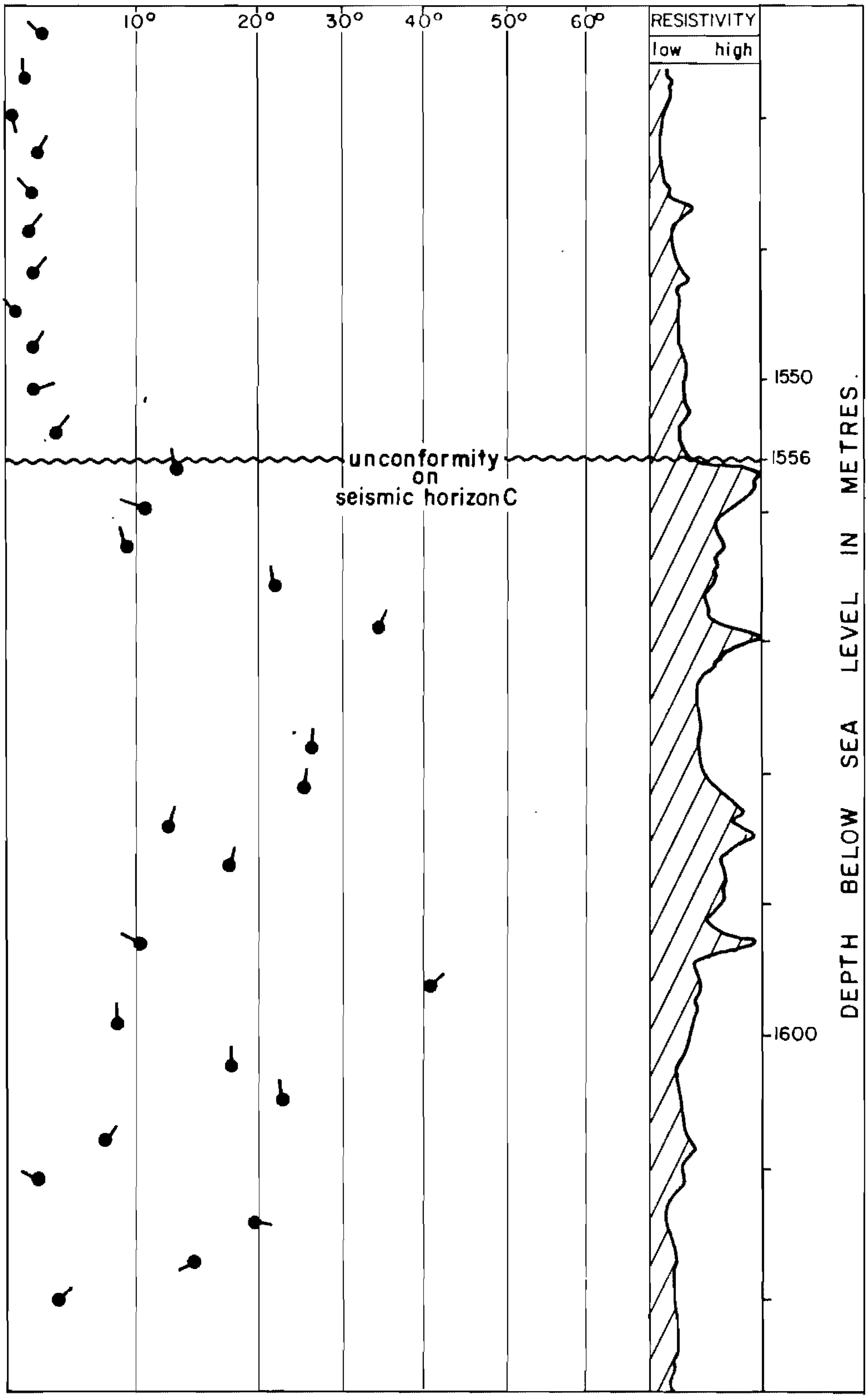

FIGURE 7: Dipmeter log (tadpole plot) in the G(b) Gemsbok /1 borehole showing interpretation of an unconformity on seismic horizon C at 1556 m below sea level.

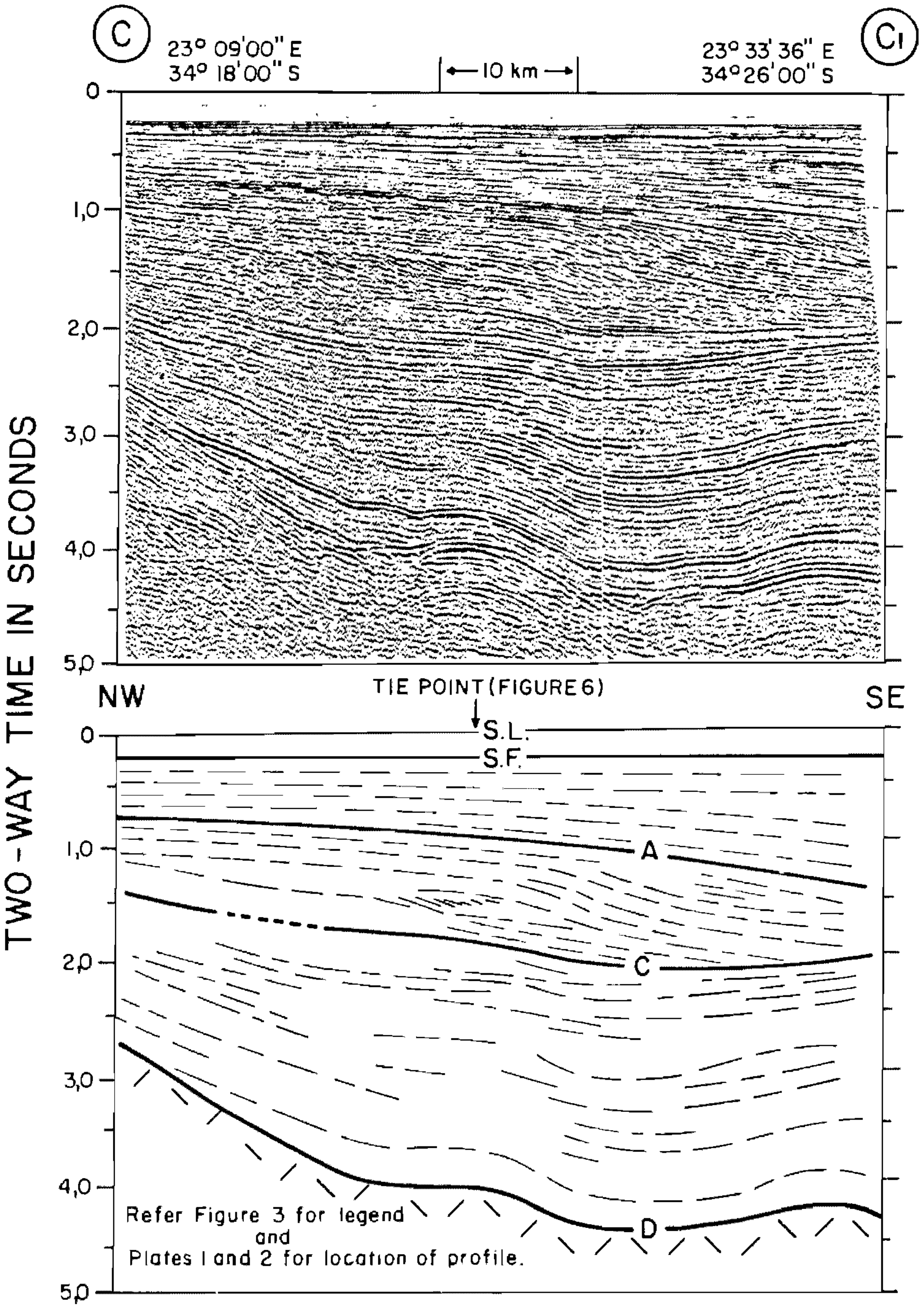

FIG. 8 NW-SE SEISMIC REFLECTION PROFILE IN THE PLETMOS BASIN NORTH OF THE SUPERIOR FAULT. PROGRADING LOWER CRETACEOUS SEDIMENTS ARE SHOWN IN THE INTERVAL BETWEEN HORIZONS A AND C.

Superior fault and the Infanta arch, but it is not as deep as the asymmetric half-grabens between the Superior and Plettenberg faults. Contours on horizon C close on a high on which the G(b) Gemsbok/1 borehole was drilled about midway between the Plettenberg fault and the *en echelon* continuation of the Superior fault. This positive feature continues in an arcuate fashion to the 200-m isobath, where horizon C attains depths ranging between 2,3 and 2,5 seconds.

Horizon C is recognised as an angular unconformity on the basis of amongst others, dipmeter evidence from the G(b) Gemsbok/1 borehole (fig. 7). The sediments immediately below C (1 556 m below sea level) dip northwards at an angle of about 20°. An angular unconformity is also present at this level on the Superior A structure, where its existence is inferred from detailed wireline log correlations between the G(a) A/1, G(a) A/2 and G(a) A/3 boreholes (see later). The onlapping relationship of reflectors above horizon C is consistent with the existence of an hiatus at horizon C. A similar onlapping of seismic reflectors onto horizon C is observed to the north of the Superior fault, where reflectors overstep each other in a south-easterly direction. To the north-west of the G(a) B/1 borehole these reflectors become a south-easterly-directed set of prograding features (fig. 8). The onlaps and progrades suggest that sediments above horizon C in the Pletmos basin were derived from the north-west.

Few of the structural features referred to above are present at the higher stratigraphic levels such as horizons A and 11. Minor faulting, which represents reactivation of the Superior fault zone, is present on horizon A, and a low south-eastward-plunging anticline is present on horizon 11 about 100 km south-east of Plettenberg Bay.

St. Francis Arch

The axis of this arcuate anticlinal feature plunges seaward from Cape St. Francis and persists to the 200-m isobath. A large number of normal faults strike sub-parallel to it and affect both horizons D and C. The St. Francis arch is bald in respect of horizon C close inshore, where it onlaps onto horizon D. Horizons A and 11 are generally too shallow and

their /29...

their identification too unreliable to allow any positive conclusions to be drawn regarding the structure at these high levels.

Gamtoos Basin

The onshore Gamtoos basin is continued seawards by a half-graben. The floor of this half-graben (horizon D) cannot be identified at depts exceeding 4,6 seconds; this is due largely to interference by sidebounces off the fault plane. It may be deepest on the downthrow side of the marginal fault in the north-east. The closely spaced contours which indicate a relatively steep dip towards the south-west may reflect the attitude of the fault plane itself.

Horizon C also dips towards the north-east into the marginal fault, which at this level is flanked by an ovate depression deeper than 2,0 seconds and a south-westward-plunging anticline. The inferred geometry of horizon C in the Gamtoos basin may be incorrect due to the sparsity of seismic reflection cover, particularly near the major fault in the north-east.

Recife Arch

A seaward-plunging anticline on horizon D extends in an arcuate manner from Cape Recife; it marks the boundary between the Gamtoos and the Algoa basins both onshore and on the continental shelf. The axis of this arch parallels the trace of the Gamtoos fault. The recife arch is bald in respect of horizon C all the way to the 200-m isobath, since this horizon onlaps onto basement on the upthrow side of the Gamtoos fault. It is clearly an early, positive feature.

Algoa Basin

The Algoa basin to the north of Port Elizabeth is situated mainly on land and is filled by Cretaceous sediments. It comprises the Uitenhage trough (half-graben) and the Sundays River trough (including the Coega embayment); these are separated by the Coega fault (Winter, 1973).

The Coega fault is shown to persist at the level of horizon D for about

30 km /30...

30 km into Algoa Bay; St. Croix Island is located on its upthrow side. Fifteen km south of its seaward termination a comparable fault commences and continues to the 200-m isobath. This structure, which is parallel to the Recife arch and is hereinafter referred to as the Port Elizabeth fault, marks the northern margin of the Port Elizabeth half-graben into which the H(b) - Hartebeest/1 borehole was drilled. The Uitenhage trough widens to about 50 km in a seaward direction; its north-eastern margin on the continental shelf is a fault referred to as the Port Elizabeth fault, which overlaps left-handed with the Coega fault in the vicinity of the St. Croix Island. The Sundays River fault is straight and is flanked by a northward-deepening asymmetric half-graben in Algoa Bay. Other more or less straight faults are present; the largest merges with the Port Elizabeth fault about 25 km south-east of Port Elizabeth.

The Sundays River trough, about 35 km wide, is flanked in the eastern part of Algoa Bay by a fault, and by the Coega fault in the west. Close inshore the basement reflector in the Sundays River trough deepens landward and away from the Coega fault.

The horizon termed "top of layer 3" is strongly unconformable on seismic reflection profiles in Algoa Bay and impinges against the arcuate fault along the eastern margin of the Algoa basin (fig. 9); it rests on basement to the east and north of this fault. In the central part of the basin "top of layer 3" also rests on basement in the vicinity of the junction of a straight fault and the Port Elizabeth fault; it will be demonstrated that the angular unconformity at the level of "top of layer 3" is overlain by Upper Cretaceous (Campanian) sediments in the H(b)-Hartebeest/1 borehole.

Apart from the minimal influence of faults, the undulating relief on the unconformity surface is due entirely to erosion. A broad channel-like feature with a comparatively smooth base runs north-east and intersects a north-west trend in the remainder of the Algoa basin.

The sediments below "top of layer 3" follow essentially conformably on horizon D so that the regional northerly dip persists upward in the

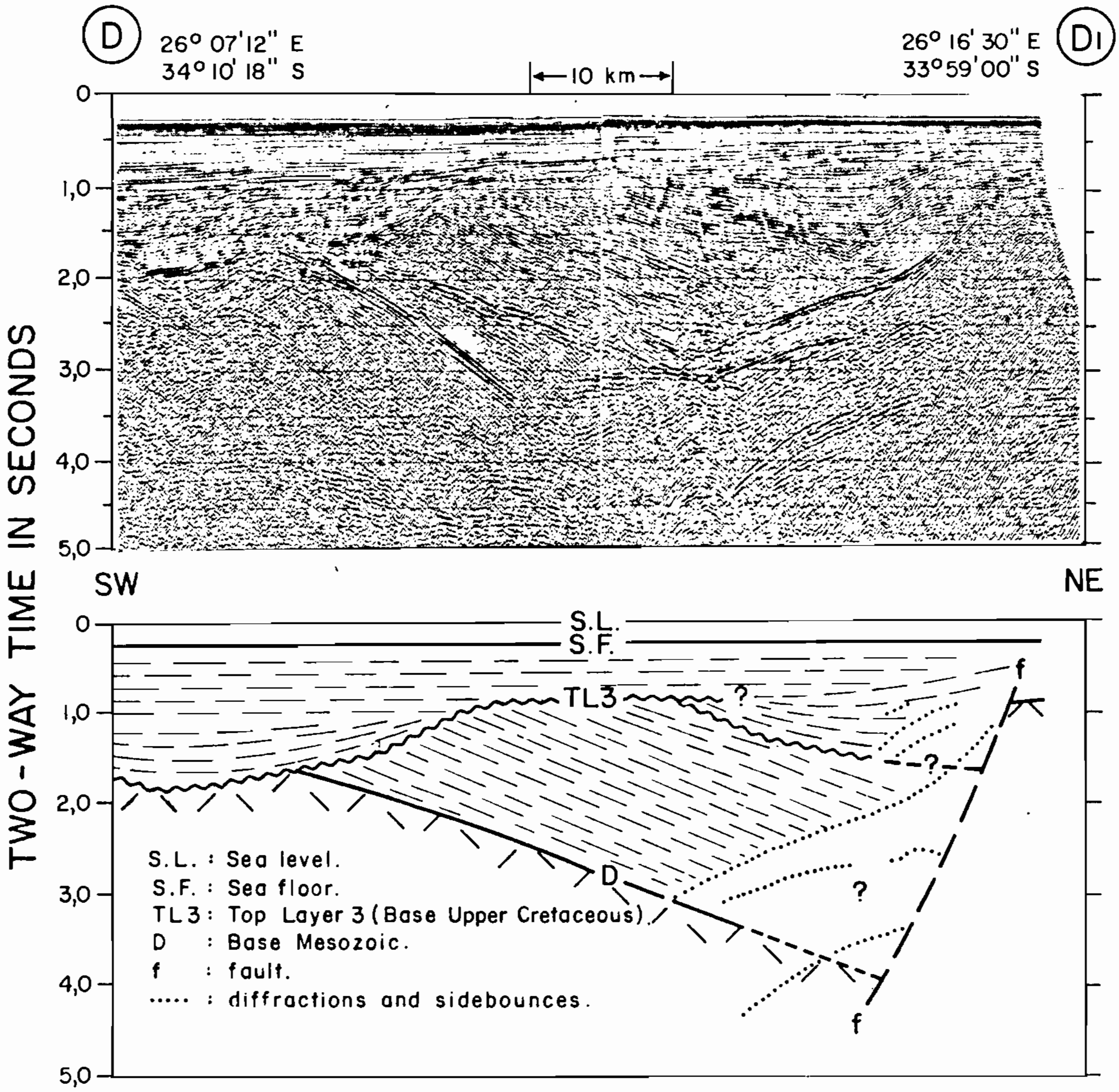

FIG. 9 NE-SW SEISMIC REFLECTION PROFILE IN THE ALGOA BASIN. AN ANGULAR UNCONFORMITY IS PRESENT TOWARDS THE BASE OF THE UPPER CRETACEOUS (TOP LAYER 3). A FAULT WHICH DEFINES THE NORTHEASTERN MARGIN OF THE ALGOA BASIN IS SHOWN.

succession to the level of the unconformity and is generally directed towards the major fault (fig. 9). It is noteworthy that in the Algoa basin on the continental shelf all the major faults are normal faults, with downthrows towards the south, south-west and west predominating. Some faults have arcuate traces while others are linear and are aligned diagonally in respect of the former.

BASIC PRINCIPLES OF FAULT TECTONICS

Stress Ellipsoid

Fundamental to the understanding of fault mechanics -- be it normal, reverse or wrench faults - is the expression of stress distribution in terms of a set of three mutually perpendicular axes. In a homogeneous isotropic material under compression, the maximum compressive stress can be represented as a force along the Y-axis which is at right angles to the minimum stress direction (X-axis); the third rectangular axis must coincide with the intermediate stress direction (Z-axis). These three forces are represented as of unequal length and describe an ellipsoid which long has been referred to as the stress ellipsoid. The planes of maximum shearing stress are parallel to the intermediate stress axis and lie at angles of 45° on either side of the maximum compressive stress. The planes of actual shear do not coincide with planes of maximum shearing stress but lie closer to the axis of maximum compression and form an angle to it called "the angle of shear". Hubbert (1951) indicates that, although the value may vary among different materials, a good average for rocks is approximately 31°. Moody and Hill (1956) consider this angle to be applicable to wrench faulting. Billings (1954) cites a figure of 30° in the same context, while Wilcox et al (1973, p. 89) quote an angle of between 20° and 48°.

The differences between normal, thrust and wrench faulting relate to the orientation of the three primary stress directions in space; the maximum compressional stress for both thrust and wrench faulting is in the horizontal plane, but for normal faulting it is vertical. Moody and Hill (1956, p. 1211) state that "this requirement obviates the syngenetic development of normal faults with wrench or thrust

faults /33...

faults except where normal faults are a secondary effect due to local deformation". The axis of intermediate stress is horizontal in thrust and normal faulting and vertical in wrench faulting.

Wrench faults

The term wrench fault is adopted from Kennedy (1946) and Anderson (1951) to describe ruptures in the earth's crust in which the dominant relative motion of one block to the other is horizontal (Moody and Hill, 1956). The term is synonymous with strike-slip and transcurrent fault. The connotations right lateral (dextral) and left lateral (sinistral) refer to the apparent relative movement of the two blocks when viewed in plan; the separation between the two blocks can also be referred to as clockwise or counterclockwise (Hill, 1947). Wrench faults form in response to horizontal shear couples within the earth's crust (Billings, 1956) and they can be simulated in clay models by moving plates beneath a clay cake (Cloos, 1955; Wilcox, et al, 1973).

The main structures associated with basic wrench-tectonic patterns are en echelon folds, en echelon conjugate strike-slip faults, the main wrench fault and en echelon normal faults (Wilcox et al, op cit p. 77). These are shown schematically in figure 10 in the context of the strain ellipsoid pertaining to a right lateral (clockwise) couple.

The term en echelon refers to the arrangements of structures along a zone so that near the termination of individual folds or faults their places are taken by parallel structures of the same kind but off-set either to the left or right-handed (Campbell, 1958). The fold axes are generally aligned at an angle of 30° to the wrench zone. Wrenching causes two sets of intersecting near-vertical conjugate strike-slip fractures to form in a predictable orientation along a wrench zone. One set ($C-C^1$) subtends a small angle of between 10° and 30° with the strike of the main wrench zone whereas the other set ($D-D^1$) subtends an angle of 70 - 90°. These conjugate fractures can be either joints or faults or both, depending on the magnitude of wrenching. The acute angle of intersection of the fracture sets is usually in the range of 60 - 70°, and this is bisected by the direction of maximum compression ($B-B^1$). The $C-C^1$ fractures are referred to as synthetic, since the

sense /35...

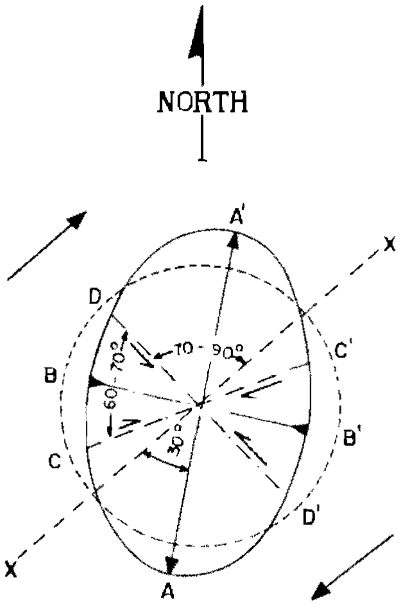

FIGURE 10: Forces and composite of structures that can result from right-lateral wrenching combined schematically with a strain ellipse. X-X' is the wrench zone; A-A' is the axis of minimum compression (fold axis); B-B' is the axis of maximum compression (tension fractures) which bisects the acute angle between the conjugate strike-slip synthetic (C-C') and antithetic (D-D') fractures.

sense of displacement on them is in the same direction as that on the main wrench fault, while the D-D^1 fractures are called antithetic.

The physical constraints emplaced on en echelon synthetic faults in a right lateral wrench system are such that these faults can only overlap in a left-handed manner, and local compression operate in areas of overlap between the synthetic faults even if the lateral offsets on them are small.

Curved fault traces are common features; the curvature in both plan and cross-sectional view is caused by the rotation of the principal direction of stress. Wrenching produces external (regional) rotational deformation; wedging on the conjugate shears produces internal rotational deformation. The counter-rotation of internal and external forces on synthetic faults results in their traces being essentially straight. The rotation of antithetic faults - often wrongly referred to as "drag" - provides an invaluable clue to the sense of displacement on a main wrench zone.

Tension faults develop parallel to the short axis (B-B^1) of the strain ellipse. En echelon tension fractures may form along a wrench zone during the initial stage of deformation; they form at an angle of 45-47° to the shear plane and are rotated during wrench movement to an angle of 60° (de Sitter, 1959, p. 172). They are easily destroyed as wrench displacement increases and compressive structures become predominant.

A similar conjugate fault pattern, wedging and external fault rotation are possible when rocks are subjected to straight external compression (Ramsay, 1967, p. 60) which result in pure shears (Thomas, 1974, p. 1312). Wrenching, however, also produces external rotational deformation which, unlike pure shear, generally is restricted to a straight wrench zone parallel to the couple and to the edges of moving crustal blocks. (Wilcox et al, 1973, p. 82).

Movement of crustal blocks may be parallel, convergent or divergent in relation to the main wrench fault. Convergent movement will enhance

compressive /36...

compressive features such as folds, reverse faulting and thrusting. The formation of tensional structures, mainly normal faults, is typical of divergent wrenching (Wilcox et al, 1973, p. 89). These investigators state (p. 94) that "an important result of divergent wrenching is an overlay of extensional block faulting on the simple (parallel) wrench pattern" and that "grabens form in preference to horsts and nearly all fractures have a tendency to develop into high angle normal faults with oblique slip".

When subjected to stress, anisotropies in basement result in faults with the same orientation being propagated upward into the overlying sedimentary succession (Yeats, 1973, p. 128). Anisotropies in basement which are orientated parallel to the B-B^1 direction, i.e. normal to the fold axis, would propagate upward as extension fractures or, under conditions of greater overburden load, as normal faults.

In a parallel wrench system basement anisotropies which are parallel to the rotating couple would propagate upward as strike-slip faults. Anisotropies that are normal to the axis of compression would result in thrust faults in the A-A^1 direction which is parallel to the theoretical fold axis.

SYNTHESIS OF MESOZOIC TECTONICS

Regional maps of four seismic reflector horizons (D,C,A and 11) show the presence of two main tectonic stages in the Mesozoic sequence on the Agulhas Bank. These stages can be referred to as early and late Mesozoic in reference to horizon C and they are discussed below.

Early Mesozoic Tectonic Stage

Characteristics

The early Mesozoic tectonic stage - observed in the vertical sequence between seismic reflector horizons C and D - is characterised by the presence of a large number of steeply-dipping normal faults which give rise to the arches (horsts) and basins (grabens) described before.

Many of these faults, basins and arches are arcuate in plan and are concave to the south-west (the Plettenberg and Gamtoos faults, the axes of the Infanta, St. Francis and Recife arches and the basins flanking these arches). The faults generally have downward displacement on their concave (southerly or south-westerly) sides.

The arcuate nature of the early Mesozoic tectonic grain appears to be a function, firstly, of the distance from the Agulhas fracture zone, which strikes roughly N 50° E and, secondly, of the tectonic grain of the Cape fold belt in the central and eastern parts of the Agulhas Bank. Faults which generally strike roughly east-west onshore and close inshore - such as those along the margins of the Riversdale, Oudtshoorn, George, Gamtoos Cretaceous basins, the Superior and Plettenberg faults, and the ones parallel to the Infanta arch in the west - veer round progressively in a clockwise direction when followed to the east. This change in strike is particularly noticeable in the central and eastern sectors of the Agulhas Bank, and particularly within 50 km of the Agulhas fracture zone, where the Mesozoic tectonic grain strikes roughly north-south.

Normal faults which have straight traces and which strike roughly N50° W are present in the Algoa basin and may well have gone undetected elsewhere. This direction is parallel to the axes of the Agulhas arch and Bredasdorp basin. The Worcester fault in the Swellendam-Worcester area has a similar orientation.

A left-hand <u>en echelon</u> arrangement of normal faults seems to be shown by the Superior and Coega faults. Areas of overlap between <u>en echelon</u> fault segments are marked by positive relief on basement level; examples of these are, firstly, the basement high at the F-B/1 drillsite along the Superior fault zone and, secondly, the St. Croix Island basement high along the Coega fault in the Algoa basin.

In the western sector, which includes large parts of the Bredasdorp basin and the Agulhas arch, the early Mesozoic trend (N 50° W) intersects the north-easterly directed Cape fold trend at almost 90°. In this sector the large tilted fault blocks are virtually absent.

Wrench model

The aforementioned characteristics of early Mesozoic tectonics are considered to be in agreement with right lateral wrenching on the Agulhas fracture zone. A right lateral sense of movement is indicated independently by the presence of left-hand en echelon faults and by the progressive clockwise curvature of faults. Wrench displacement is preferred as a mechanism over pure shear because rotational deformation on the Agulhas Bank is confined to a linear zone about 50 km wide next to the fracture zone. Rotational deformation which is a response to simple shearing is therefore at a maximum at the edge of the moving plate rather than within it; this criterion serves to distinguish between pure and simple shear (Thomas, 1974, p. 1312).

The east-west striking faults, such as the westerly segments of the Gamtoos, Superior and Plettenberg faults and those which bound the Riversdale and Oudtshoorn basins, intersect the direction of the Agulhas fracture zone at an angle of about 40°. They are all normal faults and appear to curve in a clockwise direction when traced eastwards. They could theoretically be either synthetic, antithetic or tension faults. The probability that they are antithetic faults can be ruled out because, as discussed earlier, antithetic faults tend to form at angles in excess of 70° to the main wrench zone. The east-west faults are considered to be synthetic faults because these have been shown to form at an acute angle – generally less than 30° – to the main wrench. Alternatively, and particularly since they are rotated, the east-west faults can be regarded as tension (gash) fractures which are orientated parallel to the short axes ($B-B^1$) of the strain ellipsoid, i.e. parallel to the direction of maximum compression. The rotation of the faults is such that these east-west faults assume an almost north-south orientation near the fracture zone, this is in agreement with the views of de Sitter (1959, p. 172) and Wilcox et al (1973) who illustrate that these fractures rotate during continued wrench movement.

Theoretical considerations presented earlier point towards the development of conjugate fractures or faults in such a manner that the axis of maximum compression ($B-B^1$) bisects the acute angle between them. This

being /39...

being so, the unrotated antithetic fault direction $(D\text{-}D^1)$ could be represented on the Agulhas Bank by those faults which are parallel to the axes of the Agulhas arch and Bredasdorp basin, and those faults which generally strike N 50° W. The Worcester fault has a similar orientation west of Swellendam.

Unrotated tension or synthetic faults are parallel to the east-west grain of the Cape fold belt in the central part of the Agulhas Bank; rotated tension faults and the unrotated antithetic faults are parallel to basement anisotropies in the eastern section of the study area. The anisotropies within basement are caused by the pervasive arcuate cleavage, folds, faults and differences in competency of pre-Mesozoic rock units in the Cape fold belt and may well have enhanced the development and controlled the orientation of Mesozoic faults in conjunction with the stresses outlined above, e.g. it was shown earlier that anisotropies in basement which are orientated parallel to the maximum compression direction of the strain ellipse, would propagate upward as extension fractures, or under conditions of greater overburden load, as normal faults.

The early Mesozoic tectonic style is dominated by normal, tensional faulting. The absence of notable compressional features such as folds and reverse faults, indicates a divergent wrench movement on the Agulhas fracture zone. Divergent wrenching, as illustrated by Wilcox et al (1973, fig. 17), appears applicable to the early Mesozoic on the Agulhas Bank, as it seems to have resulted in an overlay of extensional block faulting on the simple wrench pattern and caused grabens to form in preference to horsts, and nearly all fractures have a tendency to be high-angle normal faults near surface. An important aspect of curved normal faulting is that, although movement commenced during the initiation of displacement along the wrench zone, subsequent displacement on them continued for as long as the southerly block (Falkland plate) moved parallel and past the northern one (African plate). The cessation of significant fault displacement at about horizon C could conceivably be due to one of the following reasons:

(a) cessation of wrench movement on the Agulhas fracture zone. This

probability /40...

probability is considered to be unlikely unless the initial spreading axis on the Agulhas Plateau became dormant at this time and thereby caused the Falkland and African plates to move in unison.

(b) a change in the Agulhas fracture zone to more divergent wrenching, with or without a concommitant shift in the early Mesozoic spreading pole.

(c) restriction of mainly vertical faulting to an early phase of stress build-up along an incipient major wrench zone and virtual cessation of movement once a throughgoing wrench fault had developed.

Late Mesozoic Tectonic Stage

The late Mesozoic interval, herein regarded as comprising all the Cretaceous sediments above seismic reflector horizon C, is represented by a seaward thickening wedge of sediment which was deposited in response to mild continual seaward tilting, and accompanied by limited draping of late Mesozoic sediments over pre-existing topographic relief and by the reactivation of a limited number of normal faults.

Dingle and Scrutton (1974) regard the Agulhas Bank area as a sheared Atlantic-type margin and note that a progressive seaward shift of the main depocentre had taken place during the Cretaceous; this observation is confirmed by the continual seaward tilt of the continental margin during the late Mesozoic tectonic stage. Similar epeirogenic movements characterise the late history of other Atlantic-type margins (Dewey and Bird, 1970; Sleep, 1971, 1973). Dingle and Scrutton (1974, fig. 3) show that oceanic crust had been created seaward of the Agulhas marginal fracture zone by the mid-Cretaceous. It therefore appears reasonable to adopt the model proposed by Dewey and Bird (1970) to explain the subsidence of the Agulhas Bank during the late Cretaceous; this model relates continued subsidence to separation of continental fragments, the creation of new oceanic crust, its cooling and becoming more dense, thus causing progressive subsidence of the adjoining continental crust.

It will /41...

It will be demonstrated that, translated from sedimentation rates, subsidence of the Agulhas Bank during the late Mesozoic tectonic phase decreased exponentially with time and averaged 25 m per million years.

Basin Classification

General concepts

Glaessner and Teichert (1947) present a comprehensive review of the development of geosynclinal theory and point out that the following three broad lines of study have been followed in the past:

1. the lithogenetic approach, which involves the study of the sedimentary filling of the geosyncline with relatively little emphasis being placed on its structural history;

2. the orogenetic approach, which is mainly concerned with the orogenic history of the geosyncline, without primary regard to its sedimentary filling; and

3. the geotectonic approach, which relates the tectonic behaviour of geosynclines to that of other crustal units.

Due to the different approaches the definition of the term "geosyncline" has undergone corresponding chages through the years. This state of flux extends to the present day, even with the development of new techniques for studying earth features and although a better understanding of three-dimensional relationships among rocks is obtained from sub-surface exploration.

Many new principles and concepts have arisen from data obtained in geophysical studies of ocean basins and from abundant sub-surface data obtained in oil exploration. Through the years this expanding knowledge has stimulated reconsideration of many geosynclinal concepts and has resulted in the development of geosynclinal classifications that are markedly different in some respects from classical views. The historical development of the concept of a geosyncline was examined by Knopf (1960), who pointed out that Stille (1936) was a leader in broadening

the definition /42...

the definition of the term "geosyncline" to include any area which subsides or has subsided through long intervals of time. He placed no restriction on the term because of the type of sediments - marine or non-marine - and it was incidental to his classification whether or not geosynclinal deposits were subsequently folded. The term *orthogeosyncline*, introduced by Stille, refers to linear belts of tectonic instability lying between more stable oceanic or continental blocks designated as cratons. Stille also recognised intracatonic subsiding areas and termed these "parageosynclines".

Kay (1944, 1947, 1951) recognised the above-mentioned two types of geosyncline but expanded the concept of a parageosyncline to include various types of subsiding areas within a craton (exo-, auto, and zeugogeosynclines). The zeugogeosyncline receives its sediment from complementary cratonic uplifts to which it is yoked. Parageosynclines differ from orthogeosynclines in that the latter are located between cratons; depending on whether volcanism is associated with their development and on the magnitude (or intensity) of subsidence, orthogeosynclines are referred to either as eugeosynclines or miogeosynclines (less active, no volcanics).

Many investigators have proposed classifications of tectonic elements; notable amongst them are Keunen (1935) who introduced the term "intermontane troughs", Umbgrove (1947), and Bubnoff (1931), who recognised, amongst others, shield areas, shelves, geosynclines and oceanic troughs and stated that shelf areas may be stable or mobile. More recently Weeks (1952) proposed a classification of sedimentary basins of various kinds, in which graben-type basins are included as a variety that occur in stable regions.

Cady (1950) emphasises the sequence of events in geotectonic elements, as did Krynine (1951). Dewey and Bird (1970) expand on the classification by Kay (1951) and relate the genesis of geosynclines to the hypothesis of plate tectonics. An Atlantic-type continental margin is shown to be comprised ideally of a taphrogeosyncline in its lower part and of a miogeosyncline higher up. The plate-tectonics theory inspired

Klemme (1971, and in Halbouty et al, 1968) to propose a genetic classification of sedimentary basins; this classification also takes into account the geometry and chronologic evolution of these basins and their location in respect of the craton.

Mesozoic Basins of the Agulhas Bank

The Mesozoic tectonic style on the Agulhas Bank allows for the study area to be classified as sheared Atlantic-type continental margin (Dingle and Scrutton, 1974). As is the case with other Atlantic-type margins it is characterised by the presence of a taphrogeosyncline in its lower part and a miogeosyncline in its upper part. On the Agulhas Bank the early Mesozoic tectonic stage is clearly characterised by rift faulting, which gave rise to taphrogeosynclines (graben and half-graben). In Klemme's terminology the early Mesozoic Bredasdorp, Pletmos, Gamtoos and Algoa basins are of Type III (rifts).

The late Mesozoic tectonic stage is characterised by the presence of a miogeosyncline (Klemme's Type V basin) which extends beyond the limits of the underlying Type III basins. Dingle and Scrutton (1974) state in the same context that, in the study area, the early Mesozoic basins coalesced during the late Mesozoic.

STRATIGRAPHY /44...

STRATIGRAPHY

LITHOSTRATIGRAPHIC FRAMEWORK

The lithostratigraphic framework for the Mesozoic sediments intersected in boreholes on the Agulhas Bank is shown in figure 11. Where possible the existing terminology and nomenclature of the South African Mesozoic rocks have been retained; where not, new formations and reference stratotypes have been defined. The writer adopted sub-surface procedures as summarised by Krumbein and Sloss (1963, p 71 - 91). The South African Stratigraphic Code was adhered to throughout. All depths referred to in this thesis are below mean sea level.

Basement

Paleozoic Karoo and Cape Supergroup rocks, and the underlying, still older units that outcrop in the Cape fold belt, constitute the floor of the Mesozoic sediments on the Agulhas Bank as in the southern Cape coastal belt. These pre-Mesozoic rocks are collectively referred to hereinafter as basement.

A marked unconformity separates the Paleozoic and Mesozoic rocks in the southern Cape Province (du Toit, op. cit., p 373); this unconformity is equated with the Gondwana erosion surface (King, 1951, p 243) and is present throughout the study area.

The identification of basement in boreholes on the Agulhas Bank is rarely conclusive when it is based solely on cuttings samples, cores or wireline-log characteristics. Similarly, parameters such as decreasing drilling penetration rates, downhole increases in sonic velocity, shale density and resistivity are known not to provide infallible criteria for distinguishing between basement rocks and the overlying Mesozoic succession. The singularly most useful approach of identifying basement in borehole cuttings samples is petrography (de Swardt and Rowsell, 1974). In particular their observation that cleavage in folded basement rocks affects porphyroblasts of chlorite and muscovite suggests that the

Paleozoic/45...

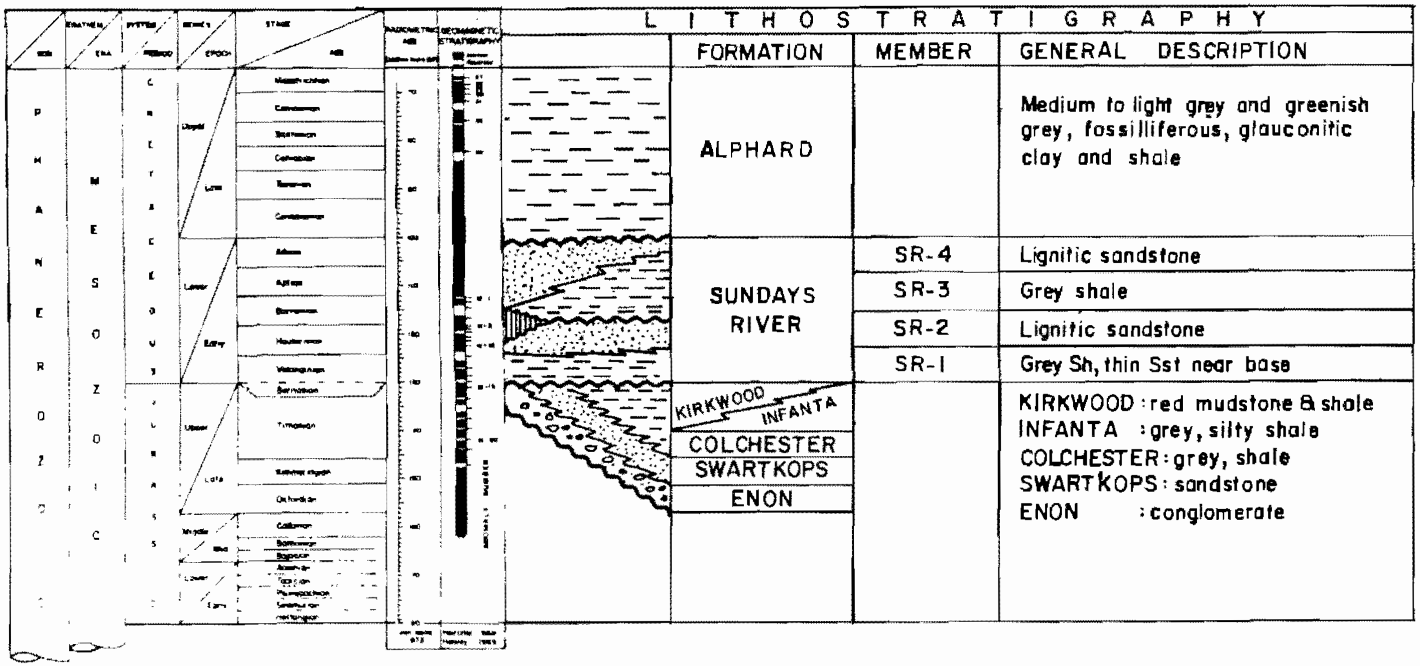

FIGURE II : Mesozoic lithostratigraphic framework on the Agulhas Bank. The comparative geochronologic, radiometric age and geomagnetic stratigraphic columns are shown only as a broad reference.

Paleozoic and older rocks had attained greenschist metamorphic facies prior to folding and their subsequent truncation by the unconformity which separates these rocks from the overlying Mesozoic rocks. Ancillary petrographic criteria which may prove useful, particularly in the coarser Paleozoic clastics are the following (de Swardt, pers comm): sutured quartz grain contacts, fractures across grain boundaries and laths of sericite which project across grain boundaries. The presence of stubby chlorite or muscovite porphyroblasts is characteristic of the Paleozoic slates, while a spaced "fracture" cleavage characterises the argillites of the Cape Supergroup, in contrast to the pervasive "mineral" cleavage generally found in the Malmesbury metasediments.

On seismic reflection profiles the base of the Mesozoic sediments is generally seen as a prominent reflector (horizon D), which also constitutes acoustic basement. Parabolic diffraction patterns often obscure this acoustic basement reflection; these emanate from point sources on the uneven floor of the Mesozoic succession, particularly in structurally complex areas.

Uitenhage Group

The historical development of the terminology and nomenclature of the Uitenhage Group in the Algoa basin has been summarised by Winter (1973). The term Uitenhage Group has been retained in the lithostratigraphic framework for the Agulhas Bank, but certain modifications are introduced in the following discussion of the subdivision of the Group.

Enon Conglomerate Formation

The type area of this formation is generally accepted to be at the Enon Mission, about 64 km due north of Port Elizabeth. The unit consists of poorly sorted, angular to subrounded boulders and red, yellow and green sandstone, and reddish-brown claystone, which also form interbeds in the conglomerate.

The pebbles of the Enon consist largely of quartzitic sandstone of the

Cape Supergroup derivation; however Rigassi and Dixon (1970) and previous investigators record the presence of pebbles derived from Karoo and pre-Cape formations. The upper boundary of the unit was defined by Winter (1973) as the first massive conglomerate below the Kirkwood Formation. Tongues of the Enon may be present in the Kirkwood. At the base of the unit there is an unconformity which cuts across Karoo, Cape and pre-Cape rocks.

The Enon Formation post-dates the Suurberg Group according to Hill (1972). This group of pyroclastics and basalt outcrops along the northern rim of the Algoa basin and has been dated by the potassium-argon method at 162 m.y. (Winter, 1973). The relationship of the Enon conglomerate to the Robberg Formation has been discussed by Rigassi and Dixon (1970) who assigned a Jurassic age to the latter. The Robberg Formation overlies the Table Mountain quartzite unconformably and is cut by a smooth unconformity at the base of the overlying Enon Conglomerate in the outcrop at the suggested type area at Robberg Peninsula near Plettenberg Bay. The unit, as defined, consists of silicified sandstone and conglomerate with tuffaceous shale beds in the lower part. It is however true that hand specimens of the Robberg Formation can easily be confused with the Table Mountain quartzitic sandstone (Rigassi and Dixon, 1970, p. 518) and that those features which are considered characteristic of the unit (silicification and lack of variegated shale) do not apply to the reference stratotype of the formation at Cape St. Blaize (Leith, pers. com.). The unit is thus not readily distinguishable from the established formations of the Uitenhage Group and has consequently not been incorporated in the lithostratigraphic framework on the Agulhas Bank.

In the type area of the unit, the Enon Conglomerate Formation is thought to represent strongly oxidised alluvial-fan or piedmont deposits. Since depositional environments do not constitute a viable part of lithostratigraphic classification, the concept of the Enon Formation has been extended in this thesis, to include conglomerate which has an unoxidised, shaly matrix.

Swartkops Sandstone Formation

This unit was hitherto given the status of an informal member of the Kirkwood Formation (Winter, 1973). It has since proved to be mappable in the sub-surface and is consequently assigned formation status on the Agulhas Bank. A detailed and suitable stratotype description is not available from the Swartkops borehole, where it was first intersected in 1908. For this reason a correlative of the unit, intersected in the G(b)-Gemsbok/1 borehole, is proposed herewith as the sub-surface stratotype (fig. 12).

The unit consists of medium- to fine-grained, poorly sorted, angular to sub-angular sandstone and quartzitic sandstone, interbedded with subordinate brownish and dark-grey shale. The top of the unit is taken at 3 256 m, at the top of the first sandstone below the Infanta Shale Formation (discussed below); this contact can be selected with the aid of the gamma ray curve (deflection towards sand line) in conjunction with changes in cuttings-sample characteristics, and an abrupt increase in resistivity. The base of the unit could not be defined, since the G(b)-Gemsbok/1 borehole was stopped within it at a depth of 3 938 m. It is suspected that towards the base the Swartkops Formation may be transitional into either the Kirkwood Formation or the Enon Conglomerate Formation, or alternatively, it may rest unconformably on Paleozoic rocks.

Colchester Shale Formation

This unit is accorded formation status by Rigassi and Dixon (1970) who describe the sub-surface stratotype from a cored intersection in the CO 1/67 borehole in the Algoa basin as follows: grey shales with subordinate siltstones and sandstones of marine-estuarine origin which interfinger with the Kirkwood Formation. Winter (1973) regards the same unit as an informal member of the Kirkwood Formation and defines its top as that of a sequence containing grey shale beds exceeding one meter in thickness near the base of the Kirkwood Formation.

The term Colchester Formation is retained in the lithostratigraphic framework for the Agulhas Bank by virtue of Rigassi and Dixon's priority of date of publication and of the proven mappability of the unit in the sub-surface on the Agulhas Bank.

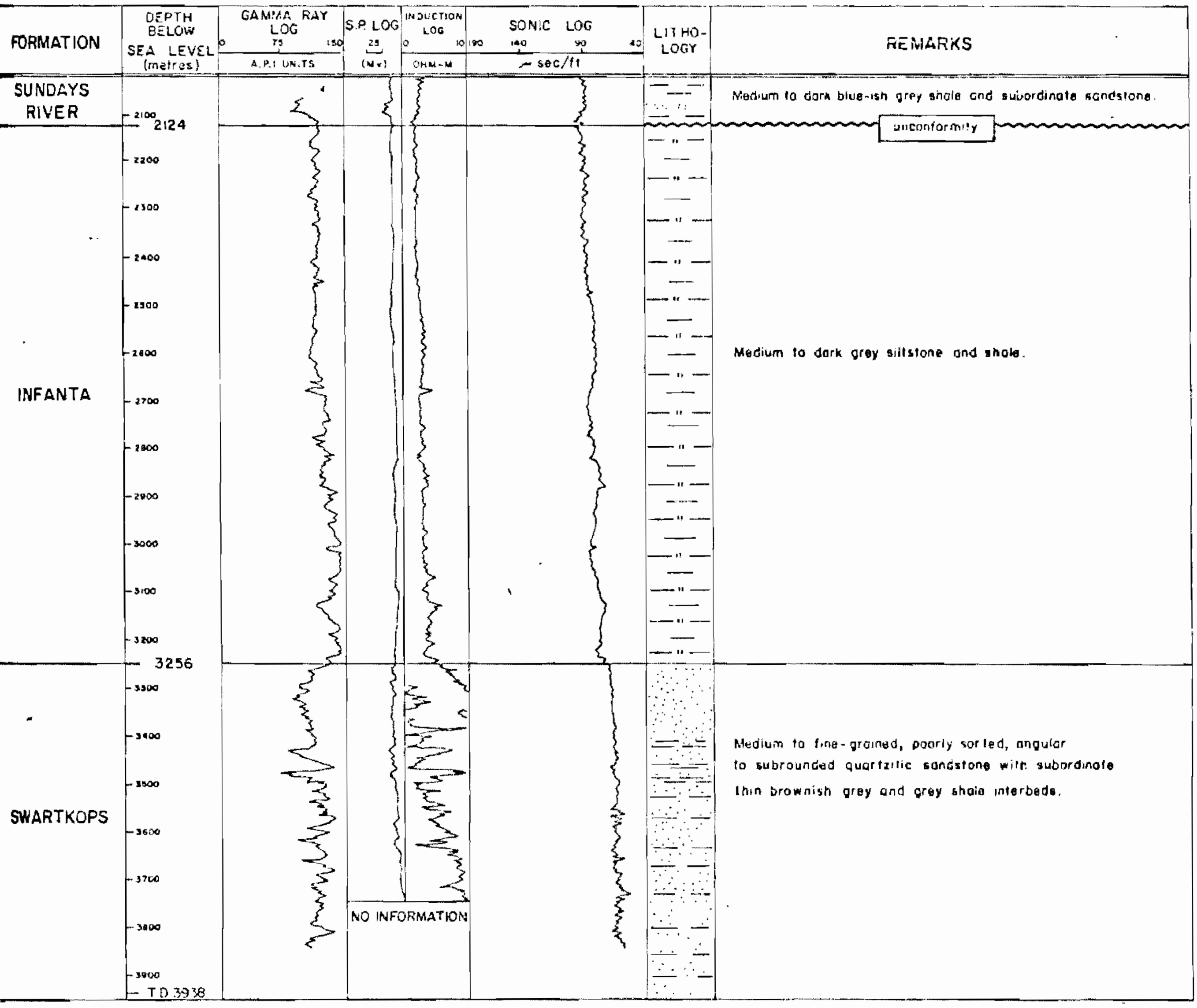

FIGURE 12: Subsurface stratotype of the Infanta and Swartkops Formations in the G(b) Gemsbok/1 borehole on the Agulhas Bank.

Rigassi and Dixon (1970) tentatively correlate an outlier at Knysna with the Colchester Formation. The Jurassic beds in this outlier (Dingle, 1971) have been accorded formation status and named the Brenton Formation (Du Toit et al, in press). This unit outcrops along the southern shore of the Kysna lagoon and is composes of grey shale and blue-grey sandstone interbeds with a marine microfauna similar to those of the Colchester Formation (Rigassi and Dixon, 1970; Dingle, 1971). However, a lithostratigraphic correlation of the Brenton Formation with the Sundays River Formation is equally credible.

Kirkwood Formation

This name was coined by Winter (1973) for thos sediments which had previously been referred to by the cumbersome and inappropriate term of Variegated Marls and Wood Beds. The unit stratotype is present in outcrops near Kirkwood, while the composite sub-surface reference stratotype is found in the CO 1/67 and CO 2/70 boreholes in the Algoa basin.

The unit is made up of reddish-brown, variegated, silty mudstones with subordinate grey shale and silty sand. The coarser clastics are represented by reddish and yellow to white and pale-grey sandstones; they are massive to crossbedded, commonly contain pebble stringers, clay pellets and fossilized plant material; they often grade upwards into siltstone and greenish-grey variegated shale.

The upper boundary of the unit at its type area is defined as the uppermost reddish-brown mudstone below the Sundays River Formation. In the Algoa basin the Kirkwood is generally believed to interfinger with the overlying Sundays River Formation as well as with the underlying Enon Conglomerate (du Toit, 1954). The unit also interfingers with the Infanta Formation (discussed below) on the Agulhas Bank. At its type locality the Kirkwood Formation is assigned a sub-aerial fluvial origin, with the coarser clastics representing lenticular channel deposits (e.g. point bars).

Infanta Shale Formation

This unit, /51...

This unit, first recognised on the Agulhas Bank, occurs immediately below the Sundays River Formation in the G(b)-Gemsbok/1 borehole, where its sub-surface stratotype is defined (fig. 12). It is present between 2 124 m and 3 256 m and consists predominantly of light-grey to medium-grey and occasionally dark-grey siltstone, claystone and shale. It is very silty in parts and slightly calcareous.

The top of the unit, which corresponds to the base of the Sundays River Formation, is clearly apparent on wireline logs. The gamma curve deflects abruptly towards the shale line at 2 124 m, while the sonic and resistivity curves show abrupt increases and changes to lower amplitudes at this level. The base of the unit is taken at the top of the Swartkops Sandstone Formation at 3 256 m. The Infanta shale is homogeneous, poorly fossiliferous and predominantly argillaceous and is readily distinguishable from the overlying sandy Sundays River Formation as well as from the underlying Swartkops Sandstone. From dipmeter and sidewall core data the unit appears to be well stratified, particularly towards its base.

The stratigraphic position of the Infanta Formation (below the Sundays River Formation) makes it a logical lateral facies equivalent of the Kirkwood and Colchester Formations, with which it may interfinger.

The boundary between the Kirkwood and Infanta Formations is likely to be a gradational one and this intraformational boundary may be a somewhat arbitrary one based on the predominance of either reddish (Kirkwood) or grey (Infanta) lithologies. Repetitive alternations may be referred to as Kirkwood-Infanta Formation.

The paucity of sandstone, the lack of lithologic differentiation, and the poorly fossiliferous and stratified character indicate that the Infanta Formation was deposited in a low-energy environment, under limited marine influence such as prevails in a lagoon, estuary or epi-continental sea (Pickard and High, 1972).

Sundays River Formation

The type section of this formation is in the cliffs on the bank of the

Sundays River /52...

Sundays River some 40 km north to north-north-east of Port Elizabeth (Winter, 1973). In this outcrop it comprises deltaic and shallow marine sediments consisting of greyish-greenish-bluish shale and siltstone with interbedded and varying amounts of sandstone. The unit rests conformably to unconformably on the underlying beds and may locally constitute the basal part of the Uitenhage Group. The upper boundary of the unit could not be defined in the Algoa basin, where the formation is truncated by an unconformity at the base of the Alexandria Formation.

The earliest known attempt at lithostratigraphic subdivision of the Sundays River Formation was by Rigassi (1970). Venter (1972) subdivides the succession in the CO 1/67 cored borehole and introduces the names Amsterdamhoek, Soetgenoeg, Addo and Vetmaak for informal members (du Toit et al, in press). Since a great may of the characteristic features in the core of CO 1/67 cannot be recognised in cuttings samples of a rotary borehole nearby, these subdivisions have limited use on the Agulhas Bank. For this reason the following four-fold subdivision is proposed as a sub-surface reference stratotype for the Sundays River Formation on the Agulhas Bank. (fig. 13):

SR-1 Member

This, the lowermost unit of the Sundays River Formation, was first recognised by the writer in the three boreholes on the Superior A structure, where it rests unconformably on the Infanta Formation. It is comprised of medium- to dark- to bluish-grey shale with subordinate, thin, fine-grained, medium-to light-trey sandstone towards the base. The basal contact is taken at the deflection of the resistivity (higher) and sonic (higher velocity) curves at 2 056 m in G(a)-A/2 (fig. 13). The density, resistivity and sonic velocity curves reveal increases which suggest an abrupt downhole increase in the state of compaction of sediments at this depth, and which, together with the diplog, is strongly indicative of the presence of a major angular unconformity at the base of the unit. The upper boundary is taken at 1 659 m in G(a)-A/2 at the base of the lowermost sandstone of the overlying SR-2 Member. The unit contains fragmentary, vitreous, black lignitic material

and is /54...

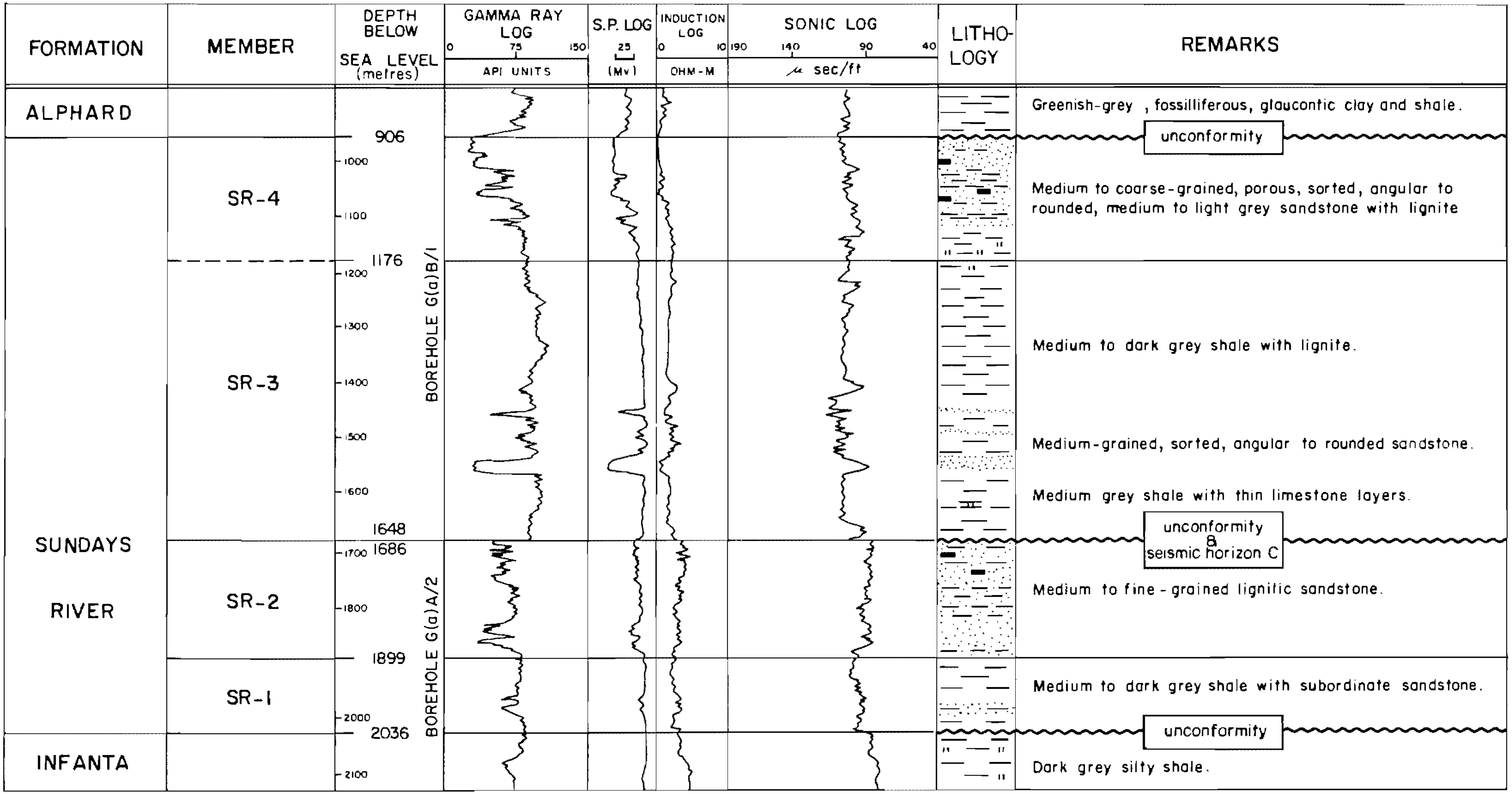

FIGURE 13: Composite subsurface reference stratotype for the Sundays River Formation on the Agulhas Bank.

and is more fossiliferous in its upper (shaly) part. The ostracode Cytherella sp 1 (Robertson Research, 1972) appears to be an index fossil for the unit, which appears to represent a transgressive marine deposit. It may be correlated with Rigassi's lower shale member and Venter's Amsterdamhoek member.

SR-2 Member

This prominent sandy unit occurs in all three boreholes on the Superior A structure. The sandstones are medium to fine grained, sorted, angular to subrounded and somewhat shaly and medium to light grey in colour. Interbedded subordinate shales and mudstones are medium to light grey, and occasionally brownish grey. The lower boundary is taken at the base of a sandstone unit, which is also the top of the SR-1 unit discussed above. The upper boundary is taken at the top of the uppermost sandstone, at 1 685 m, in S(a)-A/2. The sonic and resistivity curves are characteristic of the unit inasmuch as an abrupt downhole increase in sonic velocity and resistivity occurs at its top, which here coincides with seismic reflector horizon C. Detailed wireline log correlation between the three boreholes on the Superior A structure is strongly suggestive of the presence of an angular unconformity at the top of the SR-2 Member (see later).

The SR-2 Member in S(a)-A/2 appears to have been deposited as either delta-front sheet, distributary mouth-bar or bar-finger sands. Fragments of vitreous, lignitic material are generally present and are often partially replaced by pyrite. The SR-2 Member is tentatively correlated with the Soetgenoeg member of the Sundays River Formation in the Algoa basin.

SR-3 Member

The sub-surface stratotype for the SR-3 Member was intersected in the S(a)-B/1 borehole, where it occurs between depths of 1 176 m and 1 848 m (fig. 13). It consists of medium- to dark-grey shales and clays with subordinate sands, and contains thin,

hard /55...

hard, brownish dolomitic layers in the lower part and a fair amount of fragmentary lignite. It is putty-like when wet. At its upper boundary the unit grades through siltstone into the sandstone of the overlying SR-4 Member. The lower boundary is sharply defined by an abrupt increase in sonic velocity and shale resistivity, as well as by a shift of the gamma ray curve to the sand line; this boundary corresponds to seismic reflector horizon C.

A prominent sandy unit occurs approximately in the middle of the SR-3 Member in the G(a)-B/1 borehole between depths of 1 418 m and 1 531 m. This sandstone is clearly indicated by deflections of the gamma-ray and SP curves; it is medium grained, sorted, angular to rounded and contains lignitic material.

SR-4 Member

This unit consists predominantly of sandstone and is present in the G(a)-B/1 well between 906 m and 1 176 m. The sandstones are medium to coarse grained, porous, sorted, angular to rounded, medium to light grey and occasionally light brownish grey. Lignite layers and thin mildly radio-active layers are present. The interbedded clay-shale beds, which decrease in abundance and thickness upwards in the succession, are medium grey, sometimes brownish-grey. The upper boundary is selected on the basis of cuttings lithology in conjunction with abrupt deflections of gamma-ray and S.P. curves towards the shale line.

The lower boundary of the SR-4 Member with underlying shale of the SR-3 Member is gradational; the gradation occurs through a siltstone which is present between 1 055 m and 1 176 m in G(a)-B/1.

The presence of bounding and intraformational unconformities makes it possible that this proposed reference stratotype of the Sundays River Formation may be based on an incomplete succession.

Alphard /56...

Alphard Shale Formation

This unit was first named by Dingle (1973 b) and is present in most boreholes on the Agulhas Bank. It comprises a succession of soft, medium-grey to greenish-grey, plastic or putty-like clays, claystones and shales, with subordinate thin limestones and sands. Characteristics of the unit is the presence of fragmentary aragonitic Inoceramus prisms. Lignite is rare in the Alphard Shale Formation, in contrast to the Sundays River Formation.

The sub-surface stratotype proposed is found in the G(a)-A/2 borehole (fig. 14) where the unit is present between 507 m and 1 327 m. The upper boundary is taken at the base of the lowermost sandstone of the Alexandria Formation (see below). The base of the unit is taken at the top of the SR-4 Member, or, if this sandy unit is not present (as is the case in G(a)-A/2) it is selected on the basis of wireline log marker horizon 19. This wireline log marker is discussed below.

The Alphard Formation is also characterised by a number of readily identifiable wireline log markers which can be correlated with confidence between many boreholes. The most important of these are the following (depths in G(a)-A/2 given):

(a) Marker 11 : major increase in sonic velocity at 969 m;
(b) Marker 16 : Anomalously low sonic velocity and resistivity at 1 199 m;
(c) Marker 17 : a characteristic peak on the sonic and resistivity curves at 1 212 m; and
(d) Marker 19 : thin mildly radio-active layer (gamma ray curve) which is associated with a resistivity low at 1 327 m.

The wireline log characteristics of marker horizons 16 and 19 are consistent with the presence of thin, black, carbonaceous shale beds, fragments of which are present in cuttings samples at corresponding levels.

The overall nature of the Alphard shale is that of a transgressive marine

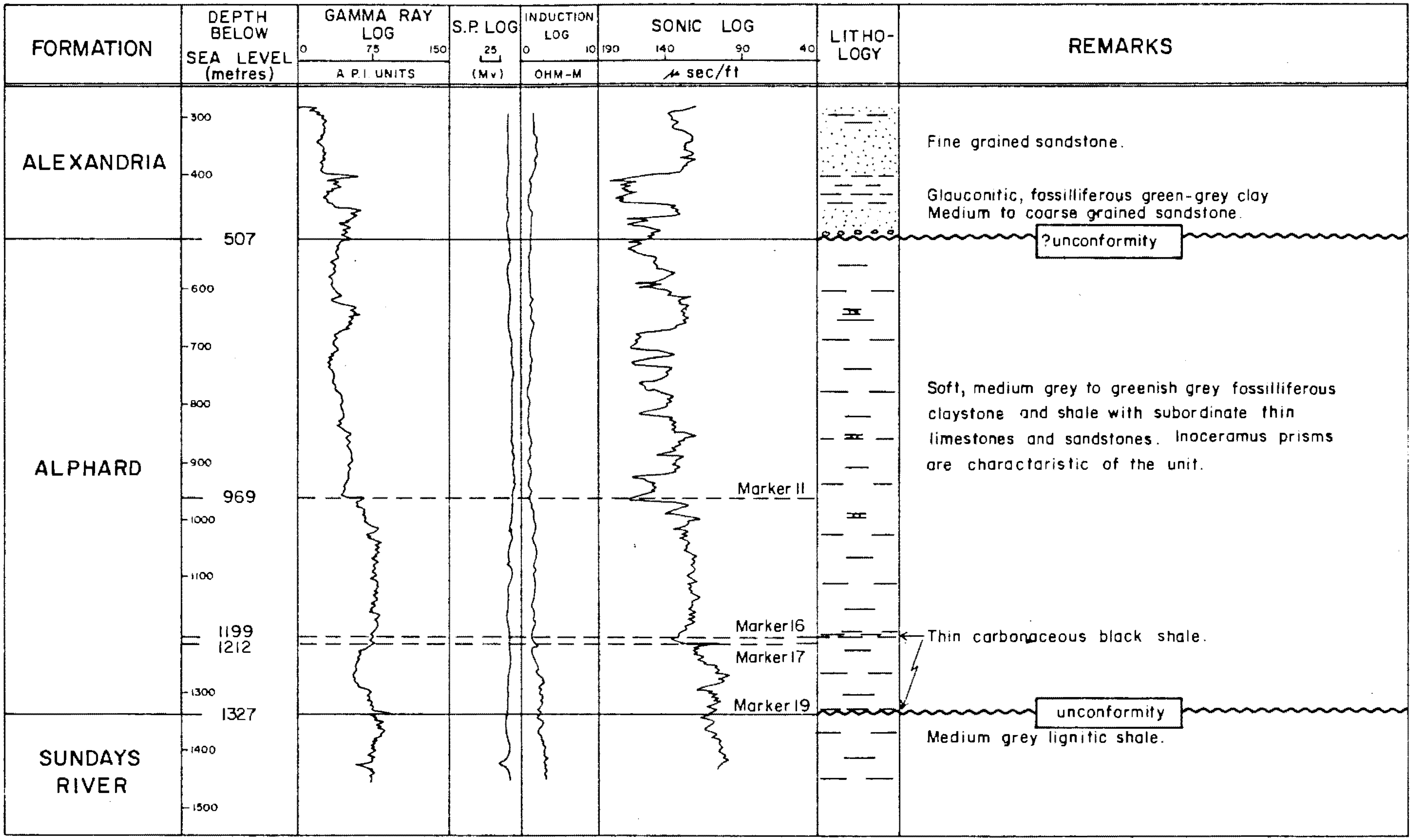

FIGURE 14 : Subsurface stratotype of the Alphard Formation in the G(a)-A/2 borehole on the Agulhas Bank.

sequence. The presence of glauconite indicates the existence of an open marine, sediment-starved basin on a fairly stable shelf. The Alphard Formation is synonymous with the Alphard Group (Dingle, 1873 b) and is Upper Cretaceous in age.

Alexandria Formation

The Tertiary strata which occur in the southern coastal regions of the Cape Province include both continental and marine sediments. The thickest and most extensive is a group of closely associated marine and aeolian calcarenites, commonly referred to as coastal limestones (Ruddock, 1973). The name Alexandria Formation is applied to marine deposits of Tertiary age (Ruddock, 1973). The overlying presumed aeolian calcarenites are assigned a late Tertiary to Recent age and are described as consolidated and semi-consolidated deposits.

The marine and aeolian limestones in the coastal belt westwards of Mossel Bay have in the past been referred to jointly and somewhat loosely as the Bredasdorp Beds or Bredasdorp Formation. Spies (1963) and de Villiers (1964) consider them to be broadly equivalent to the Alexandria Formation and older sands of the eastern Cape Province. Authors of standard text books (e.g. du Toit, 1954) have used the term Alexandria Formation and Bredasdorp Formation to embrace both marine and aeolian coastal limestone of Tertiary age. The term Alexandria Series was used by Wybergh (1920) without definition. Haughton (1928, 1969) employed it to embrace both coastal limestone and continental deposits such as silcrete and ferricrete.

The coastal limestones are described by Ruddock (1973) as follows: "the basal marine limestones range through compact crystalline limestones in which little more than fragments of oysters survived through compact gritty limestones, mainly fragments of shells to coarse, porous loosely cemented shelly friable rocks. Pebbles and boulders, mainly of quartzite, occur both as irregular discontinuous conglomerates and sporadically, either isolated or at specific horizons".

It is obvious from the above that practical difficulties are involved

in securing /60...

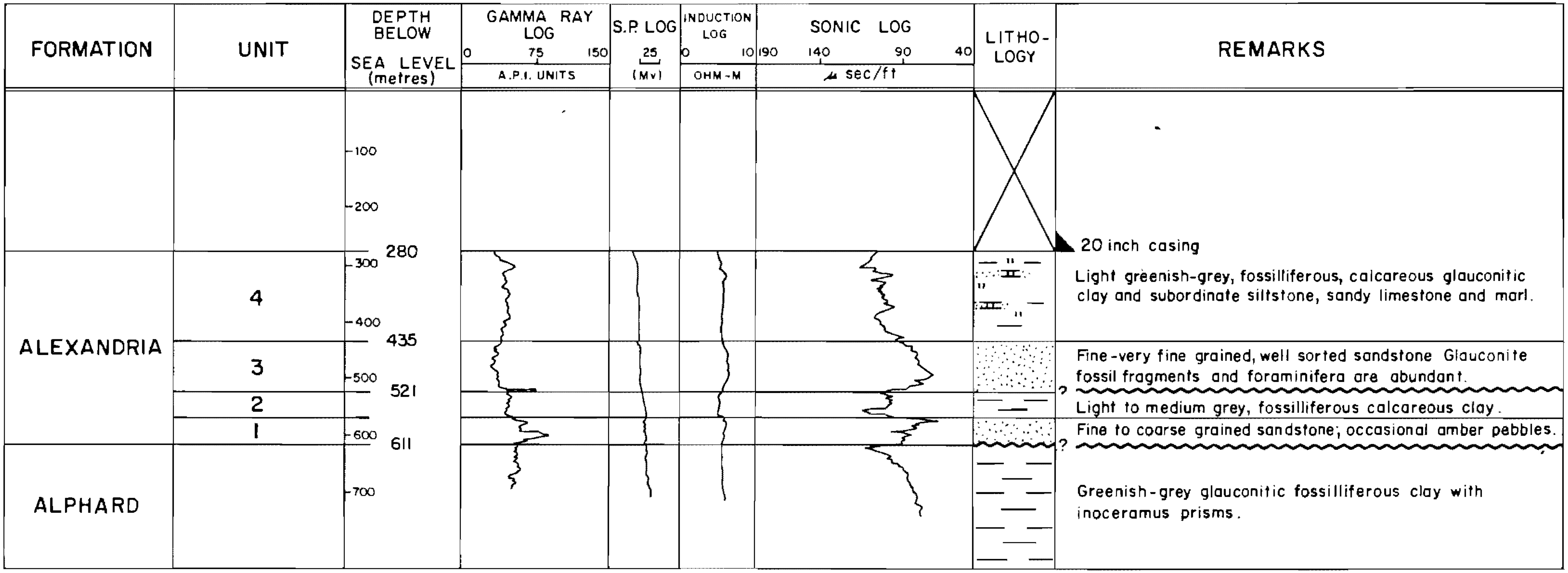

FIGURE 15 : Subsurface reference stratotype of the Alexandria Formation in the F-D/1 borehole on the Agulhas Bank.

in securing a coherent lithostratigraphic framework of Tertiary deposits in South Africa. In the absence of a stratotype which is defined in terms of the South African Stratigraphic Code the writer has elected to establish a sub-surface reference stratotype on the Agulhas Bank in the F-D/1 borehole and to refer to these sediments informally as the Alexandria Formation (fig. 15).

Tertiary Igneous Rocks

Tuffs, trachybasalt, aegirine-augite trachytes and aegirine-augite phonolitic trachytes occur in the "Tertiary igneous province" on the Agulhas Bank (Dingle and Gentle, 1972). These rocks form thin dykelets and plugs which sometimes protrude above the ocean floor to within a few meters of sea level in the western part of the study area, where they have been intersected in Mesozoic sediments in the D-A/1 well. They have been radiometrically dated (Dingle and Gentle, 1972) at 58 ± 2,5 million years (Paleocene, according to Berggren, 1971).

LITHOSTRATIGRAPHIC CORRELATION

The lithostratigraphic framework which is presented in the preceding section was applied by the writer to all seventeen boreholes on the Agulhas Bank by employing a multi-disciplinary approach, i.e. using lithologic, wireline log and seismic reflection information. The following is a discussion of the results of lithostratigraphic correlation in respect of each borehole, which are presented in plate 5 and table 11.

Boreholes in the Bredasdorp Basin

Borehole D-A/1

This borehole was drilled in the Bredasdorp Basin in the vicinity of the Alphard Bank. The Alexandria Formation is known to be very thin and patchy at this locality; igneous rocks of Tertiary age are present in this area (Dingle and Gentle, 1972)

Sundays River /62...

TABLE II

RESULTS OF STRATIGRAPHIC CORRELATION OF BOREHOLES ON THE AGULHAS BANK

(all depths in metres below sea level)

Group	Formation	Member	Unit/ Marker	G(a)A/1	G(a)A/2	G(a)A/3	G(a)B/1	F-1	MB/A/1	PB/A/1	G(a)C/1	G(b) Gemsbok/1	E-1	D-A/1	F-B/1	F-D/1	E-B/1	F-E/1	H(b) Hartebeest/1	G(b) Springbok/1
	Alexandria		4					<288	-	-	-	<308				<280	-	<258	-	<325
			3	<271	<272	<273	-	426	-	-	<280	456				435	-	424	-	-
			2	357	393	330	-	459	-	-	397	496				521		468	-	
			1	402	454	407	-	-	-	-	-	533				566	-	-	-	
	Alphard		Top	463	507	490	<280	569	-	-	465	? 631	<315	-	<251	611	<215	555	<371	?546
			11	854	939	977	467	1408	-	-	945	799	-	-	-	1251	-	1266	-	1061
			17	1066	1212	1142	607	1655	-	-	1166	-	-	-	-	1408	-	1476	-	1417
			19	1172	1327	1253	875	-	-	-	1349	-	-	-	-	1608	-	-		
	Sundays River		Top	1172	1327	1253	906	2025	-	<187	1383	1122	361	<237	453	1651	451		862	1747
U		SR-4		-	-	-	906	-	-	-	-	1122	361	237	453	-	451	-		
I		SR-3		1172	1327	1253	1176	-	-	187	-	1401	741	856	-	-	893		-	
T		SR-2		1557	1606	1614		2025	-	?454	-		863	1018	-	-	1040	1924	-	-
E		SR-1		1541	1699	1784	1648	2182	-	?554	-	1566	1047	1286	-	-	1236	2106	-	1747
N	Kirkwood						2512	2444	<192	779	1523	-	1157	-		1789	-	-	-	
H	Infanta			1736	2036	1923	-	-	-	-	-	2124	-	1376	-	-	-	2326	-	1747
A	Colchester			-	-	-	3082	-	-	1104	-		-	1891						
G	Swartkops			1970	2330	2201	3463	-	-	1475	-	3256	-	-	-	-	-	-	2112	
E	Enon			-	-	-	-	-	1098	1642	-	-								2356
BASEMENT (BELOW SEA LEVEL)				2022	2551	2433	3621	2523	-	1759	-	-	2656	Syenite 2411	901	-	1341	-	2382	2369
TOTAL DEPTH (BELOW SEA LEVEL)				2193	3209	2448	3621	2390	1273	1784	1662	3938	2759	2557	1018	1922	1930	2408	2415	2421
KELLY BUSHING (ABOVE SEA LEVEL)				9,4	28,0	26,8	26,8	28,0	26,8	25,9	26,8	29,4	33,5	33,5	33,5	34,1	33,5	33,5	33,5	33,5

Sundays River Formation (237 - 396 m)

The borehole entered the sandy SR-4 Member of the Sundays River Formation below the 20-inch casing at 237 m and passed into the Infanta grey siltstone at 1 376 m indicating a minimum thickness of 1 139 m for the formation as a whole (uncorrected for a regional dip of about 3^{0}). Judging by the presence of Senonian sediments nearby (Dingle, 1970) it is thought possible that the base of the Alphard Formation may be obscured by the 20 inch casing. The lithologic subdivisions and wireline log characteristics of the Sundays River Formation are identical with those of the composite reference stratotype in the G(a)-A/2 and G(a)-B/1 boreholes, so that this correlation is presented with confidence. In particular the inflections of the gamma-ray S.P. and conductivity logs at 1 376 m clearly mark the base of the Sundays River Formation.

Infanta (1376 - 1391 m) and Colchester (1891 - 2411 m) Formations

The grey silststone and shale with minor sand interbeds betwee 1 376 m and 1 891 m are assigned to the Infanta Formation. The grey shale between 1 891 m and 2 411 m is correlated with the Colchester Formation; the boundary between these two units is selected on the basis of inflections of the conductivity and sonic log curves. A core cut over the interval 2 304 - 2 312 m confirmed the presence of thinly bedded to massive, dark-grey fossiliferous shale with impressions of ammonites.

Syenite (2411 - 2489.15 m)

The borehole was abandoned after 78,5 m had been drilled into a foyaitic syenite, the top of which occurs at 2 411 m. This intrusive was dated by the potassium - argon method at 59 ± 3,5 m.y. (Rowsell, pers. comm.) and is clearly correlatable with the Tertiary igneous suite. (Dingle and Gentle, 1972). Dark greenish-grey aegerine-augite trachyte was intersected at various depths below the 30-inch casing at 640 m; these presumed intrusives are clearly indicated on the gamma log by their radio-active nature (> 100 A.P.I. units) on the conductivity log by their high resistivity (circa 100 ohm/m), and on the sonic log by their high velocity (ca. 60/usec/ft).

Seismic /63...

Seismic reflector horizon C occurs at a depth which closely corresponds to the top of the sandy, lignitic SR-2 Member, thereby confirming the validity of the correlation, particularly in respect of the Sundays River Formation as a whole.

Borehole E-1

This borehole was drilled near the northern rim of the Bredasdorp basin. The fossiliferous, glauconitic, clayey Alphard Formation is present between the 20-inch casing (315 m) and the top of the Sundays River Formation at 361 m. Seismic horizon A has been mapped from a depth corresponding to the base of the Alphard Formation at 395 m.

The Sundays River Formation (361 - 1 157m) is notably sandy and strongly lignitic, except for the SR-3 shale Member which, in conjunction with seismic reflection horizon C at the top of the SR-2 Member, affords a confident correlation to the type section and to the other boreholes.

The Kirkwood Formation is present between depths of 1 157 m and 2 565 m. Seismic reflection data indicate that the contact with the Sundays River is a marked unconformity and that the lower boundary with cored intensely folded and fractured basement may be a faulted one (Crous, pers. comm.). A notable feature of the Kirkwood Formation in this borehole is the general lack of sands and coarser clastics.

Borehole E-B/1

This borehole was drilled on a basement horst near the northern flank of the Bredasdorp Basin 13 km south-west of the E-1 borehole.

The Alphard Formation is typically developed and is present between 215 m (20-inch casing) and 451 m; its argillaceous nature is clearly evident on the gamma log, and its presence is confirmed by the presence of reflector horizon A at about 451 m.

The Sundays River Formation (451 - 1341 m) is identical to its equiva-

lent in /64...

lent in the E-1 borehole, particularly in respect of its sandy, lignitic nature, the presence of the SR-3 shale and the position of seismic reflector horizon C at the top of the SR-2 sand. The Sundays River Formation rests unconformably on highly indurated, homogeneous grey slate with microscopic characteristics identical to those of Bokkeveld slates although it could belong to other Paleozoic or older basement rocks. The base of the Sundays River Formation is marked by an abrupt downhole deflection of the conductivity curve to higher (10 ohm/m) values at 1341 m; the sonic curve devlects to higher (90 μ/sec/ft) values at this depth.

Borehole F-1

The Alexandria Formation (288 - 569 m) and its subdivisions were identified almost entirely from cuttings samples, since only the Induction and S.P. logs were recorded above the 13-3/8-inch casing depth of 920 m. The basal sandstone (unit 1) of the formation contains a few pebbles set in a matrix of calcareous sand with yellow and ochre grains. The transition into the underlying Alphard Formation at 569 m is abrupt.

The Alphard Formation (569 - 2 025 m) is typically developed and contains a conspicuous 50-m glauconitic sand and thin, brownish limestone layers below a depth of 1 408 m, which marks the position of seismic horizon 11. Wireline log marker 17 is correlated to the resistivity inversion at a depth of 1 655 m, where an increase in sonic velocity is evident from the sonic log (fig. 16). A seismic reflector at this depth has been labelled and mapped as horizon A; it is 370 m above the base of the Alphard Formation in the borehole and close to the top of Cenomanian sediments.

The Sundays River Formation (2 025 - 2 444 m) is identified on the basis of its position above the Kirkwood red shale and is distinguished from the overlying Agulhas Formation by virtue of the overall sandy nature of the succession below 2 025 m. Seismic horizon C, which elsewhere occurs near the top of the SR-2 sandy Member, was identified at a depth of approximately 2 025 m. This implicates that the SR-3 and SR-4 Members are absent, due to nondeposition (see later, fig. 19) in the F-1 borehole. The contact between the SR-1 and SR-2 Members in the F-1

borehole /65...

borehole is a gradational one and is placed at the first downhole appearance of Cytherella sp 1 (Robertson Research, op. cit.) at 2 182 m, on the assumption that this ostracode is an index fossil for the SR-1 Member.

The Kirkwood Formation (2 444 - 2 523 m) may be unconformably overlain by the Sundays River Formation, judging by an abrupt change in structural attitude at 2523 m. An alternative explanation may be that the junction is a faulted one. The base of the Kirkwood is selected entirely on the basis of the presence of a grey-black slate in cuttings samples below 2 523 m; these slates show cleavage and chlorite porphyroblasts which are indicative of folded basement rocks (de Swardt, pers. com.).

Borehole F-E/1

The subdivisions of the Alexandria Formation (258-555 m) are identical to the reference stratotype in the F-D/1 borehole and are readily correlatable to the F-1 borehole.

The Alphard Formation (555 - 1 924 m) is closely comparable to its equivalent in the F-1 borehole. Seismic horizon 11 has been mapped at the top of the 50-m sandstone which occurs below 1 266 m; this horizon is correlated with confidence to the F-1 borehole and to others further afield on the basis of its character, the presence of a well-sorted glauconitic sand and an increase in sonic velocity at 1 266 m (fig. 16).

Wireline log marker horizon 17 and seismic horizon A is selected at a depth of 1 476 m on the basis of a peak on the sonic log which occurs a few metres below a conspicuous low. A small downhole increase in resistivity is also evident at this level. The Alphard Formation is considered to be present to a depth of 1 924 m.

The Sundays River Formation (1 924 - 2 326 m) is characterised by its sandy nature, which is clearly shown by the deflections of the gamma-ray curve to values less than 75 A.P.I. units. As in the nearby F-1 borehole, the boundary between the SR-1 and SR-2 units is arbitrarily chosen.

Seismic /67...

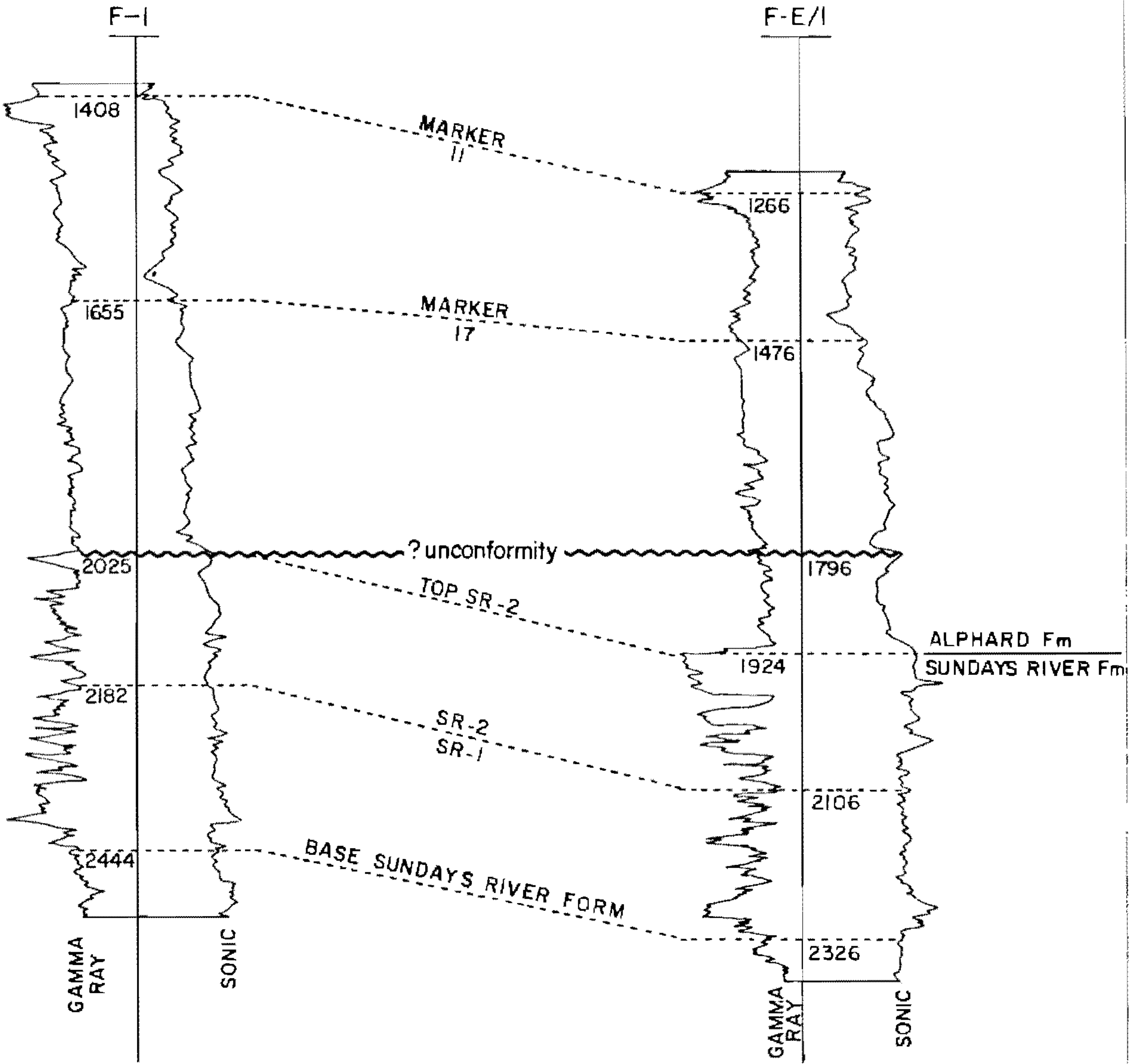

FIGURE 16

Detailed wireline log correlation between F-I and F-E/I boreholes showing possible unconformity between Alphard and Sundays River Formations in F-I .

Seismic horizon C has been mapped at the top of the uppermost sand at 1 924 m.

The grey silty shale between 2 326 m and 2 408 m is correlated with the Infanta Formation on the basis of its stratigraphic position below the Sundays River Formation. A core cut at 2 404 m showed characteristics which are quite incompatible with the correlation with the basement rocks below the Kirkwood Formation in the F-1 borehole.

A noteworthy aspect of detailed sonic-log correlations between the F-1 and F-E/1 boreholes (fig. 16) is that, irrespective of which lithostratigraphic units are involved, the deflection of the sonic log at 1 796 m in F-E/1 may be equated with a similar response in F-1 at a depth of 2 025 m. This sonic log correlation indicates

a) a mere 29-m difference of the thickness of the interval in the two boreholes between marker horizon 17 and the correlated sonic log anomaly; and

b) a possible angular unconformity may be present on the correlated sonic log marker; this unconformity may eliminate 132 m of shale which is present only in F-E/1, above the SR-2 Member, which lies directly underneath the unconformity in F-1. This unconformable relationship may have significance as a trapping mechanism for the gas accumulation that was discovered in the SR-2 Member in the F-1 well.

Boreholes on the Infanta Arch

Borehole F-D/1

This borehole was drilled on the southern flank of the Infanta arch. The lithological subdivisions of the Alexandria Formation in this borehole constitute the sub-surface reference stratotype and was presented earlier (fig. 15).

The Alphard /68...

The Alphard Formation (611 - 1 651 m) is typically developed, except for the sandstone which is elsewhere associated with marker horizon 11 (1 261 m). It is questionable whether its absence is due to erosion on an unconformity, faulting or non-deposition. Marker horizons 17 (1 408 m) and 19 (1 608 m) can be readily identified as deflections of the sonic curve and are both associated with mild radio-activity indicated by gamma-ray peaks.

The base of the Alphard Formation is placed at 1 651 m on the basis of the first downhole appearance in cuttings samples of brownish-grey, lignitic shale and sandstone. This boundary may be either conformable or disconformable; seismic reflection and diplog data are inconclusive.

The Sundays River Formation (1 651 - 1 789 m) could not be correlated at the member level with any confidence; the shales are light brownish-grey and lignitic and the thin subordinate sandstones are comprised of fine-grained quartzose grains, specked with glauconite. Mildly radioactive layers are present in the lower part of the unit.

Seismic horizon 11 was mapped at a depth of 1 261 m, horizon A at 1 651 m, while horizon D was recognised a short distance below the bottom of the borehole. The baldness of the Infanta arch in respect of seismic horizon C(pl. 2) serves to indicate that the Sundays River sediments in this borehole may be stratigraphically above the SR-2 Member.

The succession between 1 789 m and 1 922 m consists of reddish-brown to brick-red shale and mudstone, and pebbly, light- to medium-grey, lignitic sandstone. The presence of the latter is clearly evident on the gamma-ray curve in the upper part of the interval, which is correlated to the Kirkwood Formation; it contains interbeds of Enon Conglomerate.

Borehole G(a)-C/1

The Alexandria Formation (280 - 466 m) was identified almost entirely on the basis of cuttings samples, since a full set of wireline logs was not recorded above the casing at 934 m; the lithological subdivisions are identical to those of the type section in the F-D/1 borehole, which is

located /69...

located 18 km to the south-west.

The Alphard Formation (466 - 1 383 m) is identical to its correlative in the nearby F-D/1 borehole, except that a 50-m calcareous, glauconitic sandstone is present below marker horizon 11 (945 m). Horizons 16 (1 163 m), 17 (1 166 m) and 19 (1 349 m) are readily identifiable on wireline logs.

The succession below the Alphard Formation is lithologically identical to its counterpart in the F-D/1 borehole and is made up of the Sundays River Formation (1 383 - 1 523 m) and the Kirkwood Formation (1 523 - 1 662 m), which rests on quartzitic sandstone (basement) and contains thin conglomeratic layers (? Enon).

Seismic horizon 11 was mapped from depth of the similarly named wireline log marker at 945 m, horizon A at the base of the Alphard Formation (1 383 m) and horizon D at 1 662 m.

Borehole F-B/1

The Alphard Formation (251 - 453 m) is readily identified in cuttings samples by its clayey, glauconitic and fossiliferous nature. The base of the unit is placed at the top of the first prominant sandstone and the downhole appearance of lignite. Wireline log markers 11, 17 and 19 could not be identified in this borehole.

The interval between 453 and 901 m is sandy and lignitic in the upper part (453 - 611 m), and contains red shale with interbeds of medium-grey sandstone in the middle (611 - 776 m), and light-grey shale with subordinate sandstone in the lower part (776 - 901 m). The red beds in the middle part are identical to those of the Kirkwood Formation; by implication the lowermost grey shale interval may be correlated with the Colchester Formation, and the overlying sandy lignitic unit to the Sundays River Formation.

The succession below 901 m comprises basement quartzitic sandstones, phyllites and slates. Seismic horizon A was tied into the borehole

at a depth /70...

at a depth of 453 m and horizon D at 901 m. Seismic horizon 11 is too shallow to be mapped in this area and in any event, could not be identified in the borehole.

Boreholes in the Pletmos Basin

Borehole MB/A/1

The succession penetrated by the borehole is characterised by the absence of grey shale and its correlation is relatively straight-forward. In the upper part of the borehole (192 - 1 098 m) sandy red mudstones of the Kirkwood Formation interfinger with Enon conglomerate, which is developed between 1 098 and 1 273 m.

Borehole PB/A/1

The Sundays River Formation (187 - 779 m) is characterised by its lignitic and sandy nature. The top of the SR-2 Member is established mainly from the first downhole appearance of sandstone in the cuttings samples and from the position of horizon C at about 454 m. The placing of the base of the Sundays River is also based on cuttings samples characteristics; the first downhole appearance of red shale occurs at 779 m but this lithologic change is not evident on wireline logs.

The Kirkwood Formation (779 - 1 104 m) is underlain by grey shale with sandstone interbeds between 1 104 and 1 476 m; this interval is correlated with the Colchester Formation.

Sandstones of the Swartkops Formation (1 476 - 1 642 m) are interbedded with light-grey and brownish-grey shale. Massive Enon conglomerate was encountered at 1 642 - 1 759 m; it rests on highly fractured, cleaved, splintery, black basement shale.

Borehole G(a)-A/2

The Alexandria Formation (272 - 507 m) and its subdivisions are recognised on the basis of cuttings samples and wireline log characteristics;

these /71...

these are identical to those of the type section in the F-O/1 borehole.

The type sections of the Alphard Formation and the SR-1 and SR-2 Members of the Sundays River Formation have already been described (fig. 13).

The interval between the base of the Alphard Formation (1 327 m) and seismic horizon C (1 686 m) consists essentially of lignitic clay and shale, with thin interbeds of brownish limestone in the lower part. It is correlated with the SR-3 Member of the Sundyas River Formation.

The Infanta Formation (2 036 - 2 330 m) contains a notable number of thin, hard, calcite-cemented, fine-grained sandstone beds. The sandy nature of the Swartkops Formation (2 330 - 2 551 m) is demonstrated by deflections of the gamma-ray curve to lower A.P.I. values; the abnormally high resistivity associated with these sandstones is probably attributable in part to their low porosity associated with a clayey matrix and calcite cement.

Basement quartzites below 2 330 m are characterised by higher velocities (less than 40 µ sec/ft on the sonic log) than the Mesozoic sediments above.

Borehole G(a)-A/1

The Alexandria Formation (271 - 463 m) is readily identifiable in cuttings samples by its sandy nature, particularly of unit 1 (402 - 463 m). As in other boreholes, this sandstone has a notable gamma-ray response towards the shale line (> 75 A.P.I. units), which is indicative of mild radio-activity. The shale of unit 2 stands out clearly on the sonic curve (> 140 sec/ft).

The Alphard Formation (463 - 1 172 m) is typically developed as a glauconitic, fossiliferous, green-grey shale succession, within which wireline log marker horizons 11 (654 m), 16 (1 043 m), 17 (1 065 m) can be identified by their characteristics as described in the stratotype borehole. Marker horizon 19 is placed at 1 172 m on the basis of the presence of thin, mildly radio-active peaks on the gamma-ray curve and is also equated with the base of the Alphard Formation, since lignite first appears at this depth

/72...

this depth in cuttings samples.

The Sundays River Formation (1 172 - 1 736 m) includes the SR-3 shale Member (1 172 - 1 557 m) which contains a fair amount of vitreous lignite and thin brownish limestone in the lower part and silty sandstone near the middle. Seismic horizon C occurs at a depth of 1 557 m and is marked on the wireline log curves by abrupt deflections of the gamma curve (to lower A.P.I. values), sonic curve (to higher velocities), S.P. curve (indicator of sands) and higher resistivity. These responses indicate that the sandy SR-2 Member occurs between depths of 1 557 m and about 1 641 m. The SR-1 Member (1 641 - 1 736 m) is typically developed as an upward-fining sequence with a medium- to fine-grained sandstone at its base.

The Infanta Formation (1 736 - 1 970 m) and Swartkops Sandstone (1 970 - 2 022 m) intervene between the Sundays River Formation and basement quartzite (below 2 022 m).

Borehole G(a)-A/3

The Alexandria Formation (273 - 490 m) is identified solely on the basis of cuttings samples, as is the Alphard Formation (490 - 1 253 m), within which horizon 11 (977 m) can only be tentatively identified due to the lack of a complete set of wireline logs above the 13-3/8-inch casing at 984 m. The remainder of the succession is almost identical to its counterparts in the other two boreholes on the Superior A structure, G(a)-A/1 and G(a)-A/2; within it, wireline log marker horizons 16 (1 128 m) and 17 (1 142 m) are readily identifiable.

The contacts, lithologies and wireline log characteristics of the Sundays River Formation (1 253 - 1 923), and its subdivision into SR-3 (1 253 - 1 614 m) SR - 2 (1 614 - 1 784 m) and SR-1 (1 784 - 1 923 m) correspond to those in other boreholes on the Superior A structure; the same applies to the Infanta Formation (1 923 - 2 201 m) and the Swartkops Formation (2 201 - 2 433 m).

A summary of the correlation between the above-mentioned three boreholes is shown in figure 17.

Borehole /74...

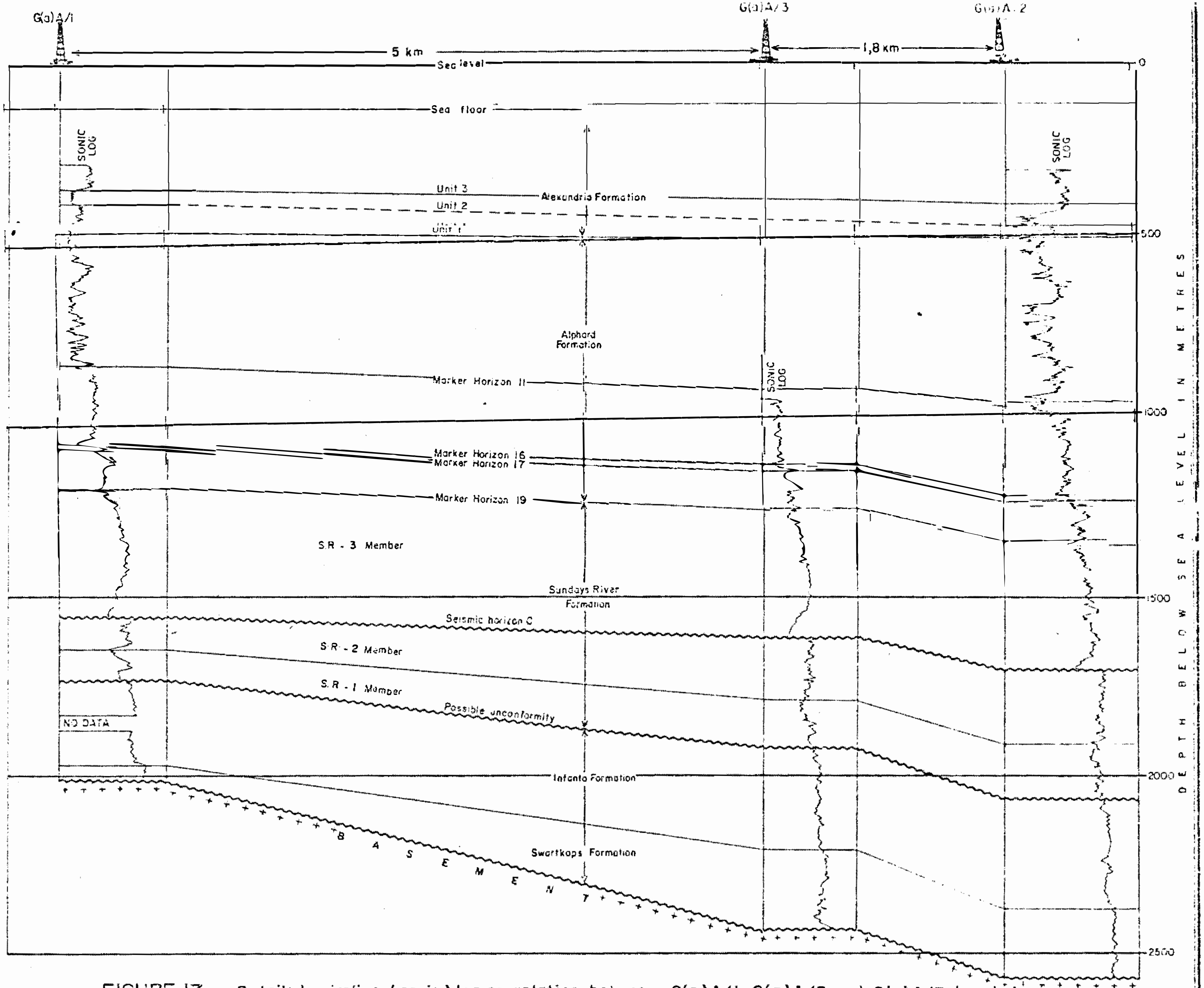

FIGURE 17. - Detailed wireline (sonic) log correlation between G(a)A/1, G(a)A/2 and G(a)A/3 boreholes.

Borehole G(a)-B/1

The borehole entered the Alphard Formation below the 20-inch casing depth of 280,2 m, and it extends down to 906 m. Wireline log markers 11 (467 m), 17 (607 m) and 19 (875 m) can be recognised and also correlated on seismic reflection profiles to the type area in the G(a)-A/2 borehole. The SR-3 and SR-4 Members of the Sundays River Formation in this borehole have been described already since they constitute a subsurface stratotype on the Agulhas Bank.

The succession below seismic horizon C (1 648 m) and above the Kirkwood red beds (2 512 m) is assigned to the Sundays River Formation; if seismic horizon C maintains its stratigraphic position, this unit (1 648 - 2 512 m) may be correlated with the SR-1 Member in the stratotype well. Seismic reflection profiles near the G(a)-B/1 borehole site (e.g. fig. 6) suggest that horizon C is an unconformity which truncates a portion of the underlying succession; a complete Sundays River sequence, including the SR-2 Member, may therefore sub-outcrop underneath horizon C on the flanks of the anticline on which this borehole was drilled.

The top of the Kirkwood Formation is marked in cuttings samples by the first downhole appearance of red and brown shaly mudstones; it is clearly discernable on wireline logs. The induction and gamma-ray curves show abrupt deflections as well as downhole decreases in the amplitudes of the deflections at this level. The occasional presence of grey shale cuttings from the Kirkwood Formation suggests that this unit interfingers with the Infanta Formation. The grey shale of the Colchester Formation predominates below 3 082 m and is lignitic in its lower part. The Swartkops Member is made up of a fine-grained sandstone between 3 463 m and 3 621 m; it is interbedded with brownish-red shale.

Borehole G(b)-Gemsbok/1

The Alexandria Formation (308 - 631 m) is identified entirely on the basis of cuttings samples. At this level in the borehole the sonic log is not a very reliable correlation tool, since its quality is adversely affected by excessive borehole diameter. The Alphard Formation (631 - 1 122 m) contains a conspicuous sandstone below 799 m; this is equated with marker horizon 11 on the basis of an abrupt downhole increase in sonic velocity at this depth. Wireline log marker horizons 16, 17 and 19 could not be identified in this borehole.

The top of the Sundays River Formation (1 122 - 2 124 m) is selected at the downhole appearance of lignitic sandstone below the shaly Alphard Formation. The Sundays River Formation is an upward coarsening sequence above horizon C at 1 556 m. The boundary between the SR-3 shale Member and SR-4 sand Member is a gradational one and is tentatively placed at 1 401 m.

As in G(a)-B/1, the succession below the unconformity on horizon C is truncated. The SR-2 sand is absent in the borehole and may well subcrop below horizon C towards the north, where an expanded stratigraphic section is present near the Plettenberg fault.

The Infanta and Swartkops Formations in the G(b)-Gemsbok/1 borehole constitute the type sections and have already been discussed. (fig. 12).

<u>Borehole G(b)-Springbok/1</u>

The Alexandria Formation (385 - 546 m) is only tentatively identified because of excessive downhole cavings contamination and large borehole diameter, which adversely affected the quality of the recorded wireline logs.

The Alphard Formation (546 - 1 747 m) rests directly on seismic horizon C; within it marker horizons 11 (1 051 m) and 17 (1 417 m) could be identified using sonic log deflections.

Below horizon C, which is clearly evident from abrupt deflections of the sonic and gamma logs, the succession is as follows (from the base upward);

Basement quartzite	below 2 369 m
Enon conglomerate, with grey shale matrix in core no. 1	2 356 - 2 369 m
Infanta Formation	1 347 - 2 356 m

Borehole /76...

Borehole in the Algoa Basin

Borehole H(b)-Hartebeest/1

The wireline logs are inconclusive as a correlation tool throughout this borehole, largely because they do not exhibit the characteristics of the succession in stratotype boreholes. The Alphard Formation (371 – 862 m) is therefore identified on the basis of cuttings samples only, particularly from the shaly succession above a sandstone (737 – 862 m) in the lower part. This sandstone is capped by a highly resistive thin limestone and contains a number of thin lignite seams which are associated with mildly radio-active clay; it may be equated with the sands which are associated elsewhere with marker horizon 11.

The succession between 862 m and 2 416 m is as follows (from base upward):

Metamorphic slates of basement	below 2 382 m
Swartkops Sandstone Formation	2 112 – 2 382 m
Uitenhage Group	8 62 – 2 382 m

The Uitenhage Group is not correlated at the formation level since except for the Swartkops, the succession intersected has afinities with the Sundays River as well as the Infanta and Colchester Formations. The group coarsens upwards; in the lower part it comprises mainly well-bedded grey shale, while in the upper part sandstones predominate. The succession contains fragments of lignite throughout, a number of thin limestones at the top of sandstone bodies, and numerous grey shale beds with macrofossils (mainly gastropoda, bivalves and belemnites). An important observation, in terms of sedimentary tectonics, is the presence of a number of cyclothems. An individual cyclothem appears to comprise the following (from the base upward):

(a) glauconitic, fossiliferous grey shale, grading upward into
(b) lignitic grey shale, grading into
(c) sandstone, which contains brownish-grey shale and lignite and has a sharp upper contact, and
(d) thin, unfossiliferous, brownish, microcystalline limestone, probably of fresh water origin.

Each cyclothem is thought to reflect intermittent fault - induced subsidence of the Port Elizabeth half-graben within which the succession occurs and to indicate filling of the graben at the end of each cyclothem.

It is considered advisable to refer to these undifferentiated Uitenhage Group sediments as the Hartebeest formation in an informal manner.

Discussion of Results

The results of the lithostratigraphic correlation of boreholes on the Agulhas Bank are summarised in Table 11 (depths below sea level), Table 111 (thicknesses of units) and are portrayed on Plate 5.

Alexandria Formation

The base of the Alexandria Formation cannot be accurately defined in the G(b)-Gemsbok/1 and G(b)-Springbok/1 boreholes. It extends to depths greater than 550 m below sea level in F-E/1 (555 m), F-1 (569 m) and F-D/1 (611 m). The regional strike at its base is nearly parallel to the shelf break at the 200-m isobath; the regional seaward dip was calculated using sea floor data (Dingle, 1970) and is less than 2°.

The minimum thickness of the Alexandria Formation could be calculated in nine boreholes. The greatest thicknesses intersected are in F-E/1 (297^{+}m), F-1 (281^{+}m) and F-D/1 (331^{+}m).

Complete intersections of the lowermoste two subdivisions of the Alexandria Formation were obtained in eight boreholes. The combined thickness of unit 1 and unit 2 range between 160 m (G(a)A-3) and 70 m (G(a)C-1, while the average is about 108 m.

Disconformities could be present in the Alexandria Formation. One disconformity is suspected to be present at the top of unit 2, where abrupt changes in lithologic and wireline log characteristics are observed; another may be present towards the base of the formation, where an abrupt change takes place from shallow-water (unit 1) to deeper water (Alphard Formation) depositional environments as indicated by lithologic characteristics.

Alphard /79...

TABLE III

THICKNESSES OF MESOZOIC LITHOSTRATIGRAPHIC UNITS IN BOREHOLES ON THE AGULHAS BANK

Formation / Borehole	Alexandria	Alphard	Sundays River	Kirkwood	Infanta	Colchester	Swartkops	Enon
G(a)-A/1	192+	709	564	–	234	–	52	–
G(a)-A/2	235+	820	709	–	294	–	221	–
G(a)-A/3	217+	763	670	–	276	–	232	–
G(a)-B/1	–	626+	1 606	570	–	381	158	–
F-1	281+	1 456	419	79	–	–	–	–
Pd-A/1	–	–	–	906+	–	–	–	175+
Pd-A/1	–	–	592+	325	–	372	166	117
G(a)-C/1	185+	917	140	139	–	–	–	–
G(b)-Gemsbok/1	323+	491+	1 002	–	1 132	–	682	–
E-1	–	46+	795	1 499	–	–	–	–
D-A/1	–	1 139+	–	515	520	–	–	–
F-B/1	–	202+	448	–	–	–	–	–
F-D/1	331+	1 040	158	133	–	–	–	–
E-B/1	–	236+	890	–	–	–	–	–
F-E/1	297+	1 369	550	–	82+	–	–	–
H(b)-Hartebeest/1	–	491+	1 250	–	–	–	270	–
G(b)-Springbok/1	161+	1 201	–	–	609	–	–	13

Alphard Formation

The base of the Alphard Formation was intersected in 14 boreholes at depths ranging from 361 m (E-1) to 2 025 m (F-1). In conformance with the regional dip of about 3° at the level of seismic horizon A(pl.3), the deepest intersections were recorded in those boreholes which are closest to the shelf break at the 200-m isobath (F-1 at 2 025 m F-D/1 at 1 651 m and F-E/1 at 1 924 m). The Alphard Formation was intersected in all except three boreholes; two of these (PB/A/1 and MB/A/1) are close inshore and in the third (D-A/1) the unit may be present above the casing depth of 237 m.

A complete intersection of the Alphard Formation was made in seven boreholes on the Agulhas Bank. The maximum thicknesses were recorded in F-1 (1 456 m); F-E/1 (1 369 m); F-D/1 (1 040 m), G(a)-C/1 (917 m) and G(b)-Springbok/1 (1 201 m); all these boreholes are near the 200 m isobath and the results confirm that the Alphard Formation is present on the Agulhas Bank as a seaward-thickening wedge of sediments.

This is clearly shown in figure 18, where the base of the unit occurs a short distance (circa 100 m) below a prominent reflector which coincides with wireline log marker horizon 17. This marker, in turn, occurs at the base of a seaward prograding set of reflectors which are stacked in such a fashion that they occur at progressively higher stratigraphic levels in a seaward direction. Marker horizon 11, which occurs within a conformable set of seismic reflectors close inshore, becomes part of a prograding set of reflectors in a seaward direction. These two wireline log markers within the Alphard Formation therefore have expression on seismic reflection profiles; they cannot be used to formally subdivide the Agulhas Formation since they may conceivably transgress lithostratigraphic boundaries.

The Alphard Formation, on lithologic character alone, is clearly transgressive in respect of underlying stratigraphic units. In boreholes in the Bredasdorp and Plettmos Basins it rests on the Sundays River Formation; in those basins seismic horizon A, which is an approximation to the base of the Alphard Formation, occurs at the base of a conformable set of

reflectors /81...

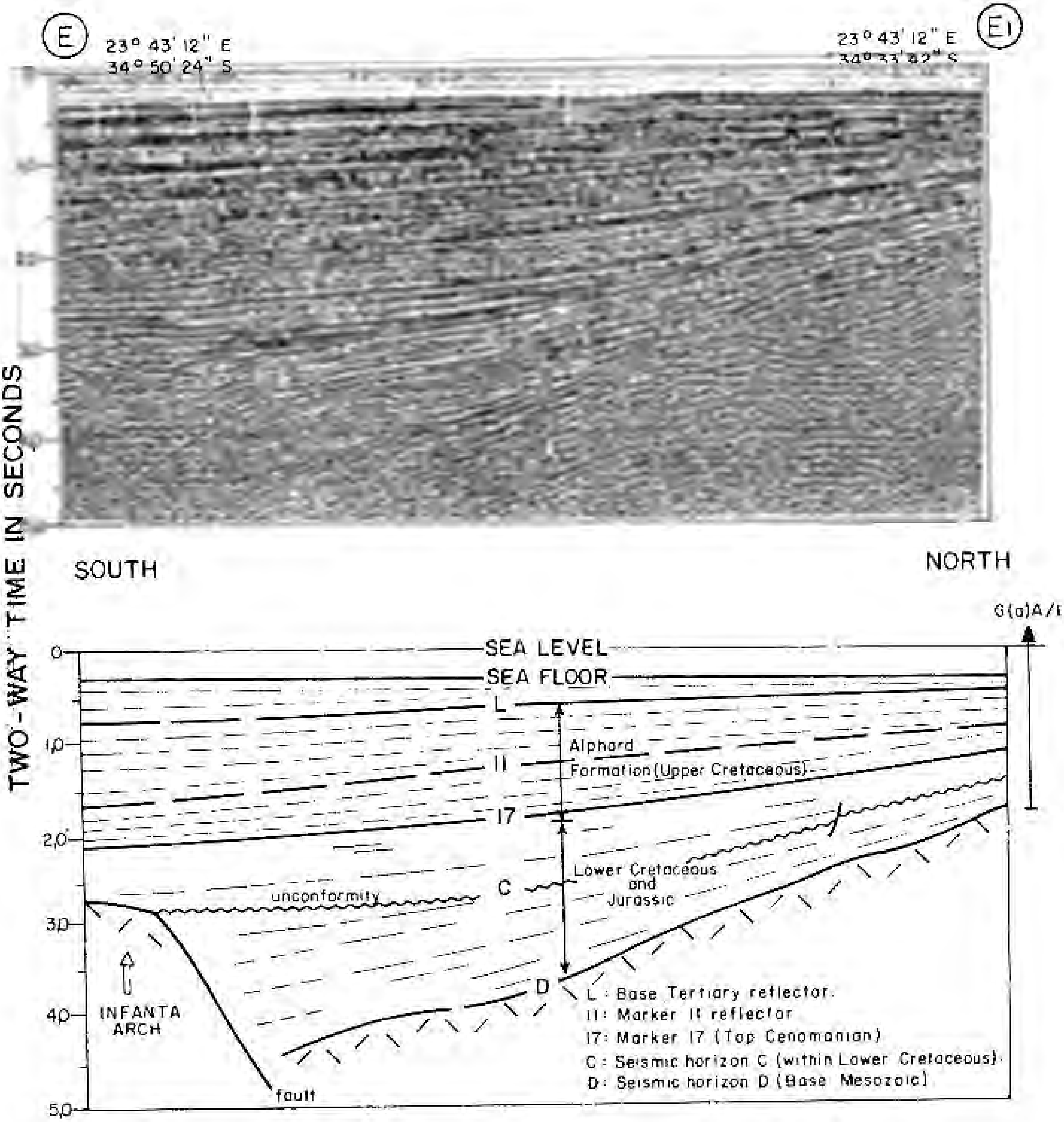

FIG. 18 N-S SEISMIC REFLECTION PROFILE FROM THE G(a) A/I WELL TO THE SHELF BREAK AT THE 200 m ISOBATH

reflectors which overstep one another and which converge in a shoreward direction. Seismic reflection evidence is therefore in agreement with the concept of the Alphard Formation being a transgressive unit. In the Bredasdorp Basin, a herringbone effect is observed locally; this is produced on seismic reflection profiles by the attitude of unlapping and subcropping reflectors which envelop horizon A and is clear evidence in favour of an unconformity towards the base of the Alphard Formation.

The fact that the Alphard Formation rests on different members of the Sundays River Formation in boreholes in the Pletmos Basin and farther west does not necessarily imply erosion of units at the level of its base; lateral lithofacies variations within the Sundays River Formation affords an equally plausible explanation for this phenomenon.

In the Port Elizabeth half-graben the Alphard Formation rests unconformably on undifferentiated Uitenhage Group sediments in the H(b)-Hartebeest/1 borehole and is the only place where a basal sand is known to be present. The unconformable seismic horizon, termed top of layer 3, occurs at the base of a conformable seaward-thickening wedge of reflector horizons; the unconformity is onlapped by individual reflectors within the wedge in a landward directon.

Sundays River Formation

The Sundays River Formation was intersected in 15 of the boreholes on the Agulhas Bank, if the undifferentiated Uitenhage Group sediments in the H(b) Hartebeest/1 are included in this formation. Disregarding this borehole, the thickest intervals were recorded in the G(b)- Gemsbok/1 (1 002 m) and G(a)-B/1 (1 606 m) wells in the central part of the Pletmos basin and in the D-A/1 well (1 139^{+} m) in the Bredasdorp basin. On the Infanta arch it has already been shown that the lowermost two members of the Sundays River Formation are absent; the thin intersections in the F-O/1 borehole (150 m) and G(a)-C/1 (140 m) are therefore not surprising. The Sundays River Formation was not encountered close inshore in the MB/A/1 borehole, and is absent in the vicinity of the G(b)-Springbok/1 borehole as a result of non-deposition above and erosion below the unconformity on the horizon C.

Depths to the base of the Sundays River Formation fluctuate more than for overlying units primarily because of the horst-and-graben tectonic style at lower levels, particularly below seismic horizon C. The Formation attains depths of over 2 000 m in the Pletmos basin as shown by the G(a)-B/1 (2 512 m) and G(b) Gemsbok/1 (2 124 m) boreholes, and in the Bredasdorp basin in the F-1 borehole (2 444 m). The Sundays River Formation attains depths of between 1 641 m (G(a)A/1) and 1 859 m (G(a)-A/2) on the southern (upthrow) side of the Superior fault; these elevations are comparable to those on the crest of the Infanta arch (G(a)-C/1:1 523 m and F-D/1:1 789 m).

The base of the Sundays River Formation has already been shown to be an unconformity along the northern flank of the Bredasdorp basin in the vicinity of the E-1, E-B/1 and possibly the F-1 boreholes; elsewhere it is either conformable or disconformable.

The lithofacies and boundary relationships of the Sundays River Formation on the Agulhas Bank must now be discussed. In the Bredasdorp basin these relationships can be demonstrated by referring to boreholes E-1 and F-1 (fig. 19). In the E-1 well the SR-3 and SR-4 Members of the Sundays River Formation are bounded by seismic reflector horizons A (top) and C (base); these two units are not present in F-1 due to depositional thinning which is shown by a southeasterly set of prograding reflectors which onlap onto horizon C. Seismic horizon A was mapped at the level of wireline log marker 17; this marker horizon occurs in F-1 at a depth of 1 555 m which is 45 m above the top of the Cenomanian and 85 m above the top of the lower Cretaceous. The Alphard Formation in F-1 extends down to horizon C (top Sundays River) at 2 025 m. In the E-1 well horizon A coincides with the top of the lower Cretaceous Sundays River Formation. It therefore appears that

1. the Alphard Formation extends into the uppermost lower Cretaceous in F-1
2. an unconformity exists between the Alphard and Sundays River Formations as is shown by the herringbone effect of prograding reflectors below and onlapping reflectors above this formation boundary.

The SR-1 /85...

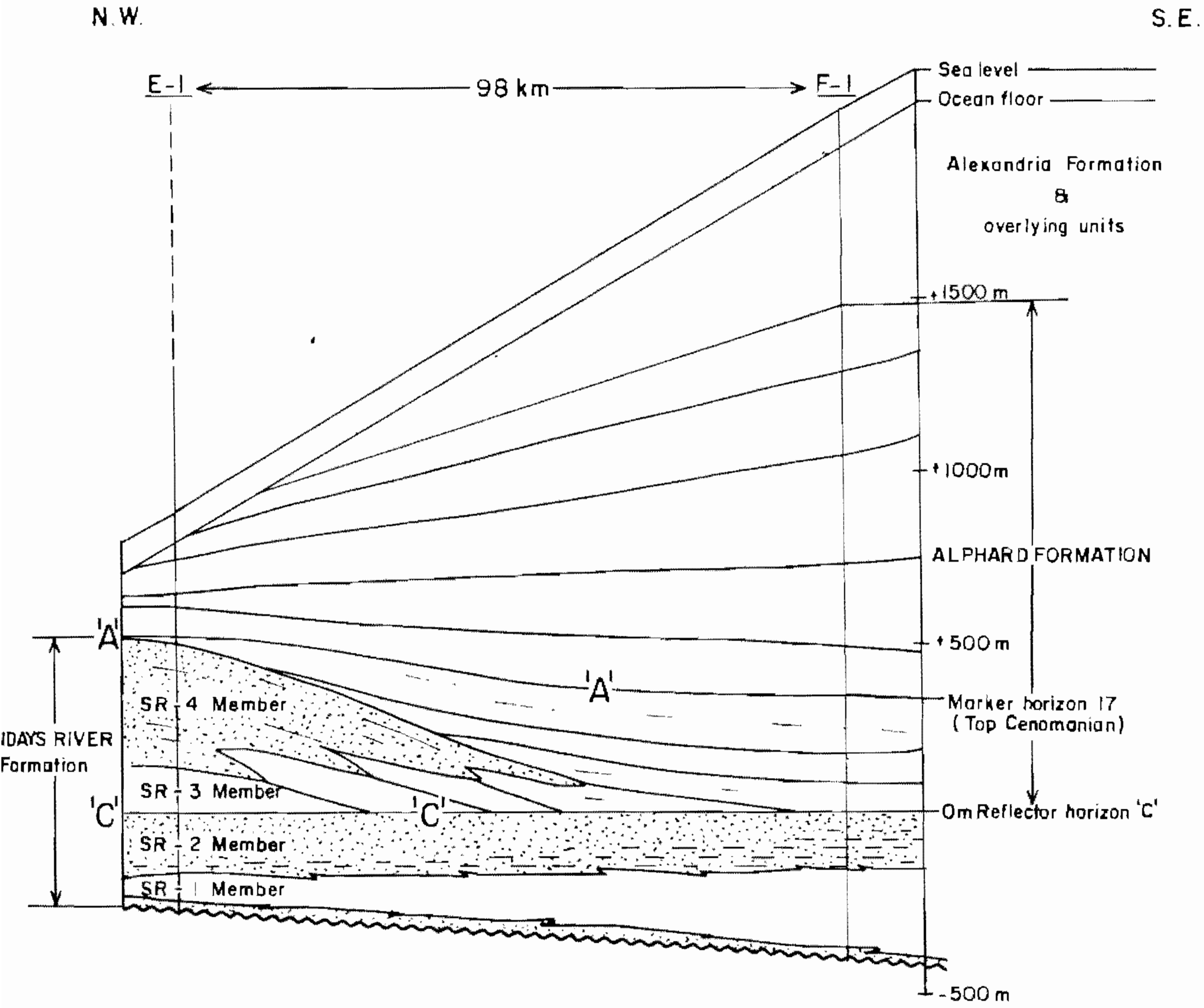

FIGURE 19 Stratigraphic correlation of the Sundays River and Alphard Formations between the E-1 and F-1 boreholes in the Bredasdorp Basin. Top of the SR-2 Member (seismic reflector horizon 'C') is used as horizontal datum plane.

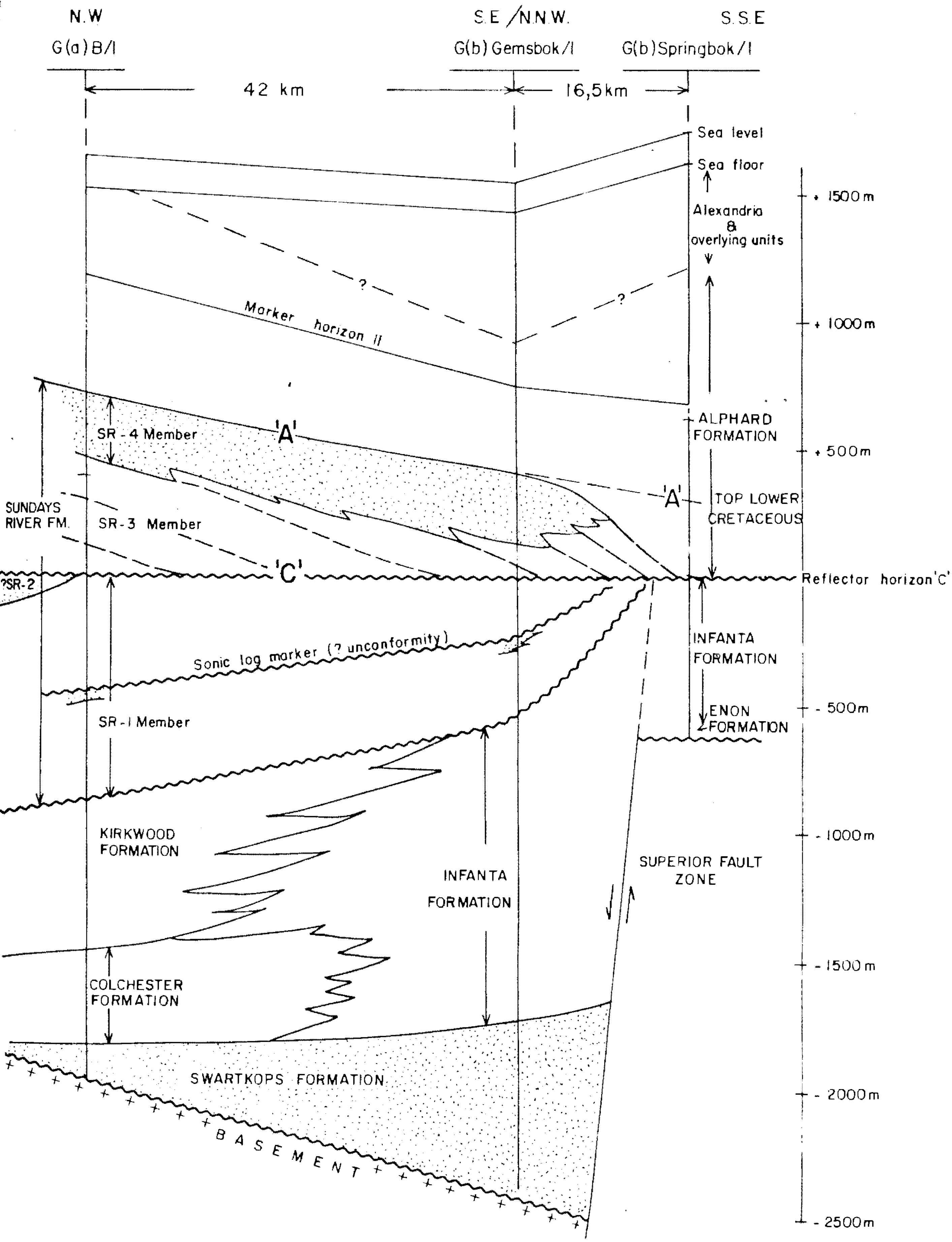

FIGURE 20: Stratigraphic relationships of sediments in the G(a) B/I, G(b) Gemsbok/I and G(b) Springbok boreholes in the Pletmos Basin. Seismic reflector horizon C is used as a horizontal plane of reference.

The SR-1 and SR-2 Members of the Sundays River Formation collectively thicken in a southeasterly direction and rest unconformably on the red beds of the Kirkwood Formation in both E-1 and F-1. A hiatus is shown to be present on horizon C by the southeasterly directed progrades.

The above-mentioned relationships also pertain to the Sundays River and Alphard Formations in the Pletmos Basin (fig. 20). In G(a)B/1 and in G(b)-Gemsbok/1 the top of the Sundays River Formation is coincident with the top of the Lower Cretaceous and seismic horizon A. In G(b) Springbok/1, however, horizon A coincides with the top of the Lower Cretaceous and is 307 m above the base of the Alphard Formation (on horizon C at 1747 m). As is the case in the F-1 borehole in the Bredasdorp basin the lowermost portion of the Alphard Formation extends into the Lower Cretaceous in G(b)-Springbok/1. The herringbone effect described above also signifies an unconformable relationship between the Sundays River and Alphard Formations; this unconformity is overstepped by progressively younger sediments in a northwesterly direction.

Seismic reflector horizon C has already been shown to be an angular unconformity in G(b)-Springbok/1 where it rests on the Infanta Formation and in G(b)-Gemsbok/1, where it overlies the SR-1 Member. The lowermost two members of the Sundays River Formation are thought to be separated from underlying units by an unconformity which cuts across the Kirkwood (in G(a)-B/1) and Infanta Formations (in G(b)-Gemsbok/1 and G(b)-Springbok/1). The thinning of the SR-4 and SR-3 envelope towards G(b)-Springbok/1, and the development of a compound unconformity on horizon C, may be related to syn-sedimentary displacement on the Superior fault.

The unconformable relationship of the Sundays River Formation to the Kirkwood Formation conflicts with presently held views of the partial synchronuity of the stratotype sections of these two units on land in the Algoa basin (du Toit, 1954; Rigassi, 1972; Winter, 1973).

Kirkwood Formation

The Kirkwood Formation was intersected in seven boreholes on the Agulhas Bank; these are located along the northern flank of the Bredasdorp basin (E-1 and F-1),

/86...

(E-1 and F-1), on the Infanta arch (F-D/1 and G(a)-C/1) and along the northern flank of the Pletmos basin (PB/A/1, MB/A/1 and G(a)-B/1).

The elevation of the boundaries of the Kirkwood Formation is highly variable due to the prevalence of faulting at its stratigraphic level and the variation in its thickness is due amongst others to the presence of a major unconformity at the base of the overlying Sundays River Formation. The varying depths to the top of the unit are shown by the intersections in G(a)-B/1 (2 512 m), F-1 (2 444 m), MB/A/1 (above 192 m), G(a)-C/1 (1 523 m), E-1 (1 157 m) and F-D/1 (1 789 m). The maximum thickness of the unit was encountered in the E-1 borehole (1 499 m) in the Bredasdorp basin.

As previously said the Kirkwood Formation is separated from the Sundays River Formation by an unconformity, and it rests conformably on the Colchester Formation in G(a)-B/1 and PB/A/1 and on the Enon Conglomerate in MB/A/1, and unconformably on basement in F-1, F-D/1, and G(a)-C/1. The Kirkwood Formation interfingers with the Enon Formation in the MB/A/1 borehole and with the Infanta Formation between G(a)-B/1 and G(b)-Gemsbok/1 (fig. 20) and perhaps in G(a)-B/1 itself, where a subordinate amount of grey shale was observed in cuttings samples below the Sundays River Formation.

Infanta Shale Formation

The Infanta Formation was intersected in seven boreholes on the Agulhas Bank. Like the Kirkwood Formation its present elevation is variable due to block-faulting and its thickness is influenced to a large extent by erosion on the overlying unconformities. The maximum depth to the top of the unit was recorded in F-E/1 (2 326 m) in the Bredasdorp basin and the greatest thickness was intersected in the G(b)-Gemsbok/1 borehole (1 132 m), where the stratotype is defined.

The Infanta Formation rests conformably on the Swartkops Formation over the Superior A structure (G(a)-A/1, G(a)-A/2 and G(a)-A/3) and in G(b)-Gemsbok/1. It rests conformably on the Enon Formation in G(b)-Springbok/1 and on the Colchester Formation in D-A/1. Its grey silty

shales /87...

shales interfinger with the Kirkwood Formation in the Pletmos basin.

Colchester Shale Formation

The grey shales of the Colchester Formation occur in only three boreholes on the Agulhas Bank; the elevation of ots top ranges between 3 082 m (in G(a)-B/1) and 1 104 m (in PB/A/1 in the Pletmos basin). The maximum recorded thickness is in the D-A/1 borehole (520 m). The colchester Formation is conformably overlain by the Kirkwood Formation and in turn rests conformably on the Swartkops Formation; these relationships are shown in figure 20, which also shows that the Colchester is a tongue of the Infanta Formation and that both are laterally equivalent to the Kirkwood Formation.

Swartkops Sandstone Formation

The sandstones of the Swartkops Formation have been intersected in seven boreholes on the Agulhas Bank and varies in thickness from 682 m in the G(b)-Gemsbok/1 borehole to 52 m in G(a)-A/1. The top of the unit ranges in depth from 3 256 m in G(b)-Gemsbok/1 to 1 476 m in PB/A/1. The junction with the Infanta Formation is conformable over the Superior A structure and in G(b)-Gemsbok/1; it has a conformable relationship with the Colchester Formation in boreholes G(a)-B/1 and PB/A/1. The Swartkops Formation rests on basement on the Superior A structure and in G(a)-B/1, and conformably on Enon Conglomerate in the PB/A/1 well. It is conceivable that the Swartkops Formation may interfinger laterally with the Enon, Colchester and Infanta Formations.

Enon Conglomerate Formation

Enon Conglomerate was encountered in three boreholes on the Agulhas Bank; the deepest intersection of its upper contact was made in G(b)-Springbok/1 (2 356 m) and the thickest intersection in M2/A/1 (175 m^+). The Enon rests unconformably on basement and is conformably overlain by the Infanta, Swartkops and Kirkwood Formations. It may interfinger with the overlying units, as is indicated by intersections in the G(a)-C/1 and F-O/1 and F-D/1 boreholes on the Infanta arch.

CHRONOSTRATIGRAPHY

General Statement

The South African Stratigraphic Code defines a chronostratigraphic unit as a subdivision of rock considered solely as the record of a specific interval of time. The boundaries of such units are defined by objective criteria in their respective type areas; these boundaries can be extended geographically as criteria of time equivalence become available and then only within the limits of accuracy imposed by physical or paleontologic criteria.

Paleontologic criteria provide the most successful means of world-wide correlation of all ranks of Phanerozoic chronostratigraphic units; in fact, biochronology is commonly cited as the only basis for establishing operational time-stratigraphic boundaries (Krumbein and Sloss, 1963, p 41).

The task of establishing a viable time-stratigraphic framework for sediments in boreholes on the Agulhas Bank was initially performed by service companies such as Paleolab (G(a)-A/1) and Robertson Research International (G(a)-A/2, G(a)-A/3, G(a)-B/1, MB/A/1, PB/A/1, F-1, G(b)-Gemsbok/1, G(a)-C/1, F-D/1). A paleontologic laboratory was established in Soekor to study the boreholes that were drilled during 1972 and 1973 and to re-examine material from earlier wells. Provision was made for both microfaunal (foraminiferal and ostracodal) and microfloral investigations, and these were carried out under the direction of Mr. I.R. McLachlan. The responsibility of integrating paleontologic results with the broad seismic-stratigraphic framework rested with the writer up until the time of writing.

In accordance with standard oil-field practice most of the material studied came from ditch-cutting samples; sidewall and conventional bottom-hole cores were seldom available for paleontologic studies in those boreholes which were drilled prior to 1972. It is common knowledge that in oil exploration boreholes the emphasis is placed

on the /89...

on the determination of the first downhole appearance (extinction tops) of those microfauna which have time - stratigraphic significance. The converse is true in respect of microflora, which generally range upward in the stratigraphic column from their first evolutionary appearance (extinction base). Downhole cuttings contamination poses a serious problem in the determination of microfloral bases; for this reason cores and sidewall cores are more vital for microfloral than microfaunal studies of borehole sections.

On the Agulhas Bank the Tertiary end Upper Cretaceous chronostratigraphy is based to a large extent, if not entirely, on foraminifera; particular emphasis and importance was attached to planktonic Beneath the level of the Cenomanian, however, the microfaunal content is very much lower. Some correlations in the Lower Cretaceous and older sections have been made on the basis of benthonic foraminifera, ostracodes and microflora.

Detailed descriptive biostratigraphy is beyond the scope of this thesis; for this reason the ensueing discussion draws liberally on reports compiled by Robertson Research International (1972) and by Soekor paleontologists.

Tertiary

Middle and Upper Eocene

A local zonation established by Robertson Research International (1972) comprises four zones containing sediments of Middle and Upper Eocene age (table IV); it is based on the international classification proposed by Bolli (1957, 1966) and Blow (1969). Apart from the species listed, an Upper Eocene dating is confirmed by the presence in many boreholes of Globorotalia increbescens, Hantkenina primitiva, Globorotalia crassata and Globorotalia centralis.

Lower Eocene /91...

TABLE IV

GENERALIZED MICROFAUNAL ZONATION OF EOCENE SEDIMENTS IN BOREHOLES ON THE AGULHAS BANK

(after Robertson Research, 1972)

Faunizone	Age
Globorotalia cerroazulensis Zone Globigerapsis semiinvoluta Zone *[1]	Upper Eocene
Truncorotaloides rohri Zone Orbilinoides beckmani Zone	Middle Eocene

*[1] : Globigerapsis semiinvoluta = Globigerapsis index

Lower Eocene - Paleocene

Compared to the overlying interval, this sequence is characterised by a sudden reduction in the numbers of planktonic foraminifera, which become sparse and even rare. Species used for dating include the following: *Globorotalia cf. broedermani*, *Globorotalia cf. rex (= Truncorotalia rex)*; *Globorotalia cf. formosa gracilis*, *Globorotalia pseudomenardii/Globorotalia elongata*, *Globorotalia cf. simulatilis*, *Globorotalia pseudobulloides*, *Globorotalia triloculinoides*, *Globorotalia cf. aequa*, *Globorotalia cf. compressa*. An unconformity is considered to be present at the top of the sequence since, apart from the reduction of planktonic species, these is an apparent absence of beds directly referrable to the older part of the Middle Eocene and upper part of the Lower Eocene.

Upper Cretaceous

The generalized Upper Cretaceous biostratigraphic subdivisions established by Robertson Research are shown in Table V.

Maestrichtian

This interval is characterised by the following calcareous benthonic forms: *Neoflabbellina* spp., *Anomalina rubiginosa* and *Praebulimina carseyae* in addition to those listed in Table V. Agglutinating foraminifera include *Gaudryina cf dividends* and *Clauvulinoides spp.* The faunal elements recovered from this interval are considered to be insufficiently diagnostic to warrant a more detailed subdivision of the Maestrichtian Stage.

Campanian

The planktonic element is not abundant in this interval which may be identified on the basis of the following: *Globotruncana linneiana*, *Globotruncana ventricosa*, *Globotruncana marginata* and *Globotruncana spinea*.

Santonian -/93...

TABLE V

GENERALISED MICROFAUNAL ZONATION OF UPPER CRETACEOUS SEDIMENTS IN BOREHOLES ON THE AGULHAS BANK

(after Robertson Research, 1972)

FAUNIZONE	AGE	
Bulimina arkadelphiana/Epistamina spp./ Brazilina incrassata zonule	Maestrichtian	UPPER CRETACEOUS
Globotruncana linneiana (S.l.) zonule	Campanian	
Globotruncana linneiana coronata/ Globotruncana careneta zonule	Santonian ? Coniacian	
Globotruncana cachensis/Hedbergella spp. zonule	Lower Coniacian-Upper Turonian	
Praeglobotruncana stephani zonule	Lower Turonian	
Rotalipora spp./Spirelectinata annectens zonule	Cenomanian	

Santonian - ? Coniacian

The section as a whole is poorly fossiliferous. The Santonian dating stems largely from the species listed in Table V. No definite evidence of the existence of Coniacian beds has been found and it is possible that the Upper Coniacian, at least, is absent.

Lower Coniacian - Upper Turonian

The upper boundary of this interval is marked by a strong influx of globogerine planktonic foraminifera. Specimens of unquestionable *Praeglobotruncana stephani* do not occur within this interval. A single specimen of *Praeglobotruncana loeblichi* recovered in G(a)-A/1 supports a lower Coniacian to younger Turonian dating.

Lower Turonian

Apart from the incoming of *Praeglobotruncana stephani* rare specimens of *Globotruncana helvetica* and *Praeglobotruncana turbinata* are found in this interval.

Cenomanian

The Cenomanian interval is generally clearly indicated in most boreholes by *Rotalipora spp.* and *Spirolectinata annectens* and by a concomitant decrease in the size of *Hedbergella spp.* *Spirolectinata annectens* is first recorded within this zone and adds weight to the belief that it is a significant marker fossil for the Cenomanian.

Lower Cretaceous - Jurassic

The micropaleontological study of the interval between the base of the Cenomanian and basement is based on foraminifera, ostracodes and palynomorphs. The assemblages recovered from each of these microfossil groups have been sparse. Preservation is usually poor and the specimens themselves infrequent. Furthermore the limited bibliography relating to the Lower Cretaceous in South Africa is of a very sketchy nature, and consequently paleontologists have tended to place emphasis on correlations and

comparisons /94...

comparisons with the Majunga basin (Malagasy) and with the European type sections.

Up to now greater importance has been attached to stratigraphical conclusions resulting from studies of ostracodes; these are consistent with a three-fold subdivision of the interval below the Cenomanian (table VI).

1. Lower Cretaceous (possibly Albian or Barremian to Valanginian)
2. Lower Cretaceous - Upper Jurassic (probably Valanginian to Portlandian).
3. Upper Jurassic or older.

A fourth interval is recognised locally upon ostracode evidence alone and the top of the unit is indicated by the first downhole appearances of the following Valanginian forms; *Neocythere cf. uitenhagensis*, *Cytherella cf. inequivalva*, *Amphicytherura cf. theloides* and *Rostrocytheridea chapmani*.

Foraminiferal assemblages noted from below the base of the Cenomanian also suggest a Lower Cretaceous-Upper Jurassic age since the general ranges of the forms would be consistent with an overall Barremian - Portlandian dating. However, it also appears that the forms present over the major part of the interval are more representative of zone D of the succession recorded in the Majunga basin by Espitalie and Sigal (1963), which would imply a dating more in keeping with Valanginian - Portlandian.

It would appear that the Lower Cretaceous cannot be dated from foraminifera and that the Cenomanian - Albian boundary cannot be recognised. The first important form is *Lenticulina nodosa*, which in north-west Europe is a Hauterivian - Valanginian species, but, as *Lenticulina cf. secans var angulosa* in the Majunga basin, it ranges from Barremian (and possibly younger) to Berriasian. A less widespread but apparently more restricted form is *Astacolus microdictyotus*; in the Majunga basin it is restricted to Zone D of Espitalie and Sigal (1963) i.e. Valanginian-Portlandian.

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TABLE VI

GENERALISED MICROFAUNAL ZONATION OF THE LOWER CRETACEOUS AND JURASSIC SEDIMENTS ON THE AGULHAS BANK

(after Robertson Research, 1972)

FAUNIZONE		
OSTRACODS	FORAMINIFERA	AGE
Isocytheresis sealensis	*Lenticulina nodosa*	Lower Cretaceous (Albian or Barremian – Valanginian
Cytherella sp 1	*Astracolus microdictyotus*	Lower Cretaceous/ Upper Jurassic (Valanginian – Portlandian)
Cytherella cf. index *Cytherella colliosa*		Upper Jurassic or older

The occurrence of presumed reworked Epistomina spp. in the Upper Cretaceous of the G(a)-B/1 borehole provides support for the suggestion that the uppermost Lower Cretaceous has been eroded away.

Palynological studies undertaken by Robertson Research suggest that the larger portion of the Lower Cretaceous - Jurassic sequence is no younger than Aptian and no older than Bajocian, and in certain cases may even be restricted to the Lower Cretaceous.

Chronostratigraphic Correlation

The suggested chronostratigraphic correlations of the succession intersected in boreholes on the Agulhas Bank are shown in table VII, which was compiled by the author from information contained in various reports by Robertson Research International and by Soekor paleontologists. The preliminary nature of these results must be stressed; a critical review of the coastel and offshore Mesozoic biostratigraphy is at present in progress in Soekor's paleontological laboratory.

The thicknesses of three major groupings of chronostratigraphic units are shown in Table VIII, which was compiled from information contained in table VII, supplemented were possible by table II. The following is a brief discussion of the results shown in tables VII and VIII.

Tertiary

Sediments dated as Tertiary - more specifically Paleocene and Eocene - were encountered in 10 boreholes on the Agulhas Bank. The maximum depths to the base of the Tertiary were encountered in the G(b)-Springbok/1 (670 m), F-D/1 (645 m), F-E/1 (600 m) and F-1 (600 m) boreholes which are relatively close to the shelf break. Because of their regional seaward dip (Dingle, 1971 b) the Tertiary and younger sediments are thickest in these same boreholes, e.g. G(b)-Springbok/1 (545 m), F-D/1 (514 m), F-E/1 (486 m) and F-1 (491 m). Though intersections in boreholes of the base of the Tertiary sediments are few and far between they indicate an approximate regional strike of N 80° E and a seaward dip of about 2°. This is in general agreement with the views expressed by Dingle (1971(b)).

TABLE VII

RESULTS OF CHRONOSTRATIGRAPHIC CORRELATION OF SEDIMENTS IN BOREHOLES ON THE AGULHAS BANK

(all depths in metres below sea level)

System or Period	Series or Epoch	Borehole No. / Age or Stage	G(a)A/1	G(a)A/2	G(a)A/3	G(a)B/1	F-1	MB/A/1	PB/A/1	G(a) C/1	G(b) Gemsbok/1	E-1	D-A/1	F-B/1	F-D/1	E-E/1	F-E/1	H(b) Hartebeest/1	G(h) Springbok/1
TERTIARY	[illegible]	Eocene (Upper)	<271	<272	<273		<288			<280					<280		<258		[illegible]
		Eocene (Middle)	290	335	340		385			380					480		380		450
		Eocene (Lower)	350		420		510				<308?				540		430	<371	510
		Paleocene		480						420	380				560		510	450	500
CRETACEOUS	UPPER	Maastrichtian	470	535	520	<280	600			500	520				645		600	460	670
		Campanian	720	740	690	405	981			740	720				955	<215	1020	680	920
		Santonian	820	770	720	455	1100			780	780			<280	1005	425	1155	Absent	1005
		?Coniacian		975	880	610	1230			835	870			340	1070		1255	Absent	1140
		Turonian	870	1675	970					1035				390	1190	?490	1445	Absent	1130
		Cenomanian	1070	1220	1175	750	1700			1195	1070	<315			1455		1850	Absent	1220
	LOWER	Albian	1155	1370	1250	890	1740		<187	1335	1210	?425	<237?	445	1495	517	1910	Absent	1440
		Aptian													1530	?347		Absent	
		Barremian	1220	1410	1340	1410							910	495		1150		950	Absent
		Hauterivian									1370			580			2115	1750	1710
		Valanginian	1590	1550	1430	1670	1825		210	1450	1590		1495		1600		2180	1625	1890
Lower Cretaceous and Upper Jurassic or older			?	2120	2090	2290	2212	? 192	580	1495	1800		1750		1750			2350	
Paleozoic or older			2021	2551	2433	3621	2523	Below 1273		Below 1632	Below 3938	Below 2556	Below 2411	901	Below 1922	1341	Below 2418	2392	Below [illegible]

TABLE VIII

THICKNESS IN METRES OF MAJOR MESOZOIC AND CENOZOIC CHRONOSTRATIGRAPHIC UNITS IN BOREHOLES ON THE AGULHAS BANK

UNIT / BOREHOLE NUMBER	TERTIARY AND YOUNGER	UPPER CRETACEOUS	LOWER CRETACEOUS AND/OR JURASSIC
G(a)-A/1	353	685	867
G(a)-A/2	419	835	1 181
G(a)-A/3	463	730	1 183
G(a)-B/1	153	610	2 731
F-1	491	1 140	783
MB-A/1	132	132	1 081
PB-A/1	106	106	1 572
G(a)-D/1	395	835	327
G(b)-Gemsbok/1	396	690	2 728
E-1	239	110	2 231
D-A/1	150	150	2 174
F-B/1	150	194	456
F-D/1	614	850	427
E-B/1	140	302	824
F-E/1	466	1 310	498
H(b)-Hartebeest/1	342	500	1 422
G(b)-Springbok/1	545	770	929

Upper Cretaceous

Sediments of this age were intersected in 14 of the 17 boreholes on the Agulhas Bank. The depths to the base of the unit range from 425 m and less close inshore to 1 740 m in F-1. The regional strike at the base of the Upper Cretaceous (N 80° E) corresponds roughly to that of the base of the Tertiary, and the seaward dip is approximately 3°. This structural attitude is in agreement with that of seismic horizon A (pl.3) which in turn corresponds closely to the base of the Alphard Formation.

The Upper Cretaceous sediments on the Agulhas Bank form a seaward-thickening wedge up to the 200-m isobath, which comprises all the Upper Cretaceous stages ranging from Maestrichtian to Cenomanian. Sediments of Upper Maestrichtian age may conceivably be absent, while small hiatuses in the succession may occur within the Coniacian and Turonian intervals. (Brenner, pers comm). In the boreholes the Upper Cretaceous attains a maximum thickness of more than 1 000 m in F-1 (1 140 m) and F-E/1 (1 310 m); the minimum thickness of 500 m (Maestrichtian and Campanian only) was encountered in the H(u)-Hartebeest/1 well.

Lower Cretaceous and/or Jurassic

Sediments of this interval were encountered in every one of the 17 boreholes on the Agulhas Bank; the elevation of the base is highly variable due to block-faulting. Maximum thicknesses were thus encountered in the Pletmos basin, e.g. G(b)-Gemsbok/1 (2 728 m), G(a)-B/1 (2 731 m) and in the Bredasdorp basin, e.g. E-1 (2 221 m), D-A/1 (2 174 m). Boreholes sited on the regional positive features intersected considerably thinner Lower Cretaceous and/or Jurassic sediments; on the Infanta arch thicknesses of the order of 300 m to 450 m were recorded in the F-D/1 (427 m), G(a)-C/1 (327 m) and F-B/1 (456 m) boreholes.

The age of the Lower Cretaceous sediments range from possibly Albian or Barremian to Valanginian.

SYNTHESIS /100...

SYNTHESIS OF STRATIGRAPHIC RESULTS

The integration of the stratigraphic results discussed so far which are derived from lithostratigraphic, wireline log, chronostratigraphic and seismic studies was the responsibility of the writer during the past five years. In the following discussion an attempt is made to integrate these results within the lithostratigraphic framework established for the time-rock units.

Alexandria Formation (Eocene - Paleocene)

The Alexandria Formation comprises four readily identifiable subdivisions. The top of the formation is generally abscured by casing in the boreholes. As shown in table IX its base is practically coincident with that of sediments of Tertiary age (Paleocene - Eocene).

In respect of G(b)-Gemsbok/1 and G(b)-Springbok/1 the difference between the base of the Tertiary and the Alexandria Formation reflect on the tentative positions of the base of the Alexandria Formation; in the H(b)-Hartebeest/1 borehole it could not be identified in cuttings samples or on wireline logs. In the remained of the boreholes the differences in depths between the chronostratigraphic and lithostratigraphic units are within the practical lower limits of the sampling interval at shallow depths where the drilling penetration rate is of the order of 10 metres per minute.

The top of unit 2 of the Alexandria Formation, dated as Middle Eocene, is about 40 m above the top of the Lower Eocene-Paleocene interval in F-1, F-E/1, F-D/1 and G(a)-A/1, while in G(a)-A/3 the top of the same unit is of Upper Eocene age. Although the evidence is rather scanty, it is possible that the rapid downhole decrease in the number of planktonic forms in unit 2 signifies that unit 3 is transgressive and rests unconformably on the underlying shale and that it progressively youngs shorewards.

The Alexandria Formation and the sediments of Tertiary age as discussed above, is correlatable with the Paleogene ("Lower" Tertiary) unit identified and mapped by Dingle (1971(b)).

TABLE IX

COMPARISON BETWEEN DEPTHS TO THE BASE OF THE ALEXANDRIA FORMATION AND THE BASE OF TERTIARY SEDIMENTS IN BOREHOLES ON THE AGULHAS BANK

UNIT BOUNDARY / BOREHOLE NUMBER	BASE ALEXANDRIA FORMATION (A)	BASE TERTIARY (B)	DIFFERENCE (A) - (B)
	metres below sea level	m below sea level	metres
F-1	569	600	-31
F-E/1	555	600	-45
F-D/1	611	645	-34
G(a)-E/1	466	500	-34
G(a)-A/1	463	470	-7
G(a)-A/2	507	535	-28
G(a)-A/3	490	520	-30
G(b)-Gemsbok/1	?631	520	?+ 111
G(b)-Springbok/1	?546	670	? -124
H(b)-Hartebeest/1	? 371	460	? -89

Alphard Formation (Upper Cretaceous; Maestrichtian – Cenomanian)

The Alphard Formation is made up predominantly of glauconotic fossiliferous greenish-grey shales and clays. The upper boundary of the formation corresponds closely to the Cretaceous-Tertiary boundary. The base of the Alphard Formation, which corresponds to the approximate level of horizon A, is virtually coincident with the base of the Upper Cretaceous in the majority of boreholes (table X); significant exceptions are observed in five boreholes and may be due to a combination of the following:

1. the diachronous nature of the formation boundary;
2. the limitations of the accuracy of chronostratigraphic determinations as result of downhole sample contamination, the large sampling interval, and the paucity of Lower Cretaceous microfossils with time-stratigraphic significance;
3. reworking of Lower Cretaceous fauna on unconformities and their incorporation in sediments of Upper Cretaceous age;
4. the present preliminary nature of chronostratigraphic determinations; and
5. unreliable lithostratigraphic boundaries.

It would appear from microfaunal and seismic reflection evidence that major unconformities are not present within the Alphard Formation. A complete sequence, ranging in age from Maestrichtian to Cenomanian, is locally present on the Agulhas Bank, however, it is possible that late Maestrichtian sediments may be absent below the unconformity at the base of the Alexandria Formation, particularly close inshore. As shown in figure 18, seaward thickening of the Alphard Formation takes place by way of a corresponding thickening of chronostratigraphic units.

Wireline log marker or seismic horizon 11 generally occurs within sediments varyingly dated as Santonian, (G(a)-B/1, G(b)-Gemsbok/1, Coniacian (G(a)-B/1), and Turonian (F-1, F-E/1, G(a)-C/1 and G(a)-A/3; the limits are between Campanian in G(b)-Springbok/1 and Cenomanian in F-D/1. Whilst this horizon may be locally used as a stratigraphic marker, its value as a regional marker within the Upper Cretaceous is seriously in doubt. By

contrast /104...

TABLE X

COMPARISON BETWEEN DEPTHS TO THE BASE OF THE ALPHARD FORMATION AND THE BASE OF THE UPPER CRETACEOUS SEDIMENTS IN BOREHOLES ON THE AGULHAS BANK

BOUNDARY BOREHOLES NO.	BASE ALPHARD FORMATION	BASE UPPER CRETACEOUS	DIFFERENCE
	metres below sea level	metres below sea level	metres
G(a)-A/1	1 172	1 155	+ 17
G(a)-A/2	1 327	1 370	- 43
G(a)-A/3	1 253	1 250	+ 3
G(a)-B/1	906	890	+ 16
F-1	2 025	1 740	+285
G(a)-C/1	1 383	1 335	+ 46
G(b)-Gemsbok/1	1 122	1 210	- 88
E-1	361	425	- 64
F-B/1	453	445	+ 8
F-D/1	1 651	1 495	+156
E-B/1	451	517	- 66
F-E/1	1 924	1 910	+ 14
H(b)-Hartebeest/1	862	960	- 98
G(b)-Springbok/1	1 747	1 440	+307

contrast, wireline log marker horizon 17 occurs within 50 m of the top of the Cenomanian (table XI) in six boreholes (G(a)-A/1, G(a)-A/2, G(a)-A/3, F-1, G(a)-C/1, and F-D/1). In the remainder - G(a)-B/1, F-E/1 and G(b)-Springbok/1)- some of the reasons listed before may explain the observed discrepancies.

A significant hiatus is present towards the base of the Alphard Formation in the H(b)-Hartebeest/1 borehole, where sediments of Campanian age rest unconformably and directly on Lower Cretaceous sediments.

Sundays River Formation (Lower Cretaceous - ? Jurassic)

While there can be no question that the Sundays River Formation is of Lower Cretaceous age on the Agulhas Bank, a more precise dating is made difficult by the general sparsity of fauna of time-stratigraphic significance below the base of the Alphard Formation (Upper Cretaceous). In addition, the presence of a major erosional unconformity of seismic horizon C, which occurs within the formation, and another, towards the base of the unit, makes dating even more difficult.

The unconformity on seismic horizon C is used informally in this thesis for subdividing the stratigraphic succession. It occurs within sediments which are no older than Valanginian in any of the boreholes, and is overlain by the SR-3 and SR-4 Members in all boreholes except F-1, F-E/1 and G(b)-Springbok/1, where the SR-3 and SR-4 units are absent due to non-deposition in a basinward direction and the Alphard Formation rests directly on horizon C.

The part of the Sundays River Formation between the base of the Alphard Formation and horizon C, has been dated as late Lower Cretaceous (possibly Albian or Barremian to Valanginian); it is hereinafter referred to informally as the upper Sundays River sequence. Its stratigraphic relationships to the overlying Alphard Formation and horizon C below have already been dealt with when discussing Figures 19 and 20.

The part /105...

TABLE XI

COMPARISON BETWEEN DEPTHS TO MARKER HORIZON 17 AND THE TOP OF CENOMANIAN SEDIMENTS IN BOREHOLES ON THE AGULHAS BANK

BOUNDARY / BOREHOLE	HORIZON 17 metres below sea level	TOP CENOMANIAN metres below sea level	DIFFERENCE (m)
G(a)-A/1	1066	1070	- 4
G(a)-A/2	1212	1220	- 8
G(a)-A/3	1142	1175	- 33
G(a)-B/1	607	750	-143
F-1	1655	1700	- 45
G(a)-C/1	1166	1195	- 29
F-D/1	1408	1455	- 47
F-E/1	1476	1850	-374
G(b)-Springbok/1	1417	1250	+167

The part of the Sundays River Formation below horizon C is referred to below as the lower Sundays River sequence. It is Valanginian in age or older, and probably dates back into the Jurassic (Portlandian). As a very rough approximation, the base of the lower Sundays River sequence can be taken to indicate the Jurassic-Cretaceous boundary on the Agulhas Bank, which can, however, not be placed in the majority of the boreholes. The lower Sundays River sequence has been shown to rest unconformably on basement or on the Kirkwood Formation, but may be conformable to disconformable in relation to the Infanta Formation.

Pre-Sundays River Formations (possibly Upper Jurassic or older)

The Enon, Swartkops, Colchester and Infanta Formations make up the bulk of the interval designated Lower Cretaceous - Upper Jurassic or older. Their stratigraphic position below horizon C certainly indicates that they are older than Valanginian, if not entirely of Jurassic age. The overall sequence is clearly syntectonic, as can be deducted by its great thickness in basinal areas (graben or half-graben) in comparison with its relative thinness over highs such as the Infanta arch. The Uitenhage Group sediments below the major angular unconformity "Top of Layer 3" in the H(b)-Hartebeest/1 borehole were clearly deposited in a half-graben, in which the succession thickens towards the Port Elizabeth fault; by implication the Uitenhage Group in the half-graben is syntectonic, and it is dated as young as Barremian.

Stratigraphic Model

The stratigraphic synthesis outlined above has led to the development of a model summarising the relationships between litho- and chrono-stratigraphy, unconformities and transgressive-regressive cycles (fig. 21). The model is extrapolated beyond areas of borehole and seismic control by incorporating some of the considerations which are discussed below.

A lithostratigraphic unit is an expression (response) of a particular set of palaeo-environments. A biostratigraphic unit is often utilized

in stratigraphic /109...

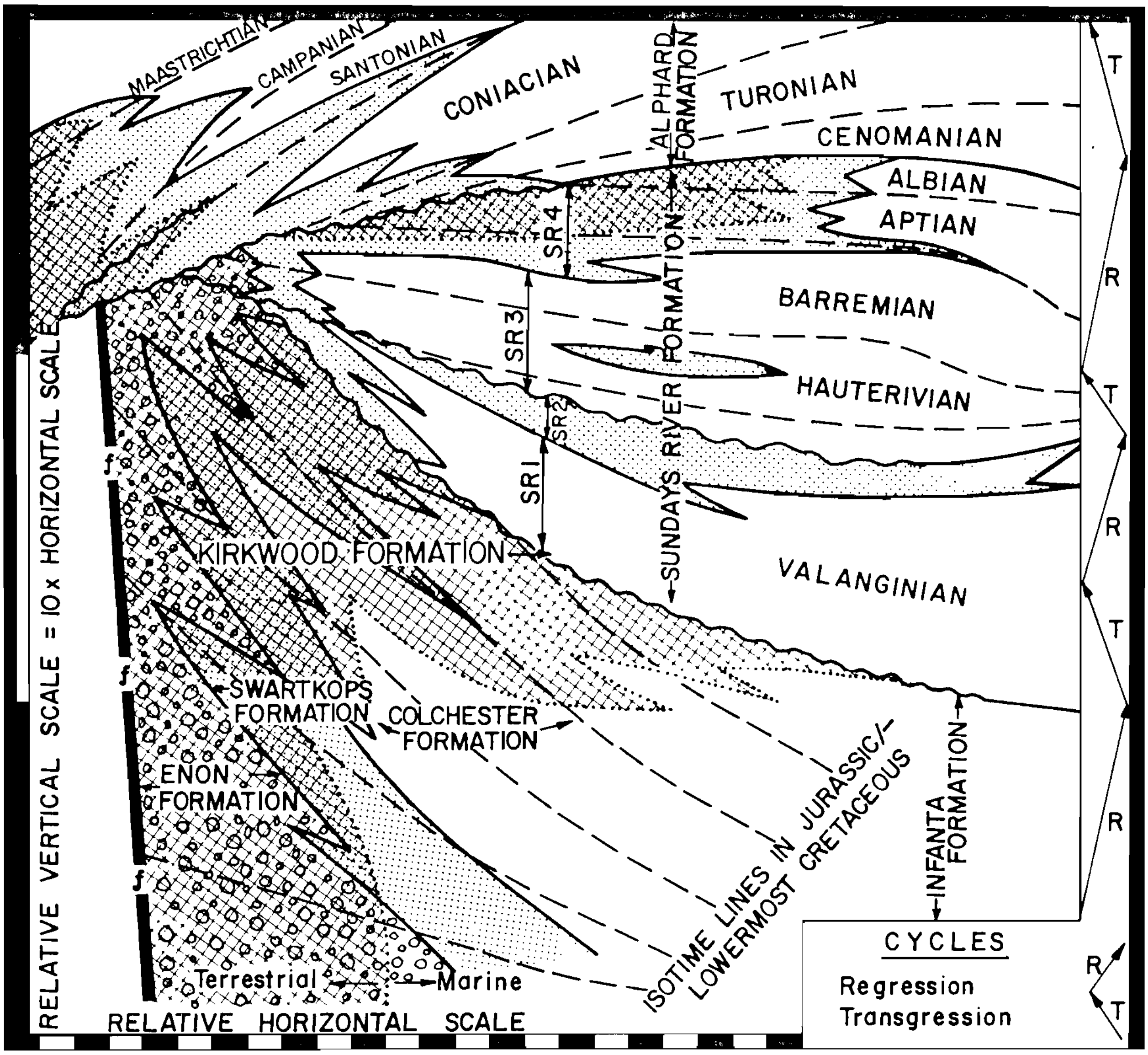

FIGURE 21.

Schematic transverse profile illustrating relationships between lithostratigraphic and chronostratigraphic units, facies, transgressive-regressive cycles and larger sequences and unconformities as applied to the Jurassic–Cretaceous interval on the Agulhas Bank.

in stratigraphic interpretation as roughly equivalent to a time interval. However, certain biota tend to be environmentally controlled, so that biostratigraphic boundaries may also behave as lithostratigraphic ones and may therefore be diachronous. Within cycles of deposition, which may be interrupted by erosional periods, the lithostratigraphic units migrate laterally in response to transgression or regression of the sea. The rate of movement is controlled by processes such as the rate of subsidence of the basin and its shape, and by the rate of deposition of sediments with different lithologies.

Subsidence is accentuated at the depocentre of a basin the margins of which may either receive sediments or be eroded depending on the amount and position of flexuring between the rising provenance and the basin, and upon eustatic changes in sea level. Figure 21 shows the effect upon the basin fill where rates of subsidence have diminished and eventually where erosion has occurred at the margin of the basin. The top of a regressive cycle merges with a surface which may still accept sediments near the depocentre, be in equilibrium with transporting media in an intermediate position, and undergo active erosion to become an unconformity landwards as the hiatus increases. This is illustrated by the abrupt cut-offs of chronostratigraphic intervals. Pre-existing unconformities may thus be truncated, adding their hiatuses to that of the overlying break in sedimentation. The sedimentary sequence at the margins of a basin may be extensively abbreviated due to the converging of a set of unconformities.

The initial transgressive phase of the ensuing cycle of subsidence and deposition may be short, resulting in a thin, poorly sorted veneer of the originally coarse sediments, or long, resulting in an onlapping sequence of chronostratigraphic units. Near the seaward termination of an unconformity the same lithology is apt to occur in both the regressive and transgressive phases, hence one can find and define apparently unbroken lithostratigraphic units in a type area which are in fact interrupted by diastems and unconformities. It is for this reason that the presence of unconformities within a lithostratigraphic unit should not be the basis for defining lithostratigraphic units.

The model is still applicable where a basin is fault-bound, as is the case with the pre-Sundays River interval. The divergence of iso-time lines towards the fault is the result of rapid influx of sediments into the asymmetric basin. Coarse detritus may have been dumpled into the marine environment under certain conditions and shaly Kirkwood redbeds may have retained their colour after having being deposited in the sea. Even though there may be disagreement as to the environment of deposition, the oxidised sediments are named Kirkwood Formation by definition.

The model illustrates another significant possibility, namely that the lower Sundays River sequence and higher stratigraphic units can laterally become a terrestrial red-bed sequence and even conglomeratic towards its landward limit, and that unconformities may occur within what is defined as Kirkwood Formation and Enon Conglomerate.

The iso-time lines in the upper Sundays River sequence illustrate prograding which is the response of sediments deposited on a steeper-than-average slope whenever a basin becomes starved of sediments. If a subsidence which causes deep-water conditions is followed by relative quiescence, the sediment-water interface advances slightly upwards, but mainly outwards, either as a delta-slope or as a prograding shelf-edge, the slope-facies advancing into the basin with time.

SEDIMENTARY TECTONICS

Sedimentary tectonics is the study of relations between tectonism and sedimentation. The relationships between sedimentary tectonics and their sedimentary responses, long recognised in general terms by stratigraphers, were more explicitly stated by Dapples, Krumbein and Sloss (1948) who expanded on pioneer work by Baily (1930), Fischer (1933) and Jones (1938).

The study of sedimentary tectonics on the Agulhas Bank is facilitated by the grouping of the Mesozoic succession into the following four informal sequences;

1. Alphard (Upper Cretaceous)
2. Upper Sundays River (Aptian or Barremian to Valanginian)
3. Lower Sundays River (Valanginian - ? Portlandian)
4. Pre-Sundays River. (Lower Cretaceous and/or Upper Jurassic or older).

Such a grouping bears no reference to the sequence concept as developed by Sloss (1953) and which refers to unconformity-bounded masses of strata of greater than group or supergroup rank. The above-mentioned four sequences are akin to genetic sequences of strata - a GSS (Busch, 1971). A GSS is defined as two or more contiguous genetic increments of strata representing more or less continuous sedimentation; within it unconformities cannot be present but disconformities of limited extent may be present. A genetic increment of strata (GIS) is defined as an interval of strata representing one cycle of sedimentation in which each lithological component is related genetically to all others; the upper boundary of a (GIS) must be a time marker and the lower boundary may be time marker, an unconformity or a facies change from marine to non-marine. A genetic increment of strata is similar to a format (Forgotson, 1954) provided that the markers that are used to define a format are time lines.

The grouping of sediments into genetic sequences or increments of strata

provides /111...

provides the geologist with an exceedingly powerful and useful stratigraphic tool; it is indeed a pity that these units do not enjoy formal status in the South African or any other stratigraphic code. The following is a discussion of sedimentary tectonics in respect of the four Mesozoic genetic sequences of strata on the Agulhas Bank.

PRE-SUNDAYS RIVER SEQUENCE

The stratigraphic relationships of the Enon, Swartkops, Kirkwood and Infanta Formation which make up this sequence has been dealt with above. The arkose or clastic wedge (Krumbein and Sloss, 1963, p. 559) model appears to provide a satisfactory sedimentary-tectonic model in respect of the pre-Sundays River sequence on the Agulhas Bank; this model is discussed hereunder.

Clastic Wedge Model

A clastic wedge (or arkose wedge if the provenance is granitic) is a type of sedimentary fill which is prevalent in fault-yoked basins. The sediments are derived primarily from the elevated upthrow side of the bounding fault. The term "molasse" would be applicable to the model under discussion, but, as pointed out by Krumbein and Sloss (1963, p. 535), this term has been used so broadly in connection with similar, but not necessarily related, suites as to have lost its original connotations.

The sedimentary facies in a clastic wedge is characterised in the first instance by the development of the coarsest clastics immediately adjacent to the uplifted block, (Enon Formation). Distally these coarse clastics grade into sandstone (Swartkops Formation) and marine or lacustrine clays (Infanta and Colchester Formations). A restricted euxinic facies is possible in the lacustrine environment. The coarsest facies occur opposite the largest fault displacement (Enon Formation in the Riversdale, Oudtshoorn, George and Gamtoos basins) and in the vertical sequence during times of active faulting; this may give rise to tongues of conglomerate and sandstone which extend into the basin and which are enveloped by a more distal lithofacies (e.g. tongues of Enon in the Kirk-

wood Formation /112...

wood Formation as in MB/A/1).

The structural attitude of a clastic wedge is such that the sediments dip into the marginal fault, especially where beds thicken in the same direction (e.g. Port Elizabeth half-graben, Pletmos basin north of G(b)-Gemsbok/1). Intermittent seismic reflectors in clastic wedges are time-equivalent surfaces. The steep flank of a clastic wedge is invariably a bounding fault (Cretaceous onshore basins) rarely a monoclinal fold (Bredasdorp basin). All large clastic wedges are fault-bound. The initial displacement can be measured by the assymmetric thicknening of a stratigraphic unit towards the fault; faulting is not triggered off by isostatic imbalance caused by sedimentation but by sub-crustal tension, although sediment load may accelerate and increase later displacements. The dip of the fault plane is usually steep, but flattens downward. The displacement on the fault is normal, but horizontal components may occur in the direction of the depocentre. Unless significant wrench movement is involved, the culmination of the uplifted block is opposite the depocentre of the basin. Clastic wedges are known to have formed against reverse faults and to have been overridden by the elevated block (Weeks, 1952) but this did not occur on the Agulhas Bank.

From the above considerations it is to be expected that basins which harbour clastic wedges are elongated parallel to the bounding fault; most of such basins on the Agulhas Bank are asymmetric in cross section being bounded by one major fault (e.g. Superior, Plettenberg, Port Elizabeth and Sundays River faults).

Sedimentary facies occur in a regular fashion within a clastic wedge. The upper flow regime of the fluvial environment is characterised by the presence of an alluvial fan, piedmont or fanglomerates (Enon Formation) and by braided streams (Swartkops and Kirkwood Formations); these may form coalescent fans. The elongation of such lithosomes are conceptually parallel to the paleocurrent direction and at right angles to the steeper flank of the basin. The braided streams of the fluvial environment give way to valley-flat environment (possibly the shaly components of the Kirkwood Formation as in G(a)B/1) with increasing deposition of red silty shale. Downstream these facies are replaced by deltaic and by lacustrine or marine environments (Colchester and Infanta Formations). The thickness and rates of sedimentation (see later) of the environmental facies are directly related to, amongst others, the intensity of tectonism. Depending on the morphology of the basin floor, the rate of change of facies may be rapid or slow; some of the facies may be absent (Kirkwood in D-A/1 and G(b)-Gemsbok/1). The deltaic facies within a clastic wedge is not likely to be prograding but to be modified by intermittent subsidence, which gives rise to cyclothems spanning the aqueous/sub-aqueous depositional interface (Uitenhage Group in H(b) Hartebeest/1). An important attribute of clastic wedges is that sedimentation keeps pace with tectonism, so that a deep-water depositional environment is rarely attained.

Within clastic wedges one can expect to find numerous diastems, local disconformities and hiatuses, particularly within the continental environment. Unconformities of more regional extent may occur in the distal portion of the wedges, where they are linked to the top of regressive cycles of sedimentation. Of importance is an unconformity that separates the trough fill from overlying sediments; such an unconformity marks the base of younger overlying basins (horizon C and "top of layer 3"). If the unconformity extends over a number of troughs (as horizon C does on the Agulhas Bank), the end of active rift tectonics is dated by the unconformity (generally Valanginian but younger than Barremian in the Port Elizabeth half-graben).

Arkose wedge associations do vary as pointed out by Krumbein and Sloss (1963, p. 463), but none of the variations serves to mask the essential similarity to the above-mentioned model in respect of comparable stratigraphic relationships, wedge-shaped geometry, immature sediments and relationships to steeply faulted basins and rigid uplifted blocks.

The writer has no hesitation in suggesting that the pre-Sundays River sequence conforms to the clastic-wedge model, even though the control points afforded by the boreholes on the Agulhas Bank are comparatively few and far between.

Isopachs /114...

Isopachs

The regional isopach (time-thickness) map of the interval between seismic horizons C (or "top of layer 3") and D reflects, to a large extent, the thickness and distribution of the pre-Sundays River sequence on the Agulhas Bank (fig. 22). It shows that the Algoa, Gamtoos and Pletmos basins are flanked by normal faults which, as conjectured in a previous discussion, are conceivably synsedimentary. The Algoa basin is complex, with a number of depocentres located on the immediate downthrow sides of major synsedimentary faults. They are all asymmetric towards the north, as is the Gamtoos basin. The Pletmos basin is also complex and is made up of segments which are asymmetric to the south (south of FB/A/1 and MB/A/1) as well as to the north (north of G(b)-Gemsbok/1,) and which dip respectively into the Superior and Plettenberg faults. Between the Superior fault and the Infanta arch there is another subsidiary trough which is asymmetric towards the fault-controlled southern flank. In pre-Sundays River times, the Bredasdorp basin was on the other hand roughly ovate with few, if any associated syntectonic faults.

The basins of the Agulhas Bank were separated geographically and were isolated by the Recife, St. Francis and Infanta arches and, individually and collectively tend to close in a seaward direction. This isolation of basins is apparently also valid in respect of the Riversdale, Swellendam, George and Oudtshoorn basins, and may explain the general paucity of planktonic fauna in the pre-Sundays River sequence.

LOWER SUNDAYS RIVER SEQUENCE

The Lower Sundays River sequence comprises the SR-1 and SR-2 Members in boreholes on the Agulhas Bank. The lower boundary of the sequence has been demonstrated to be an angular unconformity in E-1, E-B/1 and F-1; elsewhere it is either conformable or disconformable. Its upper boundary corresponds to seismic reflector horizon C which marks a major intraformational unconformity, particularly in the Platmos basin. The age of the sequence has been shown to be Valanginian or older; the dating stems largely from benthonic foraminifera and fresh-water ostracods, which are most abundant in the uppermost (shaly) part of the SR-1

Member. /116...

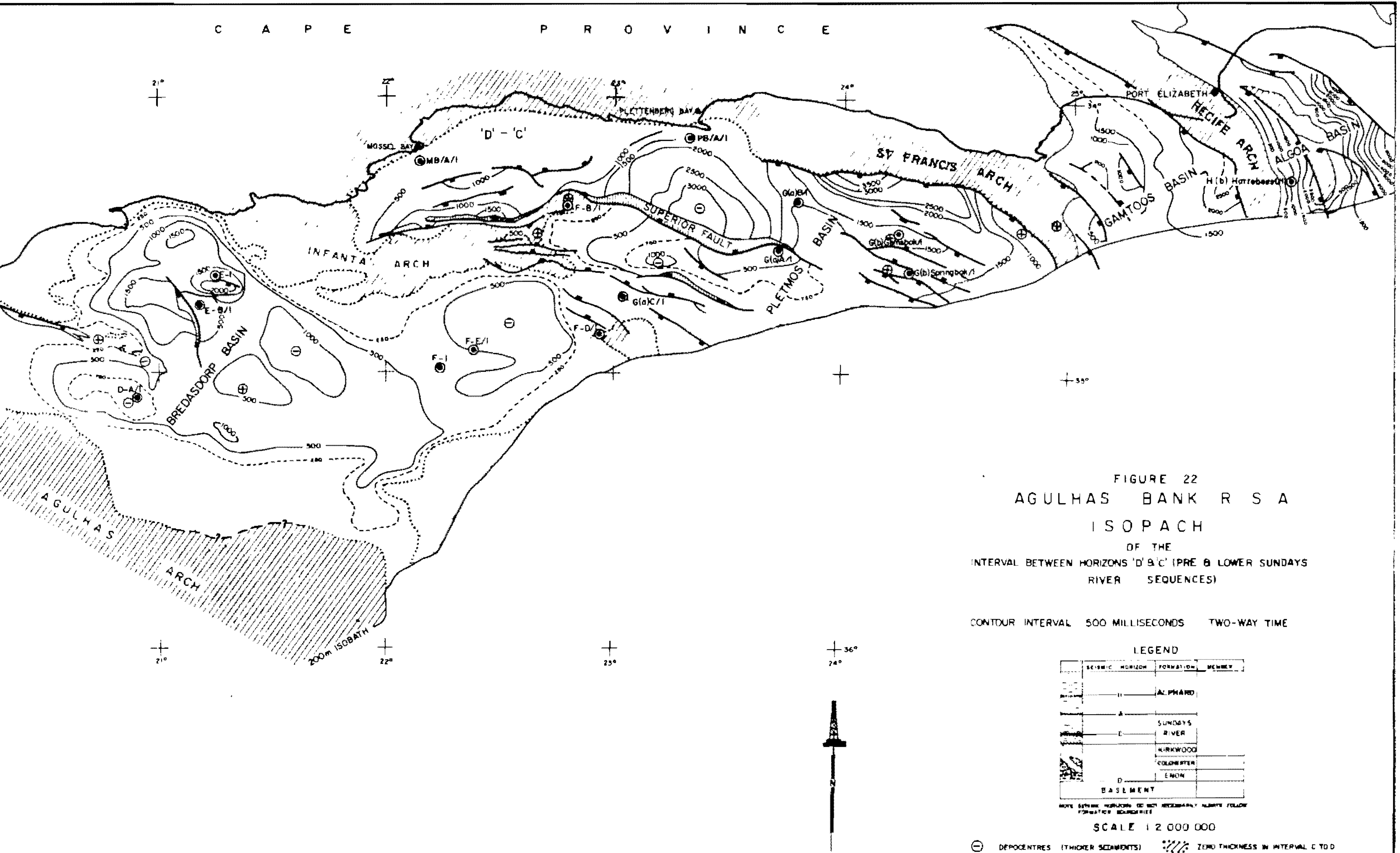

FIGURE 22

AGULHAS BANK R S A

ISOPACH

OF THE

INTERVAL BETWEEN HORIZONS 'D' & 'C' (PRE & LOWER SUNDAYS RIVER SEQUENCES)

CONTOUR INTERVAL 500 MILLISECONDS TWO-WAY TIME

LEGEND

SCALE 1 2 000 000

Member. The sequence is clearly transgressive in respect of the underlying Kirkwood and Infanta Formations and basement (in E-B/1) and is partially truncated in G(a)B/1 and G(b)-Gemsbok/1; it is absent due to erosion in G(b)-Springbok/1.

The lower Sundays River sequence is thickest in boreholes in G(a)B/1 (854 m) and G(b)-Gemsbok/1 (568 m). Elsewhere its thickness ranges from zero (on the Infanta arch) to about 400 m. The greater thicknesses on the downthrow side of the Superior fault as compared with 350 m in G(a)-A/2 on the upthrow side, suggest that the Superior fault was active during sedimentation; this is consistent with the observation that the fault also displaces horizon C.

Factors of note concerning the lower Sundays River sequence is its lateral persistence as a blanket-like unit which, barring the Superior fault and the relief of the Agulhas, Infanta, Recife and St. Francis arches at the time of its deposition, testifies to regional low relief of the depositional floor upon which the unit was deposited. The lignitic nature of the sandstones and the predominance of benthonic and fresh-water fauna within the sequence argue in favour of a shallow-water environment dominated by terrestrial influences such as exist in an epeiric sea. The sequence appears to have effectively filled in the existing minimal relief inherited from the underlying block-faulted basins which were all but filled by syntectonic sediments. Its sandy nature contrasts sharply with that of the underlying Infanta Formation. Whether this can be construed to as indicating the effects of tectonism (uplift of the source area), a drastic change in the provenance or a change in climate remains problematical.

It is indeed unfortunate that the base of the sequence cannot be mapped with any confidence on seismic reflection profiles, despite numerous attempts to do so. This interface has poor seismic definition and cannot be traced for any great distance even between relatively closely-spaced boreholes. In this light, meaningful isopachs cannot be drawn of the sequence and further perusal of the tectonic controls of sedimentation appears futile. It is not unlikely that the lower Sundays River sequence represents an aborted cycle of deltaic sedimentation.

UPPER SUNDAYS /117...

UPPER SUNDAYS RIVER SEQUENCE

The upper Sundays River sequence consists of the SR-3 (shale) and SR-4 (sandy) members of the Sundays River Formation, is Albian or Barremian to Valanginian in age and is bounded approximately by seismic horizons A (top) and C (base). The vertical and lateral stratigraphic relationships of the sequence have been discussed, and are portrayed in figures 19 and 20, which have a bearing on the discussion which follows.

In the vertical profile the sequence can be seen to coarsen to the extent that the strongly lignitic SR-4 unit overlies the fossiliferous grey SR-3 shale; the contact between these two units is gradational. Upward-coarsening sequences have often been cited as being indicative of regression (Visher, 1965, Pirson, 1970, p. 37); this is confirmed by the upper Sundays River sequence which also exhibits a shallowing of the environment upward in the sequence. The geometric arrangement of time lines (prograding reflectors) tends to support this inference. The SR-4 unit appears to represent the topset beds of a delta lobe within which the depositional surface is sub-parallel with time lines.

A feature of note in both the Bredasdorp basin (fig. 19) and the Pletmos basin (fig. 20) is that prograding reflectors impinge in a basinward direction onto the lower bounding surface of the sequence. This is so even though the fossilliferous SR-3 shale is transgressive in respect of the underlying lignitic SR-2 sandstone.

The sediments that were deposited during this transgression are either not present or too thin to be resolved on seismic reflection profiles on the Agulhas Bank. Asquith (1974) has shown that cyclic deltaic sedimentation is often interrupted by non-depositional shoreward shifts of the shoreline; this model appears readily applicable to the upper Sundays River sequence on the Agulhas Bank.

Isopachs /118...

Isopachs

The isopach (isotime thickness) map of the interval between seismic horizons A and C (fig. 23) shows the distribution of the upper Sundays River sequence on the Agulhas Bank. Two main depocentres coincide roughly with the underlying Bredasdorp and Pletmos basins and are separated by a broad area with relatively thin sediments over the Infanta arch. The upper Sundays River depocentres are therefore subdued replicas of the structure at lower levels.

The Bredasdorp basin is roughly ovate in outline and is elongated in a south-east direction. The upper Sundays River sequence has been shown to thin in a seaward direction. This is also borne out by the onlap onto horizon C of a reflector horizon which was traced by Mr. Wood in consultation with the writer from the D-A/1, E-B/1 and E-1 boreholes, where it occurs at the top of the SR-3 shale. This onlap is roughly parallel to the isopach trend. The Bredasdorp basin was therefore effectively limited in a seaward (south-easterly) direction by a combination of depositional thinning and a rising floor during upper Sundays River times.

The Infanta arch was covered by a relatively thin veneer of upper Sundays River sediments because of positive relief that was inherited from the underlying structure.

The Pletmos depobasin was irregular in outline. Depocentres were located on the immediate downthrow side of the Superior fault and on the downthrow side of the Plettenberg fault. In both depocentres the sediments thicken towards the faults which must have been synsedimentary. A third depocentre is present between the Superior fault and the Infanta arch. These depocentres coincide with those of the pre-Sundays River sequence and are therefore a reflection of deeper seated structure. The Superior fault was clearly active during upper Sundays River times; the thinning of the sequence in the south-easterly sector of the Pletmos basin has already been shown to be due to depositional thinning, this was probably accentuated by the rising area on the upthrow side of the Superior fault and by limited erosion at the base of the Alphard Formation.

The direction /120..

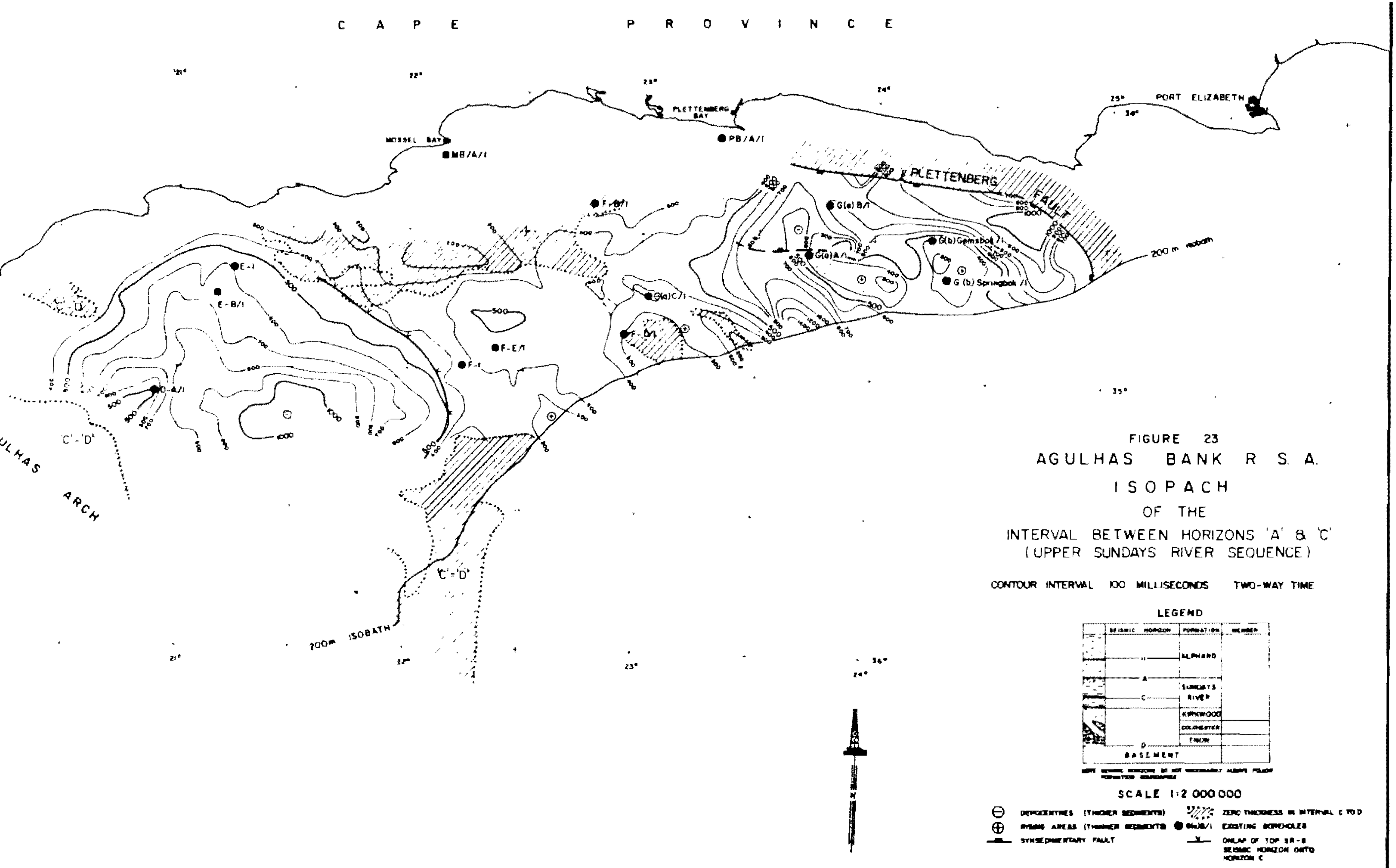

FIGURE 23

AGULHAS BANK R.S.A.

ISOPACH

OF THE

INTERVAL BETWEEN HORIZONS 'A' & 'C'
(UPPER SUNDAYS RIVER SEQUENCE)

CONTOUR INTERVAL 100 MILLISECONDS TWO-WAY TIME

SCALE 1:2 000 000

The direction of progradation of seismic reflectors indicates that the principle sources for upper Sundays River sediments in both the Bredasdorp and Pletmos basins were near their north-westerly extremities. An additional point of influx of detritus in the Pletmos basin may have been to the north-east of G(b)-Gemsbok/1.

In summary it can be said that the upper Sundays River sequence was deposited by deltas in relatively confined, ovate, epeirogenic depressions, which had restricted access to the open ocean. Low-energy conditions are therefore thought to have prevailed in the depocentres during the upper Sundays River times; euxinic conditions may have existed locally as result of the restricted nature of the basin. The principal sources of detritus were rivers which entered the basins from the north-west and north. These rivers may have been the pri-mordial Breede and Gouritz Rivers; the latter may conceivably have discharged into the Pletmos basin at this time.

The upper Sundays River sequence is thought to be absent in the Gamtoos basin since from the St. Francis arch eastwards, the unconformities on seismic horizons A and C coalesce. This is confirmed by the hiatus intervening between sediments of Campanian and Barremian age on the major unconformity in the H(b)-Hartebeest/1 borehole.

ALPHARD SEQUENCE

The Alphard sequence comprises fossilliferous, glauconitic green-grey shales and subordinate sandstones. It is an obvious marine sequence of Upper Cretaceous age. The lower boundary of the sequence lies close to seismic reflector horizon A; the sequence is transgressive and disconformable to unconformable in respect of all underlying units. The upper limit of the sequence is taken at the unconformity or disconformity at the base of the Alexandria Formation (Tertiary). Barring a possible small hiatus during the Coniacian-Turonian, the sequence is composed of a conformable wedge of sediments which thickens in a seaward direction.

The base of the sequence has been shown to be essentially planar, with

a moderate /121...

a moderate seaward dip. It was deposited during the late Mesozoic tectonic stage, which was demonstrated to be characterised by mild, continued epeirogenesis and the general absence of faulting.

The Alphard succession is otherwise characterised by the absence of a basal sandstone unit such as would be expected if a shoreline transgressed over the shallow marine and deltaic sediments of the Sundays River sequences. A situation where the rate of subsidence of the basin exceeded the supply of detritus (Sloss, 1962) and a rapid Upper Cretaceous transgression – as is indicated by the consistent Cenomanian age of basal sediments over a widespread area – may be called upon to explain the phenomena. A humid climate in a low-lying, non-granitic provenance drained by sluggish streams can also be inferred. The ubiquity of glauconite in the Agulhas sequence is taken to indicate the existence of a sediment-starved marine basin.

The uppermost part of the Alphard sequence, notably the Maestrichtian and Campanian intervals, have been shown to be relatively poor in planktonic foraminifera. The reason for this is not obvious from considerations based on lithologic or seismic reflection characters. It may be that the uppermost Lower Cretaceous was a time of regression, which was terminated by a transgression during the Lower Tertiary (Dingle, 1971 b).

As shown in figure 18, the Agulhas sequence close inshore consists of a number of reflectors which diverge seawards; farther seaward progradation persists from the level of marker horizon 17 (top of Cenomanian) to a level which corresponds to the late Campanian. These reflectors clearly indicate the progressive upbuilding of the continental shelf and the outbuilding of the continental slope (Dingle, 1974). The inflection point of the prograding sets of reflectors was traced at various levels in the vertical sequence and laterally. The results, shown in figure 24, indicate the position of the shelf break at various times during the Upper Cretaceous. The shelf break advanced rapidly in a seaward direction in the west, while it remained practically stationary elsewhere. The reason for this may be that the Breede and Gouritz Rivers, presently two of the largest rivers on the south coast, have been discharging detritus onto the western part of the Agulhas Bank since the Upper Cretaceous; during this time the rest of the area received comparatively

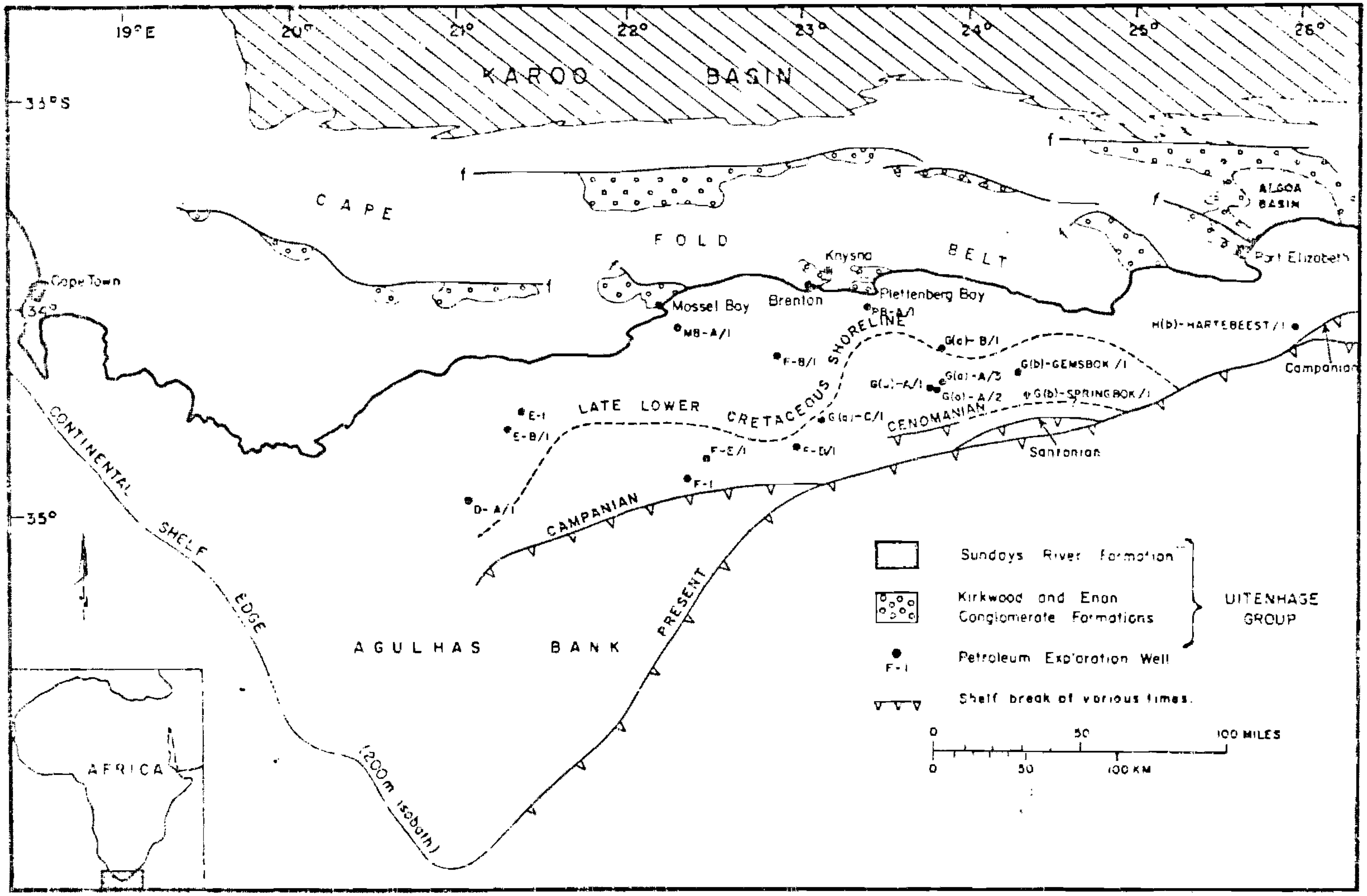

FIGURE 24: Position of the shelf break at various times during the Upper Cretaceous.

I C 274

little sediment.

The absence in boreholes of a sedimentary facies in the Agulhas sequence which can be attributed to near-shore or continental environments point to the following:

1. that the shoreline during the Upper Cretaceous was close to, if not landward of the present shoreline; and

2. that any evidence of the existence of such a shoreline is likely to have been destroyed by erosion on any one of the overlying unconformities.

SEDIMENTATION RATES

The writer used the chronostratigraphic data in Tables VII and VIII for a study of sediment accumulation rates. The results are portrayed in figure 25 in respect of four boreholes (D-A/1, F-1, H(b) Hartebeest/1 and G(a)-B/1) which are considered to be representative for the purpose of this study. Absolute ages were assigned to stage boundaries in accordance with the views expressed by Berggren (1972) for the Tertiary, van Hinte (1972) for the Cretaceous and von Eysinga (1971) for the Jurassic. Compensations which would cancel the effects of compaction and unconformities on sediment thicknesses were not applied since these factors are subjective under the circumstances. The following is a discussion of sediment accumulation rates in respect of the four established genetic sequences of strata which comprise the Mesozoic succession on the Agulhas Bank.

Pre- and Lower Sundays River sequences

In the absence of unambiguous Jurassic fauna the following two assumptions were made for the purpose of this study; the pre-Sundays River sequence is younger than the Suurberg Group (162 m.y.) and older than seismic horizon D (Valanginian, circa 130 m.y.). It was shown that the pre-Sundays River sequence (Enon, Kirkwood, Infanta, Colchester and Swartkops Formations) make up the bulk of the interval designated Lower Cretaceous and/or Jurassic in Table VIII.

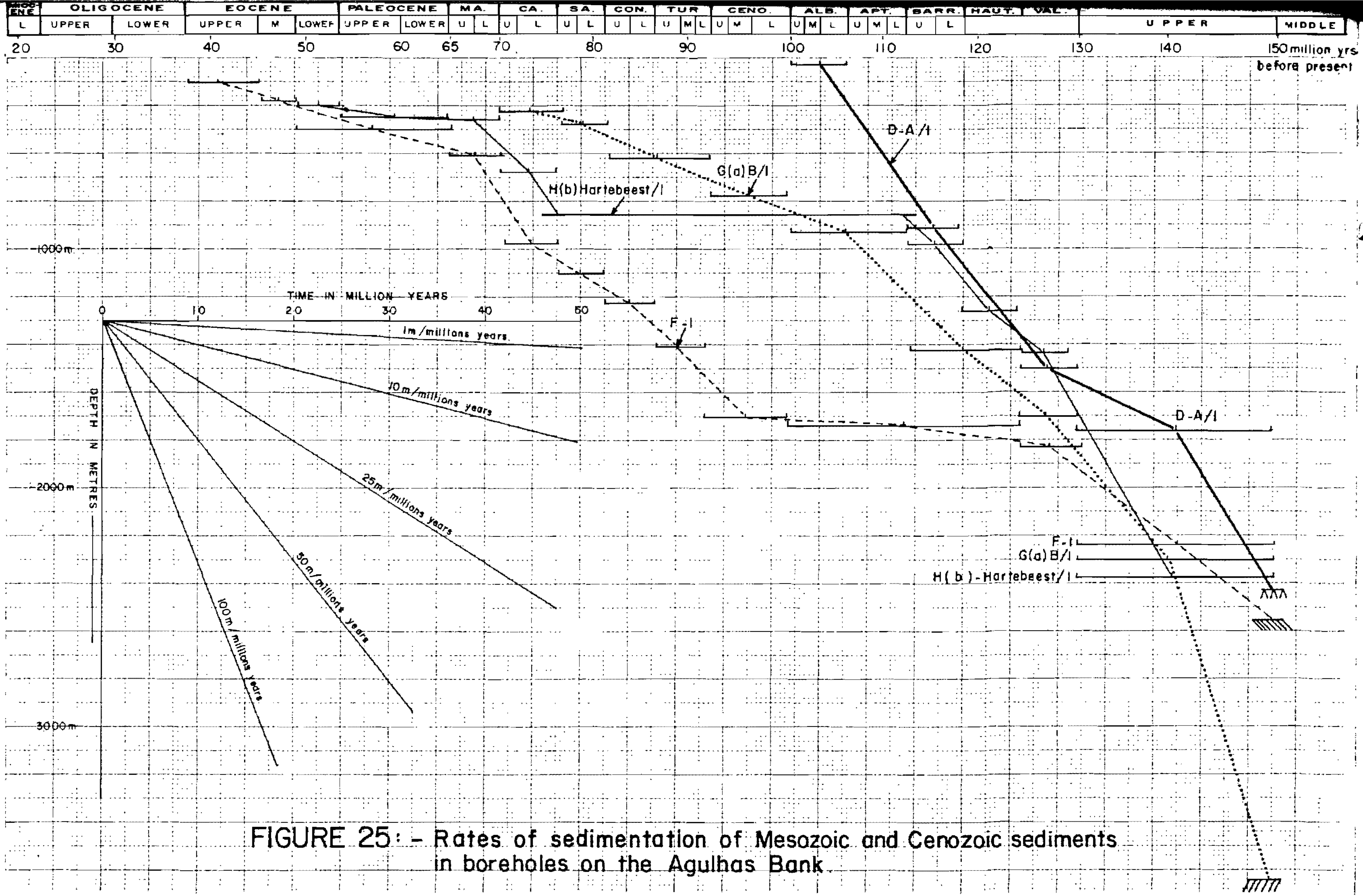

FIGURE 25: - Rates of sedimentation of Mesozoic and Cenozoic sediments in boreholes on the Agulhas Bank.

The average net sediment accumulation rates (thickness of the Lower Cretaceous and/or Jurassic sediments divided by a time span of 32 m.y.) ranges between 85 m/m.y (in G(b)-Gemsbok/1 and G(a)-S/1) and 10 m/m.y. (in G(a)-C/1). It is clear from the isopach map of the interval between seismic horizons C and D (fig. 22) and from considerations of the clastic wedge model of sedimentation (fig. 21) that the computed rates of sedimentation for the pre-Sundays River sequence will be at a maximum adjacent to the bounding fault and at a minimum in the distal part of the wedge and over paleotopographic highs. In the deeper parts of the rifted basins the sediment accumulation rates may therefore have been considerably higher than the recorded maximum of 85 m/m.y. Indeed, if allowances were to be made for compaction and if the pre-Sundays River sequence is no older than uppermost Jurassic, 85 m/m.y. may prove to be a conservative estimate of the average vertical sediment accumulation rate. This conclusion confirms the view expressed by Dingle (1975) that the early Mesozoic was characterised in the study area by relatively fast sedimentation rates in response to rifting which preceeded continental separation.

The grey shales and siltstones of the Infanta and Colchester Formations have been shown to contain fresh water ostracoda, lignitic material and marine macrofauna. In the absence of fauna and lithofacies which indicate sedimentation in water depths comparable to the isopachs of the interval between horizons C and D, it is concluded that sedimentation generally kept pace with subsidence of the depocentres. The relationship between, amongst others, subsidence and sedimentation was expressed by Gloss (1962) as follows:

S = f (Q, R, D. M) where

S = shape or external geometry of a body of sedimentary rocks

Q = quantity of material supplied to the depositional site

R = receptor value (the available volume below base level created per unit time by subsidence)

D = dispersal (removal of material from the depositional site)

M = texture and composition of the material.

The application of this relationship to the pre-Sundays River sequence

entails/126...

entails visualizing the wedge-shaped external geometry (S) of the unit as a function of the quantity of material (Q) supplied to the depositional site and subsidence of the depocentre (R); dispersal (D) could not have been an important factor when one considers the confined and isolated nature of the depocentres while the nature of the material (M) can be regarded as constant in view of the comparatively homogenous provenance dominated by Paleozoic sediments.

In terms of the relatively fast sedimentation rate during pre-Sundays River times, both Q and R must have been relatively large and larger near the bounding fault than towards the distal end of the clastic wedge. Whenever Q exceeded R, a regressive tongue (e.g. Enon Conglomerate interbedded with the Kirkwood) would have protruded towards the distal end of the wedge; the converse is true when R exceeded Q when a tongue of argillaceous clastics would have been interbedded with coarser clastics (e.g. tongues of the Colchester or Infanta Formations in the Kirkwood Formation). As shown by Sloss (1963) there is generally an intimate relationship between transgressions ($R < Q$) and regressions ($Q > R$) and sedimentation rates, e.g. the rate of sedimentation during transgressions is slower than during regressions.

The overall vertical lithofacies relationships of the pre-Sundays River sequence is such that a progressive upward fining is observed (e.g. Enon to Kirkwood). This relationship may be construed to signify a progressive decline of tectonism and consequently of the receptor value (R) and the quantity of detritus supplied (Q) to the depocentres.

Upper Sundays River sequence

This Albian or Barremian to Valanginian unit was demonstrated to be an upward coarsening, deltaic and shallow marine sequence. It was also shown (figs. 19,20) this sequence thins in a south-easterly direction in both the Bredasdorp and Pletmos basins; it is to be expected that the sediment accumulation rates should reflect on this observation. In D-A/1 and in G(a)-R/1 (fig. 25), where both the SR-3 and SR-4 Members are present, the sedimentation rate is about 30 m/m.y; in F-1 this interval is absent.

The maximum /127...

The maximum recorded rate of sedimentation for the upper Sundays River sequence (30 m/m.y.) is considerably lower than for the underlying pre- and lower Sundays River sequences (> 85 m/m.y.). This conclusion confirms the views expressed by Dingle (1975). The factors Q and R referred to previously therefore decreased at higher stratigraphic levels most probably as a result of general lack of synsedimentary faults and reduced terrigeneous input (Dingle, 1975). Since the upper Sundays River sequence is a regressive unit, Q exceeded R throughout the late Lower Cretaceous.

Alphard sequence

This unit is Upper Cretaceous in age and is present as a seaward-thickening wedge. Hiatusses of significant proportions have not been detected within the unit. As is true of the thickness of the unit (Table VIII) the average net sediment accumulation rate can be grouped in order of the distance of the boreholes from the coastline in the following manner:

0 - 15 m/m.y. : E-1, F-B/1
15 - 30 m/m.y. : G(a)-B/1, H(b) Hartebeest/1
30 - 45 m/m.y. : G(a)-A/1, G(a)-A/2, G(c)-A/3, G(a)-C/1, G(b)-Gamsbok/1, F-D/1, G(b)-Springbok/1
45 m/m.y. and over: F-E/1, F-1.

The net sedimentation in the H(b)-Hartebeest/1 well is zero in the interval between the Campanian and Lower Cretaceous (fig. 25) as a result of the hiatus on the angular unconformity towards the base of the Alphard Formation. The comparatively faster rate of sedimentation in the F-1 well during the Maestrichtian serves the confirm that a depocentre was located close to the shelf break at this time (fig. 24).

Dingle (1975) shows that the main depocentre migrated in a seaward direction during the late Cretaceous in the study area; he attributed the relatively slow overall sedimentation rate to, amongst others, low terrigeneous input which is indicated by omnipresent glauconite in the Alphard Formation. This low terrigeneous input may have been caused by a com-

bination /128...

bination of the factors listed hereunder:

1. mild epeirogenesis (subsidence) of the continental margin;
2. choking of river mouths during an Upper Cretaceous transgression which Rona (1973), Flemming and Roberts (1973) and others consider to be worldwide:
3. low relief of the provenance during the final stages of the post-Gondwana erosion cycle (King, 1951);
4. a possible change to warmer climate.

The homogenous nature of the Alphard Formation and the lack of significant hiatusses within the sequence on the Agulhas Bank precludes a detailed analysis of the lithologic responses to varying sedimentation rates during the Upper Cretaceous. It is concluded that terrigeneous input had remained relatively constant and low, that subsidence of the continental shelf had been continuous and slow and that deposition had taken place below the profile of equilibrium (van Engeln and Caster, 1952). As shown by Lewis (1974) the shore tended to lie on a seaward tilting surface near to the line of no vertical movement (zero isobase); in the study area this line was close to the present shoreline during the Upper Cretaceous.

Viewed as a whole, sedimentation rates in the Agulhas Bank area decreased exponentially with time at each point in a fashion demonstrated elsewhere by Sleep (1971, 1973) and on Atlantic-type margins (including the Agulhas Bank) by Dingle (1975).

APPLICATION /129...

APPLICATION OF THE PLATE TECTONICS THEORY

GENERAL STATEMENT

The hypothesis of ocean floor spreading as postulated by Dietz (1961) and Hess (1962) is synonymous with the theory of lithosphere plate tectonics or new global tectonics (Mc Kenzie and Parker, 1967; le Pichon, 1968; Morgan, 1968; Isaachs et al, 1968; Dewey and Bird, 1970) and continental drift (Wegener, 1912; du Toit, 1937; Holmes, 1931, and others). Plate tectonics, theory also includes the concept of transform faulting (Wilson, 1965). Evidence in support of the plate tectonics theory is provided by Sykes (1967), Heirtzler et al (1968), Pittman and Hayes (1968) and others, while Meyerhoff and Meyerhoff (1974) are foremost amongst opponents of the hypothesis.

The credibility of the plate tectonics theory has been enhanced in recent years by the recognition of linear, bilaterally symmetrical magnetic anomaly patterns ("stripes"), which link mid-oceanic ridges (Vine and Matthews, 1963), and their dating by drilling in deep ocean basins (JOIDES Deep Sea Drilling Project). The rapid evolution of the plate tectonics theory during the past 15 years has resulted in a voluminous literature.

The concept of plate tectonics implies that the earth's outer surface (lithosphere) is composed of a minimum of six rigid plates (le Pichon, 1968), which are in constant motion relative to one another (Isaachs et al, 1968). The margins of the present plates are well-known earthquake belts (Sykes, 1967) and can be classified according to the mutual interaction of plates as follows (Dewey and Bird, 1970).

1. Accreting (spreading, divergent) margins mark locii where plates are generated in the axial rift valley of oceanic ridges and by the creation of new oceanic crust through vulcanism. Examples of this type of margin, often quoted, are the Red Sea (juvenile state) and the boundary between the African and South American plates at the mid-Atlantic ridge.

Consuming /130...

2. Consuming (colliding, convergent) margins are of different types depending on the nature of the plates involved. Arc-trench systems develop where two oceanic plates collide (e.g. Tonga trench); subduction of the oceanic plate takes place when it collides with a continental plate (i.e. along the west coast of the Americas), and a folded mountain range results from the collision of two continental plates (e.g. the Himalayas between the African and Asian plates).

3. Active transform ("slide by") sheared margins. Although transform faults generally occur within plates and at right angles to accreting plate margins, they may constitute the boundary between plates (e.g. between the African and Antarctic plates).

REGIONAL PLATE TECTONIC SETTING OF THE AGULHAS BANK

The area studied is located landward of the Agulhas fracture zone, with which is associated a fracture ridge (Scrutton and du Plessis, 1973) and a linear, positive magnetic anomaly (Simpson, 1968). It is located along the 68°S small circle centred on an early opening pole at 21,5°N; 14,0°E (Scrutton and du Plessis, 1973; Franchetau and le Pichon, 1972), and accounts for the sheared, straight, narrow continental margin along the South African east coast (Simpson and Dingle, 1973; Dingle, 1973). The fracture zone strikes roughly N 50°E, truncates the Agulhas arch (Scrutton and du Plessis, 1973, fig. 3) and the early Mesozoic basins and arches between Cape Agulhas and Durban (Dingle and Scrutton, 1974, fig. 3); it is equated with the Falkland fracture zone (le Pichon and Hayes, 1971; Emery et al, 1974; Dingle and Scrutton, 1974) and has played a significant part in the break-up of west Gondwana (South America and Africa).

In a resumé of the development of post-Paleozoic sedimentary basins around southern Africa Dingle and Scrutton (1974) show that the break-up of southern Africa took place in two phases:

(i) the separation between east and west Gondwana sometime

between /131...

between 200 and 160 m.y. B.P. (Dietz and Holden, 1970; Scrutton, 1973(b) which followed shortly on the extrusion of basaltic Stormberg lavas to produce a downwarped margin parallel to the Lebombo monocline. Until such time as the existence of oceanic crust is proved in the Natal Valley (west of the Mocambique Ridge) the line of separation between west and east Gondwanaland should be taken to be along the eastern flank of the Mocambique Ridge.

(ii) the fragmentation of west Gondwana (South America and Africa) during the late Jurassic - early Cretaceous. During this time the Falkland Plateau broke away from the Mocambique Ridge perhaps by exploiting the southerly continuation of the Lebombo line as a zone of crustal weakness (Dingle and Scrutton, 1974, p. 1470). The Lebombo monocline involves continental crust and may be considered to be failed arm of a triple junction whose remaining components are the Agulhas fracture zone and the line of separation between the Mocambique Ridge and the Falkland plate.

EVOLUTION OF THE AGULHAS BANK

The following discussion of the geologic history of the Agulhas Bank is based largely on the recognition of several litho-tectonic units in the Mesozoic sequence.

Rifting Stage (pre-Valanginian)

The last major orogenic event to affect southern Africa prior to the breakup of Gondwanaland was the second and major phase of the Cape orogeny (235 - 200 m.y. B.P.). It has been shown that the Mesozoic rift faulting parallels the tectonic grain of the Cape fold belt in the central and eastern parts of the area studied. However, it is extremely unlikely that a genetic relationship exists since the Gondwana erosion cycle (King, 1951) intervenes between the Cape orogeny and Mesozoic rifting (de Swardt and Bennet, 1974); this downfaulted erosion surface can be equated with a

"rift-onset /132....

"rift-onset unconformity". (Falvey, 1974). A tectonic event, reflected by upwarping of the rim of the African continent (de Swardt and Bennet, 1974), may have been penecontemporaneous with the rifting of Gondwanaland.

The onset of the fragmentation of west Gondwanaland has been dated from magnetic evidence as 125 - 130 m.y. B.P. (Larson and Ladd, 1973). The 162 m.y. age of the Suurberg Group (Winter, 1972), and its stratigraphic position below the Enon Formation (Hill, 1972), may indicate that rifting dates back to the end of the Middle Jurassic or at least to the Late Jurassic as proposed by King (1951, p. 246) and by Maud (1961). In this context the Upper Jurassic dating of the Brenton beds (Dingle and Klinger, 1972) is often quoted as significant in terms of the timing of the break-up of Gondwanaland (Dingle and Klinger, 1971), although McLachlan et al (in prep.) indicates that unambiguous Jurassic faunas have not yet been identified in boreholes on the Agulhas Bank.

It is my opinion that the early Mesozoic rifting took place earlier than the Valanginian (before about 130 m.y. B.P.) and that it may have been initiated towards the end of the Middle Jurassic (circa 160 m.y. B.P.), i.e., after the outpouring of the Drakensberg Basalt (ca. 180-170 m.y. B.P.). The rifting is seen as the response to divergent, right lateral stresses which were ultimately responsible for the Agulhas marginal fracture zone developing into a trough-going fault. The cessation of significant rifting during the Valanginian at about the level of the seismic horizon D unconformity is taken to signify the culmination of the early phase of wrench-zone tectonics.

A paleogeologic reconstruction of the Agulhas Bank and surrounding areas during the late Jurassic - early Cretaceous (fig. 26) prior to the development of the through-going Agulhas fracture zone shows the arcuate nature of the tectonic grain and the existence of a number of block-faulted basins which conceivably may have developed also on the adjoining Falkland plateau (Newton, 1975). In its early history, therefore, the rifted basins were intracontinental features (Dingle and Scrutton, 1975).

Taphrogenic /134...

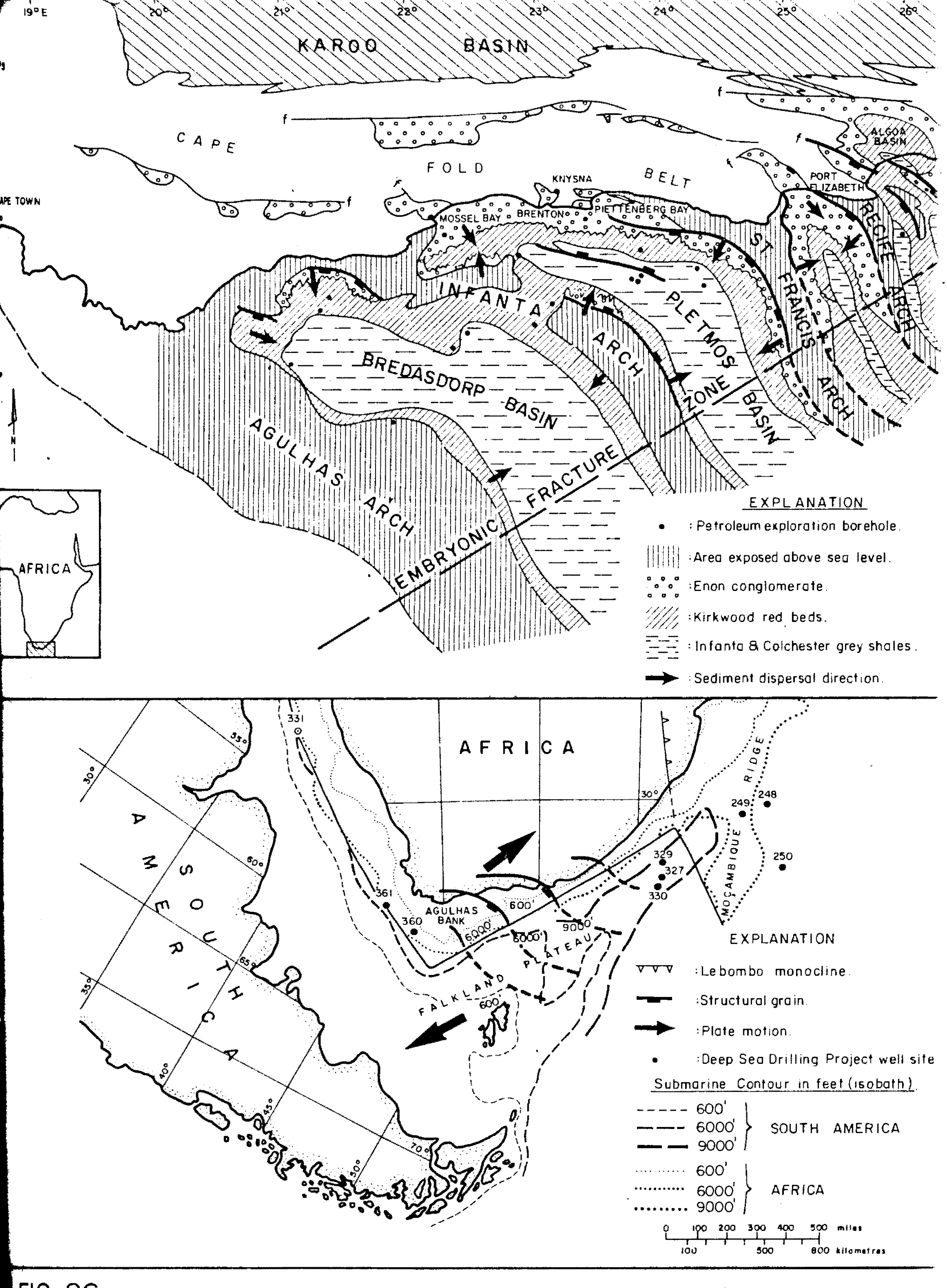

FIG. 26 : PALEO-GEOLOGIC RECONSTRUCTION OF THE AGULHAS BANK AND SURROUNDING AREAS DURING THE LATE JURASSIC - EARLY CRETACEOUS (PRE - VALANGINIAN, CIRCA 130 m.y. B.P.).

Taphrogenic sedimentation has been shown to characterise the early Mesozoic rifting stage. The Pletmos, Gamtoos and Algoa basins, and also perhaps the Bredasdorp basin, were yoked to complementary uplifts (arches) by way of normal faults. The coarsest clastics (e.g. Enon conglomerate) are thought to have accumulated near to the fault-bounded margins of these asymmetric half-graben (fig. 26). Alluvial sediments (e.g. Kirkwood Formation) and estuarine-lacustrine grey shales (Infanta and Colchester Formations) which contain a limited marine fauna, replace the Enon vertically and laterally. The elevated Agulhas, Infanta, St. Francis and Recife arches received little or no sediments, and for all practical purposes separated the Bredasdorp, Pletmos, Gamtoos and Algoa basins; these arches may have been elevated above sea level as is indicated by the red shales of the Kirkwood Formation intersected in boreholes on the Infanta arch. The Oudtshoorn, Mossel Bay, Riversdale and other onshore Mesozoic basins may be the remnants (roots) of originally much larger basins.

The directions of sediment influx into the rifted basins were controlled largely by, and were at right angles to marginal faults; significant entry points may also have existed towards the northwesterly extremities of the basins. The rate of sedimentation was shown to have been relatively fast (> 85 m/m.y.) throughout the deposition of the pre- and lower Sundays River sequences.

A pre-rift intracratonic basin, which is common although not a necessary element of continental margin development (Falvey, 1974) has not been recognised on the Agulhas Bank. It is possible, however, that the Robberg Formation (Rigassi and Dixon, 1970) and the lowermost parts of the pre-Sundays River sequence may prove to belong to a pre-rift cycle of sedimentation.

The presence of marine fauna in the Colchester and Infanta Formations does not necessarily signify access to the world ocean at the onset of separation between the African and Falkland plateau. In contrast marine fauna in the lower Sundays River sequence, which was deposited towards the end of the rifting stage, may record marine incursions onto the Agulhas Bank at the time of the break between east and west Gondwana (Dingle and Scrutton, 1974, p. 1469).

Drifting Stage (Valanginian - Upper Cretaceous)

Active rifting on the Agulhas Bank all but ceased at the time of the development of the unconformity on seismic horizon C (Valanginian, circa 125 - 130 m.y. B.P.). Reactivation of a limited number of syn-sedimentary faults occurred subsequently; this was demonstrated earlier in respect of the Plettenberg and Port Elizabeth faults at the margins of basins and by the Superior fault. It is concluded that seismic horizon C effectively marks the time of breakthrough of the Agulhas marginal fracture to the surface and to the onset of separation between the African and the Falkland plates; the Agulhas Bank therefore became the passive trailing edge of the African plate sometime during the Valanginian. Permanent marine conditions had also become established on the Agulhas Bank at this time as is the case in the onshore Algoa basin (Spath, 1930; Winter, 1972) and on the Falkland Plateau (Dingle, 1973(c).

The upper Sundays River sequence (Valanginian - Albian) was deposited on the Agulhas Bank during the period intervening between the rifting stage and the deposition of the transgressive, marine, Upper Cretaceous Alphard sequence. The upper Sundays River sequence was shown to be bounded approximately by unconformities close to seismic horizons A (top) and C (base); it is made up of an upward-coarsening, regressive, deltaic and shallow marine unit which prograded into the Bredasdorp and Pletmos basins in a south-easterly direction (fig. 27). The upper Sundays River sequence is synchronous with the late Albian regression referred to by Dingle and Scrutton (1975, p. 1471), which affected the whole southern African coastline. These above basins were roughly ovate in outline; isopachs of the sequence (fig. 23) suggest that the Bredasdorp basin may have closed in a seaward direction. Thin inter-deltaic sediments were being deposited over the Infanta arch. The Pletmos basin may have had access to a shallow epeiric sea which existed at this time, while it is not known whether the upper Sundays River sequence was ever deposited in the Gamtoos basin.

The tendency for basins to be limited in a seaward direction may be construed to indicate that the Agulhas marginal fracture ridge came into being during the end of the Early Cretaceous soon after the initial separation between the African and Falkland plates. The marginal fracture

ridge /137...

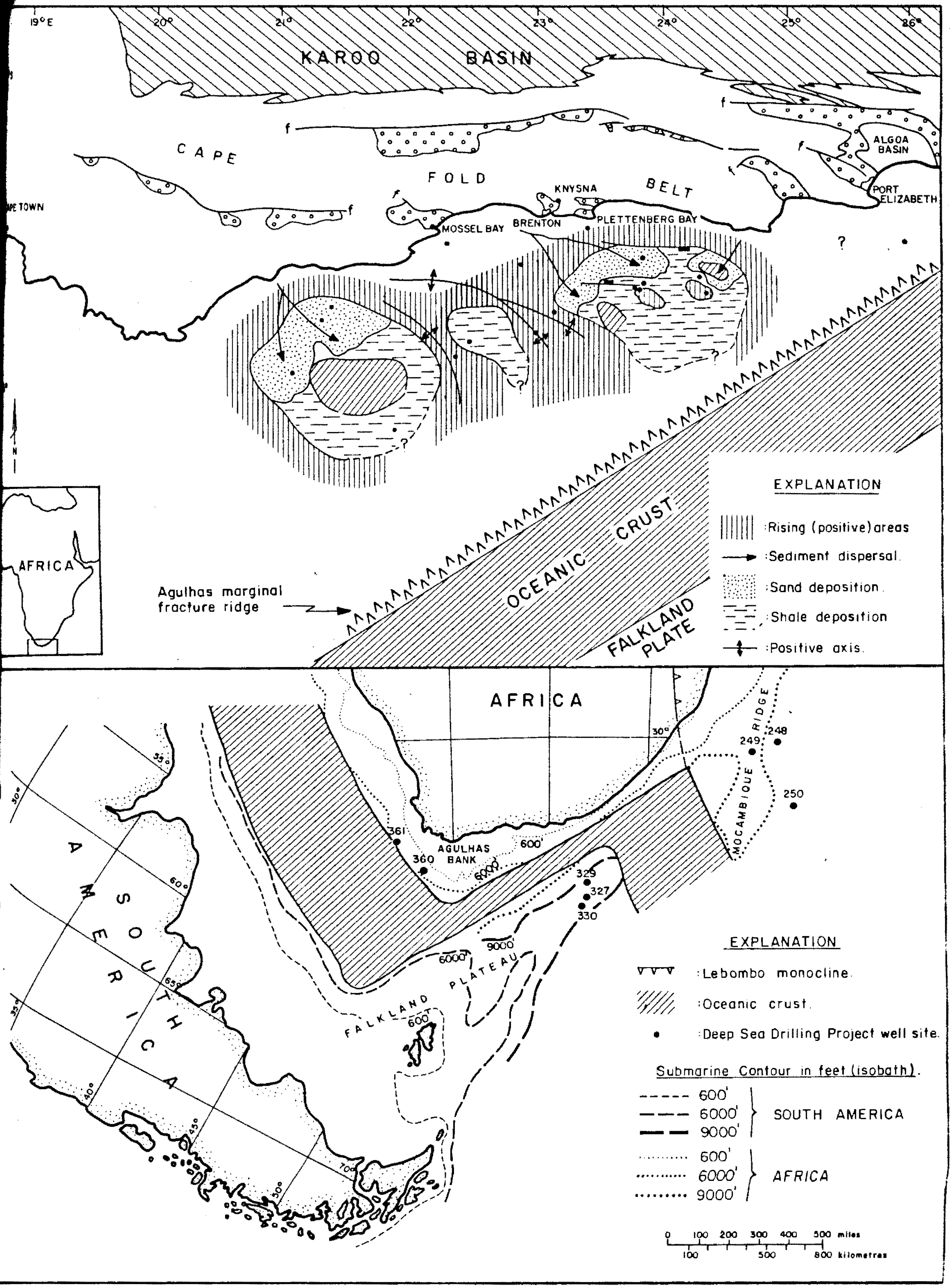

FIG. 27 : PALEO-GEOLOGIC RECONSTRUCTION OF THE AGULHAS BANK AND SURROUNDING AREAS DURING THE LATE LOWER CRETACEOUS (CIRCA 100-110 m.y. B.P.)

ridge could have inhibited overspill into the adjoining, newly-created ocean basin, since a minimal thickness of Lower Cretaceous sediments is reported from Joides D.S.D.P. drillsite 361 (McLachlan, pers comm).

Hitherto the earliest known stratigraphical discontinuity within the Mesozoic was the "mid Cretaceous" unconformity referred to by Haughton (1969) Kennedy and Klinger (1971) and Dingle (1973 (c)). The Valanginian unconformity on the Agulhas Bank pre-dates this discontinuity, is considered to mark the onset of separation between the Falkland and African plates, and may be coincident with uplift of the hinterland and the initiation of the post-Gondwana cycle of erosion (Dingle and Scrutton, 1975. fig. 5). The upper Sundays River sequence was deposited towards the end of a relatively slow drifting period of 1,6 cm/yr for the period 127 - 110 m.y. B.P. (Larson and Ladd, 1973). This slow spreading preceeded a relatively fast opening rate of 4,5 cm/yr during the interval 110-85 m.y. B.P. (Larson and Ladd, 1973).

The upper Sundays River sequence on the Agulhas Bank corresponds to the restricted marine lithofacies postulated by Dingle (1975), to the proto-oceanic sedimentary cycle (Lange, 1973), the transitional sedimentary environments (Reyment and Tait, 1972) and the post break-up stage (Falvey, 1974) in reference to Atlantic continental margins. It is within this sedimentary-tectonic cycle that major evaporitic sequences were generally deposited in those African - South American coastal Mesozoic basins which lie north of the Walvis- Rio Grande lineaments. The absence of similar lithologies on the Agulhas Bank may be due to a variety of reasons, such as inadequate silling of the basin, an oversupply of clastic material, and unfavourable climatic conditions.

During the Upper Cretaceous, when the Alphard sequence was deposited on the Agulhas Bank, there was continued subsidence of the Agulhas Bank and submergence of the Falkland Plateau (Dingle, 1975) which ensured uninterrupted access to the world ocean after the world-wide Cenomanian transgression (Fleming and Roberts, 1973). The Agulhas marginal fracture ridge inhibited detrital sediment dispersal into the adjoining Agulhas ocean basin.

Sedimentation /138...

Sedimentation rates during the Upper Cretaceous were comparatively slow (50 m/m.y.) and reflects on the progressive oceanward shift of the main depocentre with time, the low detrital input and possibly low relief on land. Subsidence of the continental margin continued in response to progressive cooling of the lithosphere and the adjoining oceanic basement and during a relatively fast episode of spreading (Larson and Ladd, 1973). The spreading centre which had been situated about the Agulhas Plateau may have become extinct at this time and conceivably shifted to a position on the mid-Atlantic ridge (Scrutton and du Plessis, 1973).

The Upper Cretaceous history of the study area was terminated by erosion during a regression which started in the Maestrichtian and produced the unconformity towards the base of the Alexandria Formation. This unconformity has been equated with the initiation of the African denudational cycle and uplift of the southern African coastal regions (King, 1951).

CONCLUSIONS /139...

CONCLUSIONS

The Mesozoic history of the Agulhas Bank was preceded by intense, arcuate, northerly directed folding during the Triassic of metamorphosed Paleozoic Karoo and Cape Supergroup sediments and possibly of older underlying rocks and by the development of a comparatively smooth denudational surface on Gondwanaland.

Normal block faulting dominated the early Mesozoic tectonic phase on the Agulhas Bank. These rift faults developed in response to right-lateral stresses along the embryonic Agulhas marginal fracture zone. The right-lateral attitude of stresses is reflected in a left-hand, en-echelon arrangement of some faults and by the progressive clockwise rotation of fault blocks from a roughly east-west orientation close inshore to a north-south one near the marginal fracture zone. The early Mesozoic tectonic grain is parallel to the trend of the Cape fold belt in the central and eastern parts of the Agulhas Bank and almost at right angles to it in the western part. A structural map of seismic reflector horizon D (acoustic basement and base of the Mesozoic sediments) reveals the presence of the following basins and intervening arches (from west to east):

Agulhas arch
Bredasdorp basin
Infanta arch
Pletmos basin
St. Francis arch
Gamtoos basin
Recife arch
Algoa basin

The basins are all deeper than 3000 m below present sea level; the half-grabens in the Pletmos basin to the north of the Superior fault and to the south of the Plettenberg fault, and those of the Gamtoos and Algoa basins may be more than 5 km deep.

The basins /140...

The basins contain the syntectonic pre- and lower Sundays River sequences (lowermost Cretaceous and Upper Jurassic or older); these are truncated locally by an unconformity on seismic reflector horizon C. An unconformity also intervenes between the transgressive Sundays River (Valanginian) Formation and underlying units and is considered to correspond approximately to the Jurassic-Cretaceous boundary. In the pre-Sundays River sequence the Enon Conglomerate Formation gives way vertically and laterally to the Swartkops Sandstone Formation, the Kirkwood Formation (red mudstones) and the Infanta Formation (grey siltstone). The Colchester Formation interfingers with both the Kirkwood and Infanta Formations. A clastic (arkose) wedge model of basin filling is envisaged for the pre-Sundays River sequence. In terms of this model the coarser and thicker detritus accumulated close to the bounding fault, subsidence of the depocentre was induced by intermittent faulting, and an intimate balance was generally maintained between subsidence and sedimentation, so that depositional environments were dominated by terrestrial influences. The sparse marine microfauna from the grey shales of the Infanta and Colchester Formations are indicative of lacustrine and estuarine conditions which are thought to have prevailed in the distal parts of the clastic wedges. Although variable, the net rate of sediment accumulation during pre-Sundays River times was comparatively fast (85 m/m.y.).

The Sundays River Formation (Lower Cretaceous, Valanginian to Albian) is made up of shallow marine and deltaic sediments within which four Members (SR-1, SR-2, SR-3, SR-4) are recognised. In the type area a major intraformational unconformity on seismic reflector horizon C occurs towards the base of the SR-3 Member; it cuts across progressively older underlying units to rest on basement on the Agulhas, Infanta, St. Francis and Recife arches and effectively marks the end of the early Mesozoic rifting stage on the Agulhas Bank; it conceivably may mark the initiation of the post-Gondwana denudational cycle. The establishment of permanent marine conditions during lower Sundays River (Valanginian) times is thought to have coincided with the commencement of separation between the Falkland and African plates (i.e. the break-up of west Gondwana) and may have been controlled in part by the separation between east and west Gondwana.

The upper /141...

The upper Sundays River sequence consists of an upward coarsening cycle (SR-3 marine shale to SR-4 lignitic sandstone), which was deposited as a prograding, regressive, deltaic unit, which onlaps the unconformity on seismic horizon C in a south-easterly direction. Two main depocentres were present on the Agulhas Bank during upper Sundays River times; these were roughly ovate in outline, coincide with the underlying Bredasdorp and Pletmos basins and tend to be closed in a seaward direction, probably as a result of the emplacement of the Agulhas marginal fracture ridge near the edge of the newly created narrow ocean basin between the Falkland and African plates.

A transgressive unconformable relationship exists between the upper Sundays River sequence and the overlying Alphard Formation (Upper Cretaceous) the base of which is close to seismic reflector horizon A. The configuration of the base of the upper Sundays River unit, that is seismic horizon C, is a subdued replica of deepseated structure, so that warp axes are superimposed over the Bredasdorp, Pletmos and Gamtoos basins, while horizon C is draped as south-east-plunging arches over underlying horsts.

The Alphard Formation (Upper Cretaceous) is comprised of soft, glauconitic-rich marine shales with subordinate sandstones and thin linestones forming a conformable seaward-thickening wedge of sediment. Its unconformable base (near seismic horizon A) is essentially planar and is rarely displaced by faults. In the Algoa basin the basal unconformity is overstepped by late-Cretaceous (Campanian) sediments; this undulating, erosional diachronous, interface (top layer 3) rests with a 20-30° discordance on the Lower Cretaceous Hartebeest formation, which is a possible lateral facies equivalent of the Sundays River Formation.

Seismic reflectors (time lines) within the Alphard Formation prograde in a seaward direction, consistent with the outbuilding of the continental shelf in response to a progressive oceanward shift of the main depocentre at the continental margin. The rate of shelf outbuilding in the western part of the Agulhas Bank was faster than elsewhere as a result of a relatively greater input of detritus by the two major rivers, the primordial Gouritz and Breede. The overall rate of sedimentation during the Upper Cretaceous was comparatively slow (< 50 m/m.y.); together with the

ubiquity /142...

ubiquity of glauconite in the Alphard Formation this testifies to the existence of a sediment-starved basin at this time and an overall exponential decline in sedimentation rates during the Mesozoic on the Agulhas Bank.

The Alphard Formation was deposited in response to continued mild epeirogenic subsidence of the continental margin, concomitant with continued fast spreading of the African and Falkland plates and a world-wide eustatic rise in sea level. The Mesozoic history of the Agulhas Bank was terminated by deposition of the Tertiary Alexandria Formation during a regression which commenced in the Maestrichtian.

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PLATE I

AGULHAS BANK
TWO-WAY TIME CONTOUR MAP OF

'HORIZON D'

CONTOUR INTERVAL — 250 MILLISECONDS
(ONSHORE GEOLOGY AFTER GEOL. MAP. S.A. 1970 ED.)

SCALE 1 : 1 000 000
10 0 10 20 30 40 50 KM

9 C 263 b

PLATE 2

AGULHAS BANK

TWO - WAY TIME CONTOUR MAP
OF
HORIZON "C"
CONTOUR INTERVAL - 100 MILLISECONDS

SCALE 1:1000 000

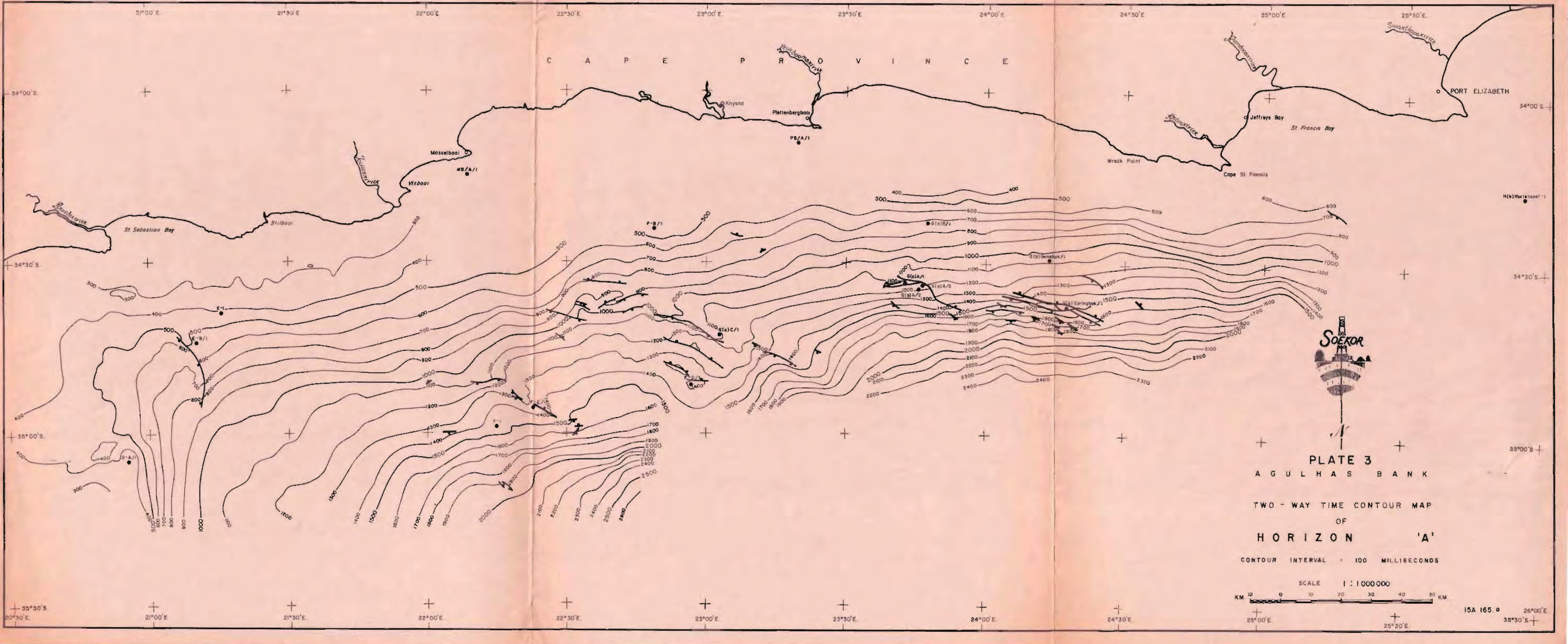

PLATE 3

AGULHAS BANK

TWO - WAY TIME CONTOUR MAP OF HORIZON 'A'

CONTOUR INTERVAL : 100 MILLISECONDS

SCALE 1 : 1000000

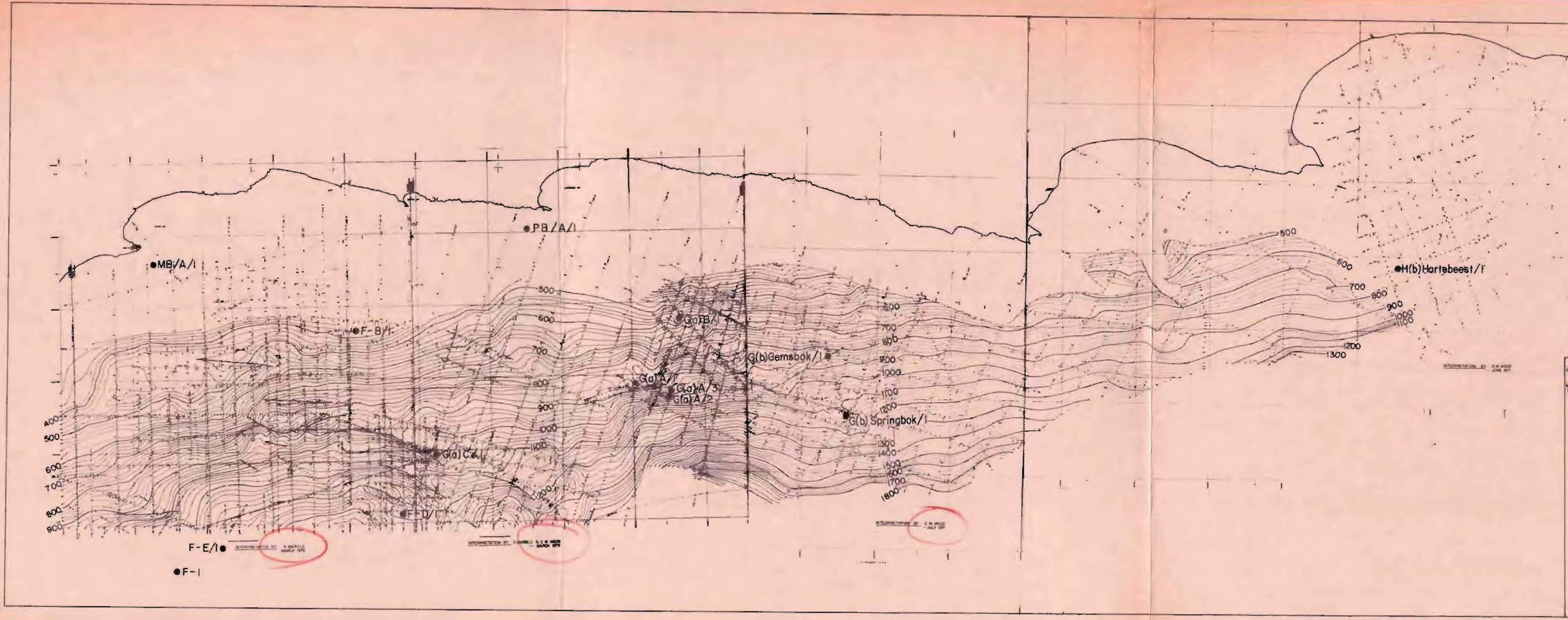

PLATE 4

EASTERN AGULHAS BANK

N

REPUBLIC OF SOUTH AFRICA
OFF-SHORE

TWO-WAY TIME CONTOUR MAP OF

HORIZON II

SCALE 1:1000 000

No IO E 16a

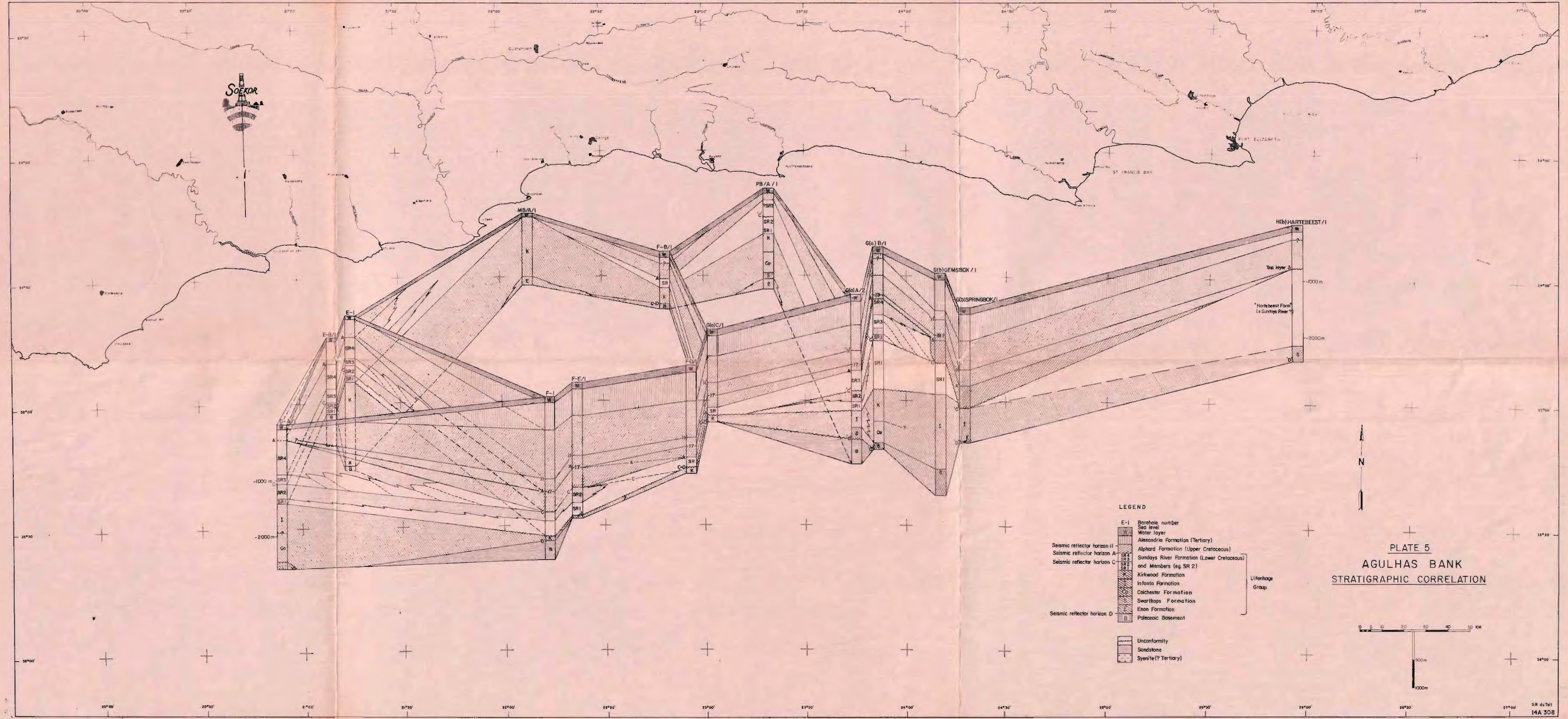

PLATE 5

AGULHAS BANK

STRATIGRAPHIC CORRELATION