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**LATE CENOZOIC SHALLOW MARINE DIAMOND PLACERS
OFF THE NORTHERN SPERRGEBIET, NAMIBIA**

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All of the photographs, figures, tables and written work in the thesis are that of the author unless otherwise referenced.

ABSTRACT

Small scale diver-assisted diamond mining has taken place since 1990 in the shallow marine (<30 m water depth) portions of Mining Licence 45 (Elizabeth Bay) between Halifax Island and Elizabeth Bay along the southwestern coast of Namibia. These operations in the northern part off the coast of the Sperrgebiet have produced almost 400,000 carats over a period of 17 years. Although sparse records remain from the early days, sufficient data from various sources were collected, collated and summarised to make meaningful observations.

From historic and current diamond diving records, 4 submarine areas which have yielded high returns were described in terms of their geomorphology, sedimentology and diamond occurrence. Using detailed geophysical survey data (Sidescan Sonar and Multi-beam Bathymetry), the deposition of diamonds at these sites were modelled in GIS-based reconstructions.

The diamond size frequency distribution (SFD) of the Shallow Marine (0 to -30 m) deposits in the study area is similar to the proximal aeolian deposit mined on land at Elizabeth Bay and the deeper Midwater (-30 to -70 m depth) deposits situated southwest of the study area. Although similar, the three deposits have distinct SFD signatures. The shallow marine deposit SFD is notably consistent over the 4 areas studied along the 30 km section of coastline. The Elizabeth Bay, Shallow Marine and Midwater diamonds were deposited at different times and sea level varied for each event. It is very likely that each deposit is comprised of a series of complicated overlapping smaller pulses of emplacement. However, continuous reworking over a considerable period of time smoothed out most of the anomalies in each deposit.

Within the study area, diamonds were widely distributed down to -30 m, which is the practical depth limit for diver-assisted operations. Significant concentrations of diamonds were encountered at -12 m, between -18 m and -21 m and between -24 m and -27 m depths. Indicating that sea level was most likely at, or about these depths for a significant period of time, allowing reworking processes to concentrate diamonds.

The geomorphology of the coastline at a particular sea still stand provides the opportunity for the accumulation, retention and reworking of northward travelling diamondiferous gravel. Although south facing embayments play a significant role, additional factors are required for the accumulation of discrete pockets of anomalously high grade diamondiferous gravel i.e. *Jackpots*. Surface roughness provided by the bedrock and/or boulders was a significant additional factor contributing to the formation of the majority of trapsites in the study area.

The appearance of *Choromytilus meridionalis* and *Aulacomya ater* shells, which occur in the gravel deposits, were used to tentatively assign ages of deposition. Where fresh blue/black coloured *Choromytilus meridionalis* and *Aulacomya ater* shells were present, deposition is inferred to have occurred between 8.0 ka and 4.5 ka ago i.e. after the Last Glacial Maximum (LGM). Deposition of gravels for the rest of the areas studied is inferred to have taken place at least 80 ka ago, i.e. before the LGM, as the gravel contained weathered, chalky, friable shells. As these deposits are generally thin (<3.0 m in thickness), it is unlikely that they could have survived several millions of years and the numerous regressional and transgressional cycles which occurred in that period. It does seem more feasible that these gravels were deposited during the late Quaternary.

The accumulations of gravel mined by the divers were generally thin (<3.0 m in thickness). Such surficial deposits are prone to erosional processes and likely to be broken down and re-introduced to the Shallow Marine conveyor during subsequent regressional and transgressional cycles. It was found that factors assisting with the preservation of diamondiferous gravel include:

- **Morphology of the trap site:** The bedrock controlled trap site provides protection from erosional processes during emergent periods and from shallow marine processes during submergent periods. In these trap sites gravel accumulated and was retained, reworked and preserved.
- **The presence of boulders** provides surface roughness which not only enhances the quality of the trap site but, it also forms an armoured lag, protecting the gravel body from erosional and shallow marine reworking processes.
- **Cementation** provides a protective capping which preserves the underlying sediments. This is an important preservation factor as about 55% of the carats recovered from the 4 areas discussed in this study were mined from features where cemented horizons were present.

Assuming that sidescan sonar and high resolution bathymetry data is available to the geologist to assist in selection of targets for diver-assisted mining along the southern Namibian coast, it is proposed that prioritisation of areas take place along the following guidelines:

1. Focus on -18 m to -21 m, -24 m and -27 m depths.
2. Focus on areas where the geomorphology of the coastline provides an opportunity to trap and retain gravel being moved northward by wave action and the longshore drift.
3. Find areas which provide space to accommodate a reasonable volume of gravel.
4. Preferentially select areas displaying rough gullied bedrock and which are proximal to fluvial drainages i.e. a supply of coarse clastic material.

Due to limitations of survey data collected in the Shallow Marine environment and as gullies and small basins are often covered by a thin layer of sand, it is usually not possible to observe the presence of boulders within a target feature. The presence and extent of preservation factors can therefore only be determined after prospecting and or mining of a target has commenced and a mining face has been opened up by the divers.

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1. INTRODUCTION

With the break-up of West Gondwana approximately 120 million years (ma) ago, the southern Atlantic Ocean opened up between the continental masses of South America and Africa. Erosional processes transported sediments from the interior where they were deposited along the coast on the continental shelf (Bremner *et al.*, 1990; Dingle & Hendey, 1984; Dingle & Scrutton, 1974). As a result of sediment accumulation, the shelf is relatively wide at the Orange River Mouth where the -200 m isobath is situated approximately 200 km west of Oranjemund. Moving away from the point source of sediment supply, the continental shelf narrows so that 250 km northward the -200 m isobath is situated approximately 45 km west of Lüderitz (Figure 1.1)

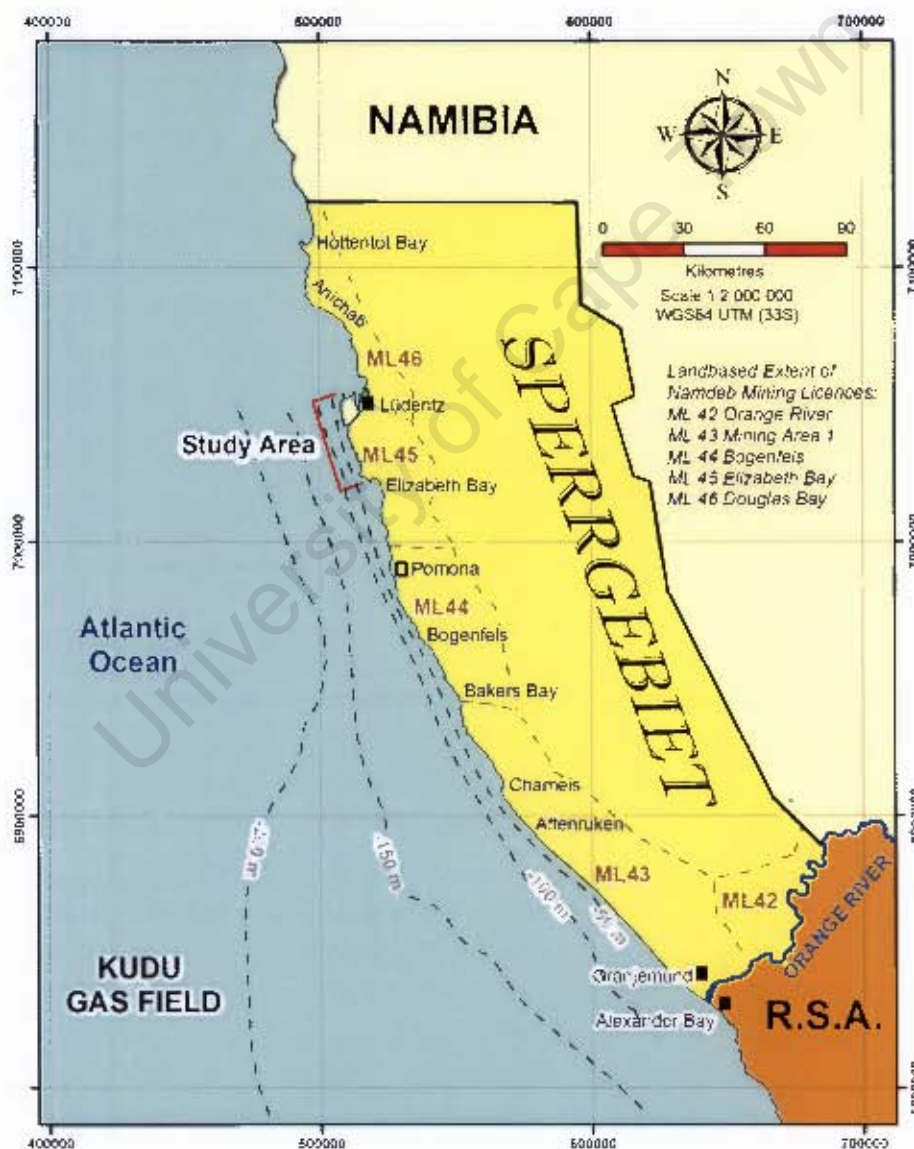


Figure 1.1: Regional location map of southwestern Namibia indicating the Sperrgebiet, the landbased extent of Namdeb-held mining licences and regional bathymetry

Since the late Cretaceous/early Tertiary the west coast of southern Africa has largely been a passive margin (De Wit, 1999; Van der Wateren & Dunai, 2001). Events of continental uplift occurred during the early Tertiary, the Miocene and the late Pliocene/early Pleistocene (Partridge & Maud, 1987; Jacob *et al.*, 1999; Wigley & Compton, 2006; Bluck *et al.*, 2007). The uplift resulted in increased amounts of erosion and fluvial transport of sediments to the western margin. Global changes in sea-level (*eustatic change*) resulted in the shoreline slowly retreating from the land (*regression*) during cold periods of glaciation when water from the world's oceans were accumulated and locked-up in ice caps. When warmer periods ensued, the ice caps melted and released water into the oceans resulting in relatively rapidly rising sea levels with shorelines encroaching on the land (*transgression*). Large volumes of sediment transported by the Orange River would be deposited seaward from where the river enters the sea (Bremner *et al.*, 1990; Dingle & Hendey, 1984; Dingle & Scrutton, 1974). During a regression this would be further out on the shelf and during a transgression it would be closer to the landmass (Pickford & Senut, 2002). Several cycles of glaciation and melting have resulted in the coastal shelf, and the sediments deposited on it, either being submerged or exposed to wind driven (*aeolian*) and coastal fluvial processes.

Diamonds occur along the western coast of Southern Africa, starting in the south from the mouth of the Olifants River to Angola in the north. It is generally accepted that the diamonds found along the southern Namibian coast originated predominantly from Cretaceous aged diamondiferous kimberlites in the interior of Southern Africa. These diamonds were released from the kimberlites through erosional processes and a significant proportion of them were carried towards the western margin of the continent by streams and rivers entering the Atlantic through the Orange River (Bluck *et al.*, 2005 & 2001; Pether *et al.* 2000; Jacob *et al.* 1999; Corbett, 1996; De Wit, 1999 & 1996; Apollus, 1995; Kuhns, 1995). There is also a school of thought that suggests that a substantial portion of the West Coast diamonds originated from pre-Karoo kimberlites which were then transported from the interior of Southern Africa via Dwyka glaciation and then redistributed into the fluvial system after being released through erosional processes from tillite deposits (Moore & Moore, 2003). After exiting the Orange River mouth the winds, currents and wave action distributed the sediments containing the diamonds largely northward along the coast (Bluck *et al.*, 2005; Bremner *et al.* 1990; De Decker, 1988, Rogers, 1977). During prolonged sea-level still stands at various elevations, diamonds were concentrated in gravels and other trapsites to form placer deposits. If not protected by being covered by other sediments or a cemented horizon, these placers were often re-worked during subsequent transgressions and other erosional processes. Subsequently, the southern coast of Namibia

hosts one of the world's two known diamond megaplacers i.e. ≥ 50 million carats (cts) at $\geq 95\%$ gem quality diamonds (Bluck *et al.*, 2005; Hallam, 1964).

The discovery of diamonds in Namibia has been accredited to a railway worker Zacharias Lewala, who in 1908 found a diamond while shovelling sand at Kolmanskop (Figures 1.2 & 1.3). Not knowing the significance of his discovery, Lewala handed over the "pretty stone" to the Railway Supervisor, August Stauch (Levinson, 1983). Unnoticed, Stauch proceeded to peg off large claims. It was only after the news of the discovery of diamonds at Kolmanskop was confirmed two months later by Dr. Range, the Government Geologist, that the news was spread by the media and Lüderitz was engulfed in a wave of prospectors and fortune seekers (Oppenheimer & Williams, 1914).



Figure 1.2. Zacharias Lewala who reportedly found the first diamond at Kolmanskop in 1908 while employed as a railway worker (Photo: Namdeb Archives).

Shortly after, in 1909, the German colonial government declared a 120 km wide strip along the coast as "Sperrgebiet" (*Forbidden Territory*), to keep illegal miners and prospectors at bay (Figure 1.1). To this day entrance into this area remains controlled and can only be entered with a permit issued by the Ministry of Mines & Energy.

Mining commenced in earnest in 1909 when the *Koloniale Bergbau-Gesellschaft*, in which August Stauch was the majority shareholder, commenced operations at Elizabeth Bay in what turned out to be the world's largest aeolian diamond placer (Oppenheimer & Williams, 1914). Between 1909 and 1921 approximately 6.7 million carats were mined from the thin superficial deposits in the wind swept coastal valleys between Kolmanskop and Bogenfels.

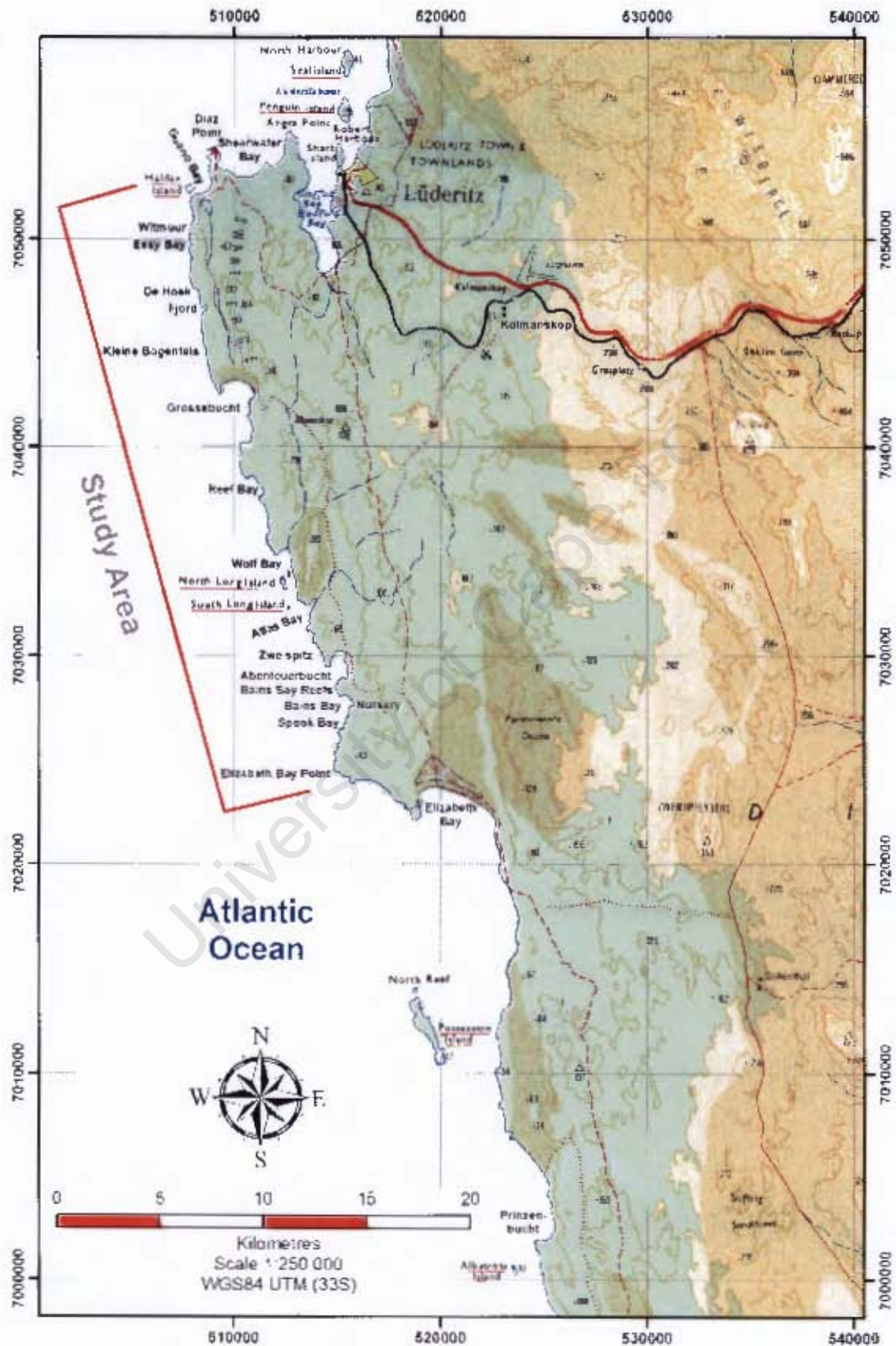


Figure 1.3: Regional location map of the area between Lüderitz and Prinzenbucht.

After the termination of World War One in 1918, South Africa took over the mandate of South West Africa from the German colonial government. In 1921 the Anglo American Corporation amalgamated 9 independent diamond companies to form the *Consolidated Diamond Mines of South West Africa* which later became *Consolidated Diamond Mines (CDM)*. By 1941 the bulk of the deflation deposits mined in the northern portion of the Sperrgebiet were depleted and the *Consolidated Diamond Mines of South West Africa* headquarters, and mining focus, were moved from Lüderitz to Oranjemund (Corbett, 2002).

In 1958 a company called *SWA Prospektoerders* owned by Mr. Johann Vivier, acquired the first offshore diamond concession between the Orange River Mouth and Diaz Point, about 250 km north. After proving the presence of diamonds in the sea, Viviers was not interested in developing a mining business. Sammy Collins, a Texan marine pipe laying contractor, purchased the prospecting concession from *SWA Prospektoerders* and formed the *Marine Diamond Corporation (MDC)*. In 1959 MDC took the lead in marine diamond mining after mining offshore marine diamonds with their converted Royal Navy salvage tug, the *Emerson K*, at Wolf Bay (Figures 1.3 & 1.4), (Williams, 1996; Corbett, 1996).



Figure 1.4: The converted Royal Navy salvage tug, the *Emerson K*, with which MDC took the lead in the mining of marine diamonds in 1959 (Photo: Namdeb Archives).

Following the successful trials with the *Emerson K*, MDC commenced offshore mining in 1962 at Chameis with mining platforms *Barge 77*, later followed by *Barge 111* and the *Pomona* (Corbett, 1996). In 1965 De Beers purchased majority shareholding in MDC and offshore mining operations continued until 1971 when the mineable ore reserves were depleted and mining ceased (Joynt *et al*, 1972; O'Shea, 1985).

Between 1968 and 1971, an investigation into the economic potential of offshore bedrock gully systems of northern Mining Area 1 was conducted (Figure 1.1). Divers were used to map the submarine area, followed by a detailed sampling programme (Figure 1.5). A total of 11 continuous, 5 m-wide, strip samples oriented at right angles to the coast were collected at 1000 m intervals. The results from this sampling programme indicated that these inshore deposits could at that stage not support a full-scale mining operation (Joynt, 1979). Exploration activities were therefore shifted to deeper water.



Figure 1.5: Diver preparing to enter the water as part of the Gully Sampling Project (Photo: Namdeb Archives).

Throughout the 1970s and 1980s De Beers continued with systematic sampling and geophysical survey programmes to establish a marine diamond resource. In 1989 De Beers Marine fitted the vessel *Louis G. Murray* with a crawler and Dense Media Separation (DMS) plant to mine and process diamondiferous gravel from depths exceeding 100 m (Corbett, 1996)

Ocean Diamond Mining Ltd. (ODM) came in to being in 1983. After a lengthy period of searching for start-up capital they commenced with full scale operations in the early 1990s, prospecting and mining off the Namibian islands. ODM was acquired by the Namibian Minerals Corporation (NAMCO) in 2000. However, NAMCO ran into financial difficulties and were taken over by the Sakawe Mining Corporation (SAMICOR). SAMICOR re-commenced the mining of the Namibian island concessions in 2004. Diamond Fields International (DFI) have been prospecting and mining with various joint venture partners in the Lüderitz area since the mid 1990s (Rau, 2003) and Gershon Ben-Tovim's companies did extensive marine mining on contract for the mining licence holders mentioned above since the late 1980s to about 2004.

The diver-assisted mining industry has been well established along the west coast of South Africa since the late 1970s (Walker & Gurney, 1985; Gurney *et al.*, 1991). However, it was not until 1990 when CDM (which became Namdeb in 1994) appointed Windvogel Diamonds as principal contractor to prospect and mine for diamonds in the shallow marine portions, not exceeding -30 m depth, of CDM-held mining licences between Halifax Island in the north and Bogenfels in the south (Figure 1.1). In addition to their own mining activities, Windvogel Diamonds sub-contracted several companies who used small (generally less than 50 tons) converted fishing vessels operating from Lüderitz as platforms for diver-assisted diamond mining operations. The cold and murky waters of the Atlantic combined with frequently stormy sea conditions make this an extreme environment for divers to work in. Diving is done in water depths less than 30 m due to practical physiological limitations of working in a pressurised environment. Working close inshore in relatively shallow depths, diver-assisted mining operations are prone to adverse weather conditions and for safety reasons diving operations are halted when the swell height exceeds 2.0 m.

The divers are used to guide flexible 8-inch diameter suction hoses to pump gravel from gullies, potholes and other trapsites. The divers must continuously remove oversize rocks by hand to prevent the nozzle of the suction hose from blocking. The gravel is pumped to the vessel on the surface. On deck, the gravel is screened to recover the 1.6 to 12 mm fraction using rotary trommel screens. The bagged gravel were transported to the Nieswandt Boatyard in Lüderitz, where Windvogel Diamonds had a facility to recover diamonds from the gravel, initially using jigs, and later a DMS plant to concentrate the gravel and a grease table for the final recovery of diamonds. In 1999 Namdeb purchased the Nieswandt Boatyard facility from Windvogel Diamonds and named it the Contractors Treatment Facility (CTF). All of the companies previously sub-contracted by Windvogel Diamonds were subsequently directly contracted to Namdeb. By the end of 2003 Namdeb constructed a new CTF on the site with a floating offload

facility, crusher, DMS and Flowsort X-ray to recover diamonds from the screened gravel delivered to the plant by the diver-assisted mining operations (Figure 1.6).



Figure 1.6: The Namdeb Contractors Treatment Facility (CTF) in Lüderitz was constructed on the Nieswandt Boatyard and was commissioned in 2004.

Since its conception in 1990 until 2003 shallow marine diver-assisted mining activities based in Lüderitz were mainly focused between Halifax Island in the north and Elizabeth Bay in the south (Figure 1.3). This was largely due to convenience as vessels could return to the shelter of Grossebucht or Lüderitz port if weather conditions turned foul. There is no safe anchorage for small vessels between Possession Island (situated just south of Elizabeth Bay) and Alexander Bay (Figure 1.1). Production from the study area peaked during the 1994-1996 period with the mining of the Zweispitz *jackpot* from which an estimated total of 80 000 cts were recovered (Figure 1.7).

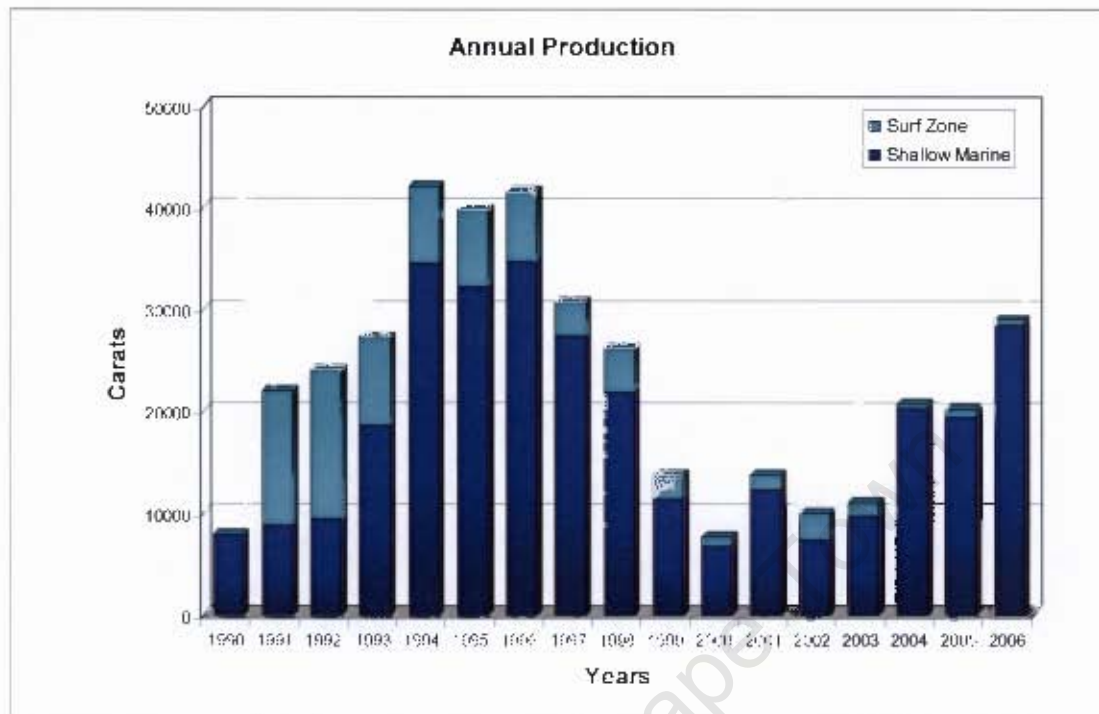


Figure 1.7: Annual production from Namdeb Surf Zone and Shallow Marine contractors

In 1990 CDM appointed Diaz Point Explorations (DPE) as a contractor to mine mainly small discrete raised beach deposits which were irregularly distributed close to the present shoreline between Grossebucht in the north and Bogenfels in the south. In addition to the mining of the raised beach deposits, DPE commenced utilising shorebased mining units in 1991 to mine diamondiferous gravel from the surf zone portions of the contract area. Using mobile tractor-driven pump units, divers entering the water from the shore pumped gravel back to land where it was screened on-site using mobile trommel screens (Figure 1.8). The surf zone operations extended no further than 200 m out to sea from the low water mark and were generally limited to water depths not exceeding -15 m. The surf zone is the most dynamic portion of the coastline which makes mining activities in this environment extremely challenging



Figure 1.8: Divers preparing equipment (4" gravel pump) to dive in the surf zone at Spook Bay area.

Production from the surf zone operations peaked shortly after operations commenced in 1992 when almost 15 000 cts were recovered (Figure 1.7). During the early 1990's there were an estimated 50 shore pumping units operating along the southern Namibian coastline within the DPE contract area. This early boom can be equated to the era of August Stauch "picking up diamonds in the moonlight" in the deflation valleys close to Pomona. A large proportion of the operators had no formal diving training and similar to the early surf zone operations in South Africa, no production records were kept (Walker & Gurney, 1985). Subsequently, production and the number of active units have steadily declined. In 2006 approximately 500 cts only were recovered by 3 operating units.

Divers based in Lüderitz have been actively mining diamonds from the sea down to water depths of -30 m since 1990. During the initial years there were no geophysical data or geological models to assist the divers in targeting mining areas. Some of the early operators literally stumbled onto diamond deposits of extraordinary concentration, the so-called *Jackpots*. A few of these *jackpot* sites turned breadline operators into millionaires in a very short period of time. As the rumours of *rags-to-riches* stories spread, the town of Lüderitz was flooded with commercial divers and colourful characters in search of fortune during the 1990s. This period was also characterised by fierce rivalry and strife between crews of the diver vessels operating for the various sub-contractors. These conflicts sprawled from the sea into the pubs of Lüderitz from time to time.

2. STUDY OBJECTIVES

The principal aim of this study is to characterise the nature of the major shallow marine (<30 m water depth) diamond placers which were mined by diver-assisted operations in the shallow marine portions of Mining Licence 45 (Elizabeth Bay) between Halifax Island in the north and Elizabeth Bay in the south (Figure 2.1).

Diver-assisted mining activities along the west coast of South Africa have been summarised by Walker & Gurney (1985) and Gurney *et al.* (1991). Joynt (1979) described a diver-assisted sampling programme in the northern part of Mining Area 1 in an unpublished inhouse Namdeb report (Figure 1.1). To date, no work has been published on the diver-assisted mining activities along the southwestern coast of Namibia. This study will be restricted to the northern part of the Sperrgebiet from which the small scale diver-assisted mining activities have produced almost 400,000 cts during the last 17 years. Although sparse records remain from the early days, sufficient data from various sources have now been collected, collated and summarised to make meaningful observations.

From historic and current diamond diving records, several submarine areas which have yielded high returns, have been selected. These will be described in terms of their geomorphology, sedimentology and diamond occurrence. Using detailed geophysical survey data (Sidescan Sonar and Multi-beam Bathymetry), the entrapment of diamonds at these areas will be modelled in GIS-based reconstructions, to build an understanding of the genesis of these shallow inshore diamond placers.



Figure 2.1: Location map of study area.

3. PHYSIOGRAPHIC SETTING

3.1 Landforms

The southern Namibian coast is characterised by a fairly extensive coastal plain which is terminated by the Great Escarpment some 100-150 km inland. This feature was formed as a result of uplift experienced by the southern African sub-continent shortly after the break-up of Gondwana about 120 ma ago. Erosion subsequently moved the Great Escarpment eastward, leaving behind the coastal pediplain occupied today by the Namib Sand Sea (Figure 3.1), (McCarthy & Rubidge, 2005; Schneider, 2004; Ward & Corbett, 1990). This pediplain, which stretches from the escarpment to the ocean, has shown very low denudation rates, in the order of 0.5-1.0 m/ma since the mid Miocene (Van der Wateren & Dunai, 2001).



Figure 3.1: The dunes of the Namib Sand Sea just north of Lüderitz occur on the pediplain which stretches from the escarpment to the ocean.

The Namib Sand Sea encompasses an area of approximately 34,000 km² between Lüderitz in the south and the Kuiseb River in the north and is one of the more significant active desert sand and dune accumulations outside the Sahara (Schneider, 2004).



Figure 3.2: Facing north, an oblique aerial view of Idatal in the Pomona area of the Sperrgebiet, displaying the *yardang* and *yardang troughs* typical of the "Trough Namib" documented by Kaiser in 1926 (Photo: Namdeb Archives – J.D. Ward).

The area of the Sperrgebiet between the coast and the escarpment has been divided into the "Plain Namib" and the "Trough Namib" by Kaiser (1926). The Plain Namib refers to the sand covered flats of the interior. The Trough Namib occurs along the coastal strip from Chameis Bay in the south to beyond Lüderitz in the north and is comprised of a series of parallel north-south trending valleys which roughly coincides with synclinal basement structures (Figures 1.1 & 3.2). The Trough Namib has developed because of the differential weathering and deflation of an initially level surface (Stocken, 1978).

Corbett (1993) showed that a wedge shaped deflation basin exists over the Trough Namib identified by Kaiser (1926). Within this deflation basin, narrow zones of high sandflow called Aeolian Transport Corridors (ATCs) occur. Yardang formation occurs within the restricted paths

of ATCs. The distribution of palaeoyardangs indicate that the deflation basin with its constituent ATCs moved in conjunction with sea level fluctuations. During regressive periods when the shoreline was situated westwards of the present shore, sand sea expansions occurred. During subsequent transgressions, the western margin of the expanded sand sea would have been reworked by nearshore marine processes and aeolian processes (Corbett, 1993).

From the mouth of the Orange River the coastline to the north is straight for 120 km to Chameis (Figure 3.3). The linear beaches which were deposited at 6 distinct elevations along this section of coast have been the focus of Namdeb's landbased mining operations since the 1940's. Northward of Chameis the coastal configuration changes to log spiral and south-facing re-entrant bays (Pether *et al.*, 2000). Elizabeth Bay forms the most significant south-facing re-entrant embayment along this coast. The study area between Halifax Island in the north and Elizabeth Bay in the south has a rocky shoreline, often with steeply dipping cliffs, with isolated sandy beach areas in sheltered embayments. Long Island North is the most significant island which occurs in the study area (Figure 1.3).



Figure 3.3. Facing south, an oblique aerial view of the straight coastline between Chameis and Oranjemund. The flooded old mining paddocks are visible on the left of the picture (Photo: Namdeb Archives).

3.2 Climate

The climate along the coastal strip of southern Namibia is dominated by meteorological forces that originate offshore in the Atlantic Ocean. The South Atlantic high pressure cell (SAH), in conjunction with the pressure field over the southern African subcontinent cause the large scale wind field. The SAH moves from a southerly position relatively close to the coast in summer (30°S , 5°W), to further north and offshore in winter (26°S , 10°W).

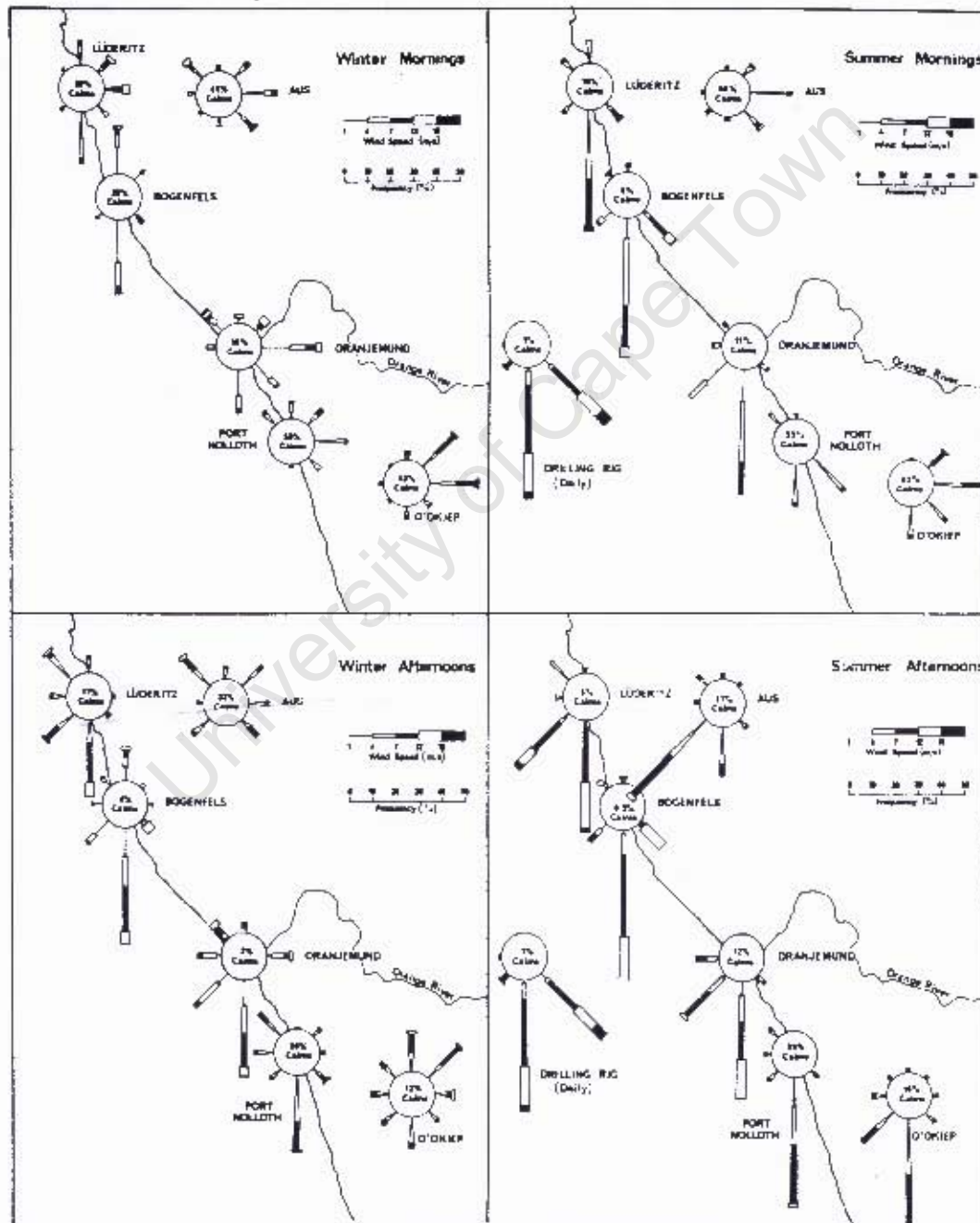


Figure 3.4: Windroses for the West Coast of Southern Africa (De Decker, 1987).

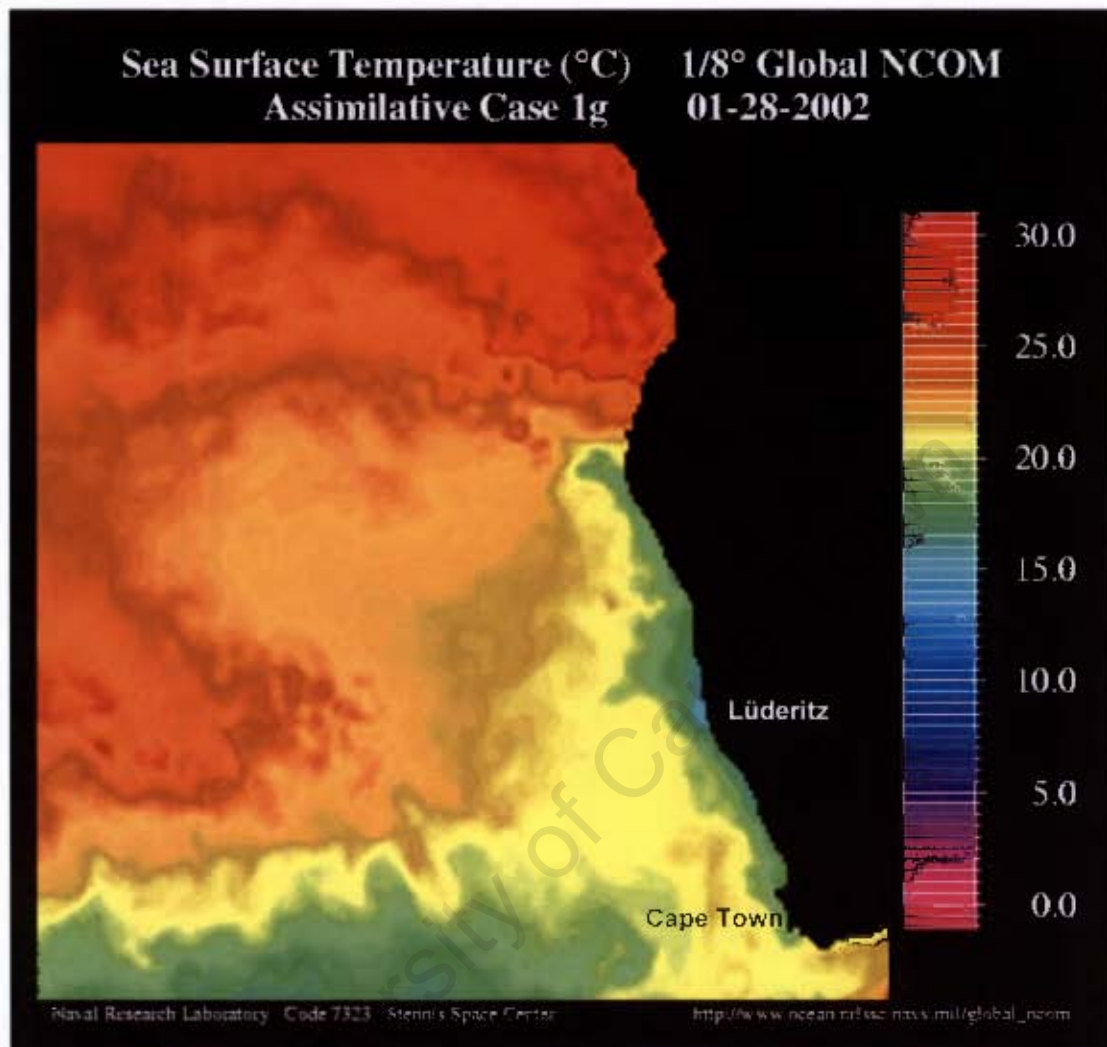


Figure 3.7: Sea surface temperatures along the West Coast of Southern Africa. The wind driven upwelling centre of the BCLME is situated near Lüderitz, as reflected by the cold surface temperatures encountered in that area (United States Naval Research Laboratory – Stennis Space Center, 2002)

An eastward moving band of cyclonic cells form the belt of westerly winds called the "roaring forties" which lie between 35°S and 40°S (Figure 3.8). These low pressure regions move approximately 3° poleward and equatorward during summer and winter, respectively. The effects of these cyclonic frontal systems are more prominent in winter as these systems move further north, closer to the African sub-continent. These low-pressure storm systems can have a central pressure of 980 mb and less. With an uninterrupted fetch, the powerful winds produced by these cyclonic systems generate enormous swellfronts. These long period swells travel considerable distances, and often over a period of several days, before they impact on the West Coast of Southern Africa and Namibia.

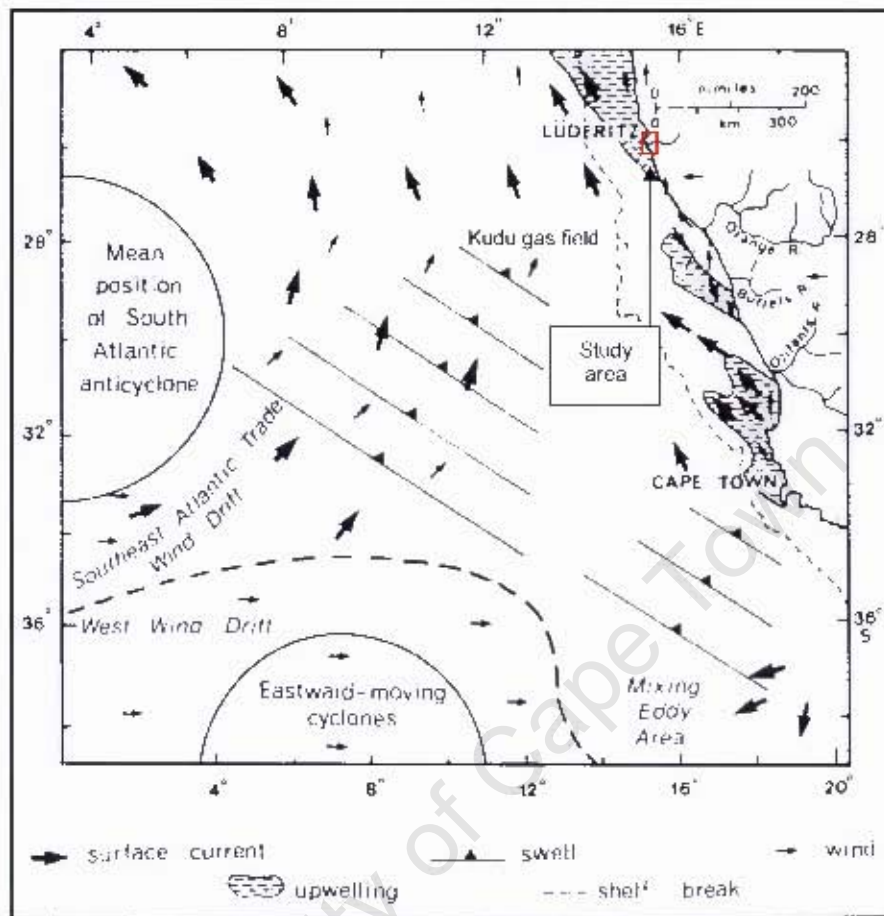


Figure 3.8: Synoptic map displaying the general meteorology and hydrology of the South Atlantic with the study area near Lüderitz indicated (De Decker, 1987)

Data collected from a 'Waverider' buoy in the region of the Kudu gas field, situated approximately 200 km west of Oranjemund, indicate that the waves originate predominantly from a southerly to a south-westerly direction with little seasonal variation (Figure 3.9). This directional distribution is relevant to the offshore area in water depths greater than about 100 m. However, closer to the coast, processes like depth-induced refraction influence the characteristics of approaching waves, in that the approach direction is rotated from a south-south-westerly direction to a south-westerly direction. The peak wave period ranges predominantly from 9 s to 16 s with the highest occurrence at approximately 13 s (Rossouw, 2002). The wave base off Oranjemund is at approximately 80 m (De Decker, 1988).

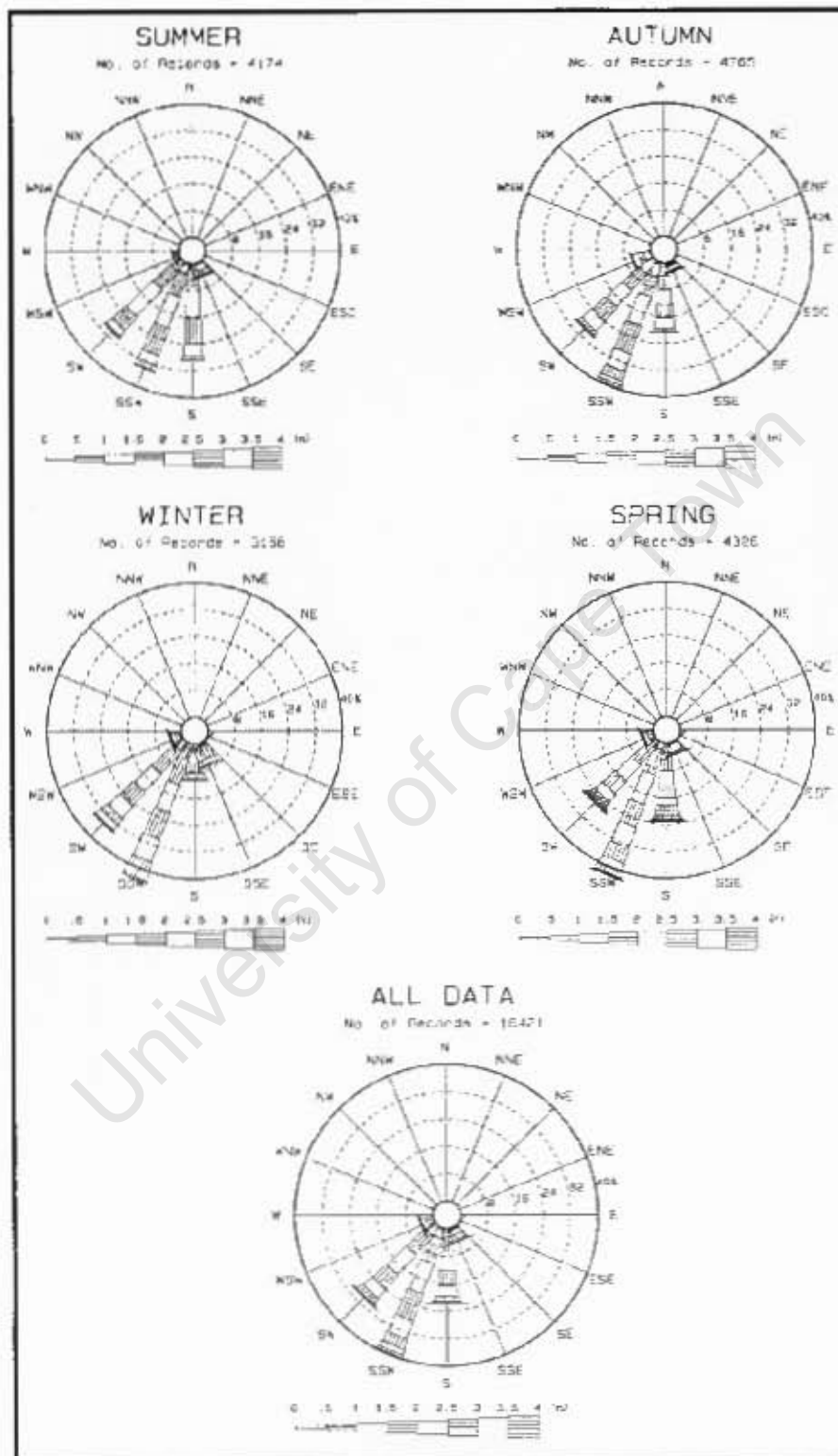


Figure 3.9: Annual and seasonal wave roses from the Kudu Gas Field which is situated approximately 200 km west of Oranjemund, indicate that the waves originate predominantly from a southerly to a south-westerly direction with little seasonal variation (Rossouw, 2002).

The wave energy impacting on the west coast of southern African coast is considered to be the most consistent in the world (Hay & Brock, 1992). These swellfronts dominate the shallow marine environment, especially during winter months and cause prolonged periods of low visibility in the water column. This is due to the continuous agitation of bottom sediments by the swell action and the absence of prolonged strong southerly winds which tends to drive the turbid coastal waters away from the coast during the summer months. When swell height exceeds 2.0 m, diver-assisted mining operations are usually halted as the flexible pipe with which the gravel is pumped to the surface becomes too difficult to control for the diver. Weather conditions therefore dictate that diver-assisted mining operations along the Namibian coast are seasonal and largely limited from September through to May. Virtually no diving takes place during the winter months from June to August.

The tidal range is less than 2.0 m and therefore falls in the microtidal range. The tidal effect on inner shelf sediment transport is considered to be negligible (De Decker, 1987).

University of Cape Town

4. REGIONAL GEOLOGY

The oldest rocks in the study area are the basal gneisses of the Namaqua Metamorphic Complex which dates back to the Meso-Proterozoic (Greenman, 1966; SACS, 1980). The Neo-Proterozoic rocks of the Gariep Supergroup lie unconformably on the basement rocks along a coast bound strip (Milne, 1985; Siegfried, 1993; Rispel, 2004). The diamondiferous sediments of the Elizabeth Bay Formation were deposited during the Miocene and the Pliocene aged Annental Beds represent remnants of a previously more extensive Namib Sand Sea (SACS, 1980; Milne, 1985). During interglacial periods of the late Quaternary, diamondiferous gravel beaches were deposited along the coast of the study area (Milne, 1985), (Table 4.1).

PERIOD	Unit	Description	Reference
	Raised Palaeo Beaches 125-5 Ka	Sandy, shell-rich matrix supported beach deposits with angular to rounded local clasts.	Milne, 1985
	Annental Beds 5.3-3.4 Ma	Highly cross-bedded, carbonate cemented, fine grained sandstone	
	Elizabeth Bay Formation 21.8-5.3 Ma	Fiskus Sand Member - cross-bedded aeolian sand and diamondiferous grits	SACS, 1980
		Grillental Clay Member - green coloured esturine clay.	SACS, 1980
Gariep Supergroup 740-500 Ma	Bogenfels Formation	Massive and banded dolomite	Milne, 1985
	Basic & Ultra-Basic Intrusives	Pyroxenite, amphibolite and hornblendite	Greenman, 1966
	Diaz Point Formation	Unit 3: diamictite comprised of a polymictic, matrix-supported conglomerate	Siegfried, 1993
		Unit 2: Severely weathered chloritic schist with extensive quartz veining	
		Unit 1: Severely weathered chloritic schist	
	Wolf Bay Formation	Dolomites interbedded with sheared quartzite, chloritic and phyllitic schist	Rispel, 2004
		Fissile quartzite	Milne, 1985
Basal clastic unit			
Namaqua Metamorphic Complex 1460-1200 Ma			SACS, 1980

Table 4.1: Summary of the stratigraphy in the study area (Greenman, 1966; SACS, 1980; Milne, 1985; Siegfried, 1993; Rispel, 2004).

4.1 Namaqua Metamorphic Complex

Basement rocks in the study area consist mainly of the Proterozoic Namaqua Metamorphic Complex (Figure 4.1), (SACS, 1980). The Namaqua Metamorphic Complex comprises much of the basement of the western portion of southern Africa including the Northern Cape in South Africa and the southern part of Namibia.

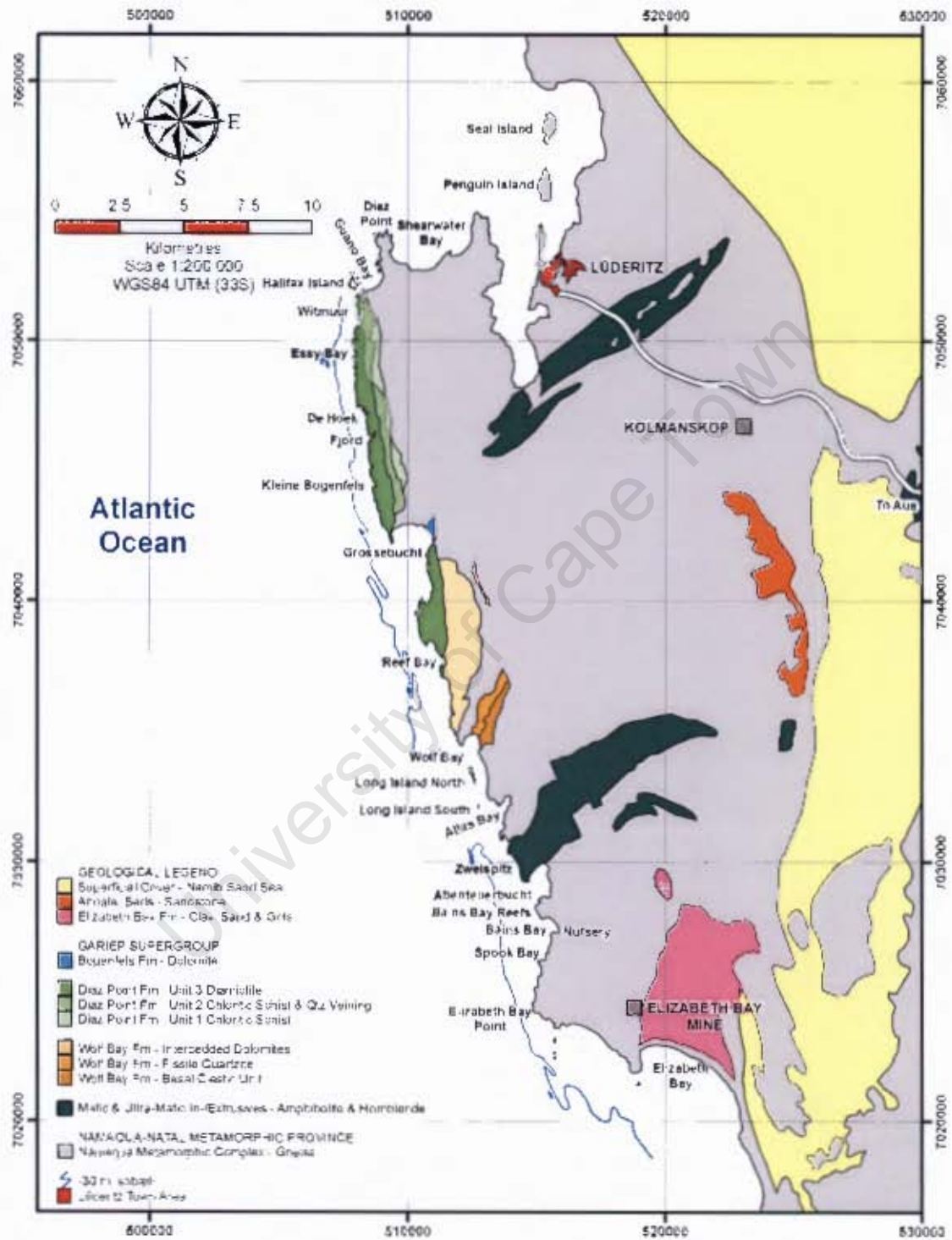


Figure 4.1: Geology map of study area (Rispel, 2004; Siegfried, 1993; Milne, 1985; Greenman, 1966)

The full extent of the Namaqua Province is not definitively known as its margins are mostly hidden by younger cover. The Namaqua Province extends eastwards beneath the Karoo Supergroup cover along the southern margin of the Kaapvaal Craton and links up with the Natal Province, which has yielded comparable mid-Proterozoic radiometric ages, to form the Namaqua-Natal Belt (Tankard *et al.*, 1982; De Beer & Meyer, 1983).



Figure 4.2: Outcrop of Namaqua Metamorphic Gneiss bedrock at Diaz Point (scale = 1.0 m).

The Namaqua-Natal Metamorphic Belt forms part of the Kibaran (or Grenville) Belts. It has been proposed that during the assembly of the supercontinent Rodinia, approximately 1100 ma ago, the margins of the constituent continents were marked by Himalyan-like mountain ranges. These mountains have subsequently been eroded to their root zones, leaving metamorphosed rocks known as Kibaran (or Grenville) Belts (McCarthy & Rubidge, 2005).

In the study area the rocks of the Namaqua Metamorphic Complex are primarily comprised of mixed gneiss, consisting of banded and more complex migmatitic material, composed predominantly of quartz diorite (Figure 4.2). Bands of quartzite and amphibolite also occur in the area. Regional mapping indicates that these lithologies belong to the Gordonia Subprovince of the Namaqualand Metamorphic Complex (Greenman, 1966; Kröner & Jackson, 1974; McDaid, 1975).

Two metamorphic episodes were recognized by Greenman (1966). The first episode was accompanied by migmatization and local mobilization of gneiss. The absence of orthoclase and the presence of muscovite in the sillimanite schist indicate that the first metamorphic event corresponds to the sillimanite-almandine-muscovite subfacies of the almandine-amphibolite facies of regional metamorphism. The second episode was characterised by epidotization. Plagioclase is commonly accompanied by epidote, the genesis of which is attributed to high load pressure perhaps augmented by nonhydrostatic stress. Due to the presence of epidote, the second episode is correlated to the staurolite-almandine subfacies of the almandine-amphibolite facies of regional metamorphism (Greenman, 1966).

4.2 Gariep Supergroup

From Halifax Island in the north to Wolf Bay in the south, the coastal geology is dominated by the Diaz Point and Wolf Bay Formations of the Gariep Supergroup, which lies unconformably on the basement Namaqua Metamorphic Complex (Figure 4.1). The Gariep Belt forms part of an extensive network of Neoproterozoic to Eocambrian aged orogenic belts which formed in western Gondwana (Frimmel, 2000). It is comprised of the rocks which were deposited in the Adamastor Ocean which formed during and after the major rifting event which separated the Rio de la Plata craton in the west from the Kalahari craton in the east during the break-up of Rodinia approximately 700 ma ago (Figure 4.3).

Towards the north the rocks of the northeast-southwest trending Pan-African Damara Belt, which is closely related to the Gariep Belt, were formed from the rocks which were deposited in the Khomas Sea between the Kalahari and Angola cratons (Frimmel, 2000). After the deposition of the Gariep Group, the closure of the southern Adamastor Ocean resulted in continental collision and is taken as the time when the passive Kalahari Plate margin entered the subduction zone and started dipping beneath the active Rio de la Plata Plate margin (Jasper *et al.*, 2000). The northwest-southeast trending coastal Gariep Belt stretches from Lüderitz in Namibia to Kleinsee in South Africa from where it continues offshore to Vredendal where it enters the continent again

as the Vredendal outlier. The Gariep Belt possibly extends to the Dom Feliciano Belt in southern Brazil and Uruguay (Figure 4.3). (Van Staden *et al.*, 2006).

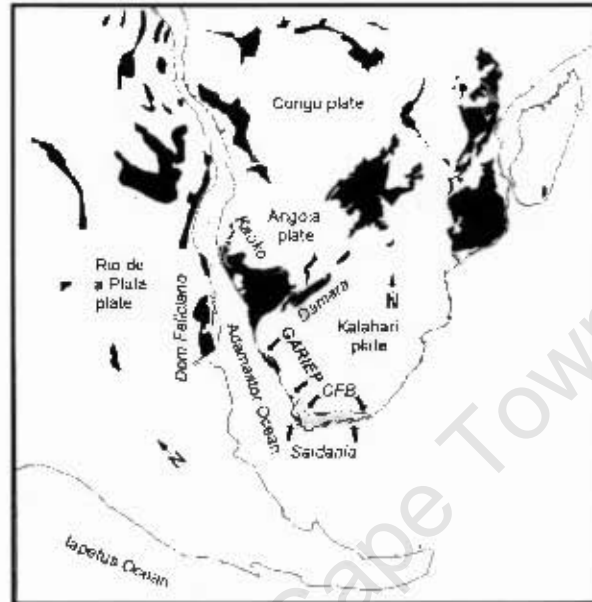


Figure 4.3: The position of the Gariep Belt within the network of Neoproterozoic/early Palaeozoic orogenic belts and the Permo-Triassic Cape Fold Belt (CFB) in parts of western Gondwana at about 150 ma ago (Frimmel, 2000).

The Gariep Belt has been subdivided into an eastern passive continental margin zone, the Port Nolloth Zone (PNZ) and the western oceanic allochthonous Marmora Terrain (MT). The Marmora Terrain has been subdivided into three tectonostratigraphic units, namely the Schakalsberge Subterrane, the Oranjemund Subterrane and the Chameis Subterrane (Frimmel, 2000).

4.2.1 Wolf Bay Formation

The rocks of the Wolf Bay Formation were first described by Greenman (1966) as '*Probable Bogenfels sediments between Luderitz and Wolf Bay*'. Later Milne (1985) described it as a sequence of Gariep aged metasediments comprised of conglomerates (basal clastic unit), arkosic grits, quartzites, limestones and calc-arenites. Work by Rispel (2004) assigned the *Limestone, schist & quartzite (Wd)* unit of the Wolf Bay Formation back to the basement Namaqua Metamorphic Complex. The calc-arenite unit described by Milne (1985) was redefined as dolomites interbedded with sheared quartzites and schists. The Wolf Bay Formation stretches in a thin strip along the coast from Grossebucht in the north to Wolf Bay in the south. It is wedged between the overlying Diaz Point Formation and the underlying Namaqua Metamorphic Complex with the contacts between these being north-northeast – south-southwest trending thrust faults (Figures 4.4 & 4.5).

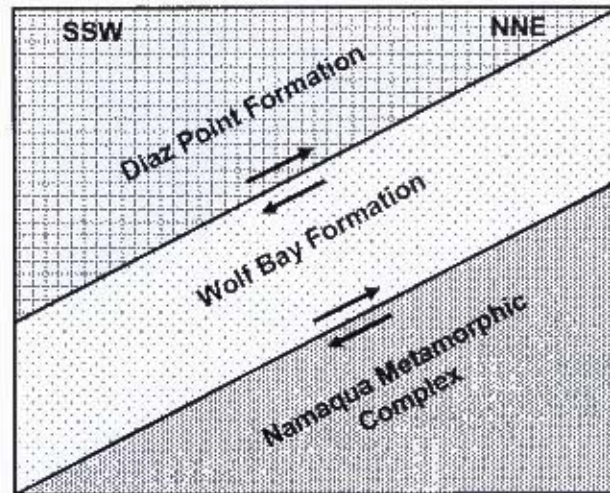


Figure 4.4: Two different thrust events resulted in the Wolf Bay Formation being sandwiched between the Proterozoic aged basement Namaqua Metamorphic Complex and the overlying Diaz Point Formation (Rispel, 2004)

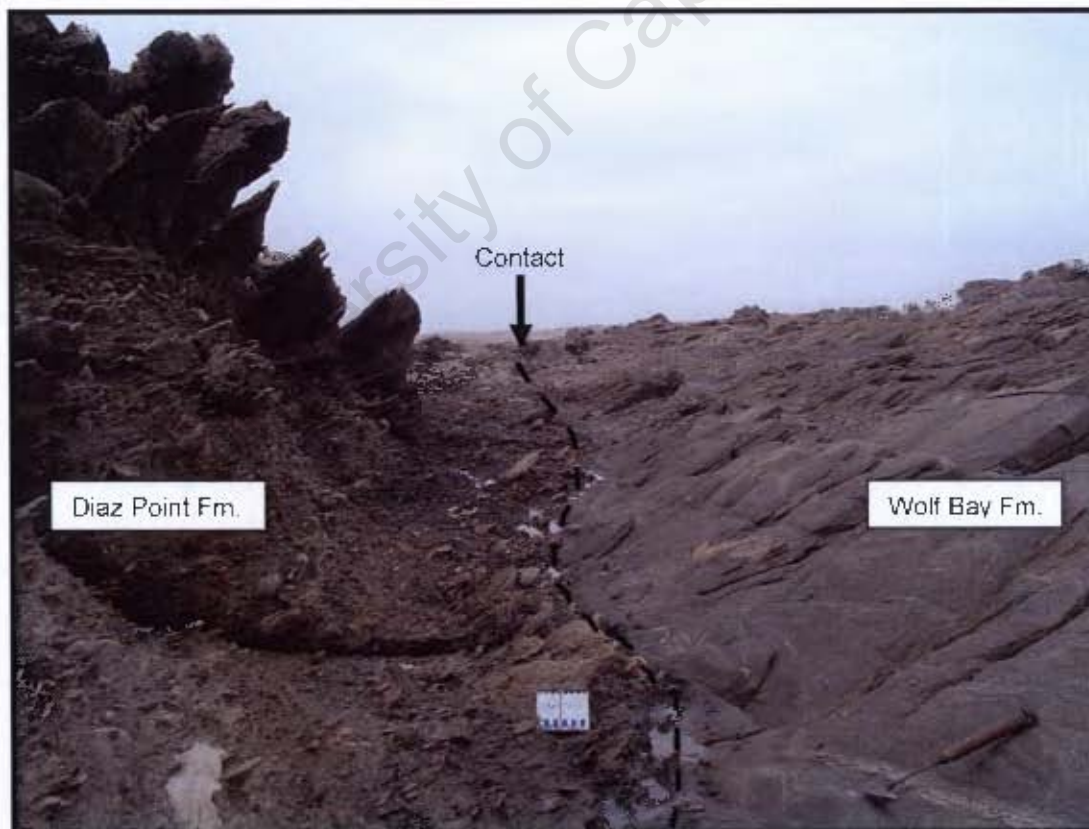


Figure 4.5: Facing north, contact between the Diaz Point Formation polymictic, matrix-supported conglomerate (Unit 3) and the dolomites interbedded with sheared quartzite, chloritic and phyllitic schist of the Wolf Bay Formation at Reef Bay (scale = 10 cm).

These correlate well to the bedding sub-parallel thrust faults which are associated with the D1 and D2 events of the structural evolution of the Gariiep Belt. The Wolf Bay Formation consists of a basal clastic unit which is overlain by fissile quartzites and a dolomite unit which is interbedded with sheared quartzites and schists (Figure 4.6). The metamorphic grade of the formation is estimated to be upper greenschist to lower amphibolite (Rispel, 2004).



Figure 4.6: Facing north from the southern end of Wolf Bay, the fissile quartzite unit of the Wolf Bay Formation (scale = 10 cm).

4.2.2 Diaz Point Formation

Between Halifax Island in the north and Reef Bay in the south a thin sliver, up to 2.0 km wide, of the highly sheared deformed metasediments of the Diaz Point Formation occurs (Figure 4.7).

These were described by Greenman (1966) to be mixites of Gariiep age with a later re-interpretation by Kröner and Jackson (1974) as reworked basement. Work by Siegfried (1993) assigned a mixed fluvioglacial origin of late Proterozoic age to the Diaz Point Formation and correlated these highly tectonised lithologies with Nosib Group sediments of the Damara Sequence in the north and the basal mixites of the southern Gariiep Group. The Diaz Point Formation has been divided into three units separated by thrust faults (Siegfried, 1993):

- *Unit 1* is the lowermost (eastern) unit and consists mainly of severely weathered chloritic schists with extensive quartz veining. In the field this unit appears as subdued outcrop in rare exposures due to its susceptibility to weathering. The faultzone contact between the lowermost Unit 1 and the Namaqua basement is displayed as the linear depression between Guano Bay and Grossebucht
- *Unit 2* is the middle unit and is also comprised of severely weathered chloritic schists with extensive quartz veining but includes rare flaggy quartzites interbedded with the schists.



Figure 4.7: View facing north to Halifax Island showing Diaz Point Formation Units 3, 2 & 1 separated by thrust faults.



Figure 4.8: Facing south at the Halifax picnic spot, Diaz Point Formation Unit 3 - contact between the cobble-rich and more schistose layers with dropstones transgressing the contact (scale with children = 1.0 m).

- *Unit 3* is the upper (western) unit and consists of quartzite overlain by diamictite with minor interbedded chloritic quartz schists. The diamictite is a polymictic, matrix-supported conglomerate with clasts of pink coloured coarse-grained leucogranite, leucocratic biotite gneiss, well-rounded quartzite boulders, quartz pebbles and occasional retrograded amphibolite clasts (Figure 4.8). Most of these clasts, except for the quartzite boulders, have been severely deformed. The matrix is composed of fine-grained quartz, feldspar and chlorite with rare biotite flakes which are usually altered to chlorite. Extensive quartz veining is present in the matrix

4.2.3 Mafic and Ultra Mafic Rocks

Amphibolites are found throughout the study area. There are numerous small lenses measuring less than 2 m in width but the most prominent of the intrusions is the 2 km wide amphibolite belt which forms the Zweispitz headland (Figures 4.1 & 4.9). The amphibolites are generally coarse grained and consistent in texture and colour. It consist of prismatic hornblende and plagioclase and the weathered surfaces generally exhibit wind fluting features aligned with the dominant southwesterly to south-southeasterly winds (Greenman, 1966; Rispel, 2004).



Figure 4.9: Facing north, the Zweispitz headland in the foreground formed by a 2 km wide belt of amphibolite oriented in an east-west direction. See Figure 4.1

4.2.4 Bogenfels Formation

In the study area the Bogenfels Formation occurs as a relatively small semi-circular outcrop in the eastern part of Grossebucht beach. It consists of massive and banded dolomite with abundant quartz veining. The banded dolomites have dark mafic bands which alternate with lighter orange-brown felsic bands. Weathered surfaces display grey-brown elephant-skin pattern whilst fresh exposures are typically blue-grey in colour (Figure 4.10).



Figure 4.10: Dolomite of the Bogenfels Formation in the eastern part of Grossebucht (scale = 10 cm).

4.3 Elizabeth Bay Formation

As described in SACS (1980), the Elizabeth Bay Formation occurs roughly in the area between Elizabeth Bay and Kolmanskop and it has two formal members namely:

- The basal *Grillental Clay Member* of early Miocene age. The green coloured clay was deposited during the Miocene under estuarine conditions when the sea level was approximately 90 m above present sea level. Although this clay horizon was subsequently partially eroded through marine and fluvial action, portions of it remained preserved, mostly in bedrock depressions (Figure 4.11).
- The *Fiskus Sand Member* consists of cross-bedded aeolian sand and diamondiferous grits interbedded with pan deposits and were deposited during the late Miocene under predominantly aeolian conditions. In portions, it has a distinctive brick-red colour due to the oxidation of the sediments following deposition. During deposition, the long-lived southerly wind regime distributed shells from the beaches in the south up the Elizabeth Bay valley towards the north. Post-depositional groundwater fluctuations dissolved the

shells which precipitated as CaCO_3 , cementing the Fiskus sands and grits during more arid periods. Cementation occurs up to about 100 m above present sea level.

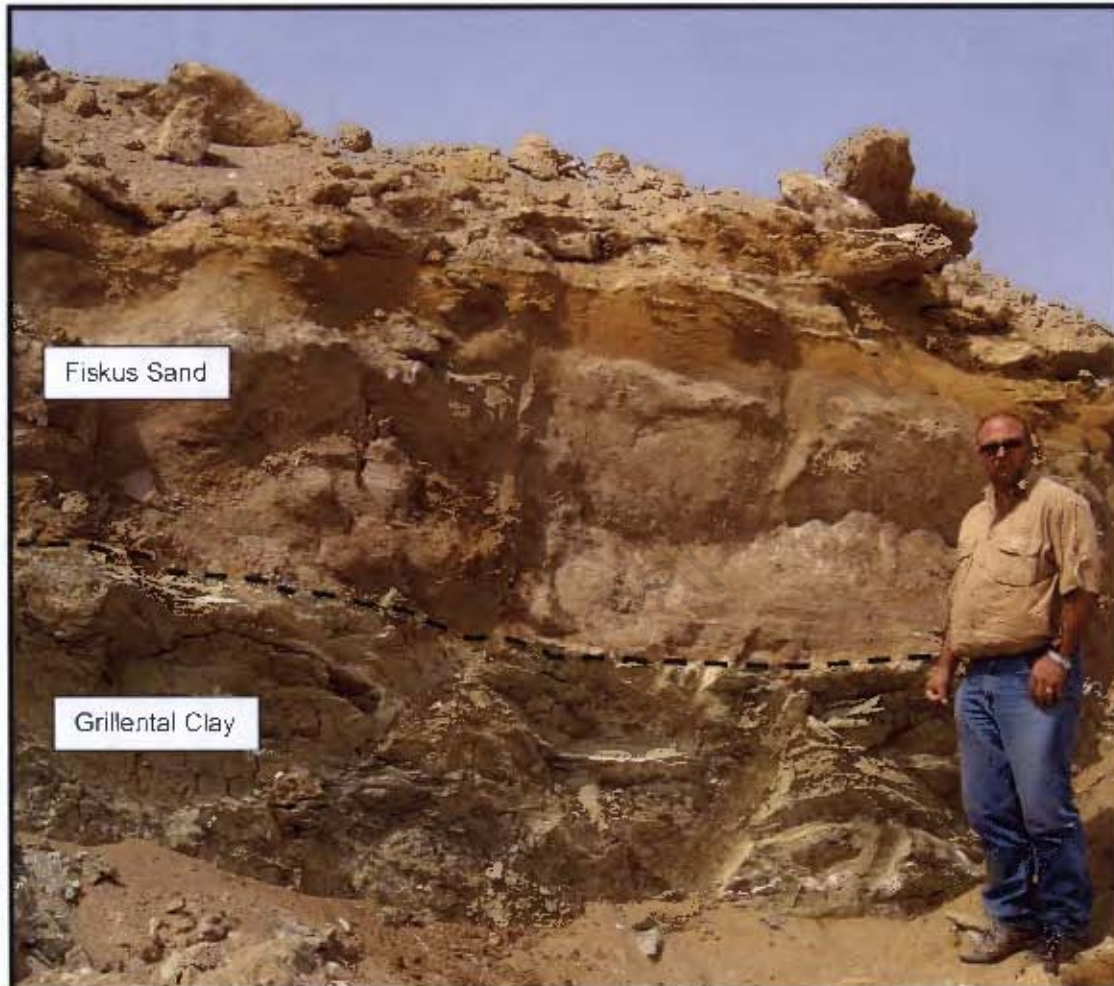


Figure 4.11: Facing east in the southern portion of Elizabeth Bay Mine, the Elizabeth Bay Formation consisting of the basal greenish coloured Grillental Clay Member topped by the Fiskus Sand Member which is cemented in places.

4.4 Annental Beds

The Annental Beds are comprised of highly cross-bedded, carbonate cemented, fine grained sandstone. It is usually well sorted but may be gritty with angular basal rubble present. Remnants of the Annental sandstone are preserved in steep sided valleys and gullies in the study area (Figure 4.12). These aeolianites are thought to be the cemented remnants of the once more extensive Namib Sand Sea and are assigned an early Pliocene age (Stocken, 1978; SACS, 1980; Jamieson & Talbot, 1983; Ward & Corbett, 1990).

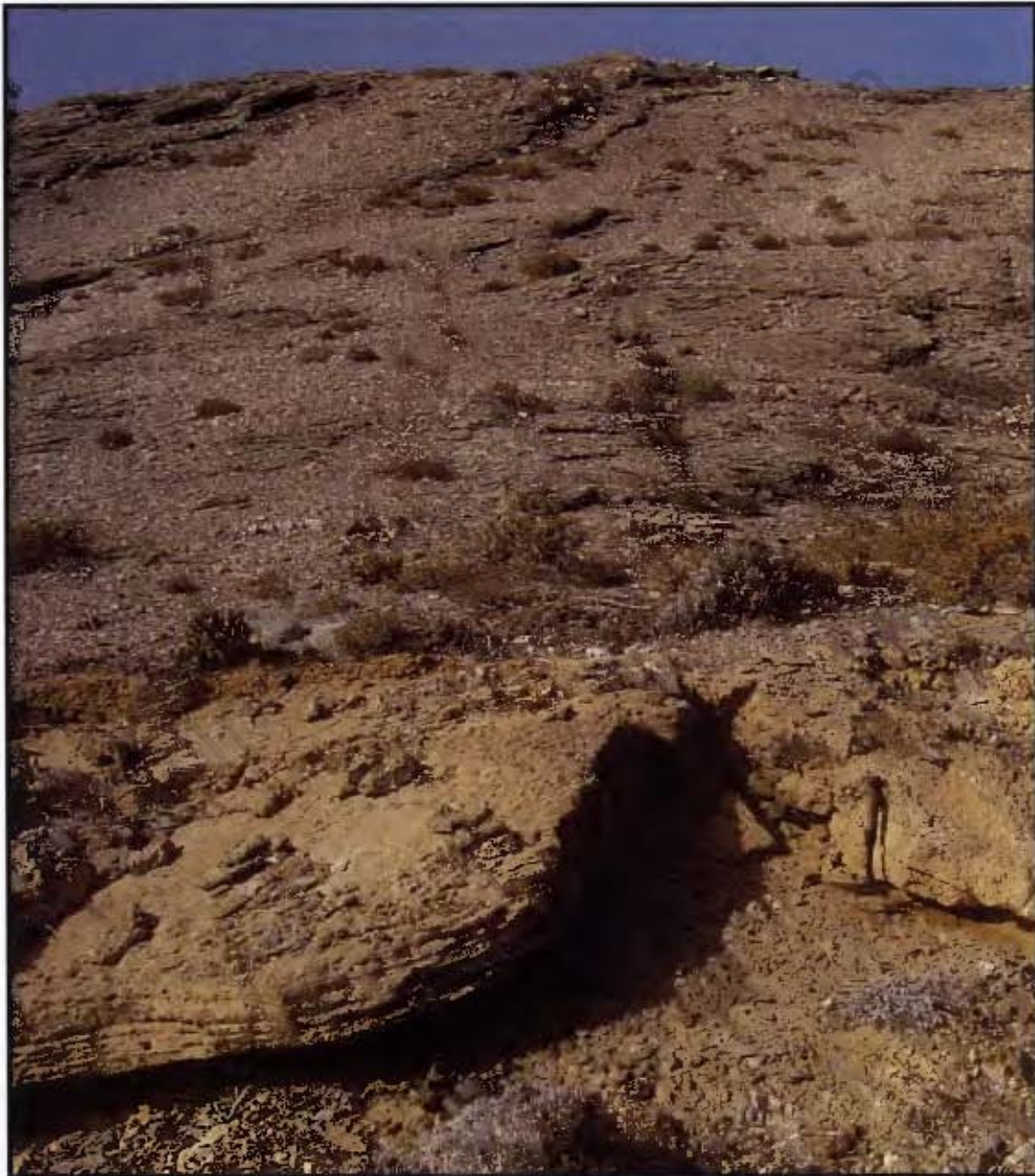


Figure 4.12: Facing east remnants of the Annental Beds sandstone resting unconformably on Diaz Point Formation rocks in the steep sided valley leading to the Fjord.

4.5 Structure

In the study area, the rocks of the Namaqua Metamorphic Complex have been subject to large scale folding on a roughly east-west trending axis. This is evident in the foliation which dips consistently north in the southern part of the study area, however in the northern part the dip changes to south. These changes in direction of inclination of dip indicate a syncline of which the axis is present in the vicinity of Albatroskop (Greenman, 1966), (Figure 4.13). Milne (1985) and Siegfried (1993) also noted a general northeast-southwest foliation with variable but generally steep dip. The oldest faults in the basement rocks strike uniformly 340° north, perpendicular to the foliation strike of the surrounding mixed gneiss. These faults are generally marked by sporadic vein-quartz ridges and they also offset gneissic and amphibolite bands by up to 100 m.

Two different thrust events resulted in the Wolf Bay Formation being sandwiched between the Proterozoic aged basement Namaqua Metamorphic Complex and the overlying Diaz Point Formation (Milne, 1985; Rispel, 2004). These correspond to the bedding sub-parallel thrust faults associated with the D1 and D2 events of the structural evolution of the Gariep Belt (Jasper, 1994).

Later northwest-southeast trending sinistral strikeslip faults cut both the Namaqua Metamorphic Complex and the Gariep rocks as well as displacing thrust faults associated with the Wolf Bay Formation and the Diaz Point Formation in the study area. The most prominent of the northwest-southeast faults is the Albatroskop Fault, which forms a marked positive topographic feature due to brecciated quartz infill along the fault plane (Siegfried, 1993; Milne, 1985; Greenman, 1966).

A series of parallel normal faults trending northwest-southeast occurs between Diaz Point and Grossebucht. These faults have a downthrow of 20 m on the southern block and preferential weathering and erosion along these faults has resulted in the formation of inlets such as Fjord, Essy Bay, Klein Bogenfels and Witmuur (Figure 4.13), (Siegfried, 1993). The rocks of the Diaz Point Formation which occurs along the coast generally dip steeply into the Atlantic Ocean to the west. The dominant foliation occurring in the Diaz Point Formation is oriented $192/16^{\circ}$. The foliation is bedding parallel and associated with intense mineral lineation trending $330/15^{\circ}$ and vein quartz. In the diamictite of Unit 3, the Qtz-granitic clasts have been severely deformed and wrapped by the matrix material (Siegfried, 1993).

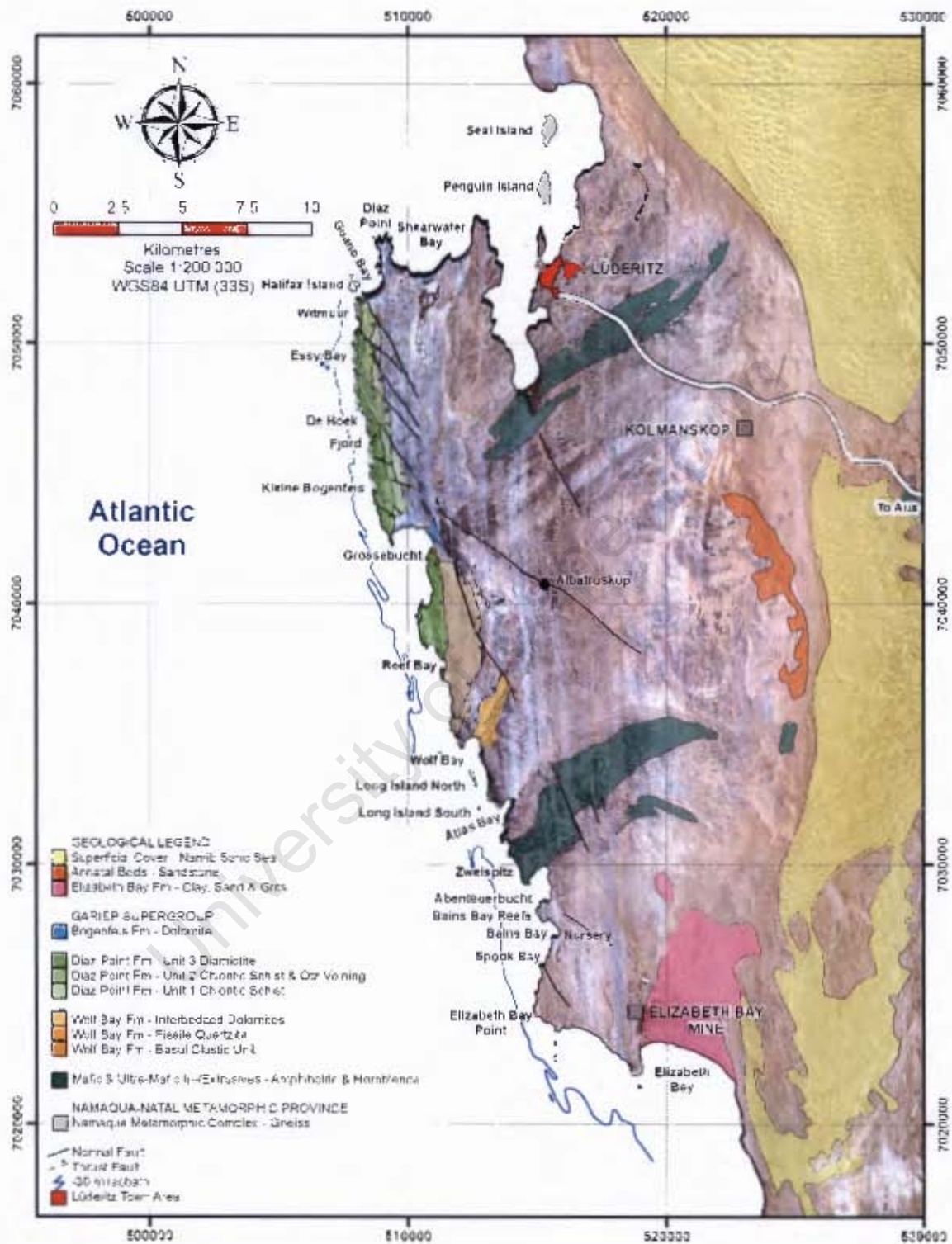


Figure 4.13: Geology of the study area displayed as a semi-transparent overlay with a satellite image as back-drop. Structural features are indicated (Rispel, 2004; Siegfried, 1993; Milne, 1985; Greenman, 1966). Also see Figure 4.1.

4.6 Diamond transport from the interior to the West Coast

Diamondiferous kimberlites were emplaced in the Kaapvaal craton in the interior of southern Africa mainly during the Cretaceous period (Figure 4.14). During the transport process from the kimberlite primary source of diamonds in the hinterland to the coast, Bluck *et al.* (2005) defined three types of diamond placers which were formed: 1. *Retained Placers* which remained on the craton; 2. *Transient Placers* when the placer is being eroded into the exit drainage and 3. *Terminal Placers* being the final depositories of the diamonds

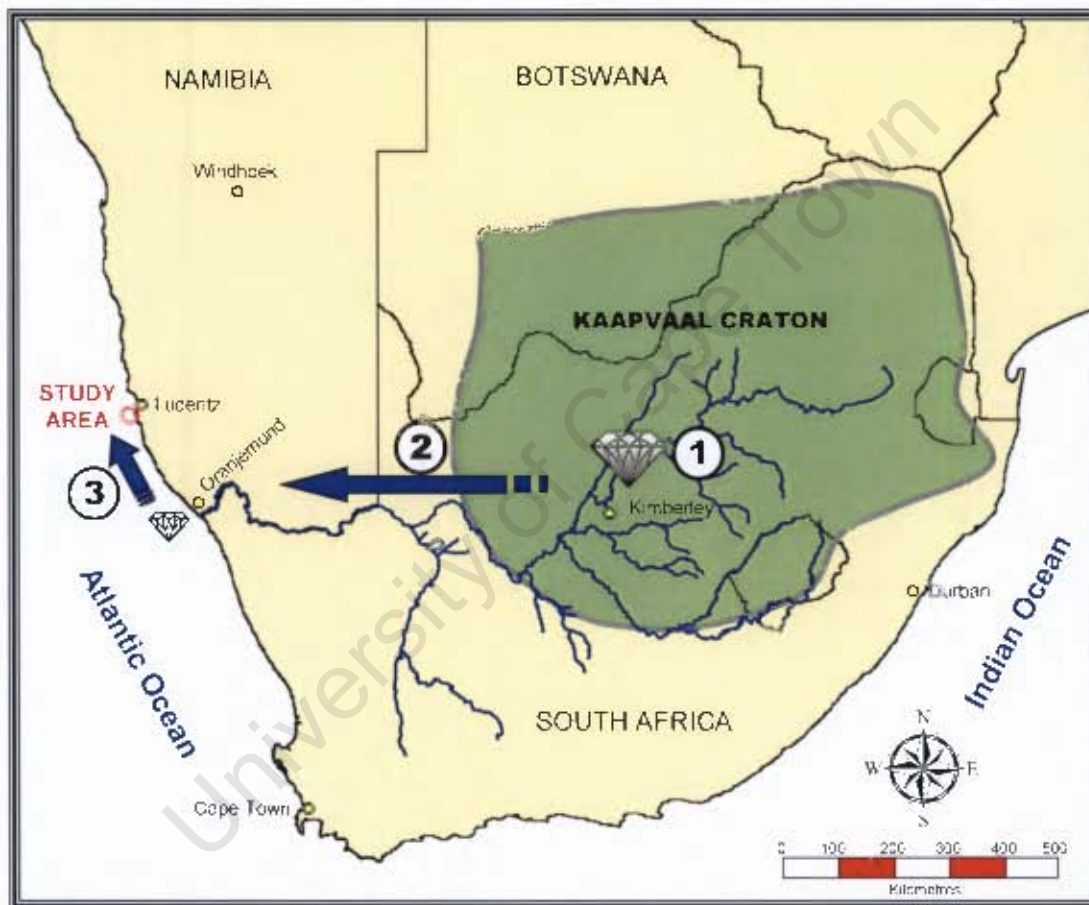


Figure 4.14: Transport of diamonds from source to sink simplified (1). Diamondiferous kimberlites emplaced on the Kaapvaal craton predominantly during the Cretaceous. Post-emplacment denudation and accumulation of diamonds occur. (2) Uplift of the interior of southern Africa results that a significant proportion of accumulated diamondiferous sediments are flushed to the coast through the Orange River drainage system in 2 major pulses. The first during the Miocene, which gave rise to the Proto-Orange Gravels, and the second during the late Pliocene/early Pleistocene forming the Meso-Orange River Gravels. (3). Transport of diamonds northward through wave action, longshore drift and wind action. Transport result in a well sorted, 95% gem quality, diamond population at West Coast.

During the humid late Cretaceous, severe erosion and subsequent denudation of the interior occurred. During this time, two major rivers drained the interior of southern Africa, a southern *Karoo River* and a northern *Kalahari River* (De Wit, 1999). During the Late Cretaceous the Karoo River channeled diamonds from the interior to the Olifants River mouth area in the south – this was a major period of transport of diamonds from the interior to the west coast (Dingle & Hendey, 1984; Kuhns, 1995; De Wit, 1999).

During the Miocene (De Wit, 1999) or the Eocene (Corbett, 1996), the Karoo River system was captured in the interior by the northern Kalahari River resulting in diamonds from the interior being channeled to the west coast via the Orange River mouth. Challenging this model, Moore & Moore (2003) suggests that a substantial portion of the West Coast diamonds originated from pre-Karoo kimberlites which were then transported from the interior of Southern Africa via Dwyka glaciation and then redistributed into the fluvial system after weathering of tillite deposits.

Walker and Gurney (1985) estimated that at least 3 billion carats were removed from known kimberlite pipes on the Kaapvaal craton by erosion. De Wit (1996) calculated that less than 1% of that remained in inland alluvial deposits.

Several major periods of asymmetrical uplift of southern Africa occurred causing an increase in interior erosional rates subsequently flushing large volumes of clastic material down rivers draining the interior. During the early Tertiary uplift of the interior (Partridge & Maud, 1987), gravel sized exotics were transported to the coast. Uplift during the Miocene gave rise to the Proto-Orange Gravels and the more recent uplift occurred during the late Pliocene/early Pleistocene forming the Meso-Orange River Gravels (Jacob *et al.*, 1999; Wigley & Compton, 2006; Bluck *et al.*, 2007). The delta front of the Orange Delta was eroded by marine processes and the wave action, longshore drift and wind distributed the diamondiferous gravels mainly northward of the river mouth (Bremner *et al.*, 1990; Ward & Bluck, 1997; Aizawa *et al.*, 2000; Bluck *et al.*, 2007). This process continued through various marine transgressions and regressions and the gravels were therefore deposited at elevations both above and below the present sea level. This marine transport system also acted as a sorting process. As a result the diamond placers along the Namibian coast display a clear size-sorted distribution of diamonds, with the average diamond size decreasing from the mouth of the Orange River northward (Hallam, 1964; Sutherland, 1982; Apollus, 1995).

4.7 Coastal diamond placer deposits

Marine, fluvial and aeolian processes shaped the terminal diamond placer along the coast of the Sperrgebiet into 4 broadly classified types namely linear beaches, pocket beaches, deflation deposits and aeolian deposits (Bluck *et al.*, 2005), (Figure 4.15).

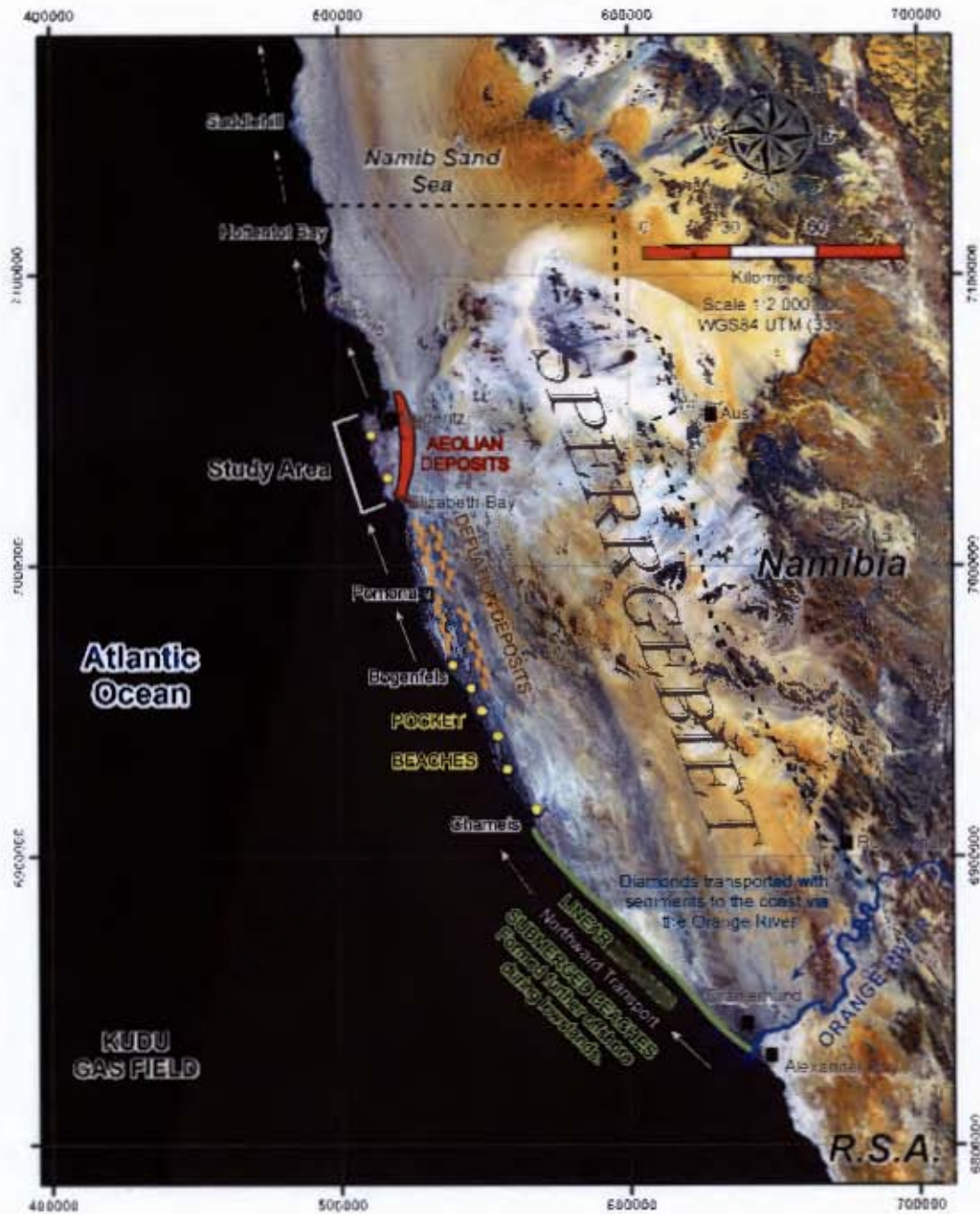


Figure 4.15: The 4 major diamond placer types found along the coast of the Sperrgebiet are linear beaches (on land and submerged), pocket beaches, deflation deposits and aeolian deposits (Source: Namdeb Archives)

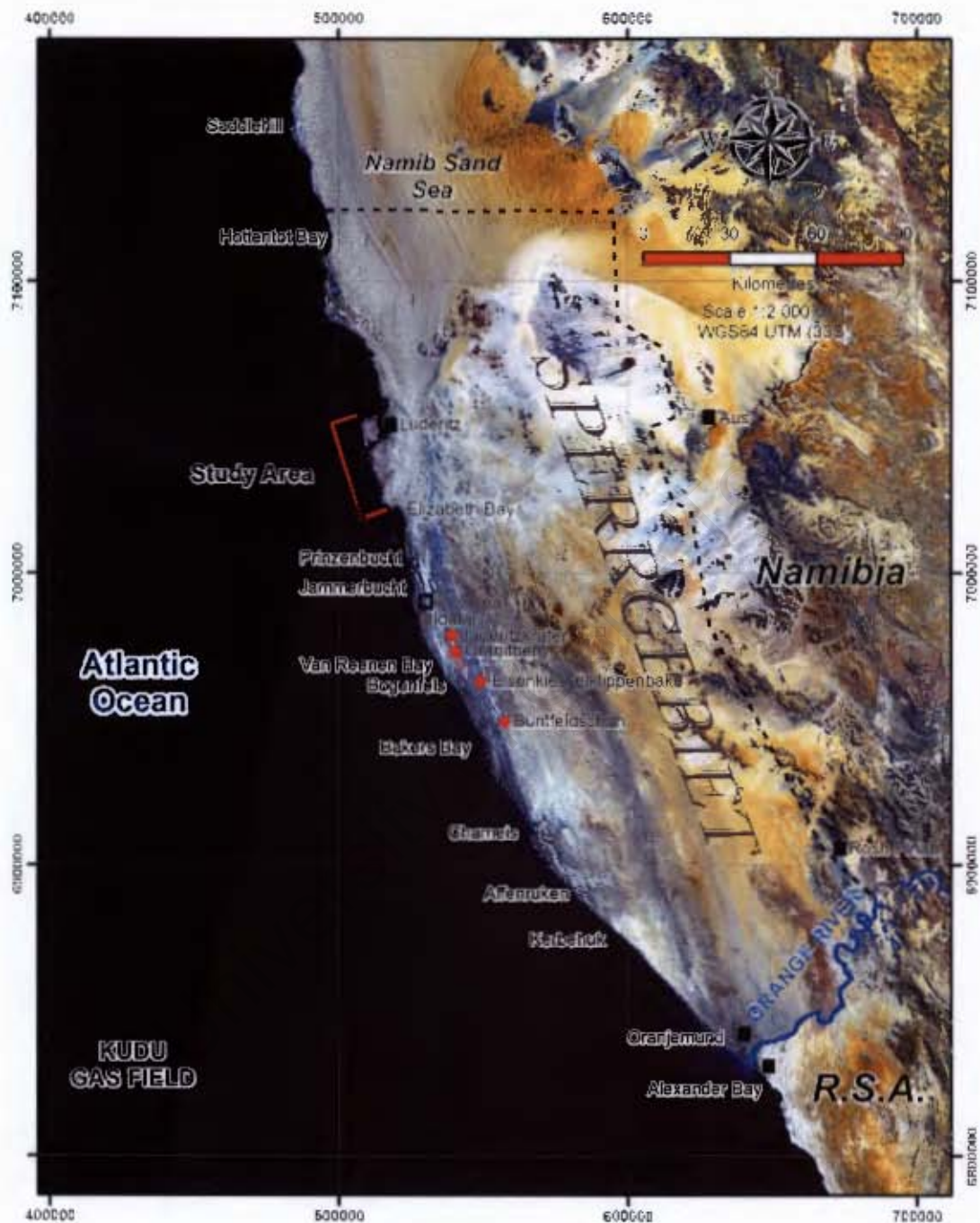


Figure 4.16: General locality map of the Sperrgebiet.

- Linear beaches:** The Plio-Holocene raised gravel beach complex is comprised of 6 shingle and basal conglomerate beaches and is partly covered by marine and aeolian sands which resulted in their preservation (Hallam, 1964). Between the Orange River Mouth and Affenrucken, 100 km to the north, the beaches have been deposited on a narrow marine abrasion platform (Figures 4.15 & 4.16). The width of the shelf varies

from 3000 m in the south to less than 200 m in the north and it has been cut by various river channels which have now been filled with silty clays and quartz rubble (Stocken, 1978; Rogers *et al.* 1990). The 6 beaches have been assigned letters A (youngest and lowest) to F (oldest and highest) for ease of identification (Figure 4.17).

The "Upper Terrace" beaches D, E & F, are characterised by warm-water fossil fauna such as *Donax rogersi* and *Crassostrea margaritacea* (Hallam, 1964; Stocken, 1978). The aggradational fluvial terraces, the Meso-Orange III River Gravels found in the lower Orange valley, are compositionally linked to the D, E & F beaches and the Namaqualand equivalent is the 30 m Package (Pether, 1994, 2008; Pether *et al.* 2000). It now seems increasingly likely that the 30 m Package was deposited during the mid-Pliocene i.e. older than 3 ma (Pether, 2008).

The "Lower Terrace" beaches A, B & C respectively occur at elevations of 2, 4 & 8 metres above mean sea level (mamsl) in the Sperrgebiet and were deposited from the mid Pleistocene to Holocene. These younger beaches are characterised by modern cold-water fauna and the absence of a red-sand or calcrete capping (Stocken, 1978). The Namaqualand equivalent of the A, B & C beaches of the Sperrgebiet is the *Recent Emergent Terraces* comprised of the 2-3 m Package, the 4-6 m Package and the 8-12 m Package (Rogers *et al.* 1990; Pether, 2008).

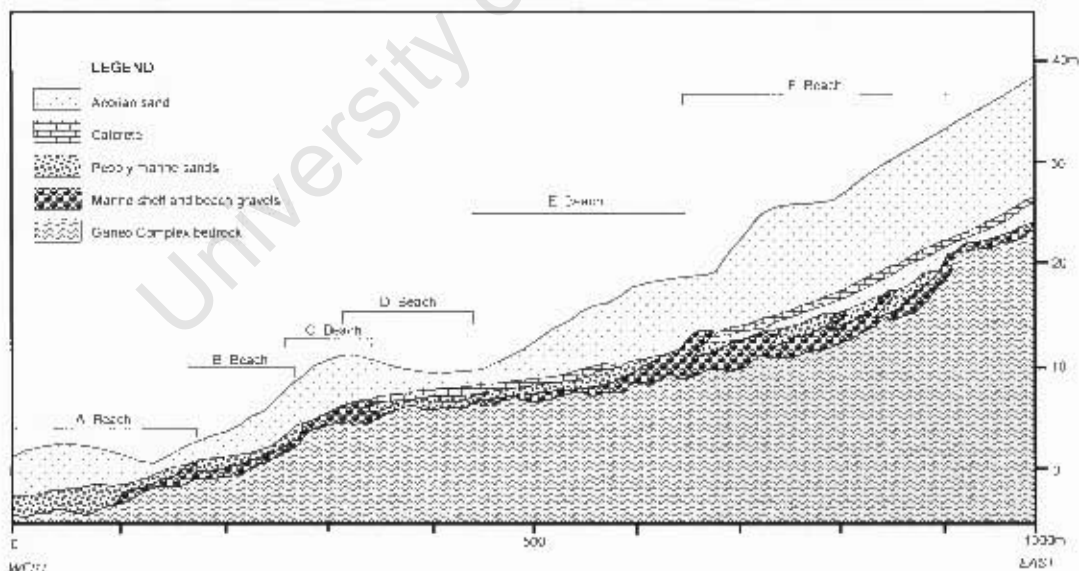


Figure 4.17: Schematic cross-section of beach terraces identified in Mining Area 1 (Stocken, 1978).

- **Pocket beaches:** Eustatic fluctuations and associated sea still stands resulted in the formation of gravel beaches both above and below present sea level. These were encountered as linear beaches along the straight coastline between the Orange River

Mouth and Affenrucken (Figures 4.15 & 4.16). From Chameis northward some of these beaches were preserved within embayments or 'pockets' along the rocky coastline (Figure 4.15). Apollus (1995) has shown that the greatest diamond concentration occurred in the northern part of the + 4m beach facies (Eemian age) in the southwest facing pocket beach of Chameis Bay in the Sperrgebiet (Figure 4.18). It was also shown that diamonds in these intertidal deposits do not necessarily gravitate to the base of the marine gravel sequence, so much so that the beaches themselves contained considerable concentrations of diamonds – not necessitating the presence of shore platform trapsites to concentrate diamonds. However, these raised gravel beaches were most likely to be destroyed during subsequent sea-level fluctuations. In the Chameis pocket beach specifically, the most important factors in diamond concentration in intertidal beach facies are the processes of beach accretion and wave energy levels. Gravel clast size appeared to have played a lesser role in the concentration of diamonds. Several pocket beach deposits of varying grade occur between Chameis in the south and Bogenfels in the north.



Figure 4.18: Facing north, the Chameis Bay pocket beach situated between two rocky headlands (Photo: Namdeb Archives).

- **Deflation deposits:** The deflation deposits occur mostly in the "talle" (valleys) of the Trough Namib north of Chameis Bay. Through transgression and regression cycles, shoreline beach sequences were deposited at various levels through time in the current



Figure 4.20: Ventifacted exotics from the remnant Eocene shoreline at Lüderitzkrater bearing evidence of the aggressive wind regime in the central Sperrgebiet. Exotics photographed include, 1. black chert; 2. agate; 3. chrysoprase; 4. jasper; 5. yellow chalcedony and 6. lutite banded ironstone formation



Figure 4.21: Facing north, the polished, wind fluted surface of a dolomite yardang near Lüderitzkrater bears evidence of the aggressive southerly wind regime in the central Sperrgebiet.

Aeolian deposits: At present times there are four major coastal point sources supplying sediment to the Namib Sand Sea. The strong, consistent southerly wind regime deflates the beaches from the Chameis Bay, Bakers Bay, Van Reenen Bay and the Prinzenbucht-Elizabeth Bay areas and the sediments are transported northward along Aeolian Transport Corridors in the form of Barchan dunes and surface sediment creep (Figure 4.22). (Corbett, 1989; Corbett *et al.*, 1993). These dunes are up to 33 m high and move 60-100 m northward per year. An Aeolian Transport Corridor (ATC) is defined as a narrow, wind-parallel zone, about 1-2 km wide, in which sediment is transported by aeolian action. The generation of ATCs are controlled by sediment supply to the aeolian system, which is governed by coastal morphology (log-spiral embayments), which in turn is a function of deflation basin geomorphology and sea-level. ATCs move in conjunction with eustatic fluctuations – parallel to the coast (Rogers *et al.*, 1990).

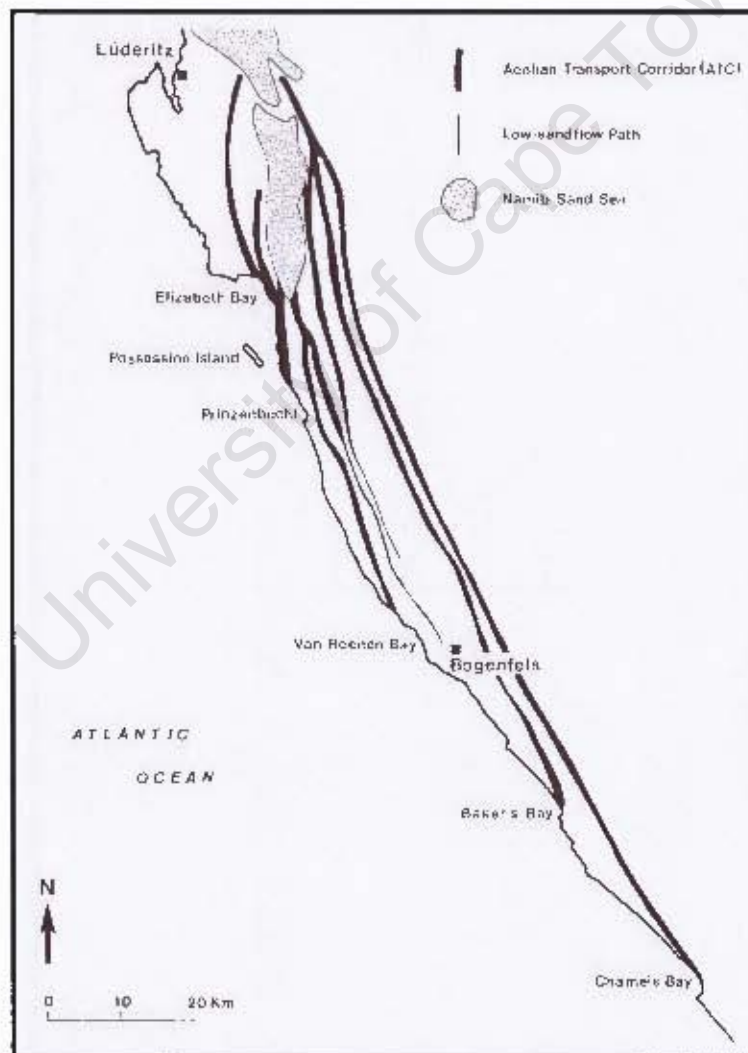


Figure 4.22: Present-day distribution of the aeolian transport corridors that maintain the Namib Sand Sea (Corbett, 1989).

The world's largest economical aeolian diamond placer is situated at Elizabeth Bay (Figure 4.23). This area of high sediment flow is particularly important to this study because it is situated at the southern end of the study area. The south-facing re-entrant embayment effectively acts as a headland bypass system whereby sediment is moved from a coastal setting into a terrestrial setting by the wind, and then re-introduced back into the marine coastal environment to the north of Lüderitz (Corbett *et al.*, 1993).



Figure 4.23: Facing west, an oblique aerial photograph of Elizabeth Bay which is the largest south facing embayment found along the Namibian coast and the location where the world's largest economical aeolian diamond placer is situated.

Mining of diamondiferous aeolian grits at Elizabeth Bay commenced in 1911 by the *Deutsche Kolonialgesellschaft für Südwestafrika* who continued mining until 1915. Following World War One, the *Consolidated Diamond Mines of South West Africa* continued the mining activities until the mine was closed in 1948 (Schneider & Miller, 1992). In 1991 the Elizabeth Bay Mine was opened for the third time and Namdeb is expecting that mining will continue well into the future.

5. COASTAL PROCESSES

5.1 Sea-level change

Along the southern coast of Namibia changes in sea-level have largely been driven by global climate change because since the late Cretaceous/early Tertiary the west coast of southern Africa has mainly been a passive margin (De Wit, 1999; Van der Wateren & Dunai, 2001). Two events of asymmetrical continental uplift, centred in the eastern side of southern Africa, occurred during the Miocene and the late Pliocene/early Pleistocene (Jacob *et al.*, 1999; Wigley & Compton, 2006). Since the Eocene there has been a global long term drop in sea-level (Figure 5.1), (Haq *et al.*, 1987).

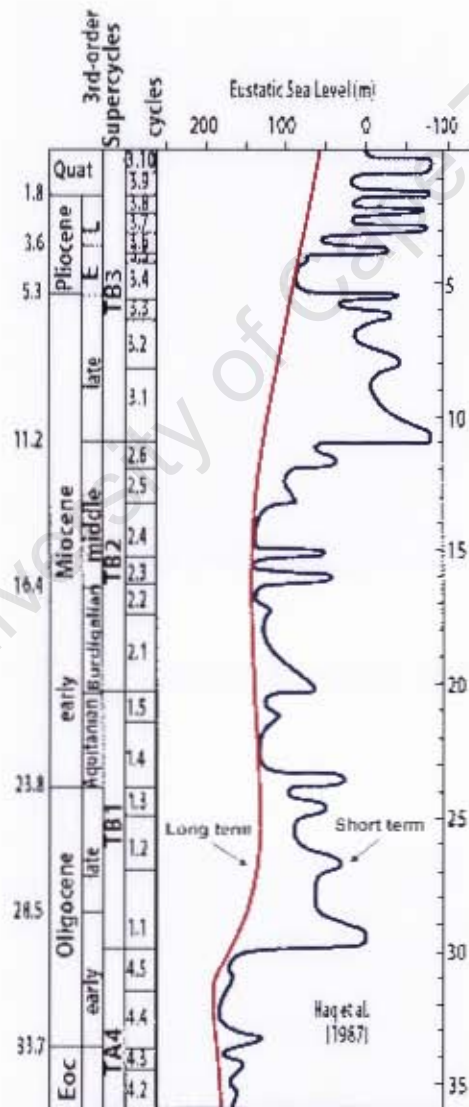


Figure 5.1: The global eustatic sea-level curve since the Eocene with the short term and long term fluctuations indicated respectively (Haq *et al.*, 1987).

Slow and erratic cooling saw the gradual build-up of the ice caps, especially the Antarctic and the Arctic, locking up water and causing global sea-levels to drop. These cold and dry periods were then briefly broken by warmer and wetter (interglacial) periods when the ice melted and the sea-levels rose again (McCarthy & Rubidge, 2005). Several of these cycles occurred at fairly regular intervals since the Pliocene (Haq *et al.*, 1987). During the Pleistocene, the earth experienced a succession of ice ages roughly every 100 thousand years (ka). The last of these cycles commenced with an interglacial period from approximately 124 ka to 116 ka ago (Figure 5.2). This was followed by a glacial period which saw sea-levels dropping. At the height of the build-up of the ice caps during the Last Glacial Maximum (LGM), about 19 ka ago, the sea-level was approximately 125 m below present day level (Fairbanks, 1990; Yokoyama *et al.*, 2000). A transgression occurred over the following 12 ka when sea-level rose by 127 m. During this period sea-level rose distinctly rapidly on two occasions when Melt Water Pulses (MWP) occurred at 14.3 ka and at 11 ka ago (Compton *et al.*, 2002).

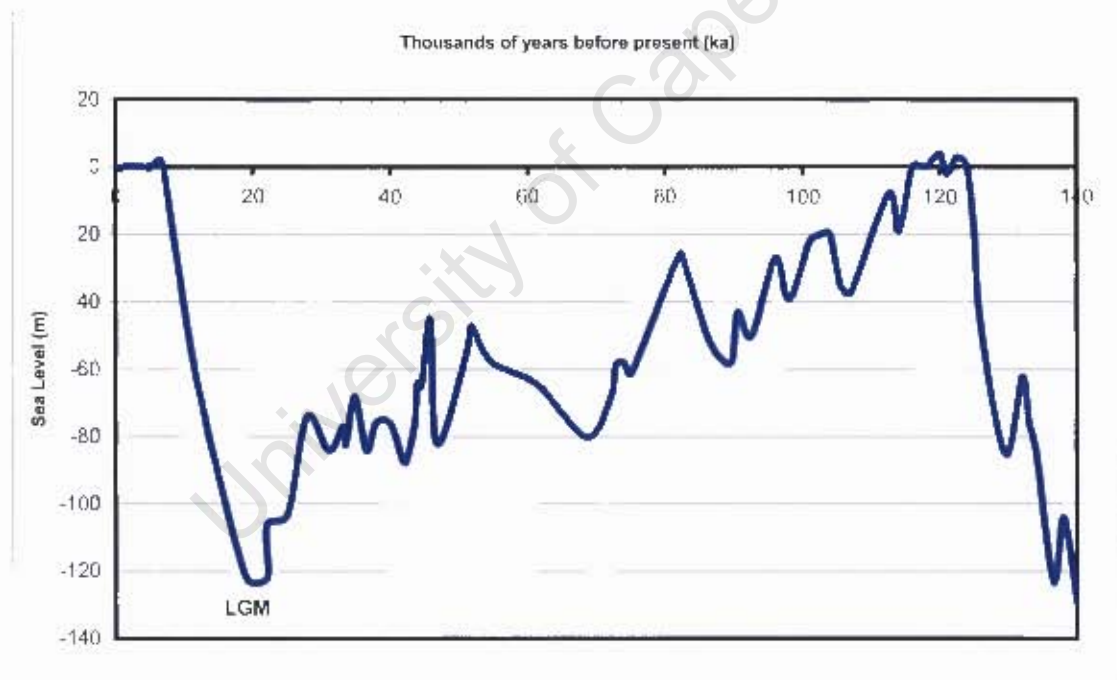


Figure 5.2: Composite sea-level curve for the last 140 ka (Compton, 2001; Compton *et al.*, 2002; Yokoyama *et al.*, 2000; Chappel *et al.*, 1996; Fairbanks, 1990; Shackleton, 1987).

Following the last MWP, sea-level rose to approximately 3 mamsl at about 6.5 ka ago (Compton, 2006). A regression followed with sea-level dropping to about -1 m below present sea-level 5.5 ka ago, where after it remained within 1 m of present sea-level (Figure 5.3).

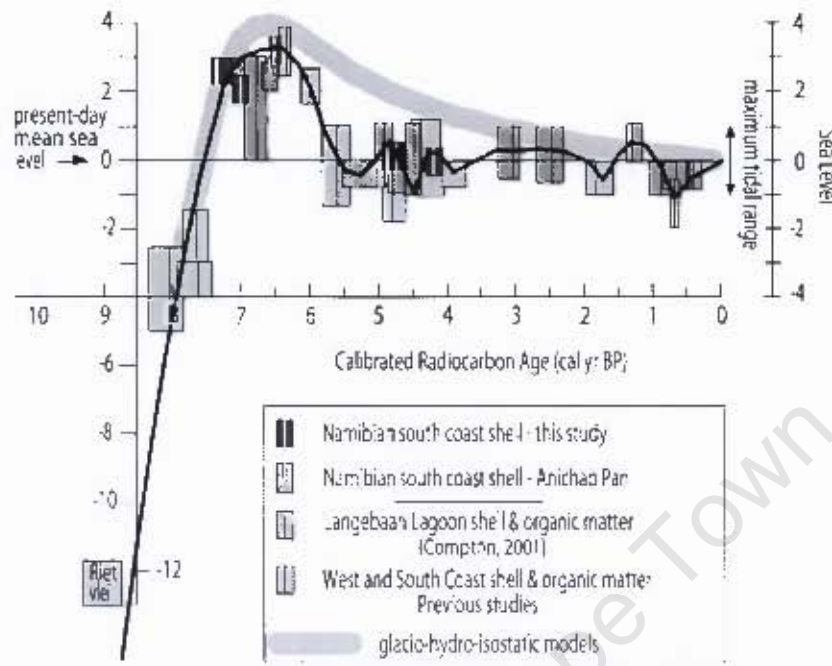


Figure 5.3: Holocene sea-level curve (dark, thin line) drawn through the data points of work in Langebaan (Compton, 2001), data from Bogenfels Pan (Compton, 2006) and Anichab Pan (Compton, 2007). The broad grey line shows the sea level curve predicted for continental margins from glacio-hydro-isostatic models assuming no eustatic changes after 6500 years BP (Compton, 2006).

5.2 Marine platforms

In southern Namibia the coast is underlain by Precambrian rocks characterised by phyllites, schists and gneiss. The footwall has been eroded by high-energy surf conditions creating marine erosional platforms at various levels above and below present sea-level. Extensive marine erosional platforms have formed along the coast in the southern Sperrgebiet due to the following factors (Jacob, 2001):

- Coarse sediments providing abrasive agents;
- Intense wave energy to provide abrasive action;
- Receptive bedrock lithology (softer than abrasive agents), dip & strike and jointing.

Horizontally bedded, relatively soft or gently dipping bedrock is more likely to have well developed terraces than steeply dipping or hard bedrock (O'Shea, 1971).

At sea-level still stands, erosion of the bedrock has formed seaward sloping terraces which usually have wave cut cliffs on the landward side. The change in gradient between the base of

the cliff and the landward end of the terrace is called the nick point. The extent (distance from coast and the magnitude of change in gradient) of the nick point incursion depends on (Anderson *et al.*, 1999):

- Duration of the sea-level highstand;
- Wave energy;
- Degree to which bathymetry dissipates wave energy.

The presence of nick points has been used to identify and map palaeo shorelines. Several such terraces have been identified on the inner shelf of the west coast of southern Africa at depths of -10 m, -14 m to -16 m, -18 m to -20 m, -22 m to -25 m, -30 m, -38 m, -44 m, -50 m, -60 m and -75 m (Rau, 2003).

Using diving surveys, Collina-Girard (2002) identified nickpoints in the western Mediterranean Sea and the Caribbean Sea at depths of -11 m, -17 m, -25 m, -35 m, -45 m and -55 m. As these notches were identified at similar depths at two geographically dispersed sites (Mediterranean and Caribbean), Collina-Girard (2002) suggested that these were formed by the same lower eustatic sea-levels during the Late Quaternary. The similarity in depths of nickpoints identified along the west coast of southern Africa adds value to this statement.

5.3 Waves and Longshore Drift

Wind-generated waves form due to the frictional stress between the air and the water when the wind blows over the water. The size of the waves is governed by the combination of wind speed, the length of time the wind has been blowing and the unobstructed distance of water, or fetch, over which the wind has blown. The wave base is half of the wavelength and this is the maximum theoretical depth at which the wave transfers energy directly to the sea-bed (Brown *et al.*, 1989).

Offshore		Nearshore			
Seaward of breaker zone		Breaker zone	Surf zone	Swash zone	
WATER MOTION	Airy - sinusoidal	Stokes (steep crests, wide troughs)	Spilling, plunging, breaking	Bore, reformed waves	Bore reflected swash
DOMINANT TRANSPORT DIRECTIONS	Onshore offshore	Onshore offshore (bedload - suspended load)	Longshore?	Longshore	Reflection, return flow
VELOCITY VECTORS	Symmetric ← ● →	Asymmetric ← ● →	Parallel to shore	Parallel to shore	← ● →
GRAIN SIZE TRENDS	coarser →	coarsest grains	← coarser →	bi-modal	
PREDOMINANT ACTION	accretion	erosion	transportation	erosion & accretion	
SORTING	better ←	poor	mixed	better →	
ENERGY	increase →	high	gradient →	oscillatory ← →	

Figure 5.4: Classification of waves and sediment transport in nearshore and offshore environments (Martinez & Harbaugh, 1993).

Work by Martinez and Harbaugh (1993) have shown that the highest energy portion of the marine wave system is the breaker zone. As a wave approaches the coast the water depth decreases. At the point where the water depth is less than the wave height, the wave breaks. This is the point where the wave has its highest energy and subsequently this is the area where the breaking wave will bring the highest amount of clastic material in suspension, and transport it (Figure 5.4). Consequently the breaker zone is also the area where the highest degree of erosion occurs and where the deepest features will be cut into the underlying strata (Figure 5.5).

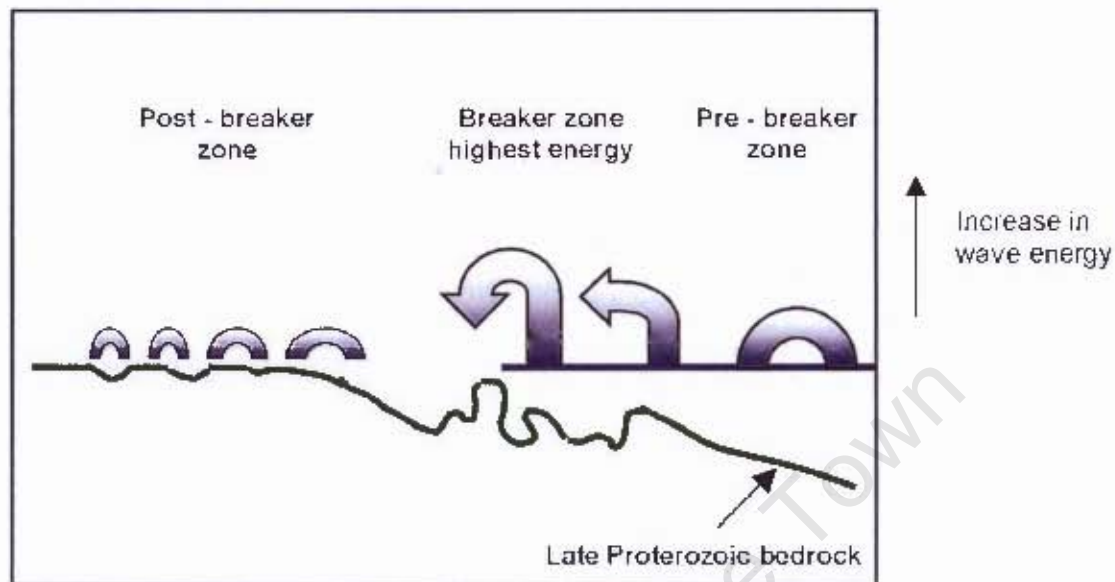


Figure 5.5: Schematic representation of wave energy and its relation to depth of incision into bedrock during a sea-level stand still (Jacob, 2001).

On the marine cut platforms erosional features form trapsites such as gullies, potholes, cliffs and wave-cut platform caves. These features create high quality trapsites for the concentration of diamonds transported northward from the Orange River mouth by the longshore drift (Hallam, 1964; Joynt, 1979; Corbett, 1996; Jacob, 2001). Based on work between Oranjemund and Chameis, Wright (1964) proposed the following ideal cycle of gully evolution (Figure 5.6):

- Incipient: Isolated potholes and aligned potholes of which the resulting trends are highly variable. Very little (<10%) of the bedrock surface dissected.
- Youthful: Coalescence of potholes into closed gullies with some uniformity of trend. Up to 50% of bedrock surface dissected.
- Mature: Coalescence of closed gullies to form an integrated drainage system of open gullies which follows a definite trend. Up to 80% of bedrock surface dissected. Maximum gully depth is reached at the start of maturity.
- Post-mature: Reduction of inter-gully area so that islands of the original bedrock shelf mark the direction of alignment.

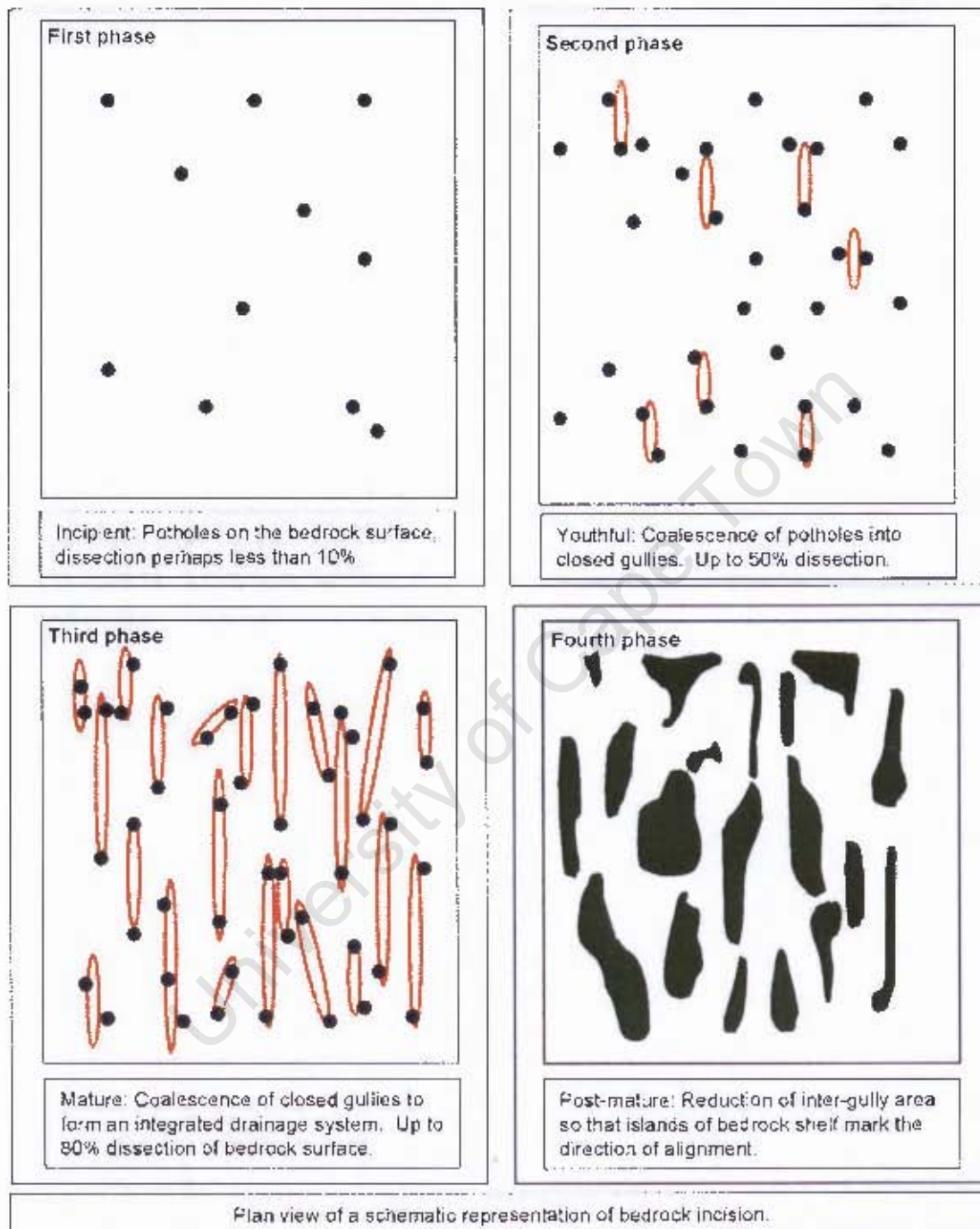


Figure 5.6: Ideal cycle of gully evolution (Wright, 1964; Jacob, 2001)

Along the coastline from the Orange River mouth northward to Chameis, a gradation of three dominant types of bedrock diamond trapsites have been identified namely: 1) Swash parallel gullies, 2) Strike gullies and 3) Joint gullies (Murray *et al.*, 1970; Jacob, 2001). The gradation is related to the availability of abrasive agents and influenced by the macro structural features in the

bedrock. Studying these features Jacob (2001) found that diamond concentration is directly linked to the availability of diamondiferous material, the quality and quantity of the trapsites, and the degree of reworking (enrichment) that has taken place.

- The quality of the trapsites increased with increasing incision into the bedrock. The deepest incision into the bedrock was found to be on the seaward end of the palaeo platforms, therefore associating the highest quality trapsites with transitions between platforms.
- The degree of reworking is determined by the degree of turbulence and the length of time the deposit underwent the turbulence or the length of the sea-level still stand.

Highly diamondiferous deposits can therefore be encountered on a smooth wave-cut platform due to prolonged exposure to high turbulence as a result of a long period sea-level still stand.

5.4 Cementation

Cementation of Cenozoic sediments in the northern Sperrgebiet is common in the terrestrial setting (Corbett, 1993; Jamieson & Talbot, 1983; Milne, 1985). Offshore in the shallow marine environment, cementation of sediments has been widely reported and documented in production logsheets by divers conducting diamond mining operations in Namdeb-held mining licences. Cemented sediments are also frequently encountered in deeper water mining operations by the De Beers Marine Namibia and related contractor mining vessels.

Using $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and $\delta^{18}\text{O}$ values Compton *et al.* (2001) showed that groundwater was involved in the formation of dolomite cement in sediments recovered from -60 m to -65 m water depth off Saddle Hill north of Lüderitz. The dolomite formed during sea-level low stands when emergent local depressions focused groundwater and weathered Precambrian bedrock. Through evaporation, radiogenic Sr was concentrated in groundwater which in turn mixed with evaporated seawater. This enhanced the dolomitization of biogenic marine carbonate in sediments deposited during the previous interglacial sea-level highstands (Compton *et al.*, 2001).

Pettijohn *et al.* (1987) states that the precipitation of dolomite is dependant on the brine being Mg-enriched relative to Ca. The brine may not be sufficiently enriched in Mg because of insufficient top-up of seawater, insufficient evaporation or constant addition of meteoric or ground water to the mixture. In such cases the solution will be relatively Ca-enriched and calcite is likely to precipitate as cement. The depletion of Ca, relative to Mg, by the precipitation of CaCO_3 from the evaporating waters can then be followed by dolomite precipitation from the Mg-enriched brine.

Through these processes, as described by Compton *et al.* (2001) and Pettijohn *et al.* (1987), it is likely that variable dolomite/calcite cementation of trapsite filled sediments in the study area were formed (Figure 5.7).

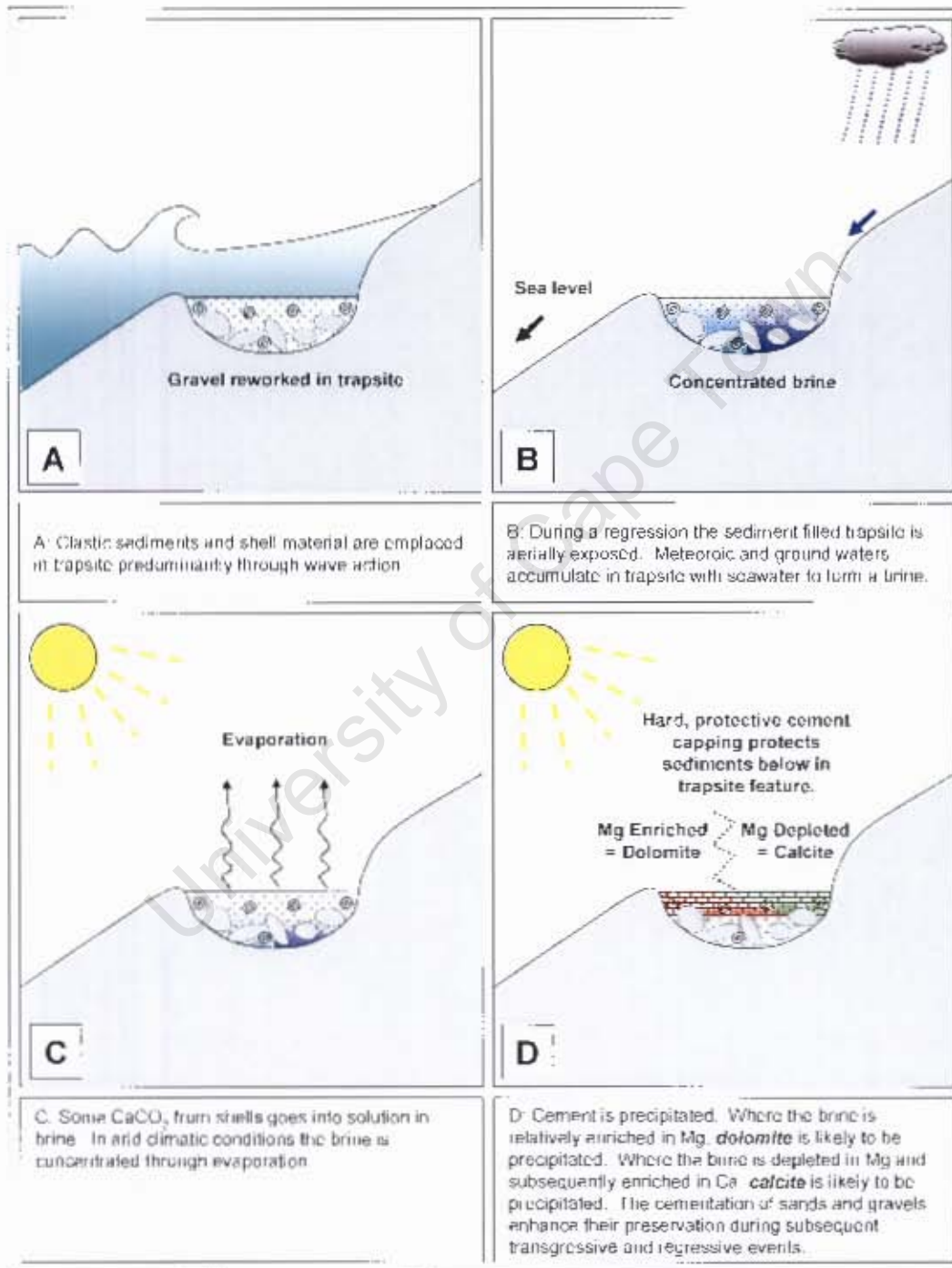


Figure 5.7: Cementation process of sediment filled depressions (Pettijohn *et al.*, 1987; Compton *et al.*, 2001).

6. METHODS

For the purpose of this study data were collected from various sources which range from informal discussions with divers to a formal and structured sampling programme as summarised in Table 6.1. The combination of several geophysical surveys in the study area provides a platform from which geomorphological observations can be made and on which the diver-assisted mining and sampling activities can be displayed in a meaningful context. The historical data sets generally have a lower associated level of confidence. Numerous interviews with experienced divers who did the actual mining were used to place historical records in context.

Apart from the results for the sampling programme, the combined dataset contain very few records which reflect "zero diamonds recovered". Basically only the areas which yielded positive results were recorded in the historical and recent production records. This situation was brought about due to the divers continuously testing their gravels for diamond content whilst at sea. Following strict security procedures gravel is concentrated using a Pletz jig and the concentrate is sorted on board with all diamonds recovered recorded in a diamond register (Figures 6.1 & 6.2).



Figure 6.1: A diver (P. Calitz) attending the jig onboard the *mv Rachel* while mining off De Hoek.

See Figure 4.1.



Figure 6.2: A diver (B. Mitchell) sorting through jiggled concentrate for diamonds onboard the *mv Rachel* while mining of De Hoek. See Figure 4.1.

If the material sorted yielded negative results it would most likely be discarded overboard. The vessels used in these mining operations tend to be small with a carrying capacity of only 20-40 tons. Divers can only spend a limited amount of time underwater each day due to the physiological constraints of working in a pressurised environment. These factors combined with the limited access to the mining grounds due to environmental conditions including swell exceeding 2.0 m in height, exceptionally strong winds and poor visibility in the water column, necessitates that only diamond bearing gravel be transported back to Lüderitz for treatment in order for these operations to be profitable.

Data Source	Information obtained	Rank
Geophysical Surveys	<ul style="list-style-type: none"> • Airborne Laser Survey (ALS), 2000 • Sidescan Sonar, using Klein 3000, 1999. • Multi-beam Bathymetry surveys using Reson Seabat 8125, 2002 & 2006. 	A
Author's Observations	<ul style="list-style-type: none"> • Dives in De Hoek and Grossebucht areas • Examination of rock samples • Field observations • 2002-2007 	A
Sampling Programme	<ul style="list-style-type: none"> • Production data, detailed logs, sketches and descriptions • Accurate positional data • Relatively accurate area measurement • 1999, 2000, 2002, 2003. 	A
Size Frequency Data (SFD) of diamonds recovered	<ul style="list-style-type: none"> • Accurate SFD's of diamond parcels for actual sampling and production data • 1992-2006 	A
Recent Production Records	<ul style="list-style-type: none"> • Production data, detailed logs, some sketches and descriptions • Positional data accurate within 30 m radius • Area measurement estimated in low visibility conditions • 2002-2006 	B
Interviews	<ul style="list-style-type: none"> • Obtained gravel log descriptions for Zweispitz and Spook Bay areas as well as general composition of sedimentary sequence • Assigned more accurate positions and depths mined to historical surf zone records. 	B
Historical Production Records – Shallow Marine Vessels	<ul style="list-style-type: none"> • Production data • Positional data at best accurate within 100 m radius, questionable in some instances • No logs, sketches, descriptions, area measurements or other data • 1990-1999 	C
Historical Production Records – Surf Zone	<ul style="list-style-type: none"> • Basic production data (cts & stones (stns)) • Positional data – only the place name from which security collected production • No logs, descriptions, area measurements or other data • 1991-2004 	C
Historical Production Records – Landbased Mining	<ul style="list-style-type: none"> • Basic production data (cts & stns) • Position and areas mined and sampled obtained from survey records • No logs, descriptions or other data • 1993-1996 	C
<p>Confidence Ranking A High confidence, accurate stand-alone records which can be referred to individually. B Medium confidence, use records in conjunction with geographically proximal records. C Low confidence, use dataset for features in conjunction with higher confidence sampling and mining records, interviews and geophysical data.</p>		

Table 6.1: Summary of data sources and associated confidence ranking.

6.1 Geophysical Surveys

Several geophysical surveys were conducted in the study area between 1999 and 2006. In 1999 a sidescan sonar and single beam bathymetry survey was completed using a *Klein 3000* deployed off a catamaran survey vessel, the *sv Villa Via*. Due to its low draught and manoeuvrability this vessel was able to survey in extremely shallow waters (2.0 m depth) in calm conditions. Multi-beam (swath bathymetry) surveys followed in the study area in 2002 using a Seabat 8125 system. A further survey in the Zweispitz area followed in 2006 also using a Seabat 8125 deployed off a converted fishing trawler, the *SW Snowgoose* (Figure 6.3)



Figure 6.3: The *SW Snowgoose*, photographed alongside in the Lüderitz port, was used for the 2006 multibeam survey.

6.2 Diver Sampling Programme

Namdeb undertook a diver-assisted sampling programme in the study area between 1999 and 2003 and focused activities between -14m and -27m depths (Figure 6.4). The objective of the sampling programme was to establish the feasibility of using diver-assisted sampling to develop a shallow marine resource of reasonable confidence to reduce the risk of the shallow marine diver-assisted operations.

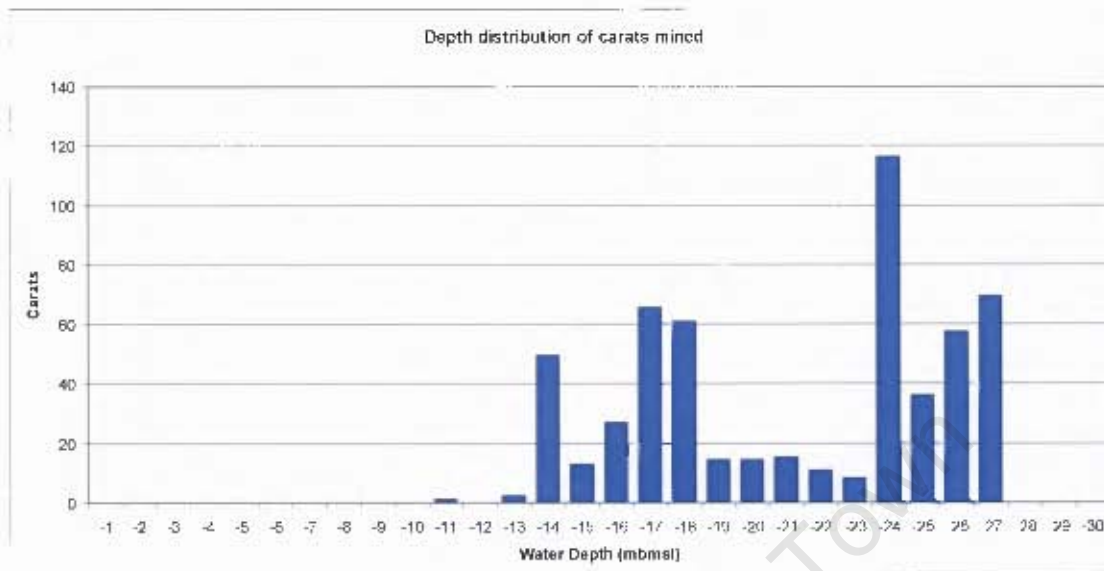


Figure 6.4: Depth distribution of diamonds mined according to the diver sampling records.

Although good results and a good data-set was obtained from the sampling programme (Figure 6.5), the combination of high sampling cost, limited access to sampling area and the inherent weather dependency of working in the shallow marine environment resulted that the programme was discontinued.

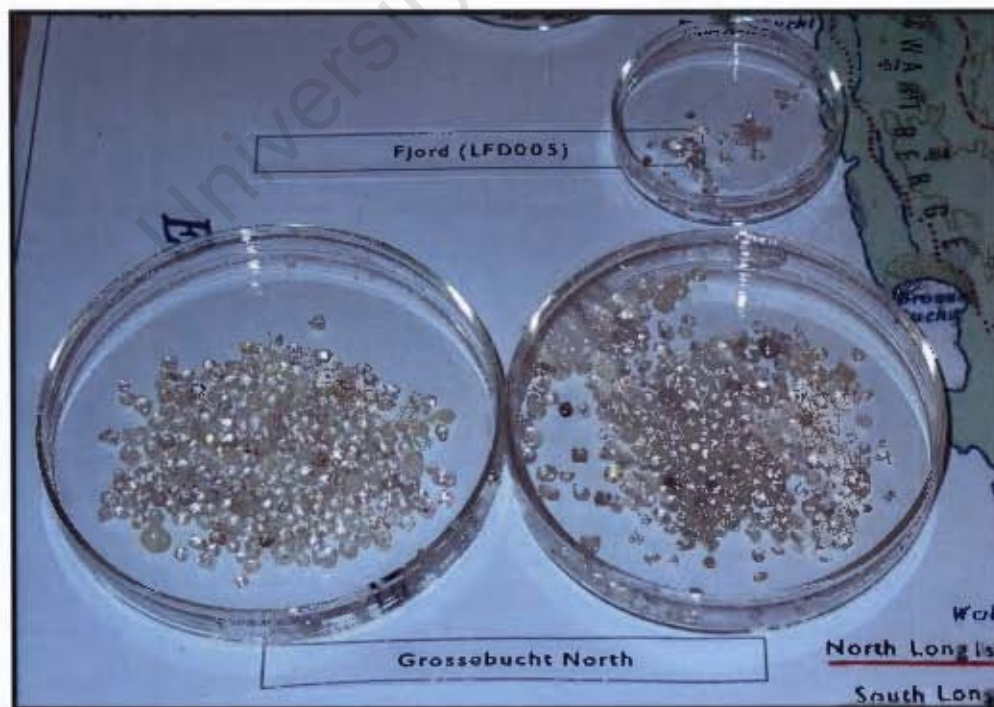


Figure 6.5: Some of the diamonds recovered during the diver-assisted sampling programme.

The diver sampling team recorded the sampling details and basic geological information for each sample, which was collected on logsheets similar to the recent production records (Figure 6.6). This information was checked and in some instances the sampling pits were inspected by the author to log gravels, ensure sampling quality and to verify the measured sample size (m^2). The diver sampling dataset contain 25% ($n=48$) zero values and therefore provides a fair reflection of the background values. A total of 192 diver sampling records representing 557 cts were used for the purpose of this study. Diamond size frequency data were obtained for 74% (411 cts) of the carats recovered in the diver sampling programme. The size frequency sieving was done by the Namdeb Geological Laboratory in Oranjemund.

University of Cape Town



NAMDEB
ON DIAMONDS WE BUILD

Contractor Operations - Diver Production Log

GENERAL

CTF OFFLOAD No.	237	CTF Bin Numbers	17
DATE (dd/mm/yyyy)	29/08/2002	LOCATION MINED	LGN 002 H
CONTRACTOR	ALMA MARINE	TYPE PRODUCT	(Gravel) (DMS Conc.)
VESSEL	REBECCA	EASTING (m) UTM 33 WGS84	508501
SUPERVISOR	P. H. HEAD	NORTHING (m) UTM 33 WGS84	7043478
No. OF BAGS	43	No. OF DIVERS	4
Kg / Bag (average)	25 kg	TOTAL DIVE TIME (hh:mm)	04 HRS 22 MIN
AREA MINED (m ²)	4 m	DIVE ACTIVITY	(Mining) (Prospecting) (Re-mining)
DURATION OF TRIP (days)	2		

RESULTS (To be completed by CTF Foreman)

HEADFEED WEIGHT (TONS) 1,075 RECEIPT NUMBERS 198

RECOVERED	STONES	CARATS
Potjie (jigged)	—	—
Plant (CTF)	201	48.72
Specifieds	—	—
TOTAL	201	48.72

LIST SPECIFIEDS N/A

SEA CONDITIONS

WATER DEPTH DIVED (m) From 24 meters To 24 meters

VISIBILITY AT BOTTOM: (<1m) (1-2m) (2-3m) (>3m)

SWELL HEIGHT: (<1m) (1-2m) (2-3m) (>3m)

SWELL DIRECTION (COMING FROM): (N) (NE) (E) (SE) (S) (SW) (W) (NW)

BOTTOM SURGE: (None) (Slight) (Strong) (Very Strong)

BOTTOM CURRENT: (None) (Slight) (Strong) (Very Strong)

CURRENT DIRECTION (FLOWING TO): (N) (NE) (E) (SE) (S) (SW) (W) (NW)

Figure 6.6: Example of a production and sampling logsheet (page 1/4).

GEOLOGY

Bedrock /Footwall

BEDROCK REACHED? (Yes) (No)

BEDROCK CONTACT: (Sharp) (Gradational) (Irregular) (Weathered) (Other)

OTHER CONTACT:

ROCK TYPE: (Gneiss) (Conglomerate) (Clay) (Schist) (Sandstone) (Other)

OTHER ROCK TYPE:

BEDROCK SHAPE: (Flat) (Irregular) (Gullied) (Potholed) (Other)

OTHER SHAPE:

BEDROCK CONDITION: (Fresh/Hard) (Weathered/Soft) (Jointed/Cracked) (Other)

OTHER CONDITION:

Morphology

FEATURE MINED (Platform) (Basin) (Cliff Base) (Against Reef) (Gully) (Pothole) (Other)

OTHER FEATURE

EXOTICS (1. Absent) (2. Rare <25%) (3. Scarce 25-50%) (4. Common 50-75%) (5. Abundant <75%)

Jasper (red) 2 Chalcedony (clear yellow) 2

Agate (blue-grey) 2 Makwassie (speckled) 1

Epidote (lime green) 2 Yellow BIF (honey) 2

Ilmenite (black) 1 Banded BIF (black bands) 2

Garnets (red) 1 Chrysoprase (dark green) 1

Other..... Other Description

EXOTICS COMMENTS: *SOME EXOTICS PRESENT IN THE OVERSIEE AND IN THE BASAL CEMENTED CONGLOMERATE.*

GENERAL COMMENTS:

.....

ROCK SAMPLE COLLECTED FOR GEOLOGIST: (YES) (NO)

Figure 6.6: Example of a production and sampling logsheet (page 2/4).

DEPOSIT DESCRIPTION

TOP	
THICKNESS: 10cm	CLAST SIZE: (Clay) (Fine Sand) (Coarse sand) (Grit) (Small Pebble) (Large Pebble) (Small Cobble) (Large Cobble) (Small Boulder) (Large Boulder) (Conglomerate) (Bedrock) DOMINANT CLAST SHAPE: (Sphere) (Disk) (Blade) (Rod) (Block) ROUNDING: (Angular) (Sub-angular) (Sub-rounded) (Rounded) GRADING: (Upward Fining) (Upward Coarsening) (Constant Grading) CEMENTATION: (None) (Poor <25%) (Moderate 25-50%) (Nodular 50-75%) (Lensoid >75%) (Totally cemented) SORTING: (Poor) (Moderate) (Well) COLOUR: (White) (Grey) (Black) (Yellow) (Orange) (Brown) (Pink) (Red) (Maroon) (Purple) (Blue) (Green) QUARTZ: (Absent) (Present) (Abundant) AND (Angular) (Rounded) SHELL: (Absent) (Rare <25%) (Scarce 25-50%) (Common 50-75%) (Abundant >75%) SHELL TYPE: <i>BLACK MUSSEL</i>
THICKNESS: 100cm	CLAST SIZE: (Clay) (Fine Sand) (Coarse sand) (Grit) (Small Pebble) (Large Pebble) (Small Cobble) (Large Cobble) (Small Boulder) (Large Boulder) (Conglomerate) (Bedrock) DOMINANT CLAST SHAPE: (Sphere) (Disk) (Blade) (Rod) (Block) ROUNDING: (Angular) (Sub-angular) (Sub-rounded) (Rounded) GRADING: (Upward Fining) (Upward Coarsening) (Constant Grading) CEMENTATION: (None) (Poor <25%) (Moderate 25-50%) (Nodular 50-75%) (Lensoid >75%) (Totally cemented) SORTING: (Poor) (Moderate) (Well) COLOUR: (White) (Grey) (Black) (Yellow) (Orange) (Brown) (Pink) (Red) (Maroon) (Purple) (Blue) (Green) QUARTZ: (Absent) (Present) (Abundant) AND (Angular) (Rounded) SHELL: (Absent) (Rare <25%) (Scarce 25-50%) (Common 50-75%) (Abundant >75%) SHELL TYPE:
THICKNESS: 50cm	CLAST SIZE: (Clay) (Fine Sand) (Coarse sand) (Grit) (Small Pebble) (Large Pebble) (Small Cobble) (Large Cobble) (Small Boulder) (Large Boulder) (Conglomerate) (Bedrock) DOMINANT CLAST SHAPE: (Sphere) (Disk) (Blade) (Rod) (Block) ROUNDING: (Angular) (Sub-angular) (Sub-rounded) (Rounded) GRADING: (Upward Fining) (Upward Coarsening) (Constant Grading) CEMENTATION: (None) (Poor <25%) (Moderate 25-50%) (Nodular 50-75%) (Lensoid >75%) (Totally cemented) SORTING: (Poor) (Moderate) (Well) COLOUR: (White) (Grey) (Black) (Yellow) (Orange) (Brown) (Pink) (Red) (Maroon) (Purple) (Blue) (Green) QUARTZ: (Absent) (Present) (Abundant) AND (Angular) (Rounded) SHELL: (Absent) (Rare <25%) (Scarce 25-50%) (Common 50-75%) (Abundant >75%) SHELL TYPE: <i>BLACK MUSSEL BARNACLE</i>
THICKNESS: 2cm BASE / BEDROCK	CLAST SIZE: (Clay) (Fine Sand) (Coarse sand) (Grit) (Small Pebble) (Large Pebble) (Small Cobble) (Large Cobble) (Small Boulder) (Large Boulder) (Conglomerate) (Bedrock) DOMINANT CLAST SHAPE: (Sphere) (Disk) (Blade) (Rod) (Block) ROUNDING: (Angular) (Sub-angular) (Sub-rounded) (Rounded) GRADING: (Upward Fining) (Upward Coarsening) (Constant Grading) CEMENTATION: (None) (Poor <25%) (Moderate 25-50%) (Nodular 50-75%) (Lensoid >75%) (Totally cemented) SORTING: (Poor) (Moderate) (Well) COLOUR: (White) (Grey) (Black) (Yellow) (Orange) (Brown) (Pink) (Red) (Maroon) (Purple) (Blue) (Green) QUARTZ: (Absent) (Present) (Abundant) AND (Angular) (Rounded) SHELL: (Absent) (Rare <25%) (Scarce 25-50%) (Common 50-75%) (Abundant >75%) SHELL TYPE:

Figure 6.6: Example of a production and sampling logsheet (page 3/4).

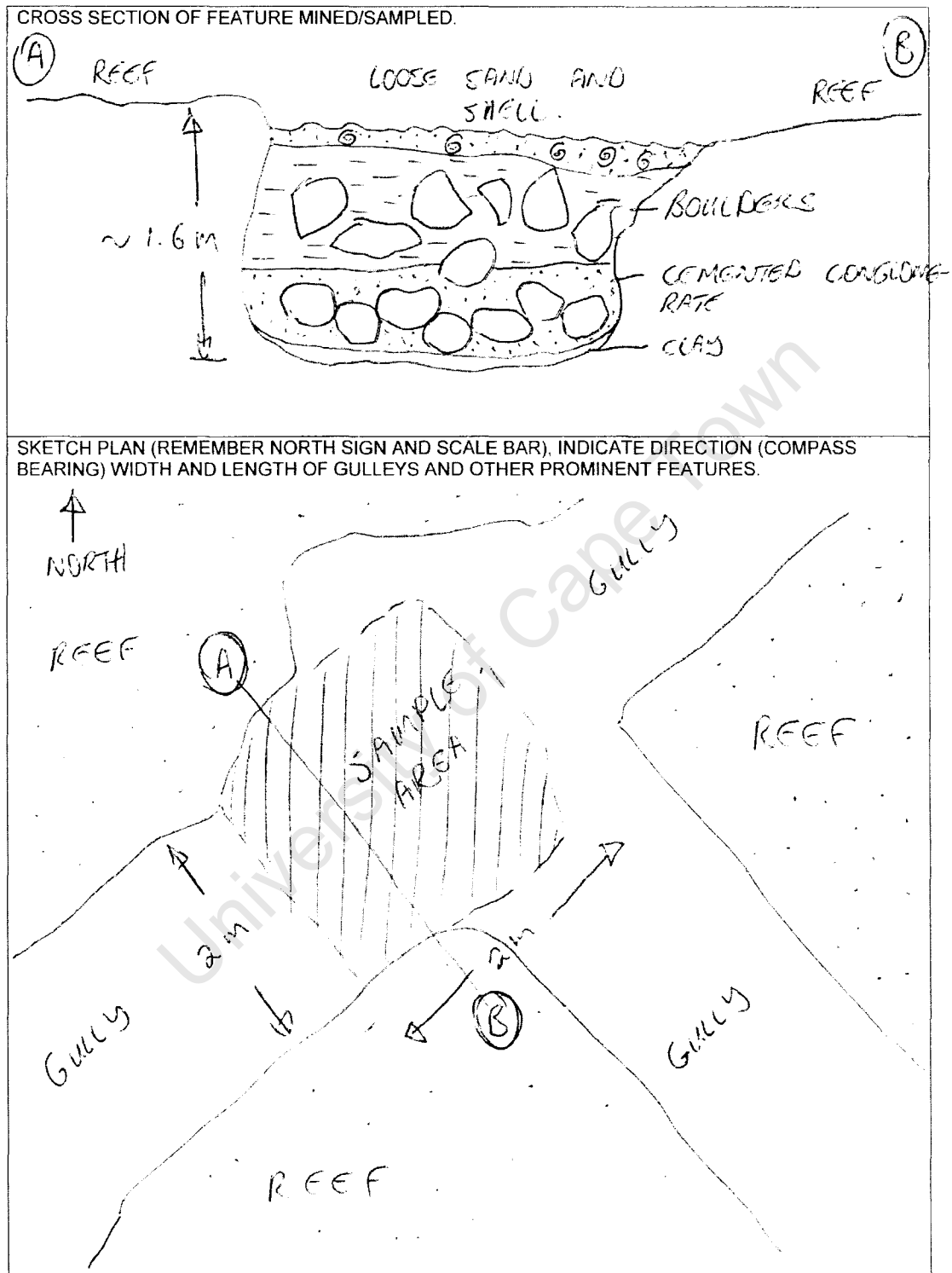


Figure 6.6: Example of a production and sampling logsheet (page 4/4).

6.3 Size Frequency Distribution of Diamond Population

The size frequency distribution data of 125,588 cts recovered from the study area between 1992 and 2006 were collected from 3 sources. The results are plotted on an industry standard diamond size frequency graph indicating diamond sieve size and the diamond sieve round aperture diameter on the x-axis (Figure 6.7). The equivalent Wentworth size class is indicated in Table 6.2. No size frequency data could be obtained for the landbased mining as the diamonds recovered from the raised beach mining were rolled together with production from other areas during the consignment process.

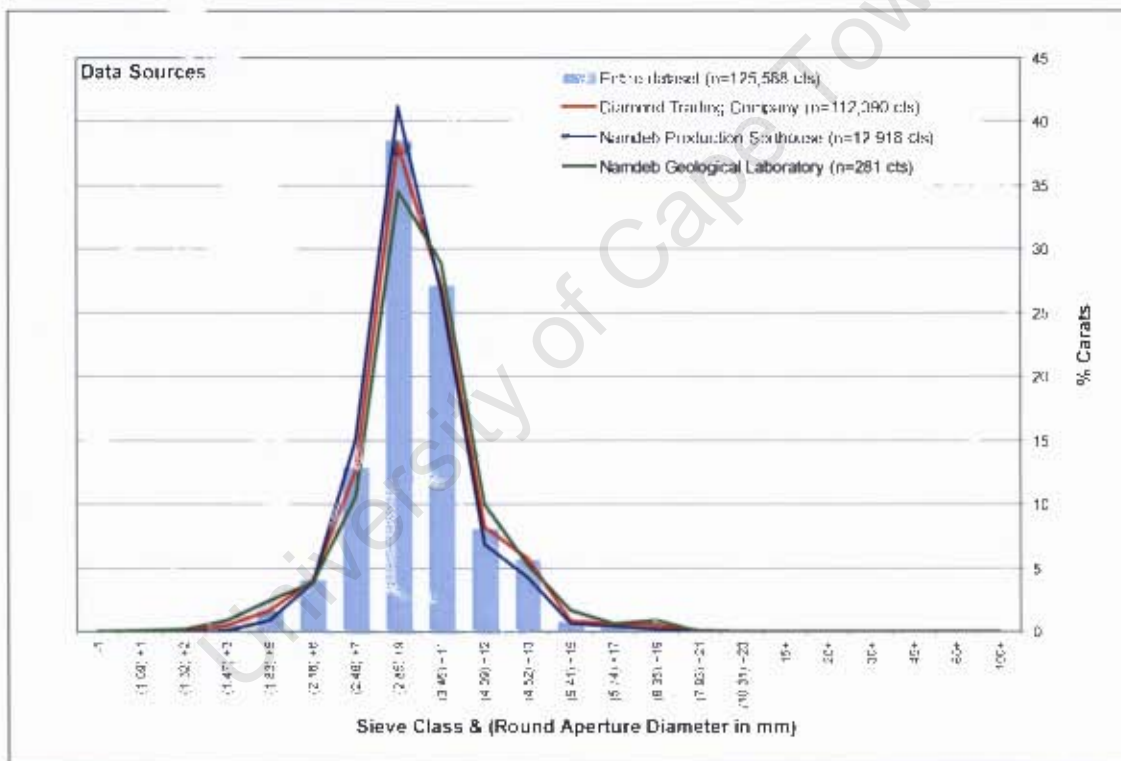


Figure 6.7: The diamond size frequency distribution data for 125,588 cts recovered from the study area between 1992 and 2006, plotted by source with the entire dataset to highlight the consistency of distribution from the 3 sources namely the Diamond Trading Company, Namdeb Production Sorthouse and the Namdeb Geological Laboratory.

Wentworth size class	Diamond Sieve Class	Diamond Sieve Round Aperture Diameter (mm)
Pebbles	+23	10.31
	+21	7.93
	+19	6.35
	+17	5.74
	+15	5.41
	+13	4.52
	+12	4.09
Granules	+11	3.45
	+9	2.85
	+7	2.46
Very Coarse Sand	+6	2.16
	+5	1.83
	+3	1.47
	+2	1.32
	+1	1.09

Table 6.2: The comparative Wentworth size class, diamond sieve class and diamond sieve round aperture diameter for the size fraction range of the diamonds recovered from the study area.

6.4 Recent Production Records

These records stretch from 2002 to 2006 for the purpose of this study and are comprised of production and basic geological information recorded by the Namdeb shallow marine diver-assisted diamond recovery operations based in Lüderitz.

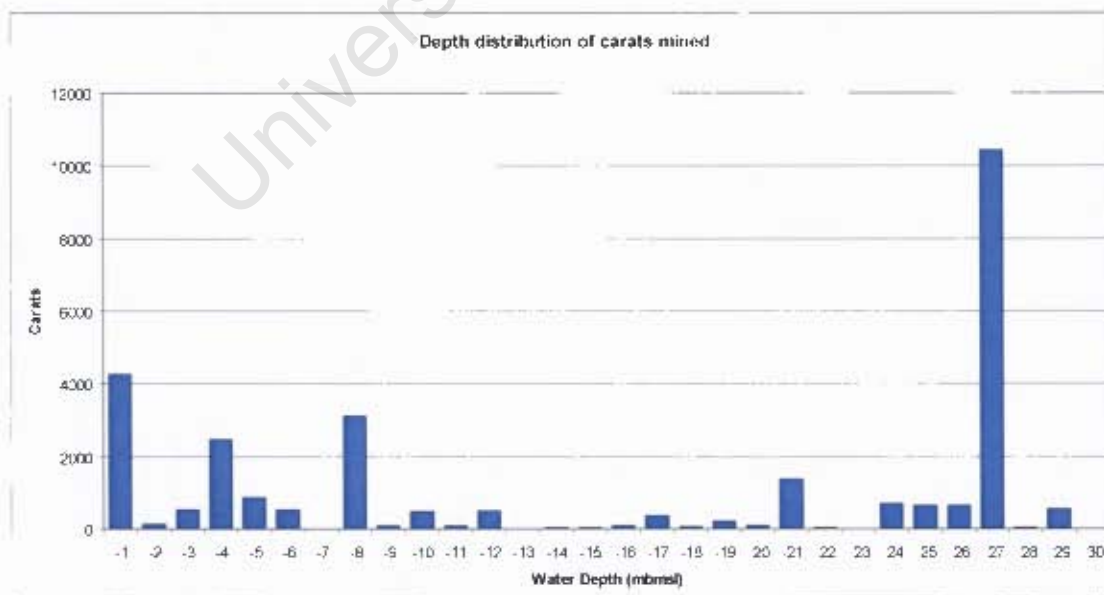


Figure 6.8: Depth distribution of diamonds recovered from the study area between 2002 and 2006, according to recent shallow marine production records.

Since 2002 the bulk of the shallow marine vessels shifted their focus to production areas further south and out of the study area. Although various vessels did some prospecting within the study area since 2002, only one vessel remained active in the area. During this period they recovered in excess of 33% of the carats recorded from -27 m depth (Figure 6.8). A total of 228 recent production records representing 28,142 cts were used for the purpose of this study. The size frequency distribution data were obtained from the Diamond Trading Company for 41% of the production.

6.5 Historical Shallow Marine Production Records

From 1990 to 1999 all of the shallow marine contractors active in the study area were sub-contracted under Windvogel Diamonds, the principal Namdeb contract holder. During this period only basic production information (location, depth, diamond recovery, grade, etc.) were recorded for the diver-assisted mining activities. These data sheets were recorded by the dive operators when they offloaded their gravel at the treatment facility in Lüderitz harbour.

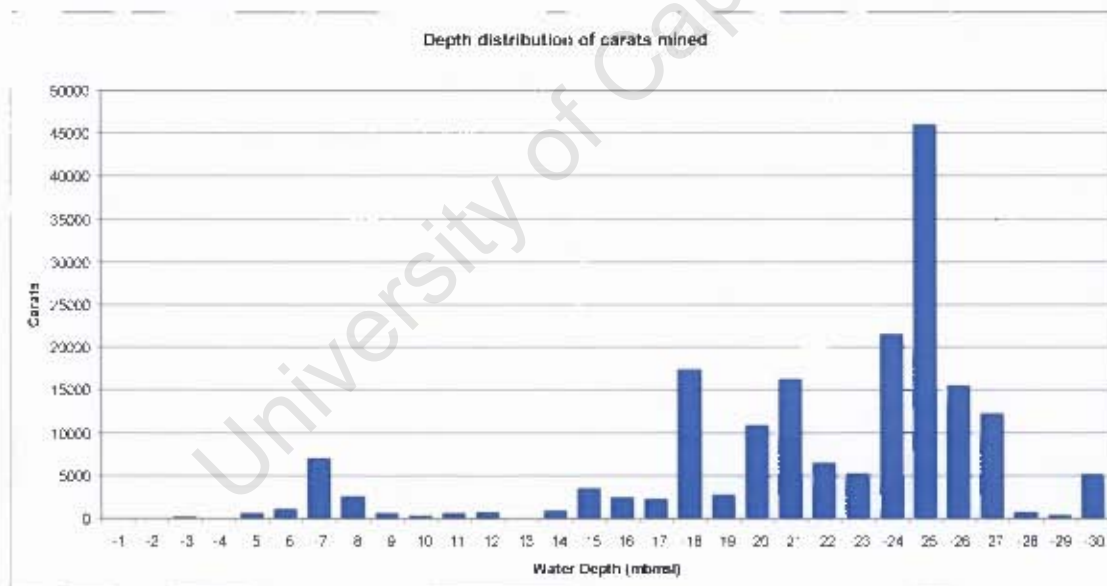


Figure 6.9: Depth distribution of diamonds recovered from the study area between 1990 and 1999, according to the historical shallow marine production records.

During the early years the diver-assisted mining activities were mostly focussed in the study area i.e. in relatively close proximity to the safe harbour of Lüderitz. Due to the exposed nature of the coastline in the study area, the vessel based diving operations mostly operate in water depths deeper than 15 m (Figure 6.9). The deeper water allows them to work in higher swell conditions. A total of 973 of the historical records representing 181,341 cts were found suitable to be used for the purpose of this study. During this period the positional data were determined using

navigational GPS and from naval charts. Due to "selective availability" of GPS satellite signals and the inherent inaccuracy of calculating positional coordinates from navigational charts, it is estimated that the positional data are likely to have an error of up to 100 metres. Some divers purposefully reported positional data incorrectly, in order to keep production sites secret. These obviously incorrect records which for instance plotted either on land or in water depths where divers could not operate, were discarded.

Size frequency data (carats per sieve class) were obtained for the Windvogel Diamonds consignments for the 1992-1999 period. The size frequency sieving was done by the Diamond Trading Company (previously known as the Central Selling Organisation) for valuation purposes. At that time the production from various subcontractors mining in different areas were combined for valuation purposes. The constituent contributors of each parcel were checked and 47 parcels totalling 112,390 cts were found to have been mined from within the confines of the study area.

6.6 Historical Surf Zone Production Records

Surf zone mining commenced in 1991 in the study area. The landbased portion of the Elizabeth Bay Mining Licence extends only to Grossebucht along the coast. Therefore surf zone mining in the study area was only conducted from Grossebucht in the north to Elizabeth Bay in the south. Due to the coastal profile the surf zone operations were generally limited to below 15 m depth (Figure 6.10).

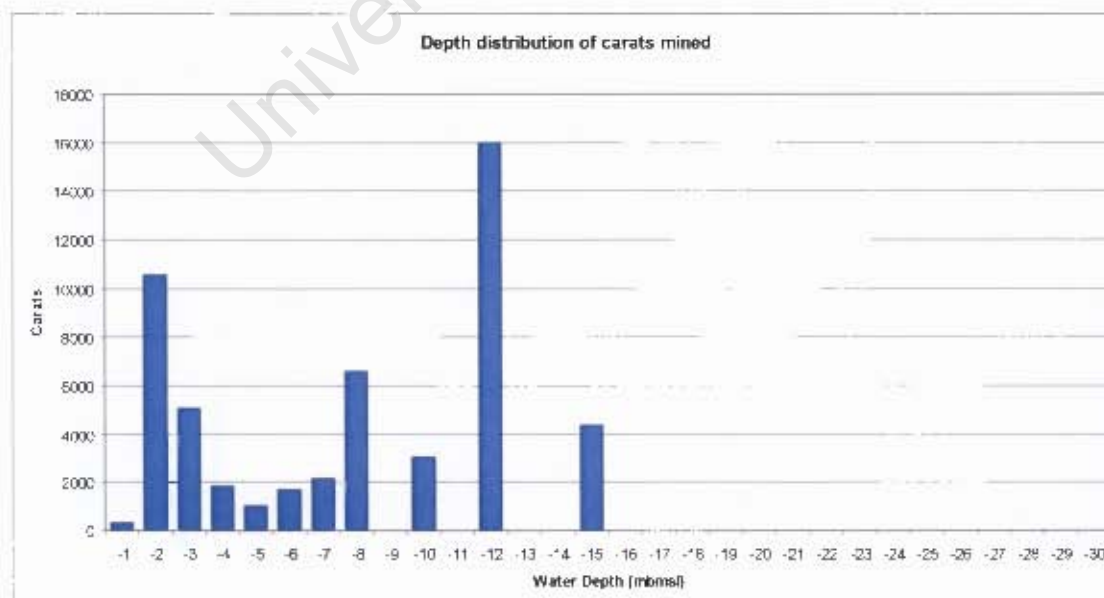


Figure 6.10: Depth distribution of diamonds recovered from the study area between 1991 and 2004, according to the surf zone records for which mining depths could be assigned

From 1991 to 2004 all of the surf zone operations were sub-contracted under Diaz Point Explorations, a Namdeb contract holder. During this period limited production information was recorded. However, the security logbook contained the records of each parcel of diamonds which were collected from the various operators along the coast. The “collection runs” were usually done on a weekly basis. In the logbook relevant production information were recorded including the carats & stones and the location name of the area from which the production was collected by the security personnel. These collection locations were fairly closely distributed along the coast so they give a fair reflection of the area from which the production was mined by surf zone divers.

The records were digitally captured and divers who have been active in the industry since 1990 were interviewed regarding specific mining locations and depths. In total 1406 records representing 69,866 cts were captured and contained suitable information to be used for the purpose of this study. From the interview data specific locations and mining depths could be assigned to 75% (52,581 cts) of the surf zone production (Table 6.3).

	n=	cts	stns	cts/stn
Records with depth data	753	52,581	199,158	0.26
Records without depth data	653	17,285	69,338	0.25
TOTAL	1,406	69,866	268,496	0.26

Table 6.3: Summary table of available surf zone production information.

For the remaining 25% (17,285 cts) of the surf zone production records, only approximate locations could be deducted from the locations from where the production were collected – no depth data exist. None of the production records included tonnage data so grade calculations were not possible. No size frequency data exist for the historical surf zone production.

6.7 Historical Landbased Production Records

Landbased mining focused on the mining of raised palaeo beach deposits. Remnants of the +2 m and +4 m beaches were mined within the Elizabeth Bay Mining Licence i.e. from Grossebucht southwards. Between 1993 and 1996 available records indicate that 20,502 cts were mined from remnant beach deposits within the study area at an average stone size of 0.20 cts/stn.

6.8 Age of deposits

All of the gravel deposits encountered within the study area contained variable amounts of sea shells and therefore marine origins for all are assumed. The shell material encountered in the gravel is broadly being divided into two categories namely "fresh" and "old" shell.

The "fresh" shells have an obviously fresh appearance. The shells are structurally competent and do not break easily or crumble when handled. The blue/purple coloured shells like Ribbed Mussel *Aulacomya ater* and Black Mussel *Choromytilus meridionalis* retain the colour in the shells – although the colour may be faded, the shells still appears blue/purple (Figure 6.11).



Figure 6.11: The "fresh" shells appear obviously fresh and are structurally competent. The blue/purple coloured shells like *Aulacomya ater* and *Choromytilus meridionalis* retain the colour in the shells – although the colour may be faded, the shells still have a blue/purple appearance. The blue/purple appearance of a "fresh" shell accumulation is evident on a modern day beach situated just south of Grossebucht in the study area.

The "old" shells appear weathered. They are usually chalky and friable, breaking and crumbling easily when handled. Shells usually blue/black in colour like *Aulacomya ater* and *Choromytilus meridionalis* appear orange/brown (Figure 6.12).

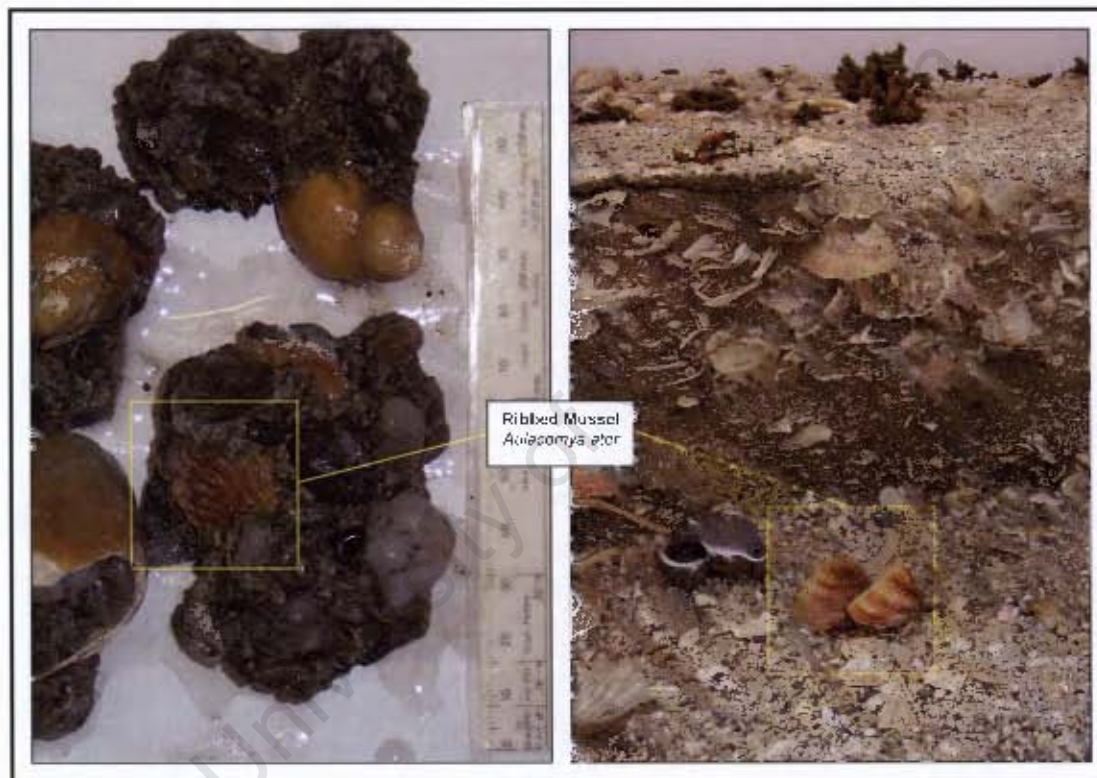


Figure 6.12: The "old" shells have a weathered appearance. These shells are chalky and friable and break easily when handled. Shells usually blue/purple in colour like *Aulacomya ater* and *Choromytilus meridionalis* appear orange/brown. The brown discolouration of "old" *Choromytilus meridionalis* shells can be seen in the hand specimen of conglomerate from the De Hoek area and from a raised palaeo beach situated just south of Grossebucht in the study area

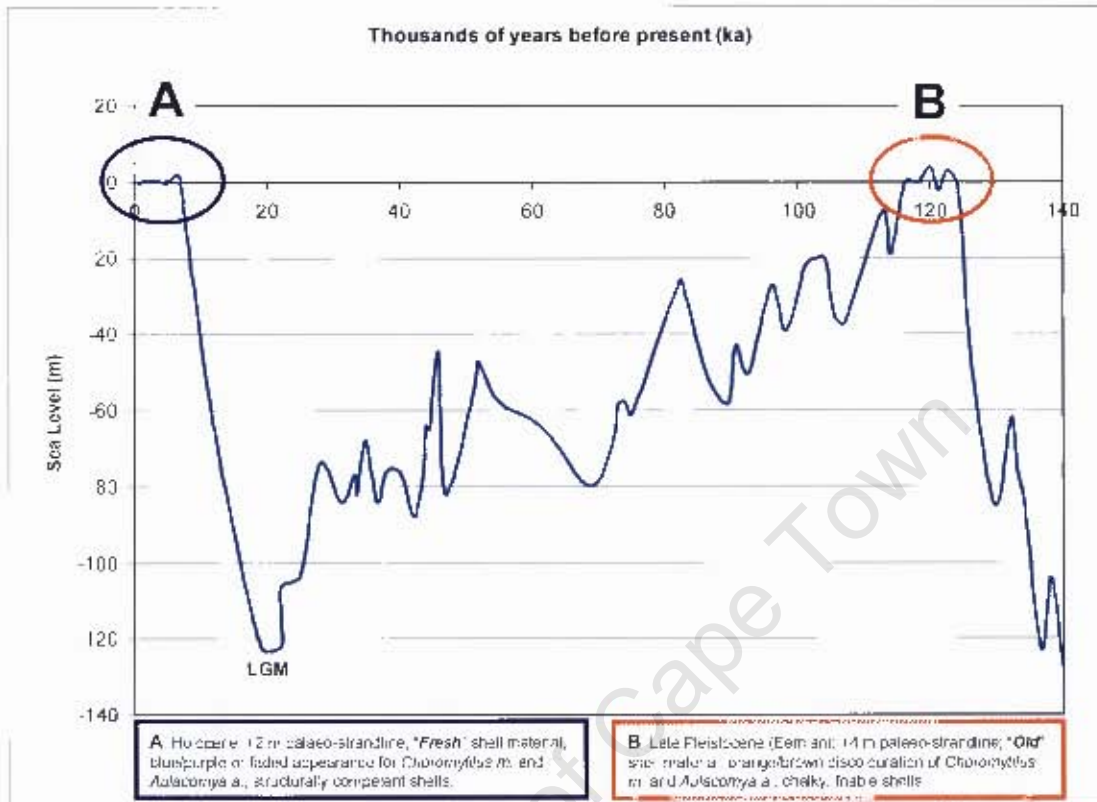


Figure 6.13: Composite sea-level curve for the last 140 ka highlighting **A**: The Holocene +2 m palaeo-strandline which is informally identified along the West Coast by the presence of "fresh" shell material and **B**: the Late-Pleistocene +4 m palaeo-strandline which is informally identified by the presence of "old" shell material (Compton, 2001, Compton *et al.*, 2002; Yokoyama *et al.*, 2000; Chappel *et al.*, 1996; Fairbanks, 1990; Shackleton, 1987).

Field observations of archaeologists and geologists conducting work on the marine beaches along the West Coast have noted that the blue/purple colouration of shells like *Aulacomya ater* and *Choromytilus meridionalis* is retained or faded in Holocene deposits i.e. +2 m palaeo-strandline. However, the shell colour changes to an orange/brown colour in samples older than the Holocene and associated with late Pleistocene (Eemian) deposits i.e. +4 m palaeo strandline (Figure 6.13).

The blue/purple colouration in the shells are caused by a protein which breaks down over time and changes colour to orange/brown after about 10 ka. *Aulacomya ater* and *Choromytilus meridionalis* encountered in the above -30 m elevation which have a blue/black colouration (fresh) were therefore deposited no more than 10 ka ago as this was the first time that this elevation of the coast would have been submerged after the Last Glacial Maximum (LGM), (Figure 6.14).

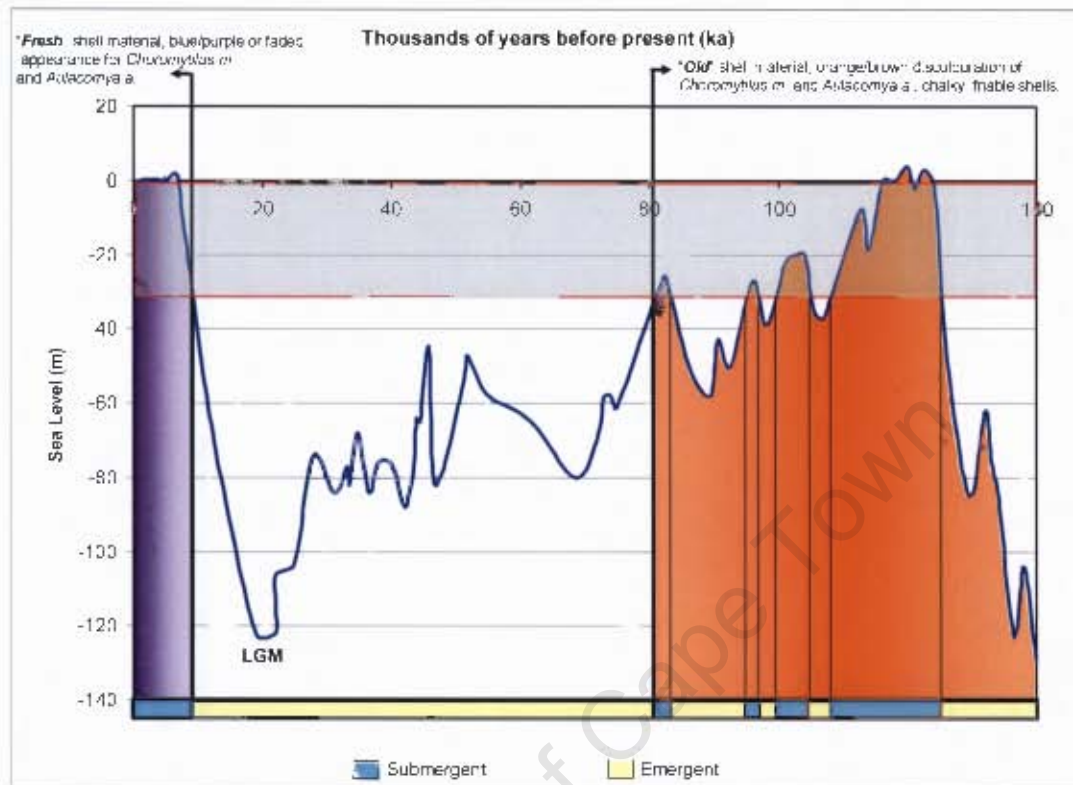


Figure 6.14: Composite sea-level curve for the last 140 ka highlighting the 0 to -30 m elevation (Compton, 2001, Compton *et al.*, 2002; Yokoyama *et al.*, 2000; Chappel *et al.*, 1996; Fairbanks, 1990; Shackleton, 1987).

Aulacomya ater and *Choromytilus meridionalis* shells which are discoloured orange/brown and which are typically chalky and friable when handled, would be older than 10 ka and have been exposed to weathering. It is unlikely that shells displaying such characteristics could have been entrapped with the diamondiferous gravel horizons and subsequently exposed to weathering conditions to attain the said characteristics, during the period of rapid rise in sea-level following the Last Glacial Maximum (Figure 6.14). The coast above the -30 m elevation was emergent from 80 ka to 10 ka ago (Figure 6.14). It is therefore assumed that 'old' weathered shells were entrapped in the gravel horizons before this emergent period. The first opportunity where the shoreline above the -30 m elevation would have been submergent – and therefore exposed to shallow marine processes, was 80 ka ago (Figure 6.14). Sedimentary horizons in which the *Aulacomya ater* and *Choromytilus meridionalis* shells occur which are discoloured orange/brown and are generally chalky and friable are therefore considered to be not younger than about 80 ka.

During observation in the field care was taken to distinguish between actual age induced discolouration of shells and Fe-staining of shells.

6.9 Cementation

To distinguish between calcite and dolomite cementation, the standard field acid test using a 10% HCl solution was used (Tucker, 1996). When the acid applied to the specimen was slow to bubble dolomite cement was assumed and when the acid was fizzing lively, calcite cement was assumed. During the tests care was taken to apply the acid to freshly broken or clean surfaces free of loose fine rock particles or shell material occurring within the matrix.

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7. DE HOEK

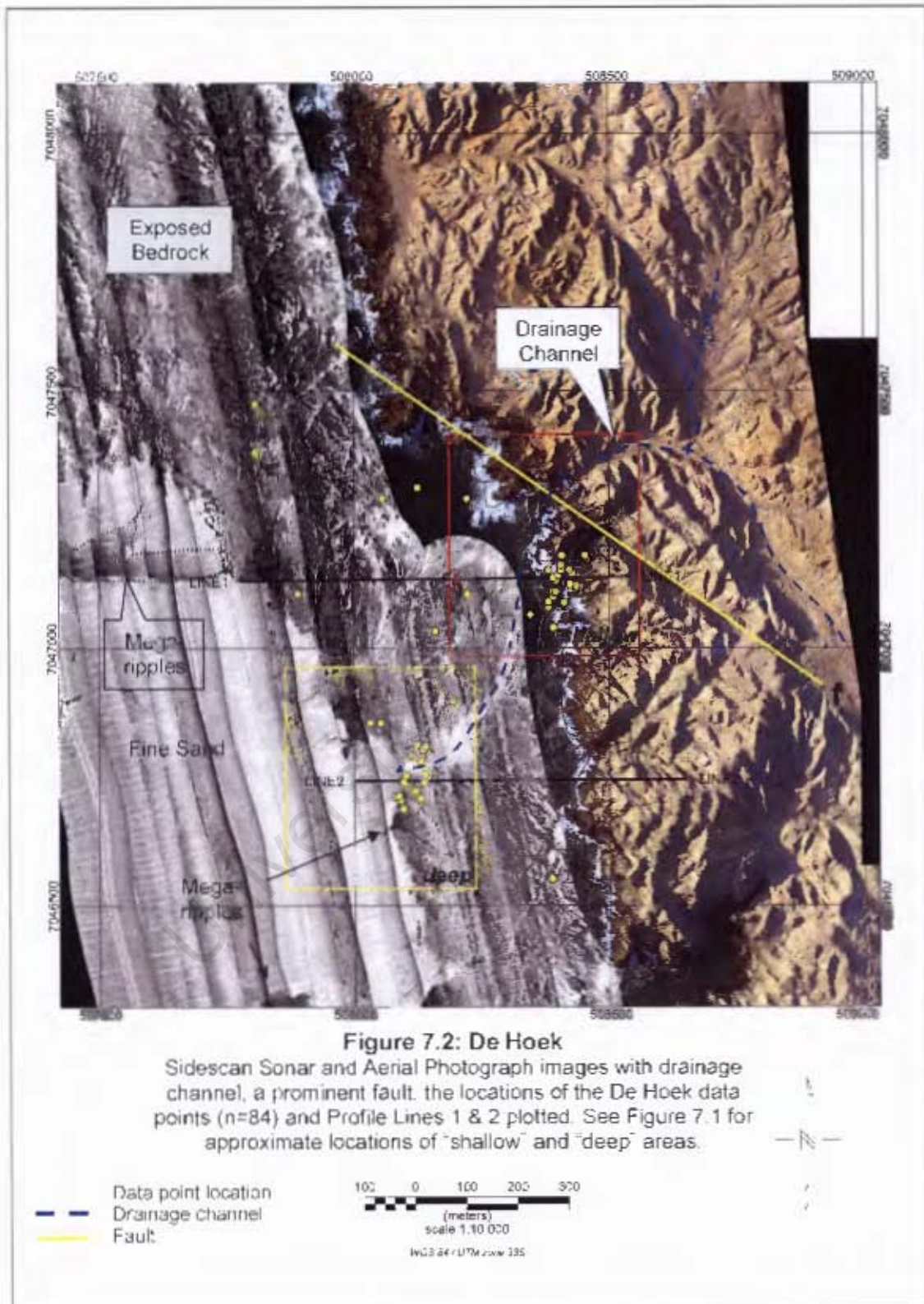
7.1 RESULTS

De Hoek (meaning "The Corner") is situated approximately 5 km south of Halifax Island, roughly halfway between Halifax Island and Grossebucht (Figures 1.3 & 2.1). The underlying bedrock consists of the Gariiep Supergroup Diaz Point Formation, in particular Unit 3, which is composed of quartzite overlain by diamictite with minor interbedded chloritic quartz schists (Figure 4.1). This is the dominant formation which occurs along the coastline between Halifax Island and Reef Bay.



Figure 7.1. Facing north-east, an oblique aerial photograph of the De Hoek area with the approximate locations of the 2 mining areas (shallow & deep) indicated.

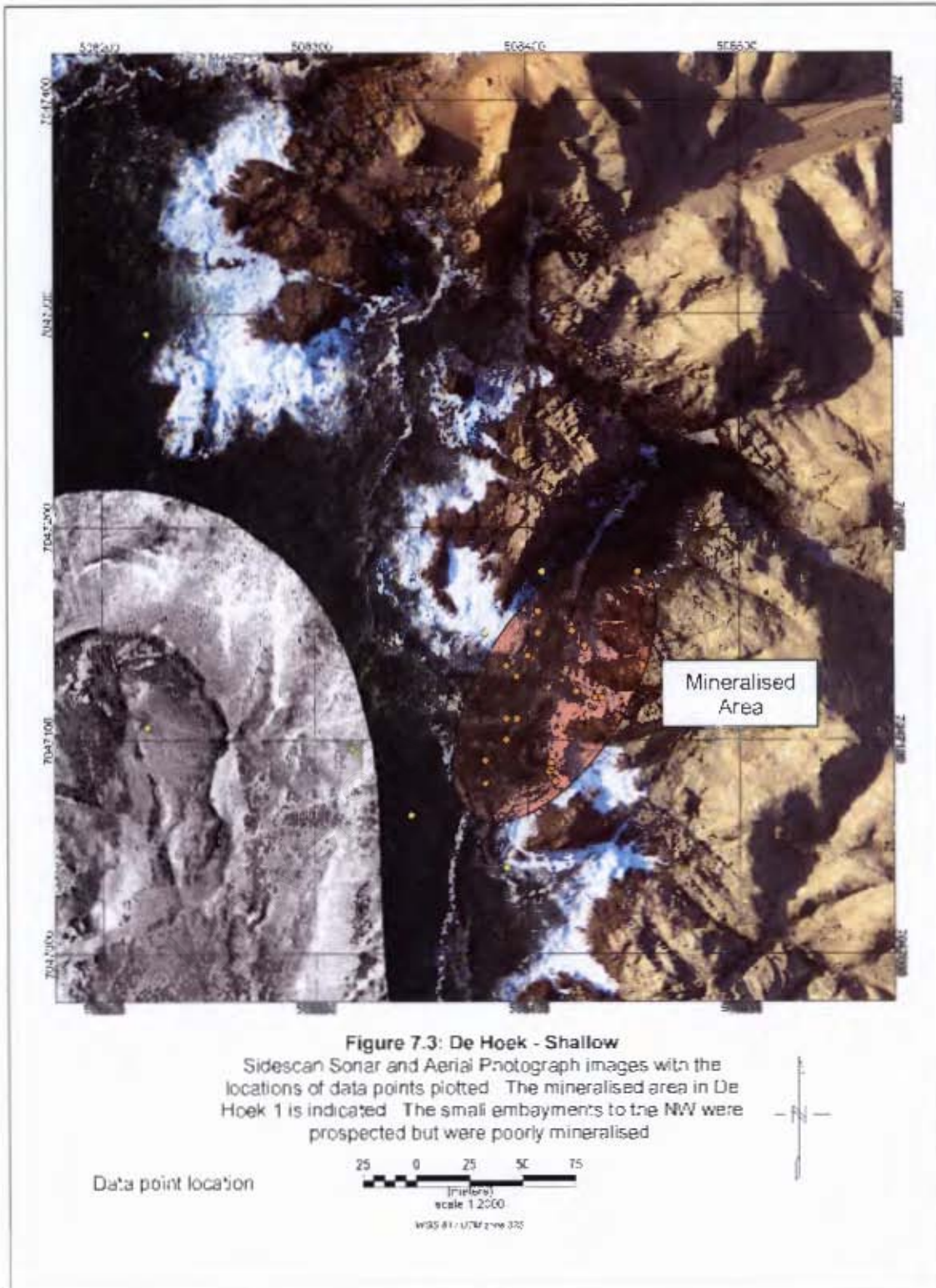
De Hoek is a south facing semi-embayment, or notch, in the fairly straight section of north-south trending rocky coastline between Halifax Island and Grossebucht (Figure 7.1). From the digital aerial photography and sidescan sonar images of the De Hoek area it is evident that the southwest facing part of the coastline coincides with a northwest-southeast trending normal fault (Figure 7.2). There are a series of parallel normal faults trending $\sim 300^\circ$ along this part of the coast. Similar basement faults and preferential weathering and erosion along these features have resulted in the formation of the inlets Essy Bay and Fjord, immediately north and south of De Hoek (Siegfried 1993).

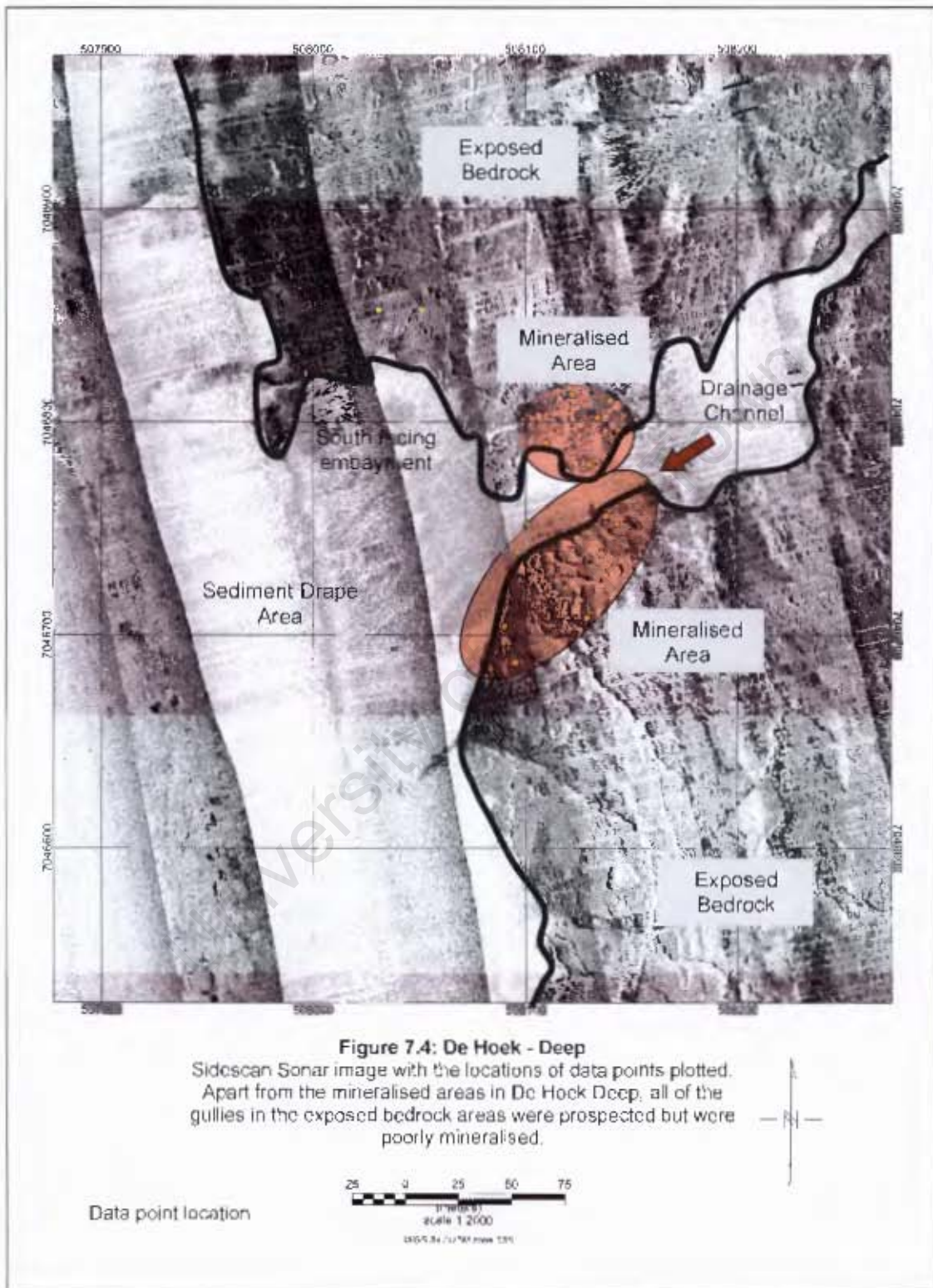


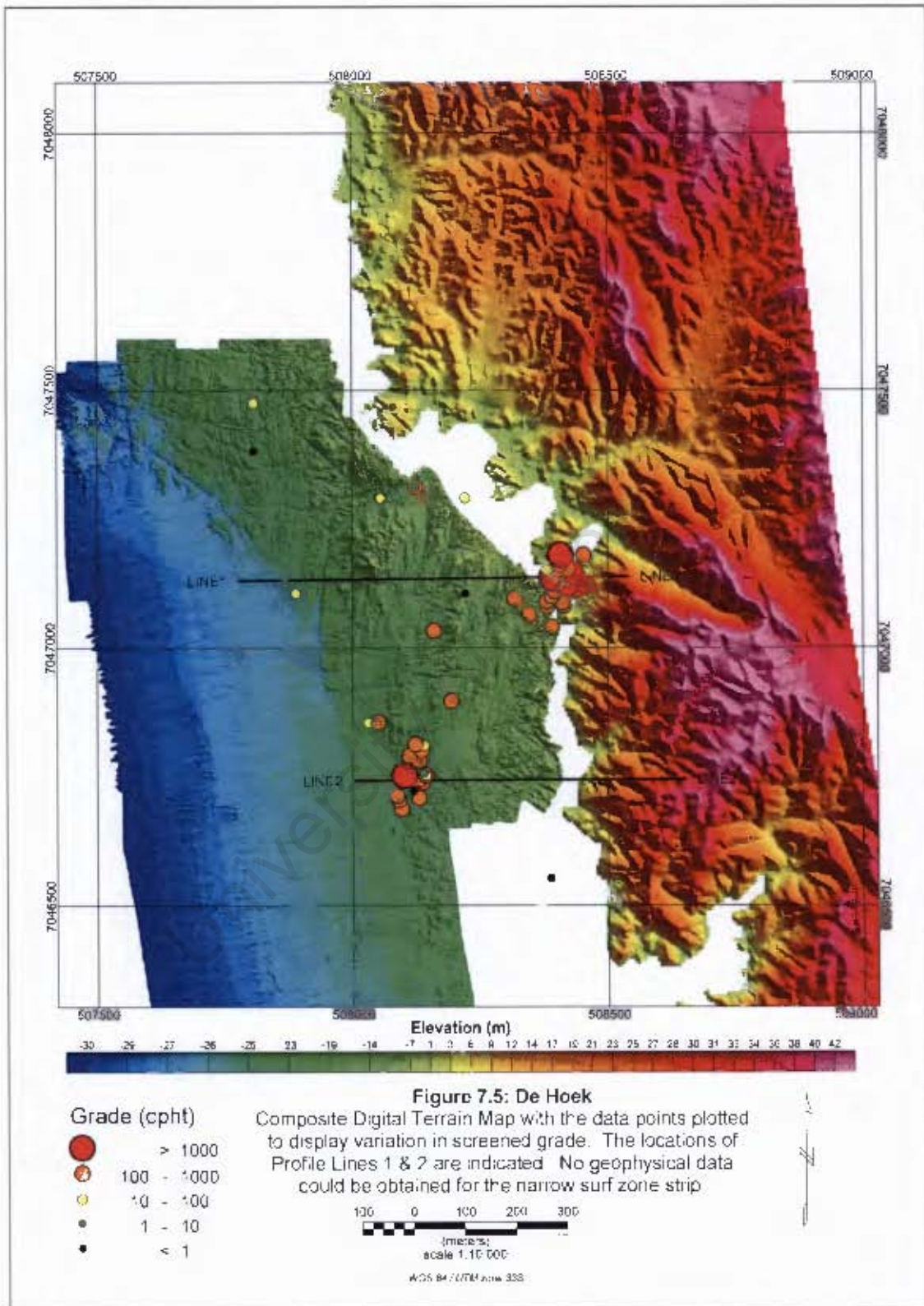
The seabed comprises exposed Pre-Cambrian bedrock within which gullies are evident (Figure 7.2). The De Hoek area is flanked on the west by a drape of fine sand, the landward margin of which lies at approximately -24 m depth. This margin is a function of the wave base (half the wave length). The minimum and the maximum dominant wave base along the southern Namibian coast are approximately -40 m and -80 m respectively (De Decker, 1988; Bluck *et al.*, 2007). The unconsolidated fine sand display a light coloured acoustic facies in the sidescan sonar image (Figure 7.2). Also present are isolated patches of a darker coloured acoustic facies within which mega-ripples can be observed. This indicates unconsolidated, rippled, pebble gravel locally known as “travel gravel” amongst the divers. A drainage channel flowing westwards into the fine sand area is also evident (Figure 7.2).

To date mining activities at De Hoek have mainly been focused on two areas: the shallow areas close to shore and the deeper areas situated approximately 350 m offshore (Figures 7.1 & 7.2). Initially, mining activities were concentrated in the shallow water depths of -1 m to -8 m (Figure 7.3). Following the depletion of the diamondiferous gravel in the shallow areas, economic diamond concentrations were identified through prospecting at depths ranging from -24 m to -27 m (Figure 7.4). The deeper mineralised area is situated where the northeast-southwest trending drainage channel meets the landward edge of the larger sediment drape.

The interim depths and related areas have been intensely prospected on a local scale and although preserved gravel packages were encountered, the associated diamond yields were of uneconomic concentrations and therefore not further pursued. Because no diamond parcels from this work were delivered for treatment at the CTF in Lüderitz, no records exist of the prospecting activities apart from the local knowledge of the divers who have been mining in this area for several years.







From historical production records and interviews with divers it is estimated that approximately 25,000 carats (cts) have been mined from De Hoek. For the purpose of this study some 84 records with geographical locations totaling 22,729 cts and numbering 91,489 stones (stns) were used. The average stone size of diamonds mined from the De Hoek area is 0.25 cts/stn which is slightly smaller than the average stone size of 0.26 cts/stn for the entire study area. The stone size for the shallower depths (-1 to -8 m) is 0.23 cts/stn and for the deeper areas (-24 to -27 m) is 0.27 cts/stn. The screened gravel (+1.6 mm, -10 mm) grade for the area is in excess of 1000 carats per hundred ton (cpht), (Figure 7.5). The average screened gravel grade of the shallow area is about double the grade of the deeper area.

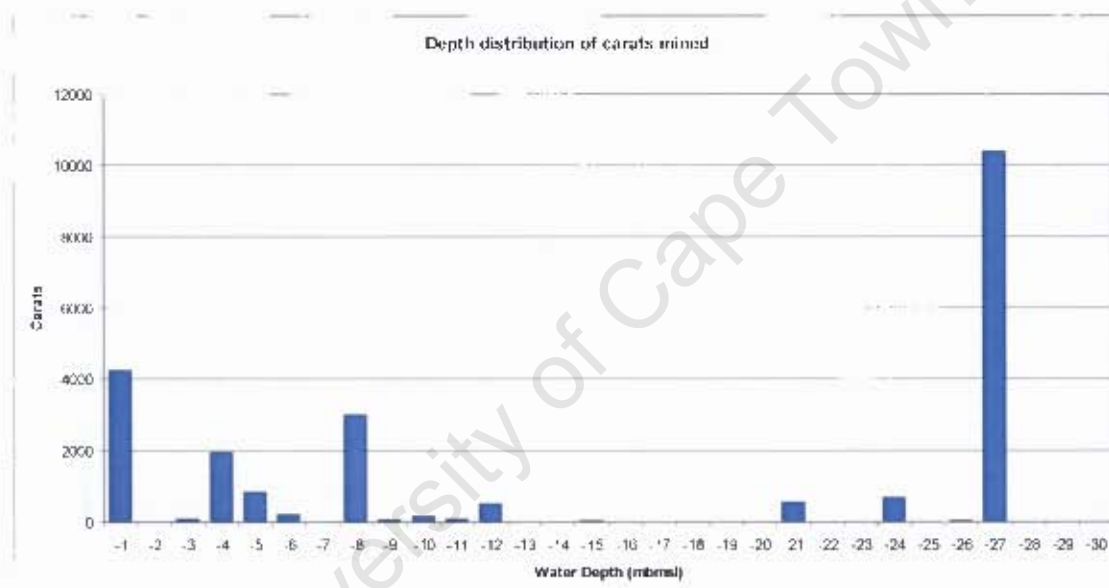


Figure 7.6: Water depth distribution of total carats mined from the De Hoek area.

The carat production by water depth graph was compiled from 84 data points representing 22,729 cts and shows that mining in De Hoek area was concentrated in shallow water depths ranging from -1 m to -8 m and that maximum production was obtained from -27 m water depth (Figure 7.6 & 7.7).

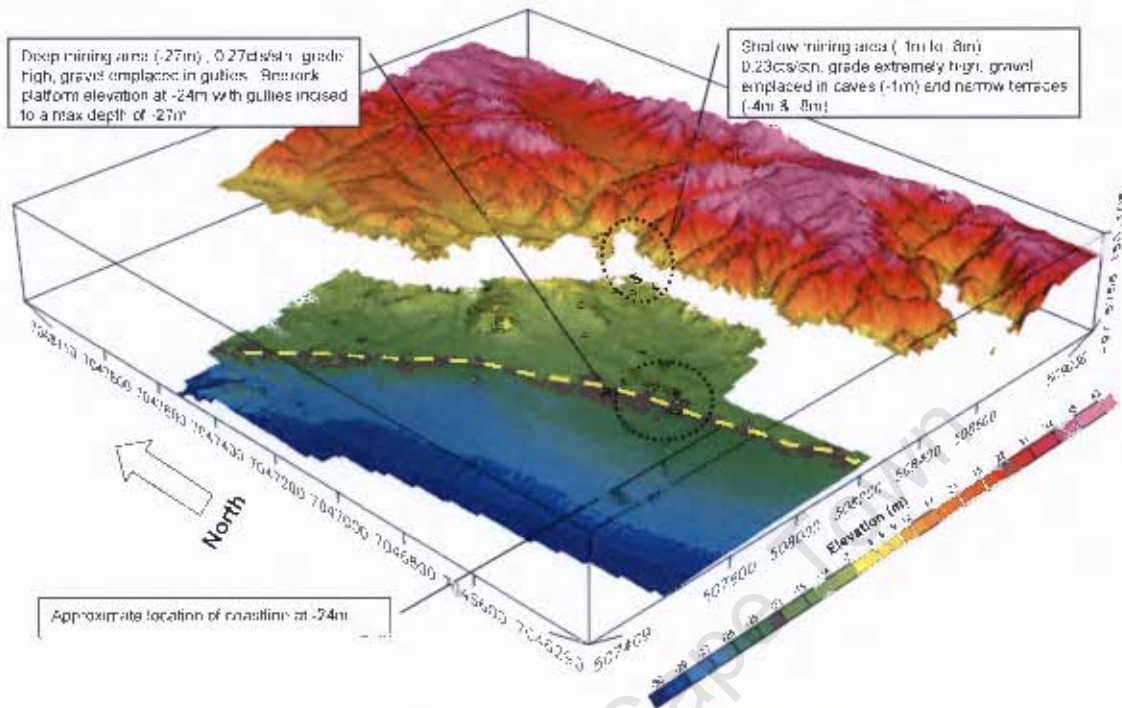


Figure 7.7: Three dimensional view of De Hoek area.

De Hoek - Shallow

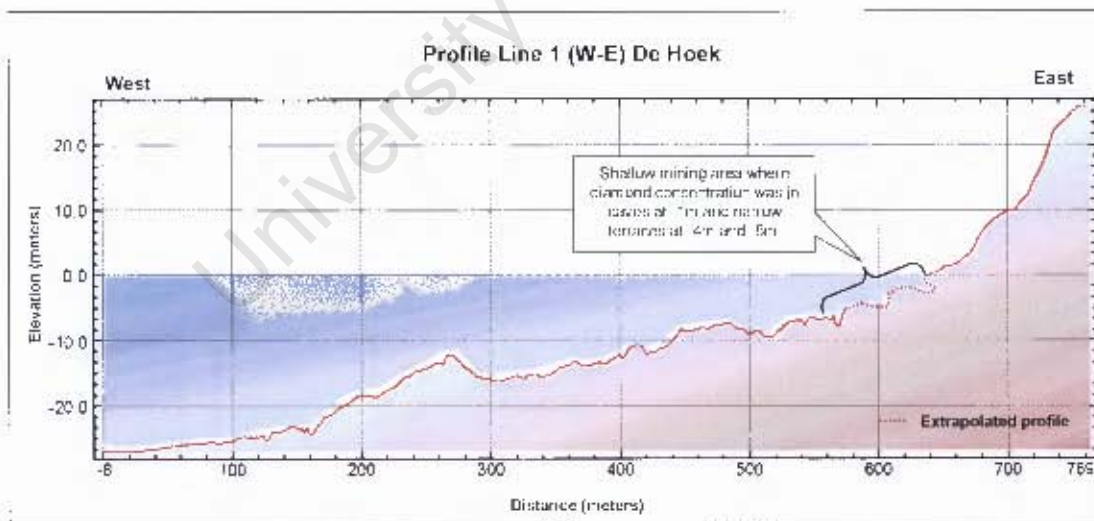


Figure 7.8: Profile Line 1 of terrain elevation in De Hoek shallow mining area.

Profile Line 1 situated in the De Hoek area (Figures 7.2 & 7.5) indicates that the steep profile of the bedrock exposed above present sea-level continues below the surface of the water (Figure 7.8). Although the shallow mining area was not covered by geophysical surveys, a schematic profile could be compiled from interviews with the divers who conducted the mining of this

feature. The feature consists of wave-cut caves which are situated at approximately 1-2 m below present sea-level. The caves extend about 3-4 m laterally with the floor sloping landward. The cave floor has large potholes incised up to 2 m deep (Figures 7.9 A, B & C).

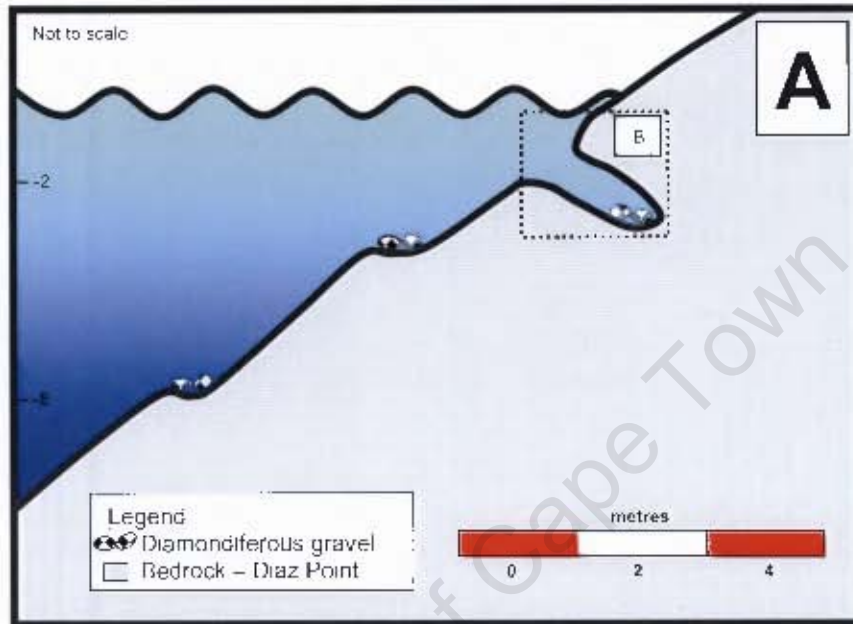


Figure 7.9 A: Schematic of wave-cut caves and narrow shelves between -1 m to -8 m depth at De Hoek.

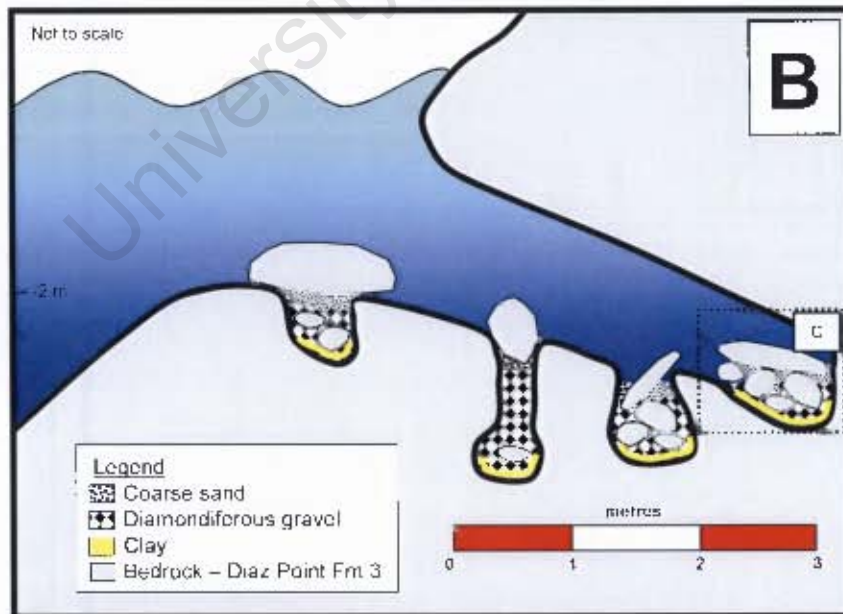


Figure 7.9 B: Schematic of the caves which extend about 3-4 m laterally with the floor sloping landward.

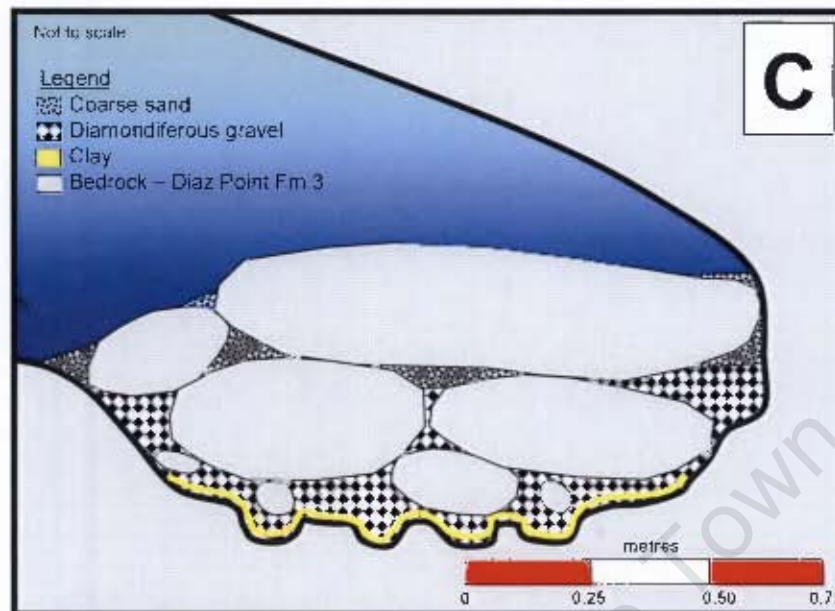


Figure 7.9 C: Schematic of the cave - the floor has large potholes incised up to 2 m deep.

A thin but continuous layer of yellow clay, Unit 2 (Figure 7.10), occurs at the bedrock (Unit 1) interface. The clay layer follows the contours of the pothole. The clay layer is topped by a horizon of well compacted, poly-modal clast supported gravel which is generally about 60 cm thick (Unit 3). Rounded to well rounded clasts include pebbles of darker schist and white vein quartz up to 30 mm in diameter.

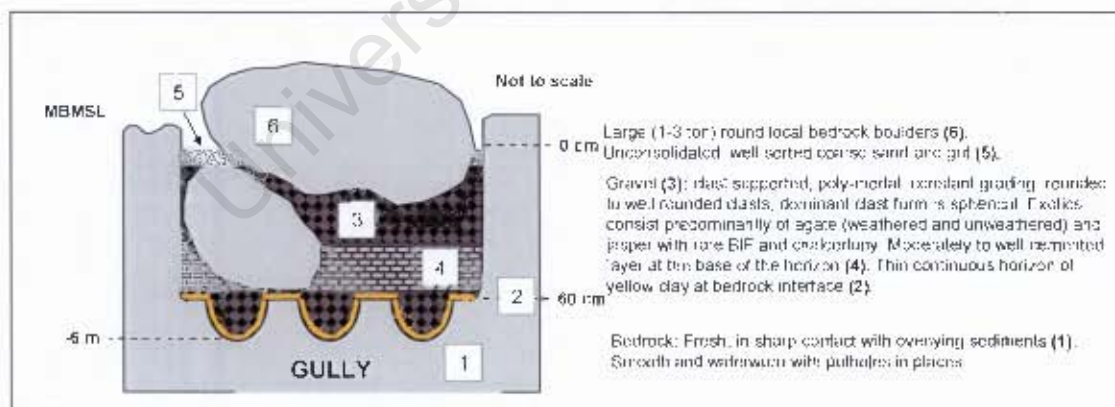
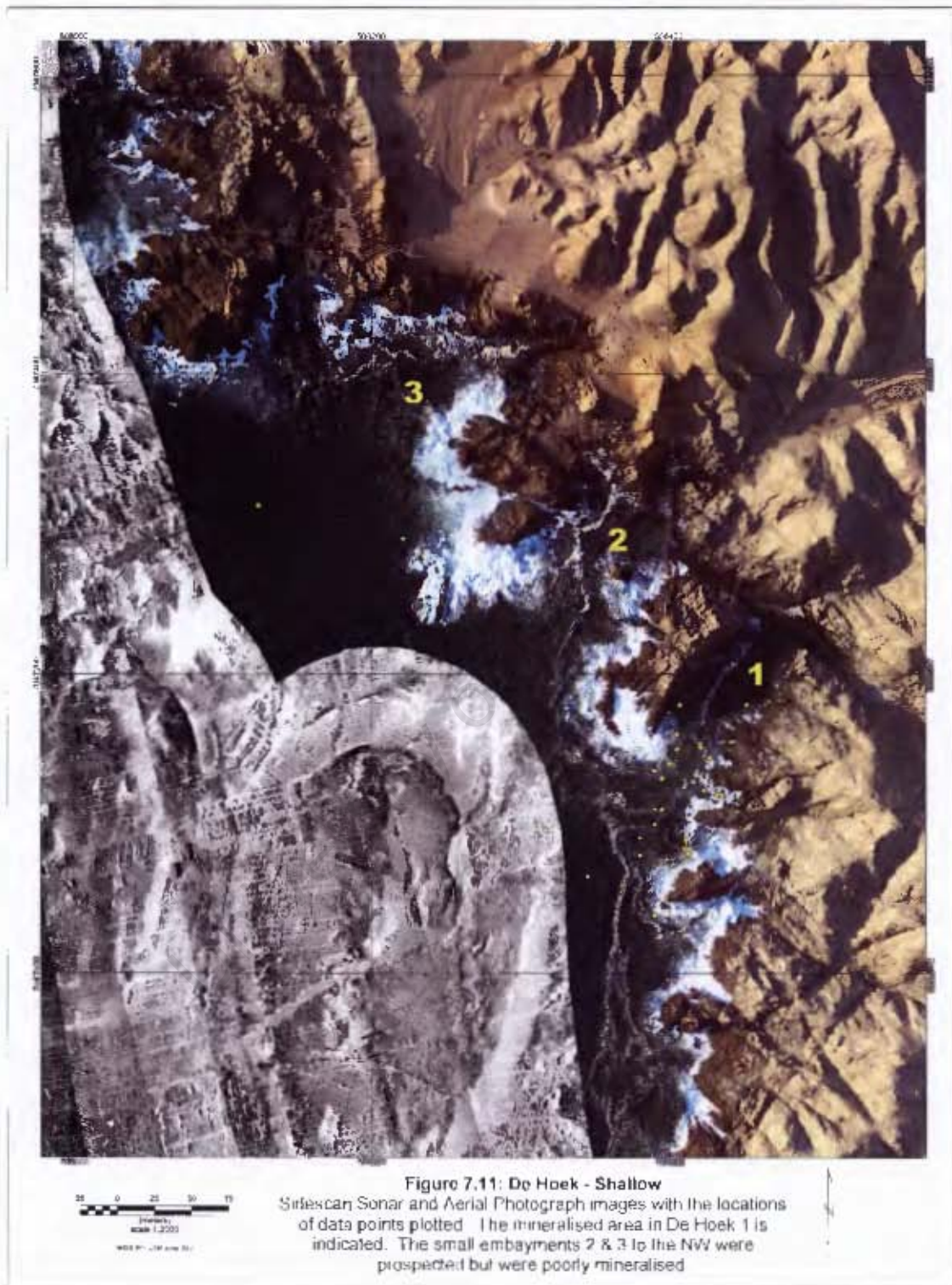


Figure 7.10: Schematic stratigraphic column of features mined in water depths between -1 m and -8 m at De Hoek.

Both white and darker coloured exotic agates, up to 25 mm in diameter, are also present. Whole and broken *Choromytilus meridionalis* shell with a distinct blue/black colour made up a significant portion of the gravel. The gravel is cemented towards the base. The cement is generally friable

but well cemented (hard) close to the edges of the boulders and the side walls (Unit 4). The cement does not extend into the potholes but rather forms a capping over the potholes. A thin layer (<5 cm thick) of unconsolidated but compacted coarse sand and grit occurs on top of the gravel horizon (Unit 5). Large (1-3 ton) rounded to subrounded boulders of local bedrock covered the gravel (Unit 6). These boulders were suspended in the gravel horizon and not in contact with the bedrock base of the features. Approximately 4,000 cts were mined from the caves situated in De Hoek 1 (Figure 7.11). The two similar small embayments (De Hoek 2 & 3), situated immediately to the northwest of De Hoek 1, were prospected by divers but were found not to be economically mineralised (Figure 7.11).

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De Hoek – Deep

All of the production mined from the deeper areas at De Hoek was obtained from gullies. Divers locate the gullies on the exposed bedrock. The gullies were then progressively mined and followed into the sediment drape area. The bedrock platform lies at -24 m depth and the gullies are incised to a maximum depth of -27 m (Figure 7.12).

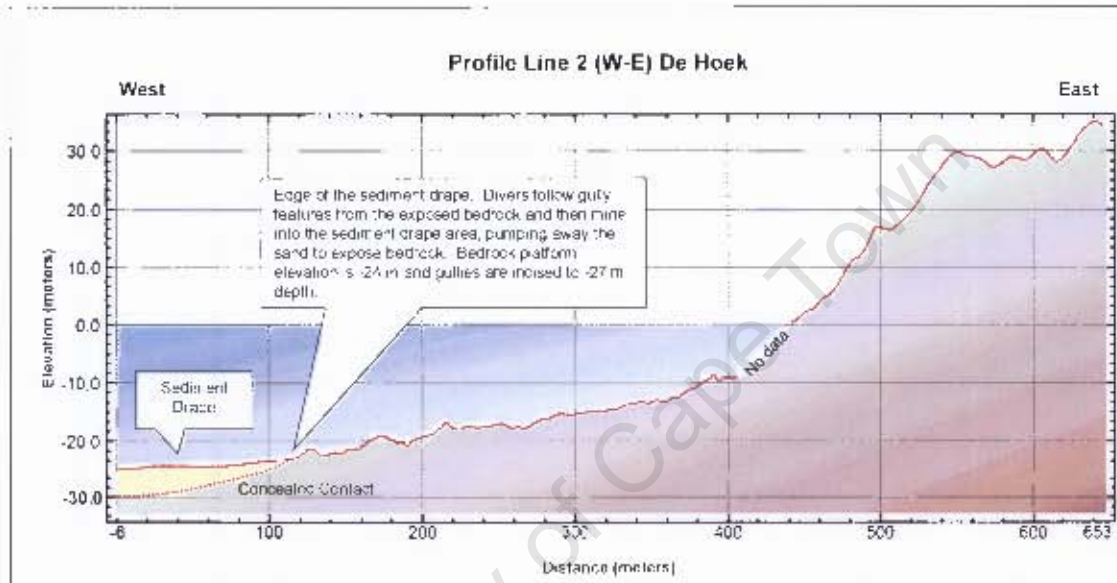


Figure 7.12: Profile Line 2 of terrain elevation in De Hoek deep mining area.

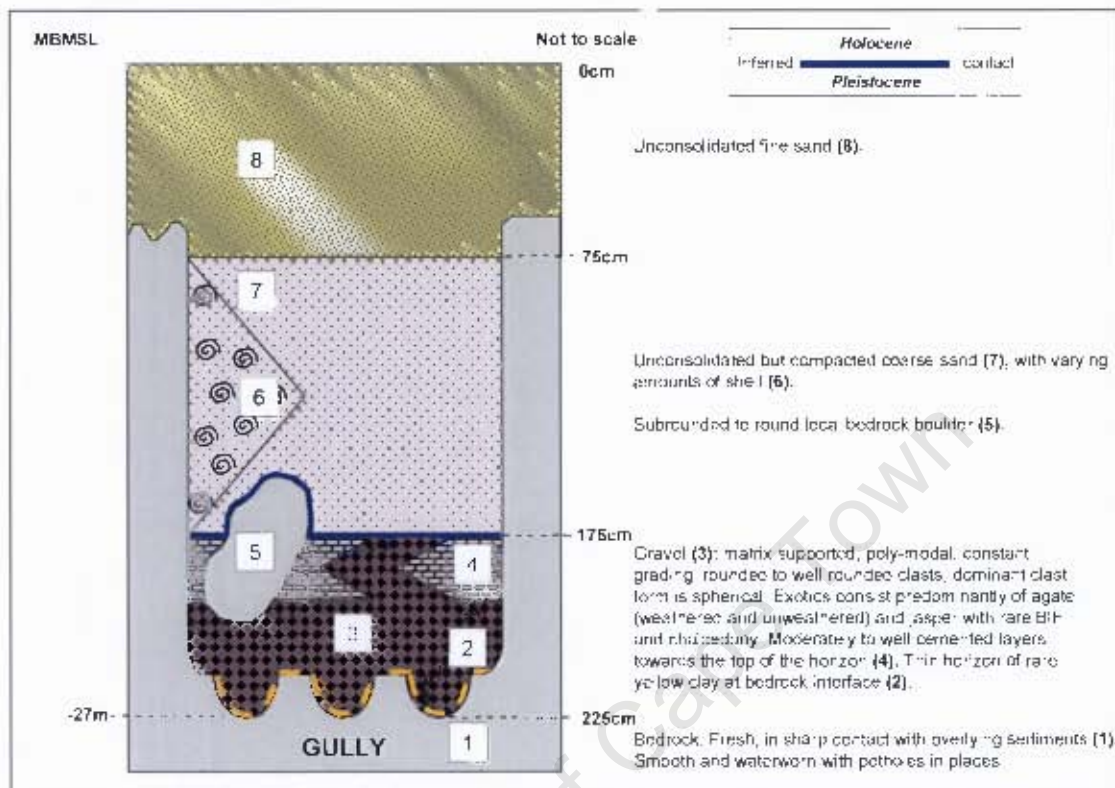


Figure 7.13: Stratigraphic column of gullies in -24 m to -27 m water depth at De Hoek.

A schematic stratigraphic column (Figure 7.13) of these deeper gully systems, has from the base of the sequence gully walls which are typically water worn and smooth with potholes in the gully floor (Unit 1). A thin discontinuous layer of yellow clay occurs at the bedrock interface (Unit 2). Above the clay occurs a dark grey coloured gravel horizon which is matrix supported and poly-modal (Unit 3). The matrix consists of friable, chalky, fine shell fragments with lesser amounts of fine to coarse sand. Shell clasts consist of mostly intact small gastropods, limpets and bivalves including Ribbed Mussel *Aulacomya ater* (Figure 7.14).

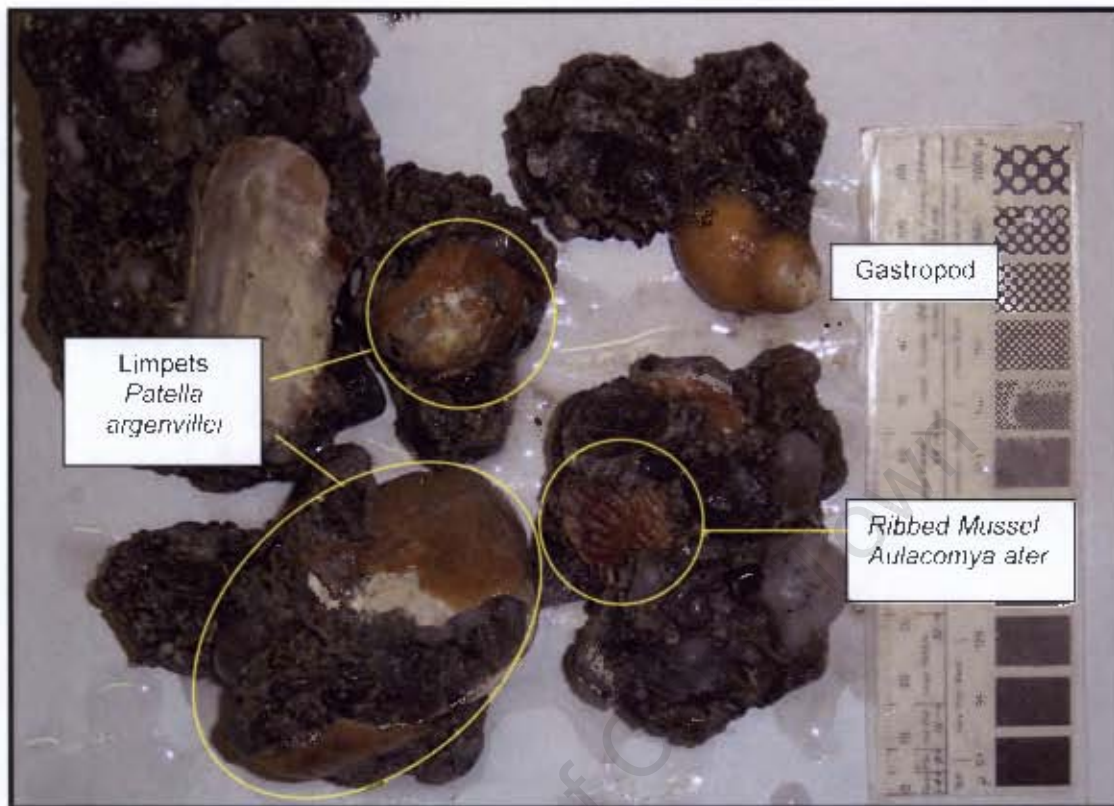


Figure 7.14: Hand specimen of cemented gravel recovered from -26 m depth in a gully at De Hoek contains various shells including fragments of brown discoloured Ribbed Mussel *Aulacomya ater*.

Lithic clasts include well rounded pebbles of darker schist and white vein quartz up to 30 mm in diameter. Well rounded exotic agates, up to 25 mm in diameter, were also present. The agates are either white in colour, indicating prolonged sub-aerial exposure and subsequent weathering, or blue-grey in colour, indicating unweathered clasts. Further exotics include jaspers, which are common, with rare banded ironstone and chalcedony. This horizon typically has constant grading and the dominant clast form is spherical. The gravel is discontinuously moderately cemented (friable) to well cemented (hard) towards the top of the horizon (Unit 4). (Figures 7.13, 7.14 & 7.15). Rounded to subrounded boulders of local bedrock are typically situated within this gravel, although these boulders are rarely in contact with the bedrock (Unit 5). The inferred Holocene/Pleistocene contact is between the lower gravels and boulders and the overlying unconsolidated sand and shell.



Figure 7.15: Hand specimen of cemented gravel recovered from -26 m depth in a gully at De Hoek – small diamond in the matrix indicated by the pen.

Above the gravel a horizon of compacted coarse sand with varying amounts of shell material is typically encountered (Units 6 & 7). The coarse sand horizon may contain minor amounts of rounded gravel clasts. The top of the sequence typically consists of a fine unconsolidated sand cover which is on average about 75 cm thick (Unit 8). However the thickness could vary depending on the underlying bedrock feature. This fine sand drape covers the bedrock and the gullies contained within.

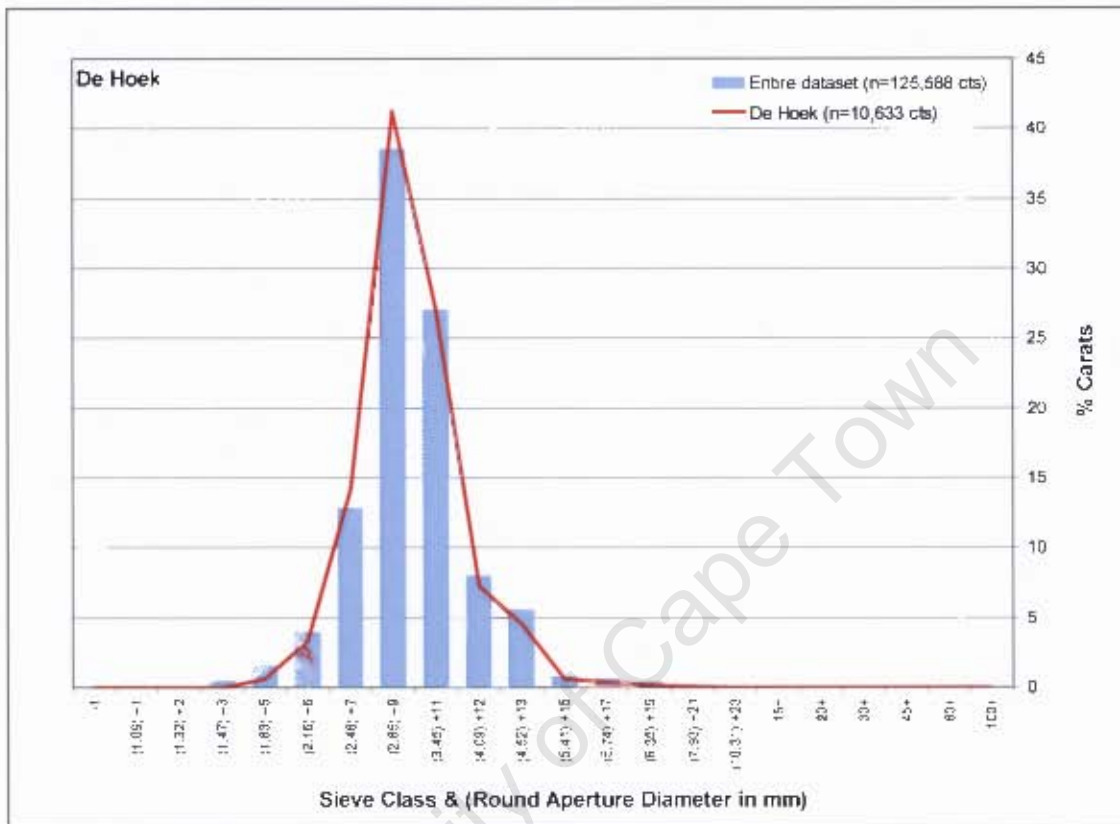


Figure 7.16: Size frequency distribution of diamonds mined from the De Hoek area plotted with the size frequency distribution of carats mined from the whole study area.

No size frequency data could be obtained for the shallow water production at De Hoek. The cumulative size frequency distribution (percentage carats per sieve class) of diamonds recovered from the deeper areas at De Hoek, display a uni-modal size distribution peaking in the +9 sieve class (Figure 7.16). It is a well sorted diamond population with 83% of the carats occurring in the +7 to +11 sieve classes. The De Hoek population (n=10 633 cts) mimics the entire population plot for the whole of the study area (n=125 588 cts).

7.2 DISCUSSION

The average stone size of diamonds mined from the De Hoek area is 0.25 cts/stn which is very similar to the average stone size of 0.26 cts/stn for the entire study area. The size frequency distribution of the diamond population mined from De Hoek is virtually identical to that of the entire diamond population for the whole of the study area (Figure 7.16). Based on the similarities in stone size and size frequency distribution, it can be assumed that the diamonds mined from the De Hoek shallow and deep areas are part of the shallow marine diamond population encountered within the study area.



Figure 7.17: Facing south-west, the *mv Rachel* mining shallow deposits in the narrow confines of De Hoek 1 on a very calm day (see Figure 7.11). The divers had to place several mooring lines on land to secure the vessel in position.

De Hoek - Shallow: At present day sea-level De Hoek forms a south facing semi-embayment with 3 micro south facing embayments (Figure 7.11). Combined with bedrock features such as wave-cut caves, potholes and gullies this configuration is conducive for the retention, re-working and concentration of diamondiferous gravel transported northward by wave action and the longshore drift (Hallam, 1964; Joynt, 1979; Corbett, 1996; Jacob, 2001). Diamonds were recovered from highly concentrated gravel mined from confined shallow caves at -1 m water depth and also narrow ledges situated at -4 m and -8 m water depths (Figure 7.17).

The bedrock in this area consists of Diaz Point Formation Unit 3 which is a diamictite containing a large proportion of coarse-grained leucogranite and quartzite boulders, as well as quartz pebbles as clasts (Siegfried, 1993). These resistant clasts would act as abrasive material when released from the conglomerate through erosion. The erosional features would have formed when sea-level, and consequently the breaker zone, were aligned with these depths (Martinez & Harbaugh, 1993). The earliest evidence for a southerly wind and swell regime driving the northward-directed longshore drift and associated aeolian activity dates back to the Eocene, although this transport system strengthened during the Neogene (Ward & Jacob, 1999; Spaggiari *et al.*, 2002). As these features (caves and narrow ledges) are not extensive, it is likely that the period of time that this level of the coast was exposed to the breaker zone and the erosional forces that formed these features were of short duration (Anderson *et al.*, 1999). However, despite the relatively short exposure to erosional forces, the diamond grade of the material mined from the shallows was double that of the deeper mining area. The small embayments situated further to the west (De Hoek 2 & 3 in Figure 7.11), were not mineralised because they are too exposed to the approaching swell regime. Gravel are therefore not retained and reworked within these features. This can be observed during storm events when approaching waves break on the shoreline of the features.

The gravel, including the cemented portions, contained broken and whole *Choromytilus meridionalis* shell which was distinctly blue/black in colour. Therefore a Holocene emplacement of less than 10 ka is assumed (Figures 6.13 & 6.14). The caves therefore provided a superior trapsite within which a very high concentration of diamonds could be accumulated within a relatively short period of time. The presence of *Choromytilus meridionalis* shell also indicates that the environmental and physical conditions during deposition were similar to the present day scenario i.e. a cold water, high energy, rocky coastline. The cementation of the gravels would most likely have occurred during sub-aerial exposure 4.5 ka ago when sea-level dropped briefly to -1 m below present sea-level (Compton, 2006). The yellow clay layer is in the form of a thin continuous drape and occurs at the bedrock-gravel interface. It is inferred that the clay was deposited after the diamondiferous gravel package was entrapped. The clay was either washed in during rain events and/or formed due to the break down of clay-forming minerals from material within the sedimentary package during periods of sub-aerial exposure while the trapsites were filled with a briny solution. The large boulders which covered the gravel acted as the primary preservation factor to protect the gravel from subsequent erosion.

De Hoek – Deep: The main area of mineralization occurs where the westward flowing drainage channel meets the larger sediment drape area. Here a bedrock platform occurs at -24 m water depth which has gullies incised to a maximum depth of -27 m (Figure 7.12). Diamonds are predominantly recovered from the north-northwest oriented gullies on the southern bank of the stream. Due to the fine sand drape, the full extent of the platform is not known. However, the gullies would most likely have been incised when sea-level was at or about -24 m below present sea-level (Martinez & Harbaugh, 1993; Jacob, 2001). The landward edge of the fine sand drape is a good indication of the location of the coastline at a -24 m sea still stand. During flash floods the stream would transport clastic material to the -24 m coastline. At the coast the stream enters a small south facing embayment approximately 100 m wide (Figures 7.4 & 7.18 A). The clastic material introduced by the small stream would act as abrasive agents in the coastal processes which would assist with the incision of the gullies. The small fan of coarse clastic material would also form a trapsite for diamonds transported northward with the longshore drift (Figure 7.18 A).

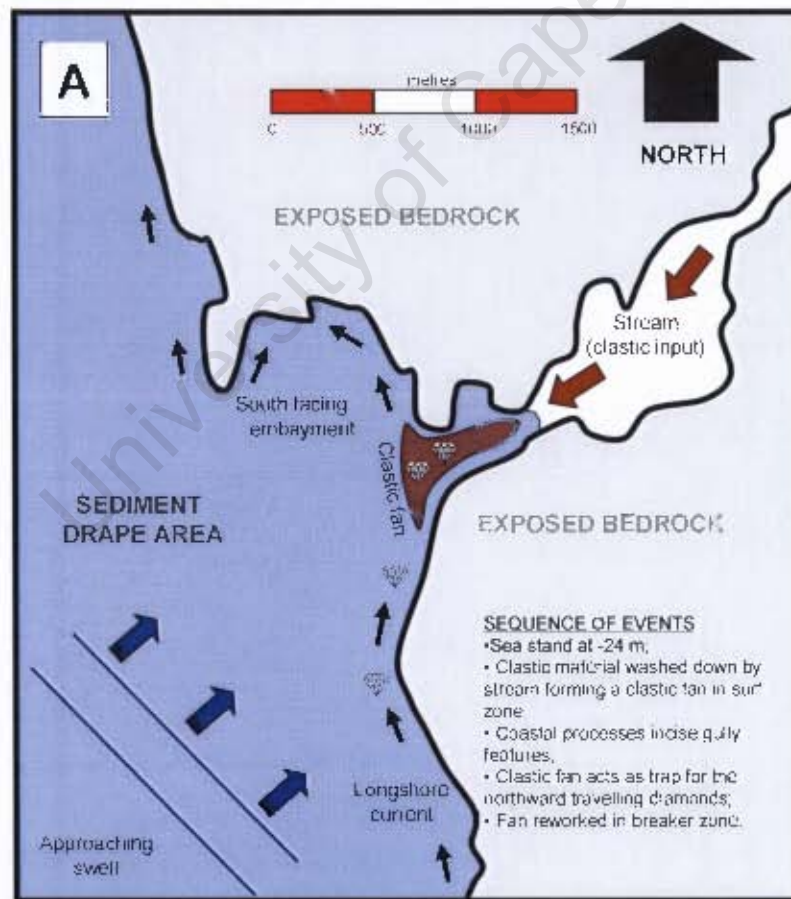


Figure 7.18 A: Depositional model for diamonds occurring at De Hoek Deep. The small fan of coarse clastic material in the surf zone portion of the -24 m shoreline would form a trapsite for diamonds transported northward with the longshore drift.

The reworked and enriched gravel would be deposited through storm events at a slightly higher elevation and therefore eastward relative to the -24 m coastline. Gravel would be deposited together with boulders in gully trapsites. The south facing embayment was fully exposed to the southwesterly oriented wave energy and gravel was not preserved in them to the same extent as the sheltered north facing gullies on the south bank (Figure 7.18 B). The boulders and cementation greatly assisted to preserve the highly reworked diamond rich gravel packages within these gullies situated on this steeply dipping, high energy, rocky coastline.

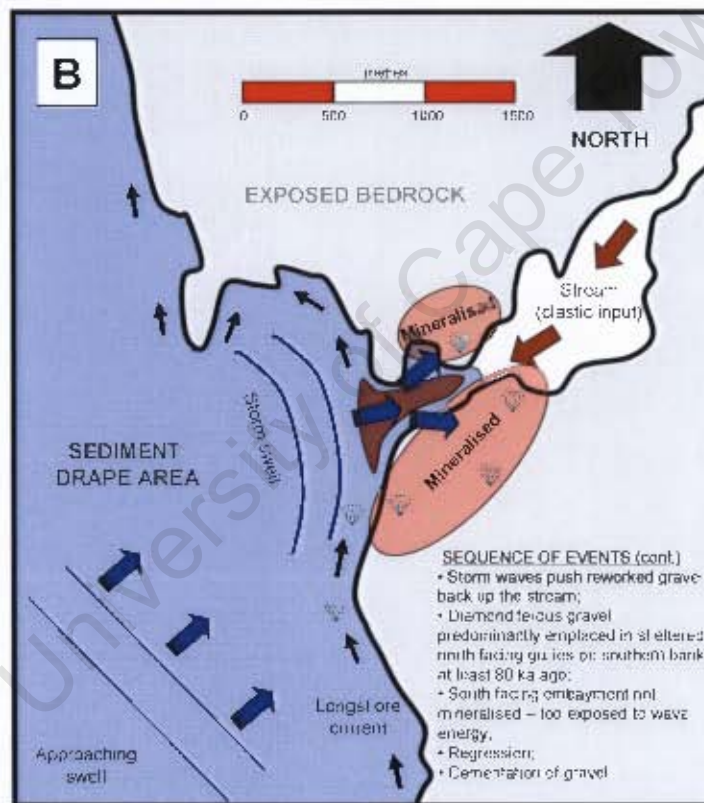


Figure 7.18 B: Depositional model for diamonds occurring at De Hoek Deep. The reworked and enriched gravel would through storm events be entrapped together with boulders in gully trapsites. The south facing embayment was too exposed to the southwesterly oriented wave energy and gravel was not preserved in this area to the same extent as the sheltered gullies on the south and north bank of the stream.

The diamondiferous gravel, including the cemented portions, contains Ribbed Mussel *Aulacomyza ater* shells which appear relatively old as they are discoloured brown and friable (Figure 7.14). It is therefore assumed that deposition of the diamondiferous gravel in the deeper gullies (-24 m to

-27 m) at De Hoek took place 80 ka ago during the Pleistocene as this was the first submergent period for the -24 m coast before the LGM (Figure 7.19).

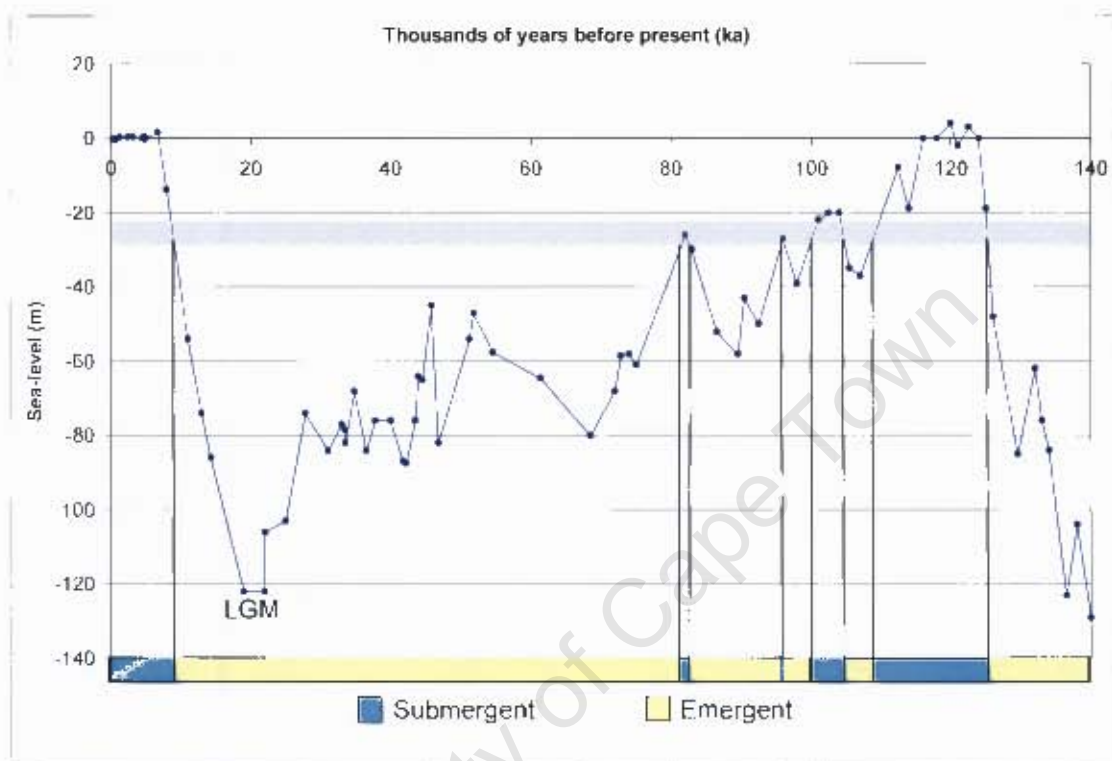


Figure 7.19. Composite sea-level curve for the last 140 ka indicating submergent and emergent periods for the -21 m to -27 m coastline (Compton, 2001; Compton *et al.*, 2002; Yokoyama *et al.*, 2000; Chappel *et al.*, 1996; Fairbanks, 1990; Shackleton, 1987).

8. GROSSEBUCHT

8.1 RESULTS

For the purpose of this study, the area "Grossebucht" refers to the area where diver-assisted mining took place between Kleine Bogenfels in the north and the Grossebucht headland in the south. The actual Grossebucht, meaning "Big Bay", is situated approximately halfway between Halifax Island in the north and Elizabeth Bay in the south (Figures 1.3. 2.1 & 8.1)

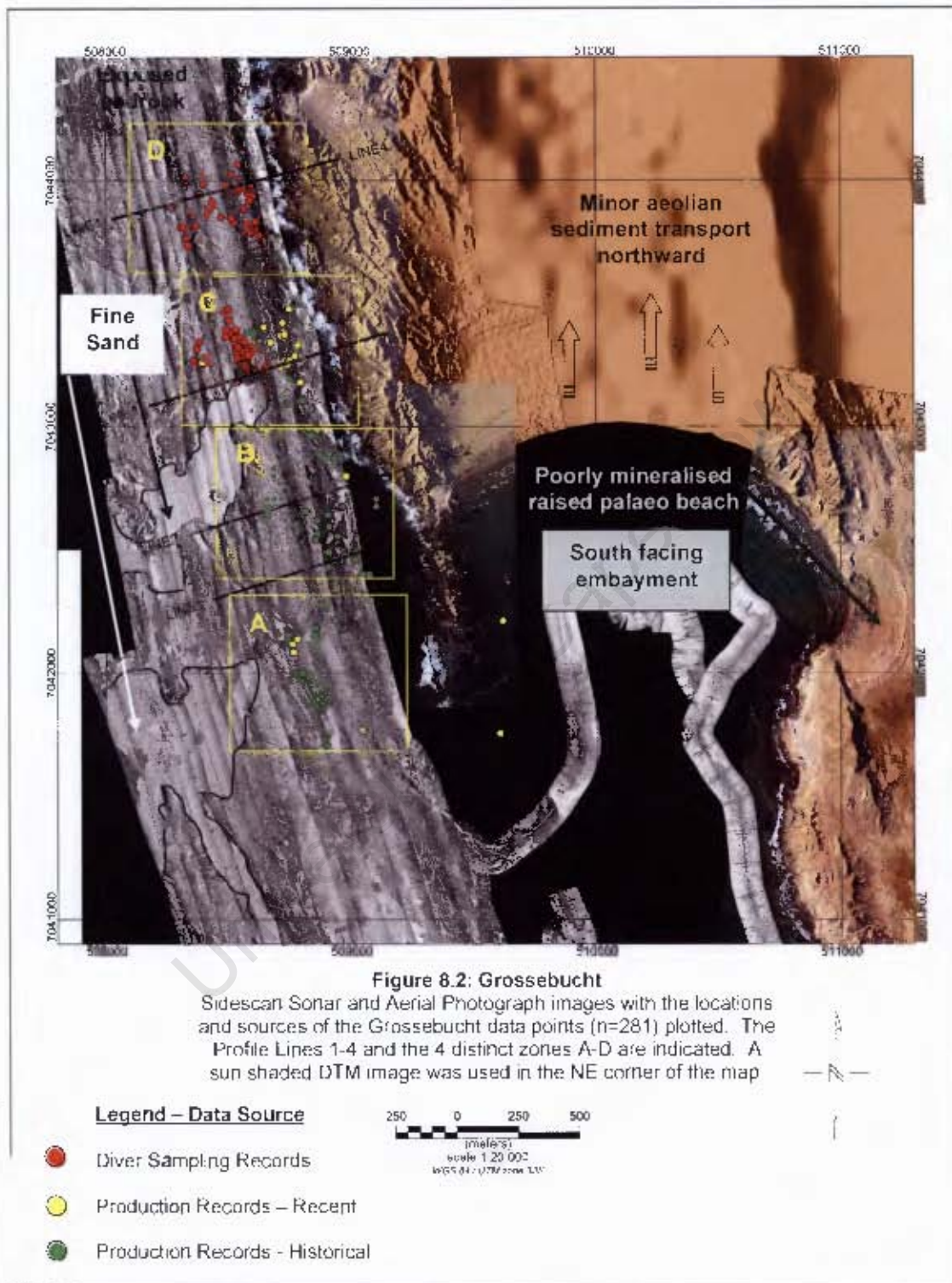
The area is mostly underlain by the Diaz Point Formation of the Gariep Supergroup. The exposed north-south trending section of rocky coastline situated to the west of Grossebucht consists of Diaz Point Formation Unit 3, which is composed of quartzite overlain by diamictite with minor interbedded chloritic quartz schists (Figure 4.1). These rocks form a straight, seaward dipping, high energy coastline. To the east of the coastline the bedrock consists of Diaz Point Formation Unit 2, which are severely weathered schists with extensive quartz veining and rare interbedded flaggy quartzites. The preferential erosion of Diaz Point Formation Unit 2 formed the Grossebucht embayment (Siegfried, 1993).



Figure 8.1: Facing north, an oblique aerial photograph of Grossebucht with the approximate location of the mining area indicated. Note the rocky coastline in the west with a series of blunders extending south to form the "foul grounds".

Grossebucht is a large south facing embayment which is fairly well protected from the southwesterly swells by a rocky headland which extends southwards forming the "foul grounds" along the western edge of the embayment. The northern portion of the bay is therefore not directly exposed to swells and consequently gently sloping sandy beaches have accumulated here (Figure 8.1 & 8.2). The inner portion of the bay is sediment filled and this large south facing embayment serves as a minor headland sediment bypass. Through the prevailing southerly wind regime, the sand deflated from the beach is re-introduced into the marine environment 9 km further up the coast at Guano Bay and Shearwater Bay, which is situated immediately to the west and east of Diaz Point respectively (Figure 4.1).

The seabed in the Grossebucht area is mostly comprised of exposed Pre-Cambrian bedrock. Two isolated areas of sediment drape also occur in this area. The sediment drape areas basically display two types of acoustic facies. The light coloured acoustic facies indicate unconsolidated fine sand. The darker coloured acoustic facies, within which mega-ripples can be observed, is unconsolidated, rippled, pebble gravel. This unconsolidated sediment drape does not extend shoreward beyond the -24 m isobath (Figure 8.2). From the aerial photograph and sidescan sonar images of the Grossebucht area, a series of parallel normal faults trending $\sim 300^{\circ}$ and an intersecting set of faults trending $\sim 210^{\circ}$ occurs along this part of the coast. These structurally controlled features extend offshore where they have been preferentially eroded to form gullies (Figures 4.13, 8.2, 8.5, 8.7, 8.10 & 8.12).



Sampling and mining activities in the Grossebucht area revealed that diamonds were roughly linearly distributed along a 3 km stretch running parallel to coast. In the south the diamonds were

found in a shallow bedrock depression, whereas towards the north, diamond occurrences were largely limited to bedrock controlled gullies (Figure 8.2).

The Grossebucht dataset accounts for a total of 281 records which have been compiled from 3 sources (Figure 8.2). Historical records for production mined between 1990-1999 accounts for 150 data points (20,310 cts). More recent production records which were recorded since 2002 account for 37 data points (1,497 cts). Diver-assisted sampling carried out between 1999 and 2003 represents 94 records (340 cts). The historical records are concentrated in the south while the more recent production records and diver-assisted sampling records are in the north.

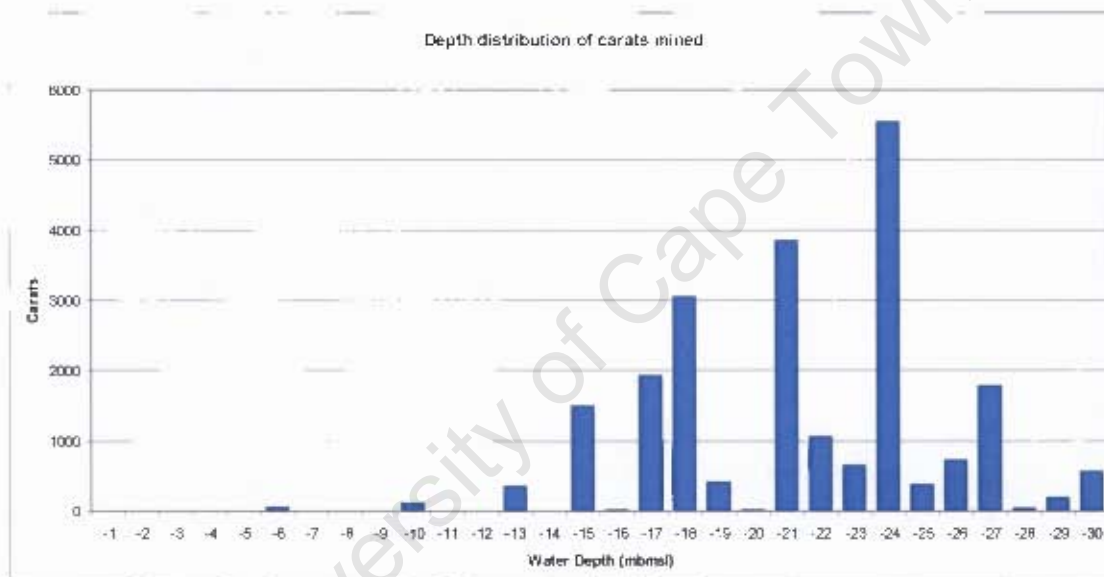


Figure 8.3: Depth distribution of diamonds mined from the Grossebucht area.

Diamonds were recovered over a range of water depths focused between -15 m and -27 m. The bulk of the diamonds were mined from between -18 m and -24 m water depths with a notable peak in production at -24 m (Figure 8.3).

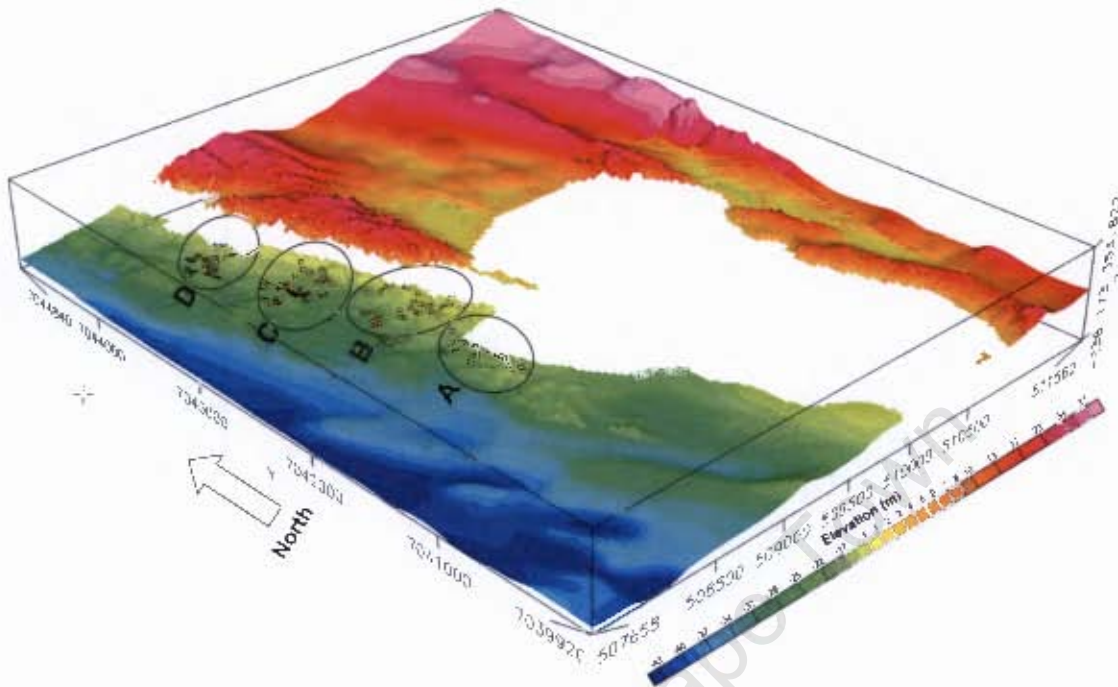
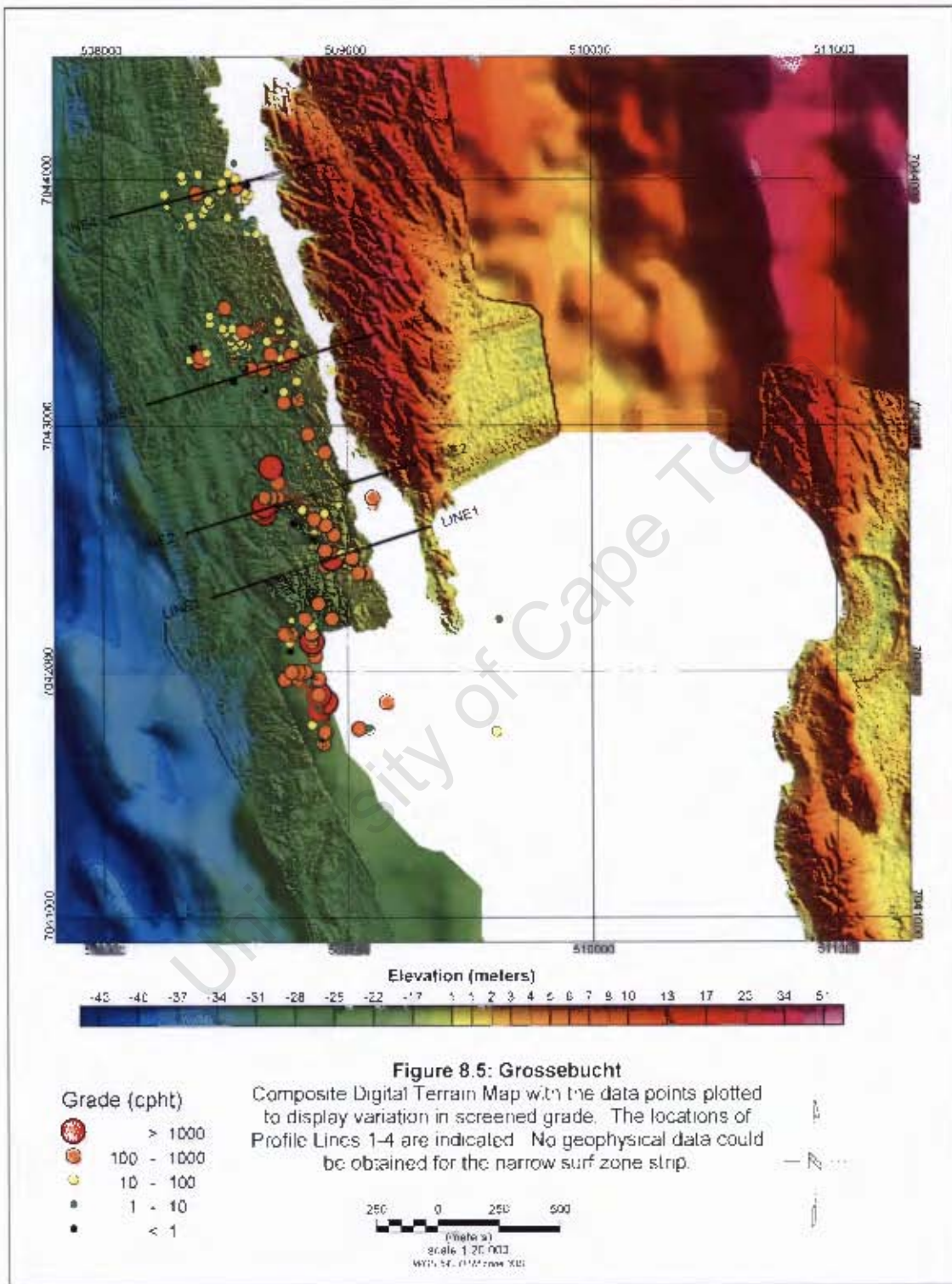


Figure 8.4: A 3D perspective of Grossebucht with datapoints and the 4 distinctive mineralised areas marked A -- D.

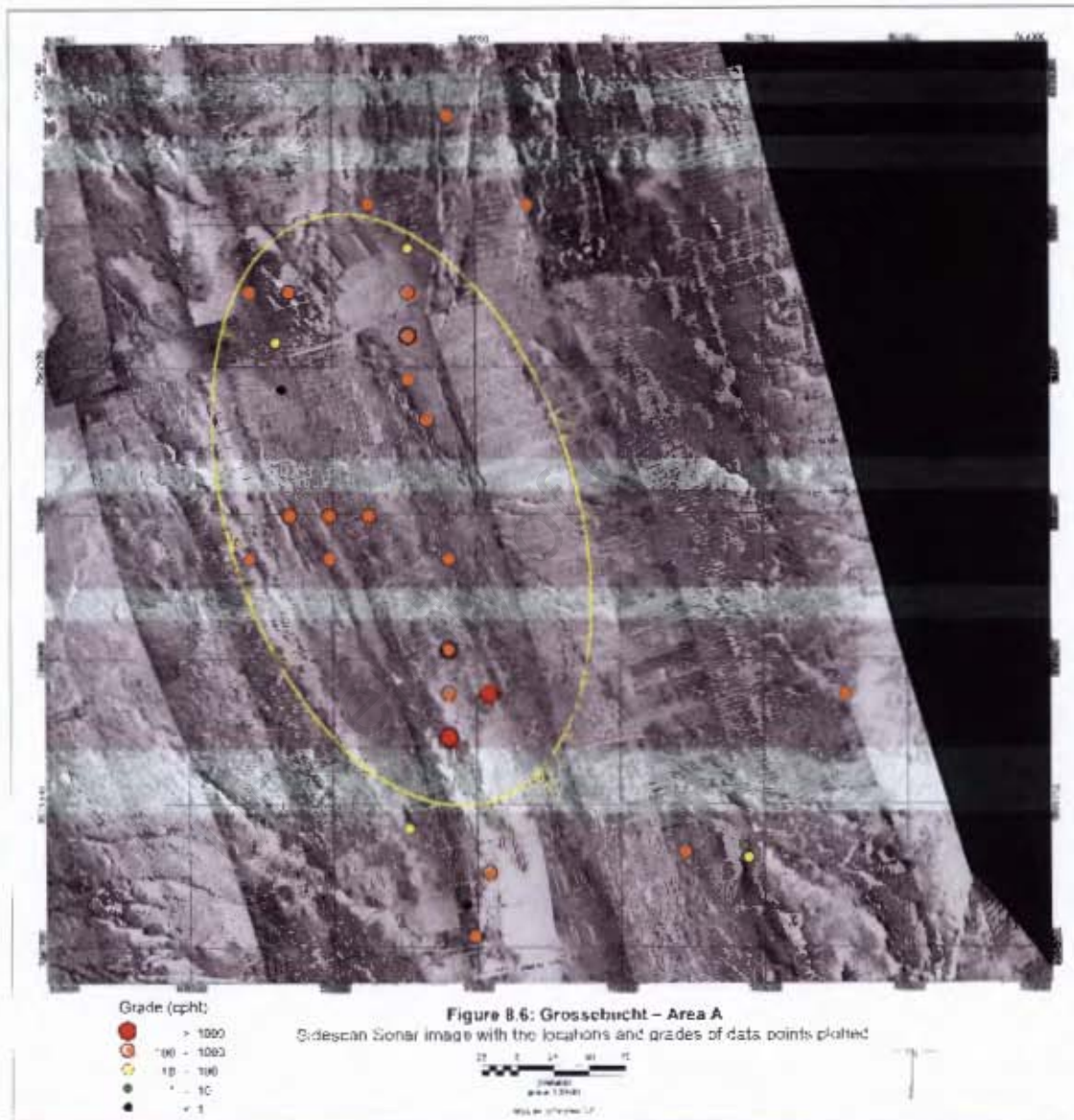
The average stone size for the diamonds recovered from the Grossebucht area is 0.28 cts/stn, which is slightly larger than that of the entire dataset which is 0.26 cts/stn. There is a notable decrease in stone size from 0.29 cts/stn in area A in the south to 0.24 cts/stn in area D approximately 3 km further north (Figure 8.4).

The average grade of screened gravel (+1.6 mm, -10 mm) recovered from the area is in excess of 1000 cpht. There is however considerable variance in grade within the Grossebucht area with the highest grade encountered in area B. The grades of screened gravel recovered in Grossebucht will be expressed as a relative percentage of the average grade of area B. The relative average grade of screened gravel was 50% in A, 100% in B, 25% in C and 6% in D (Figure 8.4 & 8.5).



Area A: The seabed in the southern end of the mineralised zone in Grossebucht is composed of exposed bedrock which on the sidescan sonar image appears relatively smooth with few incised gullies (Figure 8.6). The mineralised gravel was mined from a shallow bedrock depression with a

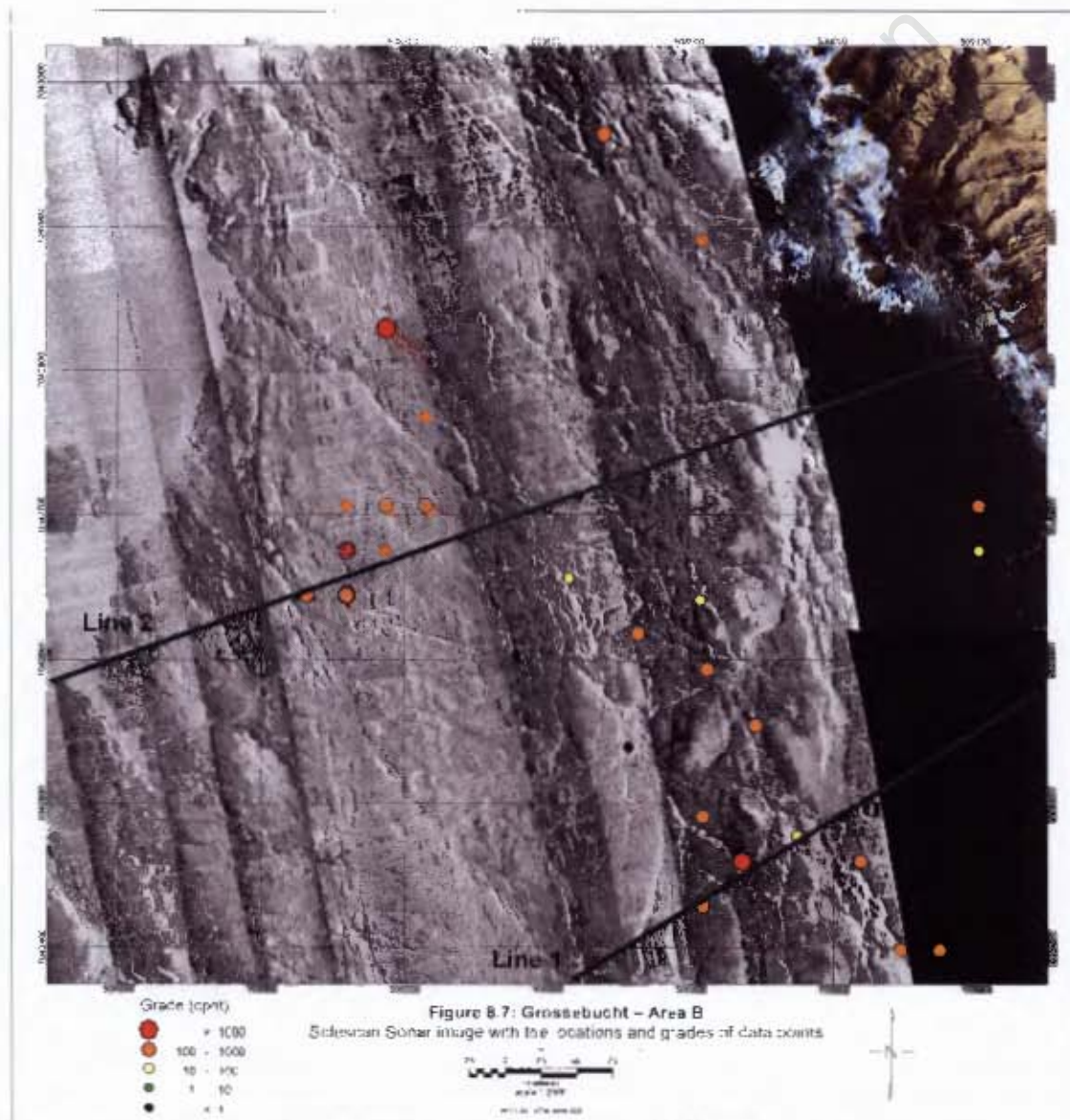
smooth floor. Although covered by the earlier sidescan sonar survey, the area was only partially covered by the multi-beam survey (Figures 8.4 & 8.5). It is therefore not possible to compile a meaningful profile across the basin area. The gravel mined by the divers from the depression was unconsolidated.



The data points are a combination of Historical and Recent Production data (Figure 8.2). Several of the Historical Records have identical location coordinates in the database. These records indicate the approximate mining positions of the vessels. Interviews with the divers confirmed that the encircled area indicated on Figure 8.6 was completely mined out. The relative average

grade of material recovered from this area was approximately 50% of the grade of the area B situated immediately to the north (Figure 8.2 & 8.5). Approximately 10,500 cts were recovered from this area at an average stone size of 0.29 cts/stn.

Area B: Situated north of the bedrock depression in area A, the seabed in area B is composed of exposed bedrock incised by gullies. A large proportion of which are generally trending $\sim 300^{\circ}$, analogous to the regional parallel normal fault features. The smooth textured light coloured acoustic facies of the landward edge of the sediment drape is visible in the west (Figure 8.7).



The data points are a combination of Historical and Recent Production data (Figure 8.2). The average grade of material recovered from this area was the highest of the 4 areas in Grossebucht (Figure 8.7). Approximately 7 300 cts were recovered from this area at an average size of 0.28 cts/stn.

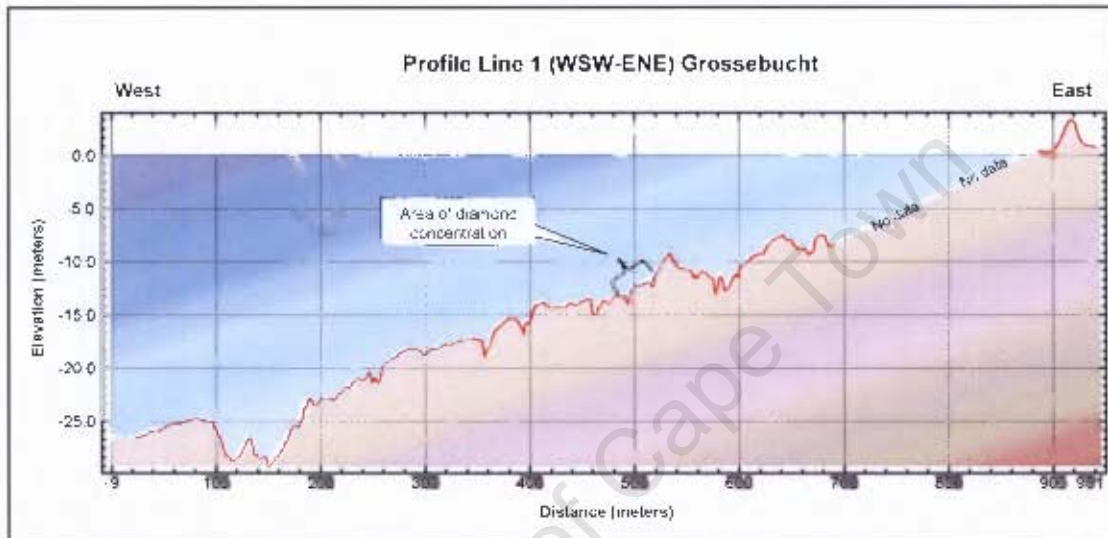


Figure 8.8: Profile Line 1 of terrain elevation in Grossebucht area.

Profile Line 1 (Figure 8.8) situated in the southern part of Grossebucht indicates the area of increased diamond concentration is associated with a depression in the bedrock at the base of a well developed 3 m cliff in -13 m water depth.

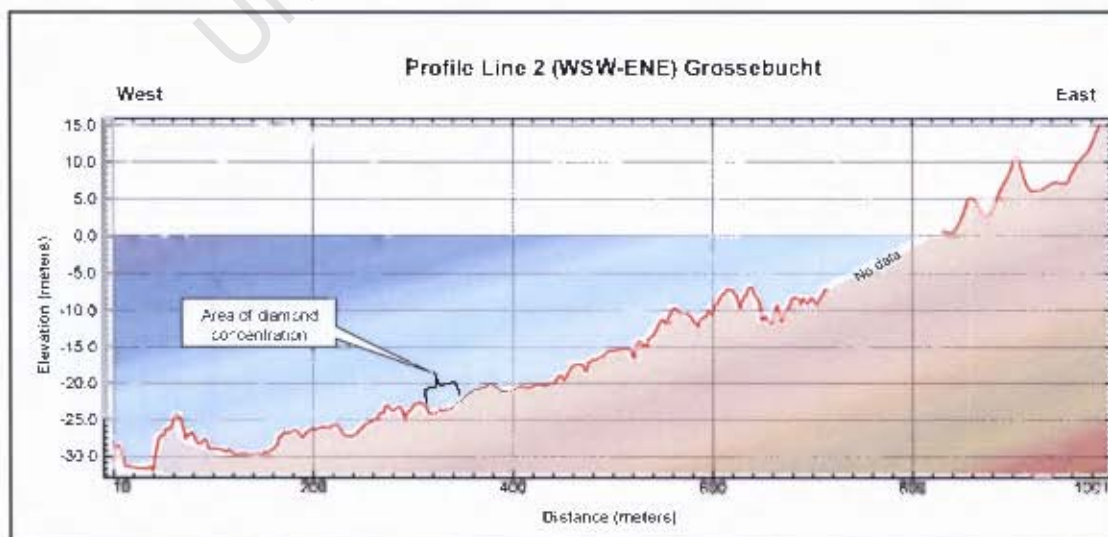
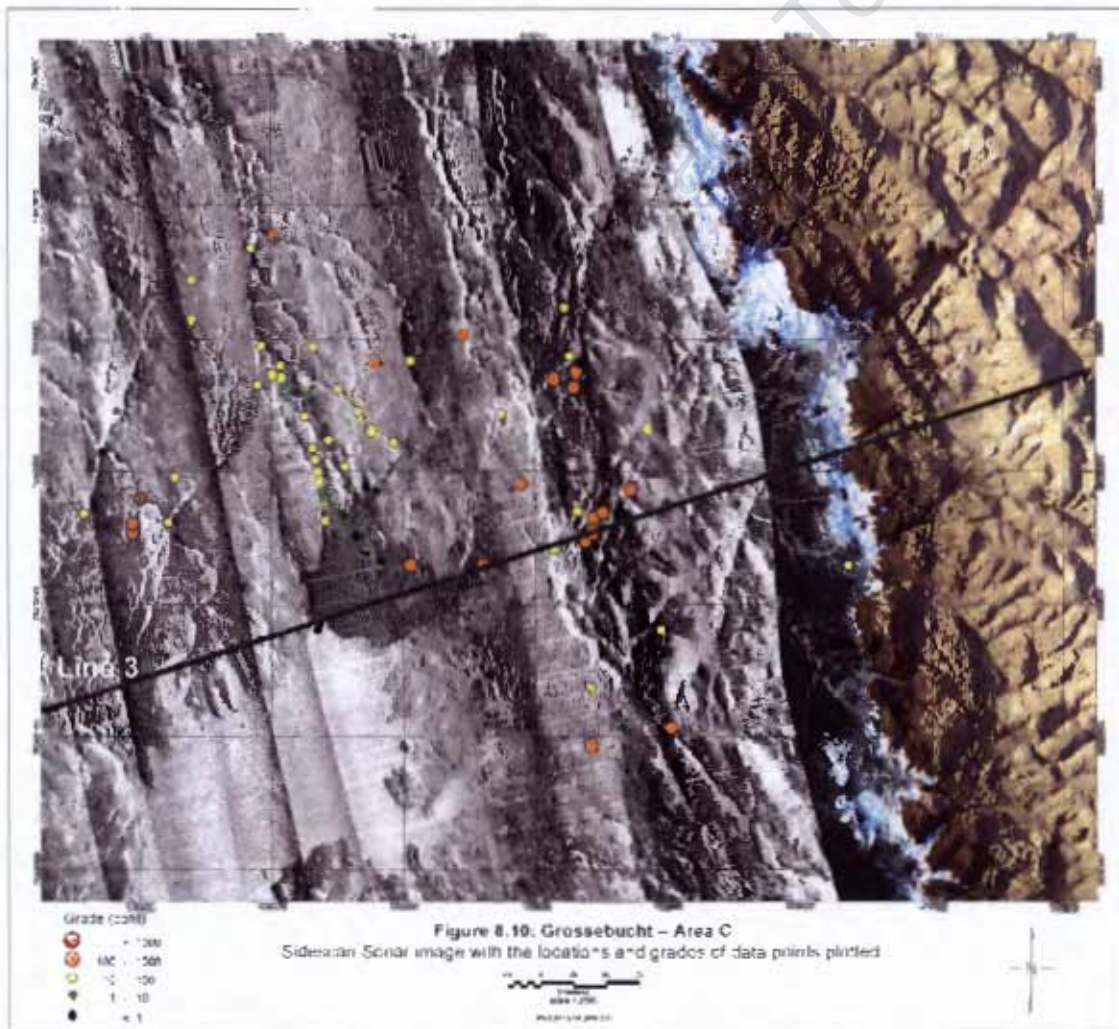


Figure 8.9: Profile Line 2 of terrain elevation in Grossebucht area.

Profile Line 2 (Figure 8.9) situated in the southern part of Grossebucht indicates the area of increased diamond concentration is associated with a depression in the bedrock at the base of a poorly developed 4 m cliff in -24 m water depth.

Area C: The seabed in area C is chiefly composed of exposed bedrock incised by gullies. The smooth textured light coloured acoustic facies of the fine sand drape is visible in the southwestern corner of Figure 8.10. A patch of darker coloured acoustic facies with mega-ripples, is situated on the northern edge of the sediment drape.



The data points are a combination of Diver Sampling, Historical and Recent Production data (Figure 8.2). The relative average grade of material recovered from this area was approximately 25% of the grade of the area B. Approximately 4,500 cts were recovered from this area at an average stone size of 0.27 cts/stn.

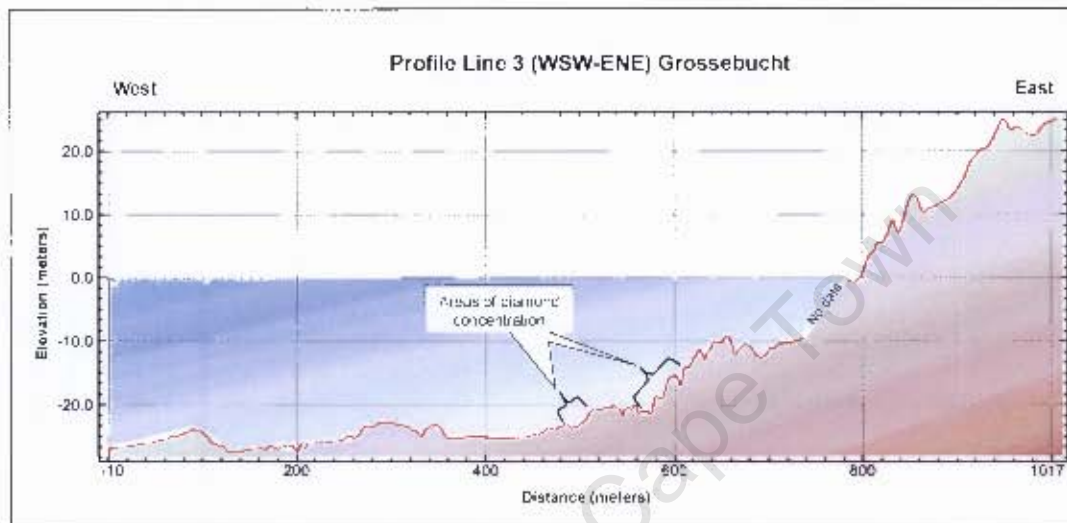
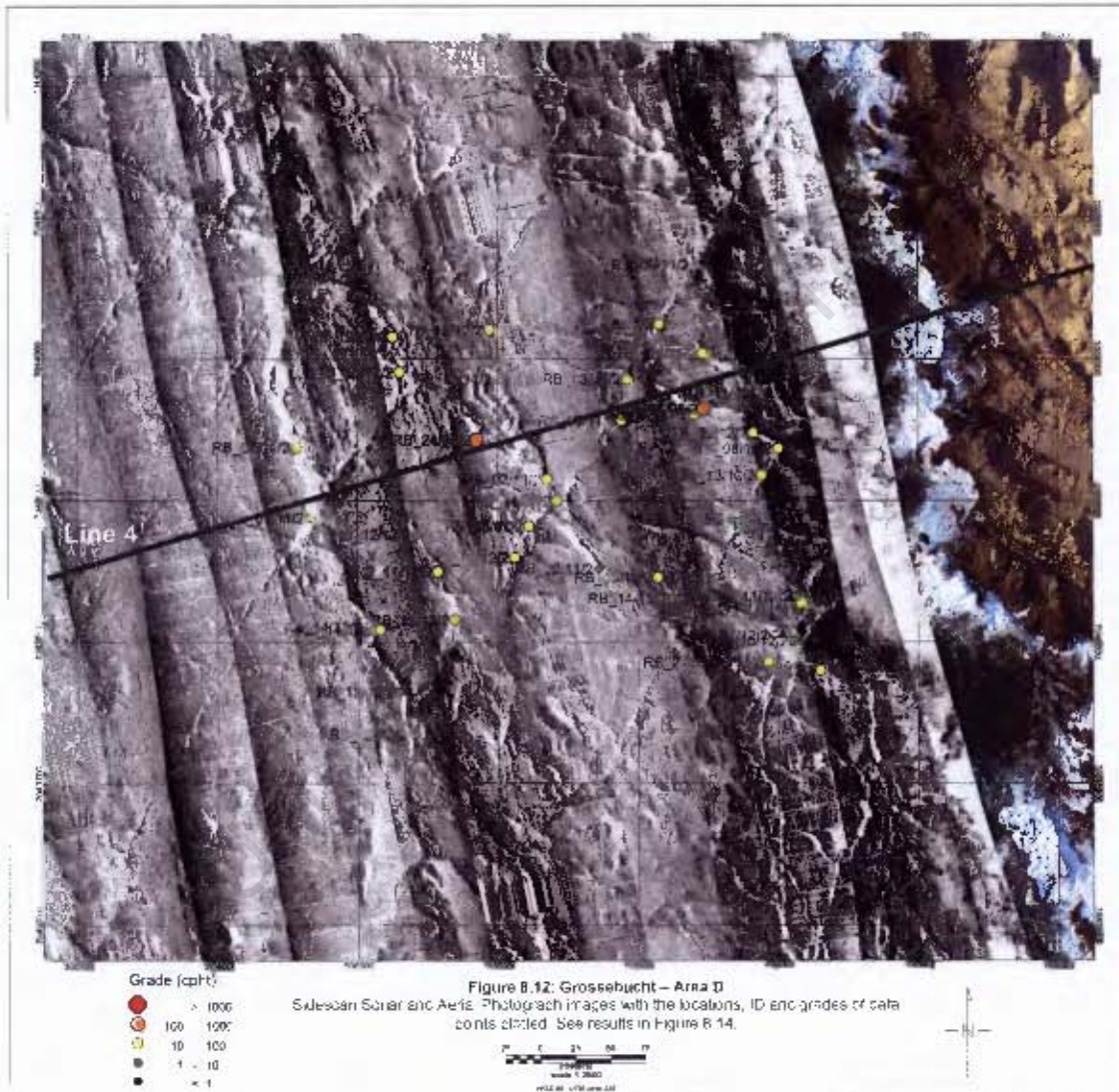


Figure 8.11: Profile Line 3 of terrain elevation in Grossebucht area.

Profile Line 3 (Figure 8.11), also situated in the northern part of Grossebucht indicates that the areas of increased diamond concentration are associated with depressions in the bedrock in water depths of approximately -24 m and -15 to -20 m.

The feature at -24 m is a depression at the base of a 3 m cliff. The profile indicates an area of relatively steeply dipping rough bedrock between -10 m and -20 m. A depression is situated at the base of the cliff at -20 m. This section of the profile line was mineralised between -20 m and -15 m (Figure 8.11).

Area D: The exposed Pre-Cambrian bedrock in area D in the northern part of Grossebucht displays intersecting sets of predominantly NW-SE and NE-SW trending structures (Figure 8.12). These structures have been preferentially eroded to form gullies. Very little sediment has accumulated on the exposed bedrock surfaces and platforms. However, within gullies and trapsites sediments have accumulated.



The data points in this area are derived from Diver Sampling data. The samples were collected and treated at the CTF in Luderitz and the DMS concentrate was sorted at the Namdeb Geological Laboratory in Oranjemund. The relative average grade of material recovered from this area was approximately 6% of the grade of the area B. Approximately 100 cts were recovered from this area at an average stone size of 0.24 cts/stn.

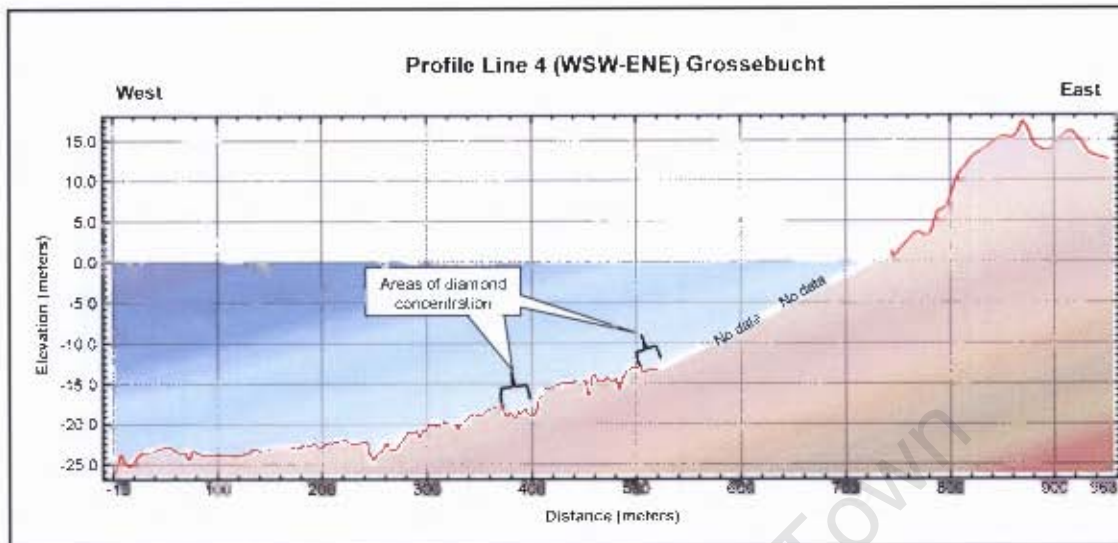


Figure 8.13. Profile Line 4 of terrain elevation in Grossebucht area.

Profile Line 4 (Figure 8.13) in the northern part of Grossebucht indicates the areas of increased diamond concentration are associated with depressions in the bedrock in water depths of approximately -19 m and -13 m. The feature at -19 m is a depression at the base of a 3 m cliff. The feature at -13 m appears to be a slight depression at the seaward end of a platform.

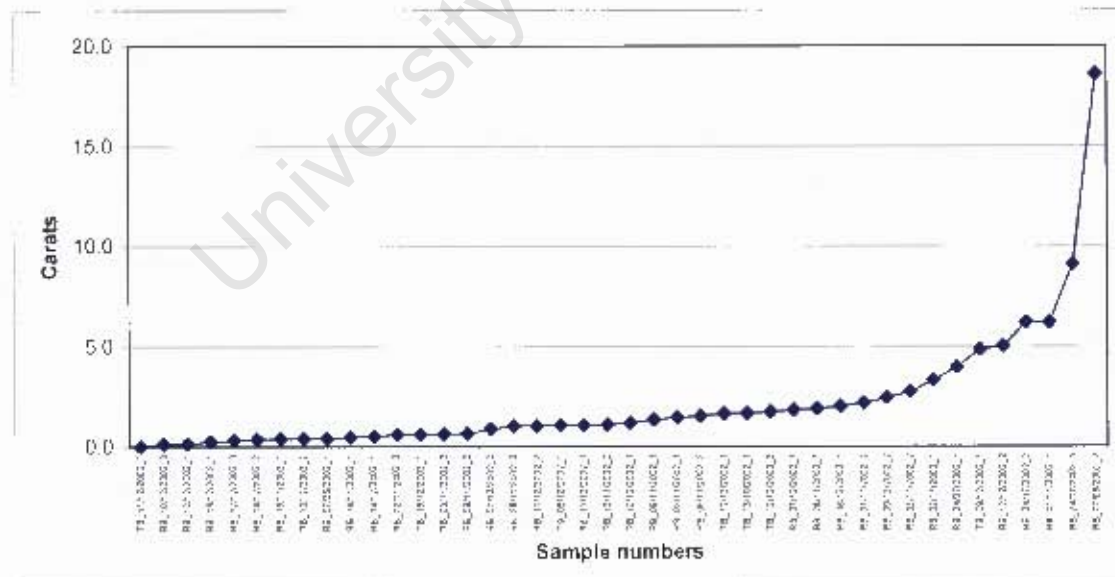


Figure 8.14: Results (cts recovered per sample) from samples collected in area D in Grossebucht. See Figure 8.12 for locations.

The results from the 42 samples which were collected display an irregular distribution of diamonds within the gully system sampled (Figure 8.14).

The gully systems in the Grossebucht area typically host two types of sequences. In the first type, a schematic stratigraphic column basically consists of gully walls which are generally waterworn and smooth (Figure 8.15 Unit 1). The gully is filled with a matrix supported package where the polymodal clasts are angular to sub-angular (Unit 2), and the matrix consisting of fine to coarse unconsolidated sand, with varying amounts of mostly fresh shell present (Unit 3). There is a notable absence of exotics and other well rounded clasts. Local bedrock clasts which are angular to subround are present (Unit 4). No cemented material and no clay are present at the bedrock interface. This sedimentary package of gully fill material is not restricted to a specific depth. These gullies are generally not mineralised.

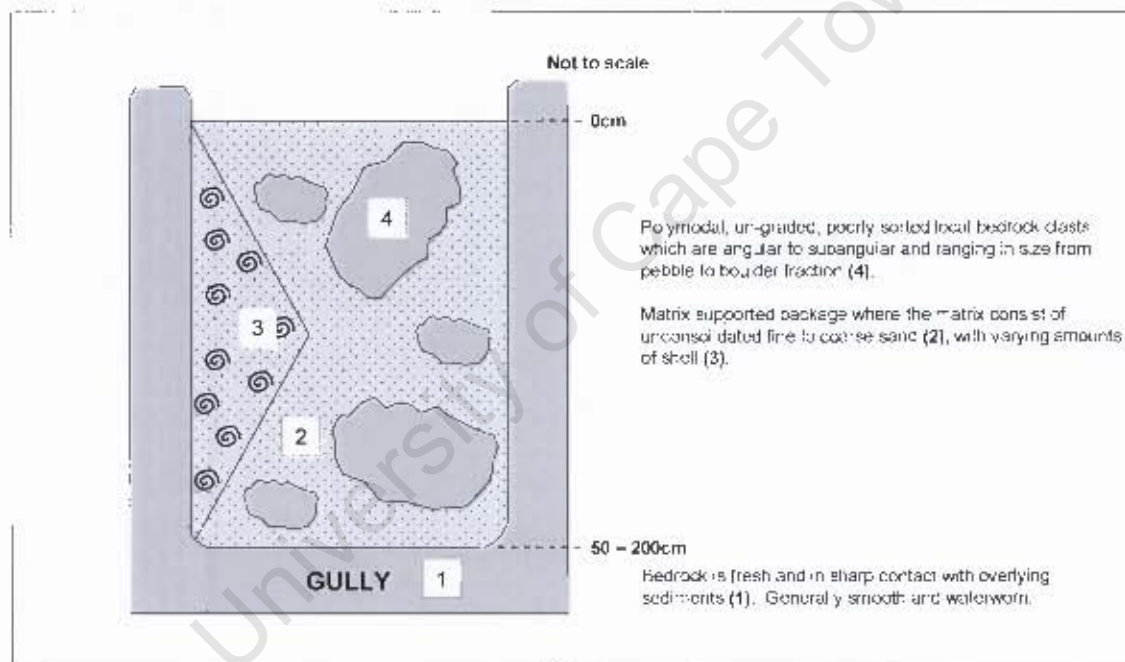


Figure 8.15: Schematic stratigraphic column of unmineralised gullies regularly encountered through the diver sampling programme in the Grossebucht area

A schematic section through the second type of gully fill can be described as follows: gully walls are generally waterworn and smooth with potholes in the gully floor (Figure 8.16, Unit 1). A thin discontinuous layer of yellow clay may be present at the bedrock interface (Unit 2). The mud layer generally follows the contours of the potholes. The gravel package (Unit 3) consists of a whitish to grey coloured, well compacted, poly-modal clast supported gravel which is generally 30-50 cm thick. Rounded to well rounded clasts include pebbles of darker schist and white vein quartz. Rare subangular to subrounded clasts of vein quartz are also present. The predominant exotic clasts present are agates, both the white and darker coloured varieties, and jaspers which

are also common. Further exotics include rare banded ironstone and chalcedony. This horizon typically has constant grading or is upward fining and the dominant clast forms are spheres and discs. The gravel is moderately to well cemented in places (Unit 4). (Figure 8.16 & 8.17). When the cemented layer is close to the base of the horizon it generally does not extend into the potholes but rather forms a capping. Sorting is generally poor with a range of clast sizes up to cobbles and sometimes boulders being present (Unit 5). Large white and brown coloured shell fragments, mostly bi-valves, make up a significant portion of the gravel. This includes brown discoloured fragments of Ribbed Mussel *Aulacomya ater*.

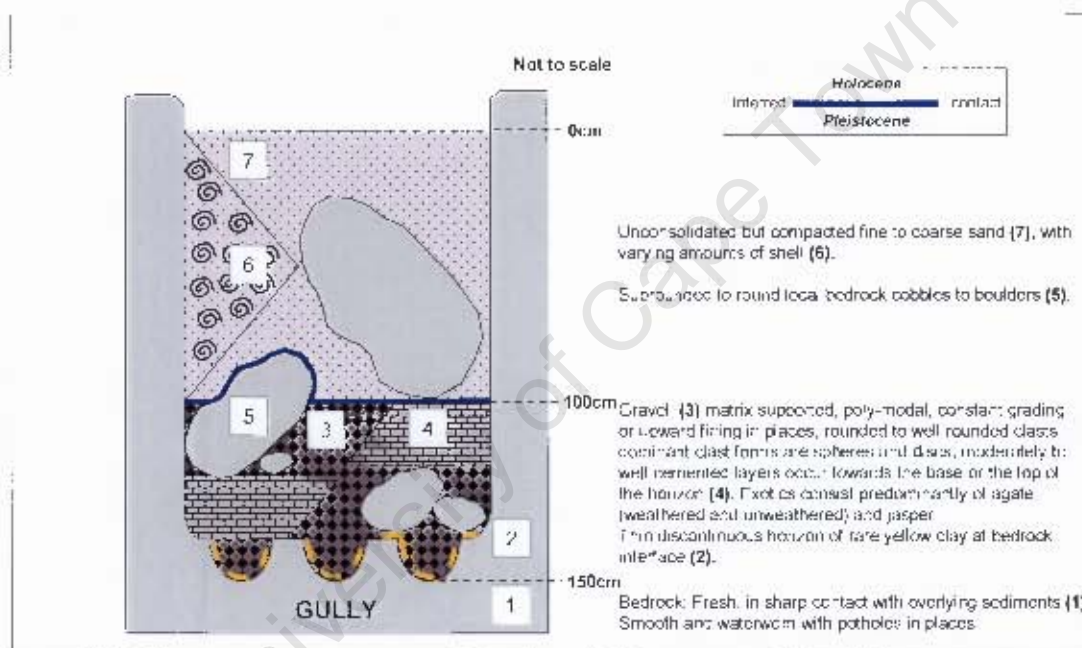


Figure 8.16 Schematic stratigraphic column of mineralised gullies encountered in the Grossebuch area.

The sequence is generally topped off by a layer of unconsolidated fine to coarse sand with varying amounts of fresh shell present (Units 6 & 7). The inferred Holocene/Pleistocene contact is between the lower gravels and boulders and the overlying unconsolidated sand and shell.



Figure 8.17: Cemented gravel (Unit 4) recovered from a gully at -24 m water depth, note the brown discoloured *Aulacomya ater* shells.

The size frequency distribution dataset for Grossebucht is relatively small as it is comprised of data obtained from the diver-assisted sampling programmes which were conducted in the area between 1999 and 2003. No size frequency data could be obtained for the diver production which was recovered from Grossebucht. The cumulative size frequency distribution (percentage carats per sieve class) of diamonds recovered from Grossebucht display a uni-modal size distribution peaking in the +9 sieve class (Figure 8.18). It is a well sorted diamond population with 74% of the carats occurring in the +7 to +11 sieve classes. Although it is a limited sample, the Grossebucht population (n=281 cts) mimics the entire population plot for the whole of the study area (n=125,588 cts) fairly closely with slightly lower percentages of carats in the +7 & +9 sieve classes and correspondingly slight increase in the +11 & +12 sieve classes.

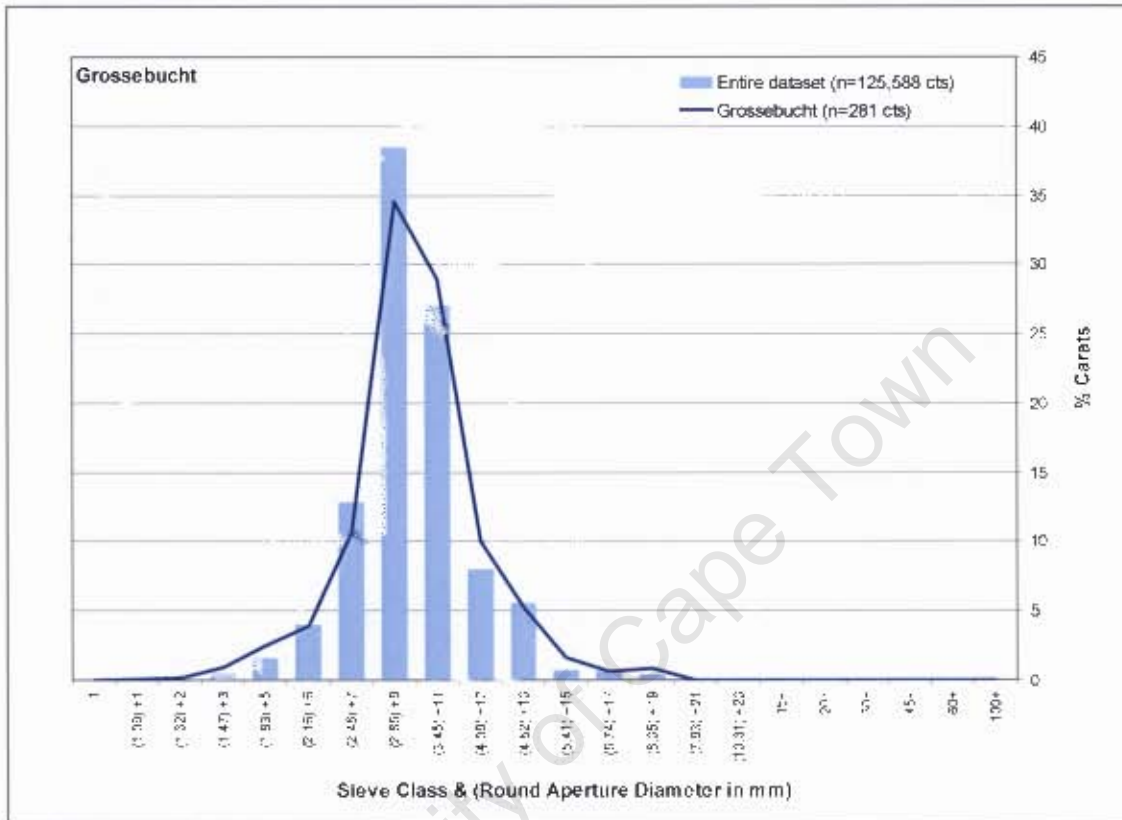


Figure 8.18. Size frequency distribution of diamonds obtained from sampling activities in the Grossebucht area plotted with the size frequency distribution of carats mined from the whole study area.

8.2 DISCUSSION

The average stone size of diamonds mined from the Grossebucht area is 0.28 cts/stn which is similar to the average stone size of 0.26 cts/stn for the entire study area. Although the size frequency distribution of the diamond population from Grossebucht is based on a relatively small sample size (281 cts), it is very similar to that of the entire diamond population for the whole of the study area (Figure 8.18). Based on the similarities in stone size and size frequency distribution, it can be assumed that the diamonds mined from the Grossebucht area are part of the shallow marine diamond population encountered within the study area.

Data points from the central and southern portions of the Grossebucht area are mostly from production records whereas the data in the north are solely derived from Diver Sampling data. The production records rarely reflect “zero diamonds recovered” records as barren material would not have been transported to the CTF for treatment. The sampling data do however give a more representative view of diamond distribution within these gully systems (Figures 8.12 & 8.14). In addition to the Diver Sampling programme, the area has also been prospected by divers trying to find extensions of the high grade material situated to the south. No such extensions were however found by the formal or informal prospecting activities except for small, isolated, preserved pockets of high grade material. Although the samples were collected with a different aim in mind than the mining production was collected in, the combined data can be used to draw meaningful conclusions from.

The diamonds were found roughly linearly distributed along a 3 km stretch running parallel to coast in water depths ranging from -15 m to -27 m (Figure 8.2 & 8.19). The bulk of the diamonds were recovered from -21 m to -24 m water depths (Figure 8.3). The quantity of diamonds recovered and the average stone size peaks in the south and decreases northward. This is typical for a diamond population which has been transported, even over short distances (Sutherland, 1982). The grade distribution does however not follow the same pattern as it peaks north of the bedrock depression in area **B** and then declines northward in areas **C** and **D** (Figure 8.19).

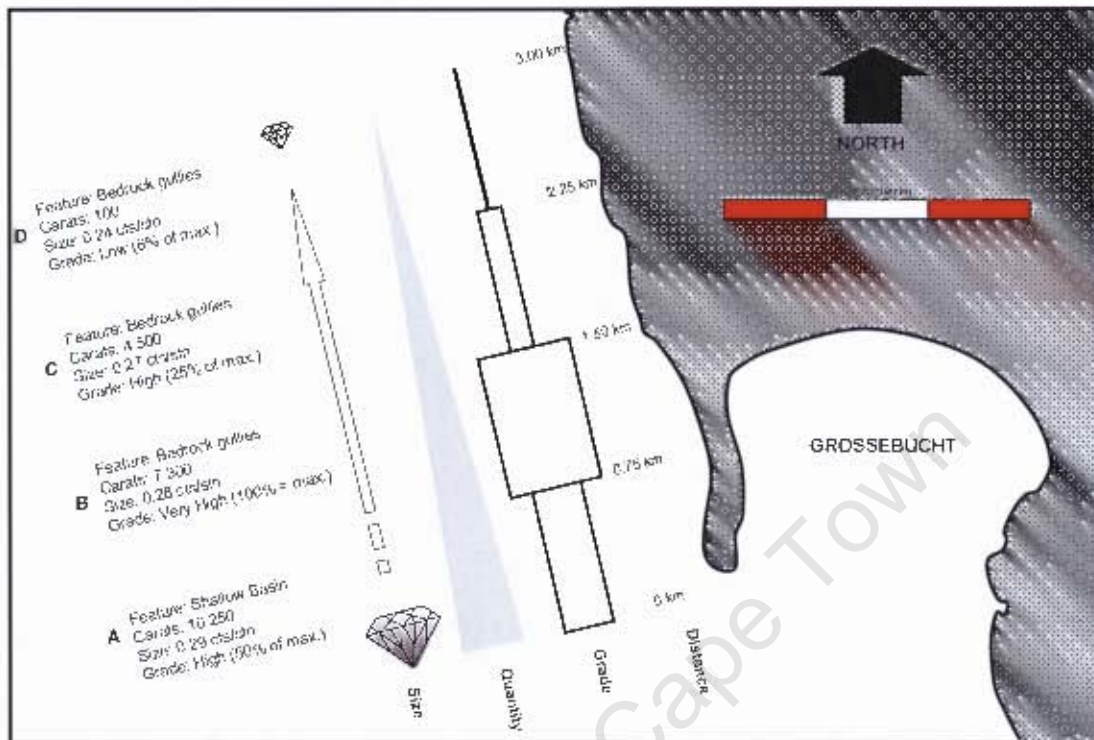


Figure 8.19: Diamond occurrence in the shallow marine environment at Grossebucht.

In area **A** the diamonds were recovered from unconsolidated gravel situated in a shallow basin or depression with smooth uncomplicated bedrock. The quantity of diamonds and the high grade of the gravel encountered in the basin indicate significant reworking. Most likely the result of prolonged exposure to high turbulence during prolonged periods of sea-level still stand (Jacob, 2001). Towards the north in areas **B**, **C** & **D**, diamonds were recovered from bedrock incised gullies. Some gullies contained material composed mostly of a sandy shell rich matrix with angular clasts (Figure 8.15). The fact that these gullies were generally unmineralised substantiated the lack of evidence of concentration processes. Conversely, the mineralised gullies were filled with gravel containing well rounded clasts and exotics with a discontinuous thin layer of yellow clay at the bedrock interface. The gravel was generally cemented (Figure 8.16), which acted as a preservation factor and prevented reworking during subsequent transgressions and regressions.

The cemented portions of gravel recovered from a gully at -24 m water depth contained fragments of Ribbed Mussel *Aulacomya ater* shell which were discoloured orange/brown (Figure 8.17). Field observations of archaeologists and geologists working on the beaches of the West Coast have noted that the blue/purple colouration of shells like *Aulacomya ater* and *Choromytilus meridionalis* is retained or faded in Holocene deposits but that the shell colour changes to an

orange/brown colour in samples older than the Holocene and associated with late Pleistocene (Eemian) deposits. The first submergent period for the -24 m coast before the Last Glacial Maximum was 80 ka ago (Figure 8.20). This horizon is therefore at least 80 ka old. Cementation would most likely have taken place during sub-aerial exposure subsequent to deposition.

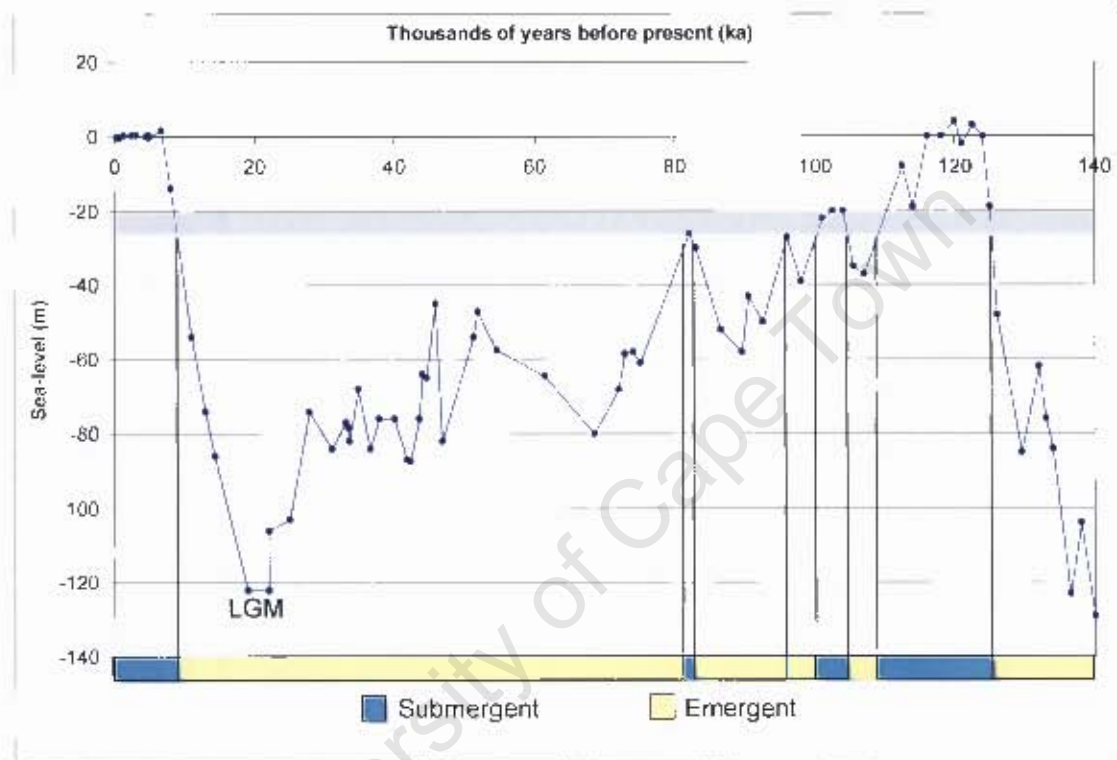


Figure 8.20: Composite sea-level curve for the last 140 ka indicating submergent and emergent periods for the -20 m to -24 m coastline (Compton, 2001, Compton *et al.*, 2002; Yokoyama *et al.*, 2000; Chappel *et al.*, 1996; Fairbanks, 1990; Shackleton, 1987).

The presence of *Aulacomya ater* shell also indicates that the environmental and physical conditions during deposition were similar to the present day scenario i.e. a cold water, high energy, rocky coastline. The cementation of the gravels would most likely have occurred during sub-aerial exposure during the last glacial period. The yellow clay layer is in the form of a thin continuous drape and occurs at the bedrock-gravel interface. It is inferred that the clay was deposited after the diamondiferous gravel package was emplaced. The clay was either washed in during rain events and/or formed due to the break down of clay-forming minerals from material within the sedimentary package during periods of sub-aerial exposure while the trapsites were filled with a briny solution.

The main area of mineralisation occurred in the southern shallow bedrock depression area between -21 m and -24 m water depth (Figure 8.21). This diamondiferous gravel package would most likely have been emplaced when sea-level was at or about -21 m below present sea-level (Martinez & Harbaugh, 1993; Jacob, 2001).

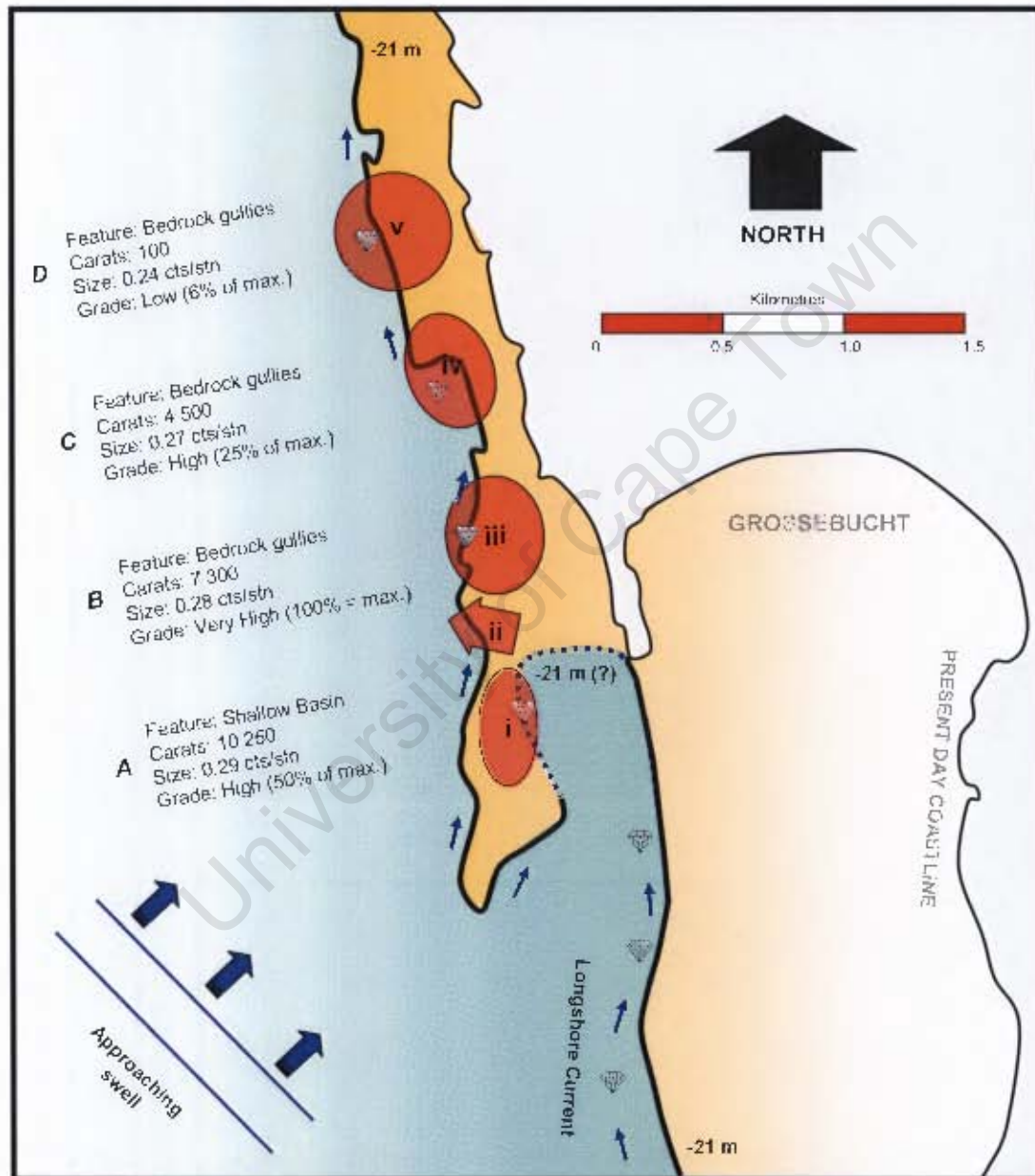


Figure 8.21: Emplacement model for Grossebucht at -21 m sea still stand.

At the -21 m sea still stand the coastline forms a south facing embayment which mimics the present day Grossebucht on a smaller scale. The embayment is narrower and therefore slightly

more sheltered than its present day equivalent. The emplacements of diamonds are proposed as follows (Figure 8.21):

- i. Diamondiferous gravel transported northward through wave action and longshore drift is retained in the NW section of the south facing embayment. Here the gravel body accumulates on a smooth bedrock surface at between -21 m and -24 m depth (area A). Prolonged exposure to reworking processes upgrade this package to a relative grade of 50%. The stone size is 0.29 cts/stn and 10,250 cts have been mined from this feature.
- ii. In the NW corner there is an area of shallow reefs which forms a breach in the headland. During periods of sea-level rise and during high tide storm events this would form a conduit for gravel to “escape” the shallow depression. The already reworked diamondiferous gravel would be re-introduced into the high energy coastal environment to the west of the headland.
- iii. Immediately north of the breach is an area where high grade gravel was mined from gullies and potholes between -17 m to -21 m depths (area B). Already reworked and upgraded material from the shallow depression would be reintroduced into the high energy environment in pulses dictated, most likely, by storm events. Here the gravel would be further upgraded in bedrock controlled trapsites (gullies and potholes) to a relative grade of 100%. The average stone size has decreased to 0.28 cts/stn and the quantity of diamonds recovered has decreased to 7,300 cts.
- iv. Approximately 1 km north, production and sampling records indicate that the relative grade of gravel within bedrock controlled trapsites has decreased to 25% (area C). The average stone size has decreased to 0.27 cts/stn and the quantity of diamonds recovered has decreased to 4,500 cts.
- v. A further 1.5km north, sampling in gully systems indicate that the relative grade has decreased to 6% (area D). The average stone size has decreased to 0.24 cts/stn and the quantity of diamonds recovered has decreased to 100 cts.

The results from the samples collected in area D give a realistic indication of the background carat count and illustrate the “nugget effect” which characterises marine diamond placers (Figures 8.12 & 8.14). The nugget effect being the small, seemingly randomly dispersed parcels of the high grade material within the gully system. During deposition, the high grade material was more extensive, but only portions of it survived subsequent reworking during regressions and transgressions. One factor which attributed to the survival of these high grade pockets in Grossebuch was the cementation which formed a protective capping over the gravel in places (Figure 8.16).

9. ZWEISPITZ

9.1 RESULTS

For the purpose of this study, "Zweispitz" refers to the area between Atlas Bay in the north and Abenteuerbucht in the south. Zweispitz, meaning "Two Peaks", is situated approximately 8 km north of Elizabeth Bay (Figures 1.3, 2.1 & 9.1). It forms the prominent headland of the shallow south facing embayment named Abenteuerbucht.

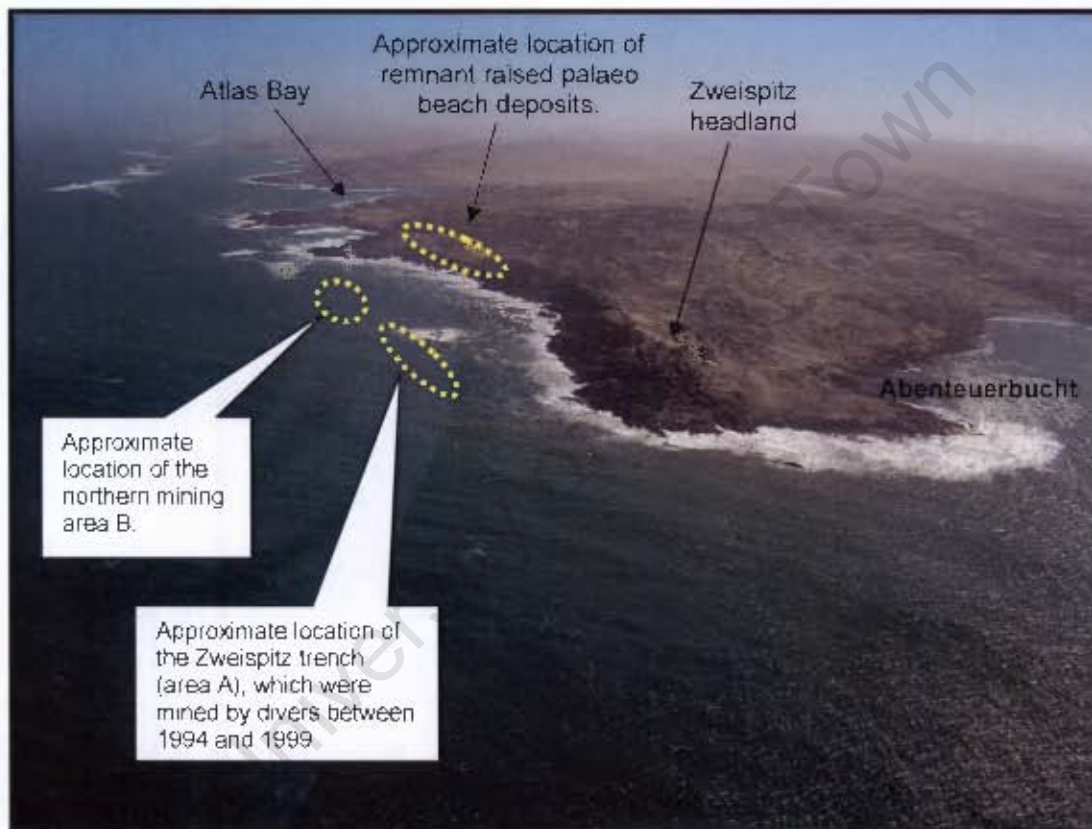
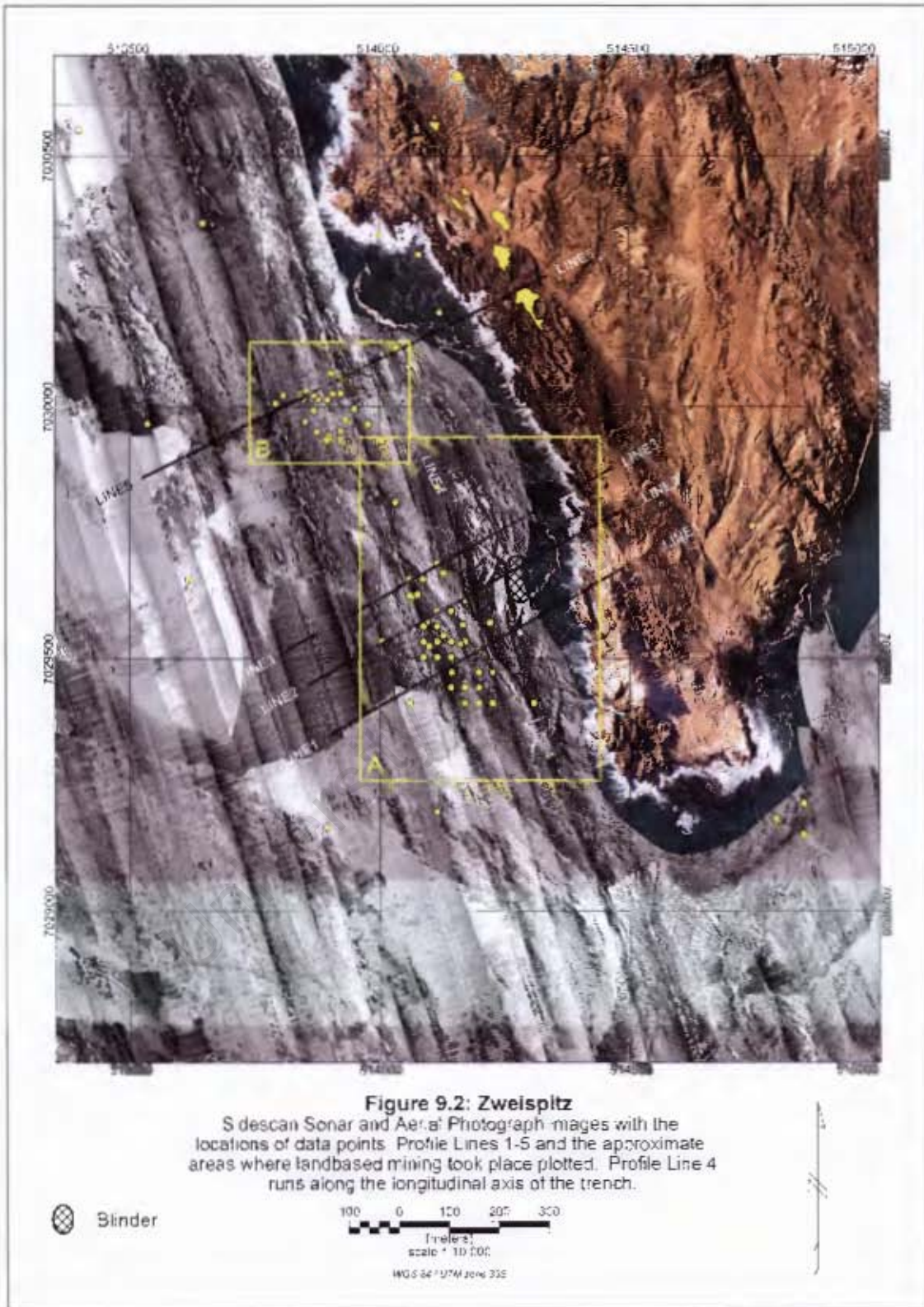


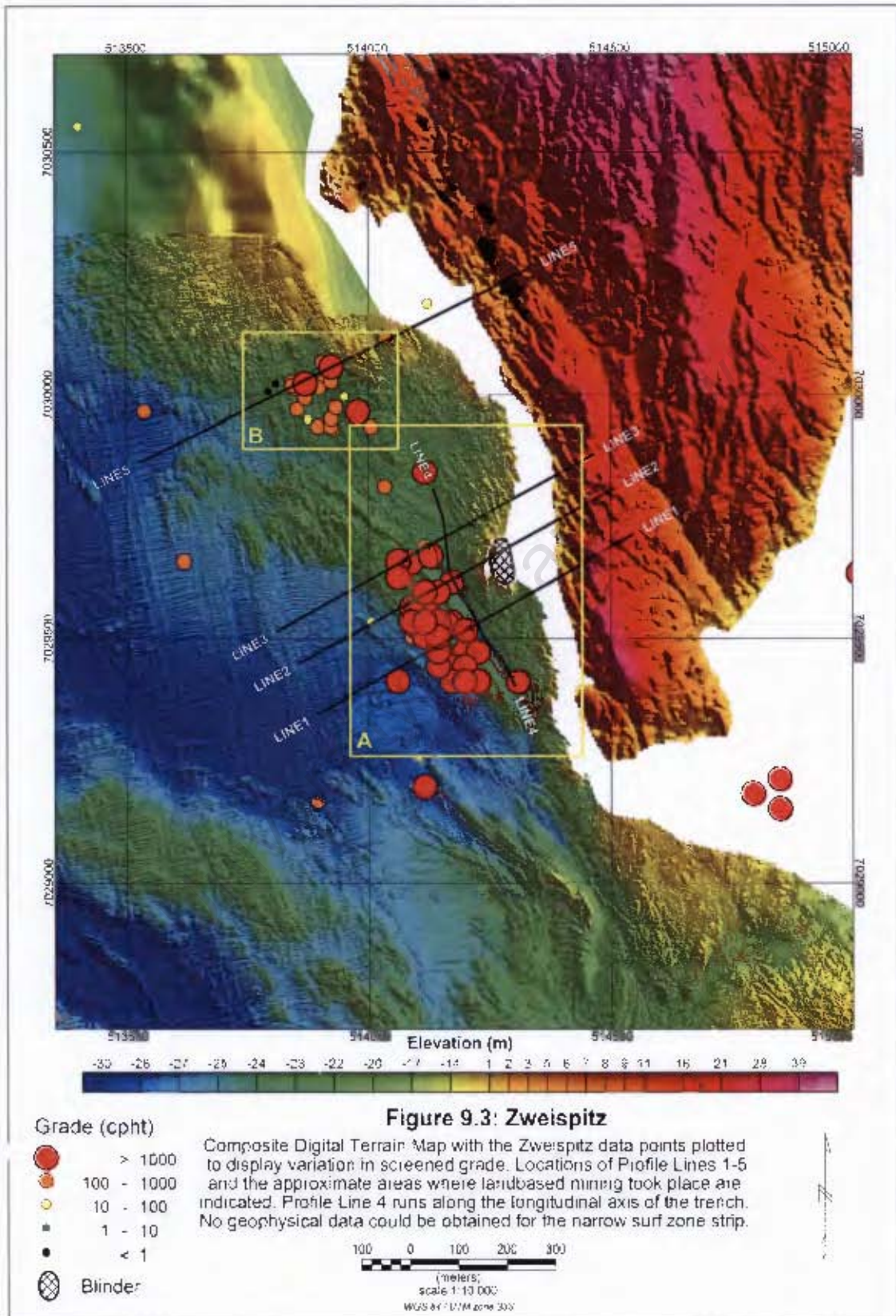
Figure 9.1: Facing north, an oblique aerial photograph of Zweispitz with the approximate location of the areas which were mined indicated.

The area is predominantly underlain by Proterozoic aged rocks of the Namaqua Metamorphic Complex in particular, a late stage amphibolite intrusion (Figure 4.1). The amphibolite forms a seaward sloping coastal profile which is steepest in the south, becoming gentler towards the north. A prominent blinder (semi-submerged rock pinnacle) with near vertical sides is situated 500 m north of the headland. The dark coloured amphibolite forms a recognisable feature on aerial photos and satellite images of the area (Figures 4.1 & 9.1).

The seabed in the Zweispitz area is mostly comprised of exposed Pre-Cambrian bedrock which displays coast parallel NNW-SSE trending features close to the headland (Figure 9.2). Westward of these features the profile dips significantly more gently towards the west (Figures 9.3 & 9.4). Very little sediment has accumulated on the exposed bedrock surfaces and platforms. An area of sediment drape is visible on the sidescan sonar image (Figure 9.2). The sediment drape displays two types of acoustic facies. The light coloured acoustic facies indicate unconsolidated fine sand. The darker coloured acoustic facies, within which mega-ripples can be observed, is an area of unconsolidated, rippled, pebble gravel and can be observed in the central portion of the sediment drape area. The unconsolidated sediment of the sediment drape does not extend shallower than -24 m depth (Figure 9.2).

In Zweispitz the main focus of mining activities was a trench situated close to the shore (Figure 9.2 A). The trench is a coast parallel NNW-SSE trending feature bounded on the landward side by a steep cliff and on the seaward side by a bedrock ridge. It is about 45 m wide in the south and 300 m northward it widens to 85 m whereafter it opens up in a trumpet like fashion. At this point the elevation of the trench floor increases from -25 m to -23 m. The mining in the trench area was carried out between 1994 and 1999. Leading from the trench approximately 300 m northward another mining site, area B, was situated.





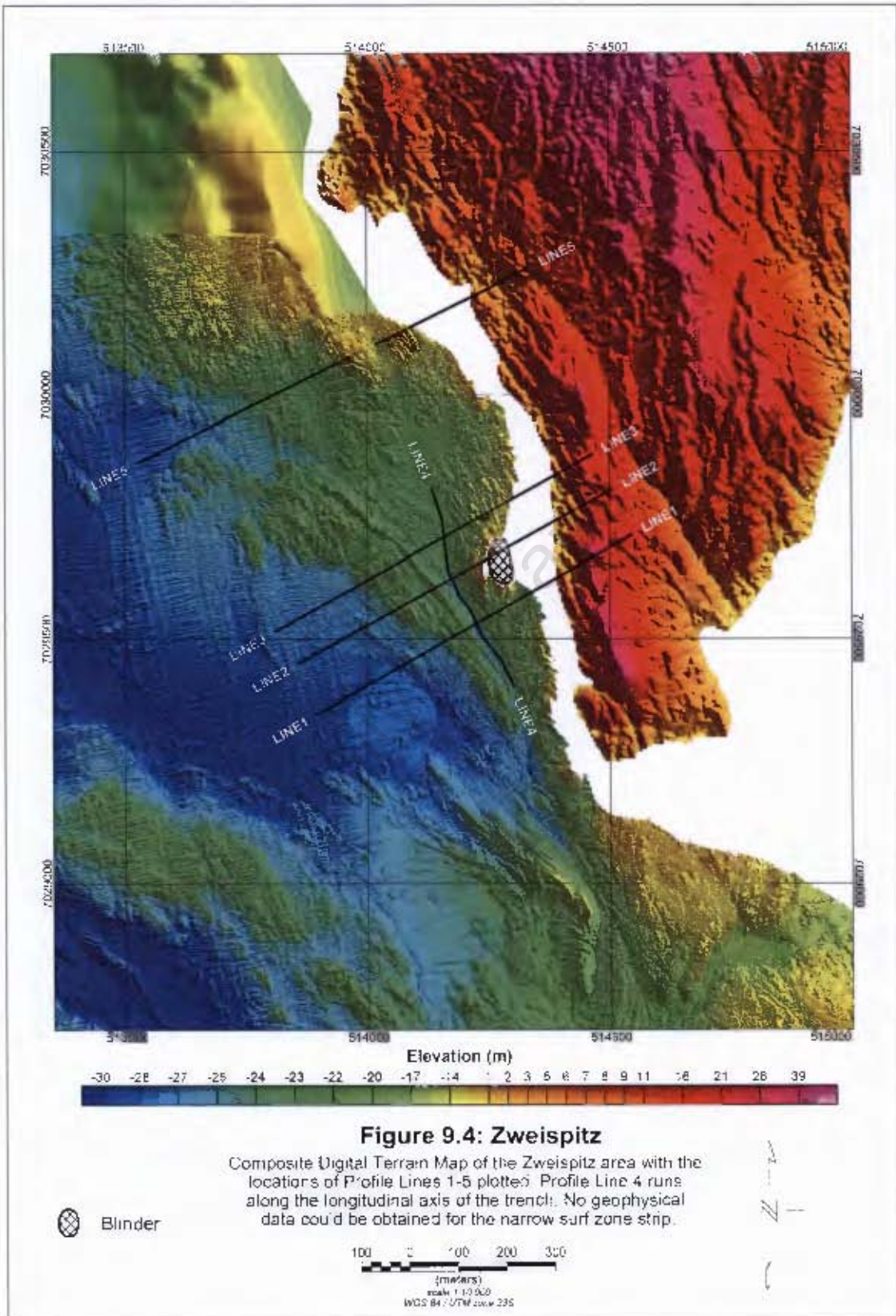




Figure 9.5: Facing west, the *mv Simonsberg* and *mv Covi V* respectively mining south and north of the blinder at Zweispitz in June 1998 (Photo: Namdeb Archives - E. Botha).

The geographical locations of the data points plot on the western edge of the trench, indicated by Profile Line 4 in Figures 9.2 & 9.3. However, from interviews with divers who conducted the mining and the depths from which mining took place it is clear that the bulk of the activities were focussed within the trench. The slight offset to the west of the data points is most likely because the divers recorded the positions of the vessels and not the actual location of the divers. Early on in the mining of Zweispitz the area was divided in two. The position of the blinder and beacons, which were erected on shore, were used to indicate the boundary between the two areas. This was an attempt to regulate the mining activities and to prevent encroachment by the vessels on each others mining areas (Figure 9.5).

Some 265 records representing 94% of the marine production for the Zweispitz area have the depth from which the production were mined recorded. When considering carat production by depth, it is clear that the bulk of the diamonds in the Zweispitz area were mined from between -24 m and -27 m depths with a notable peak in production at -25 m (Figure 9.6). The bulk of the surf zone production was mined from -15 m depth

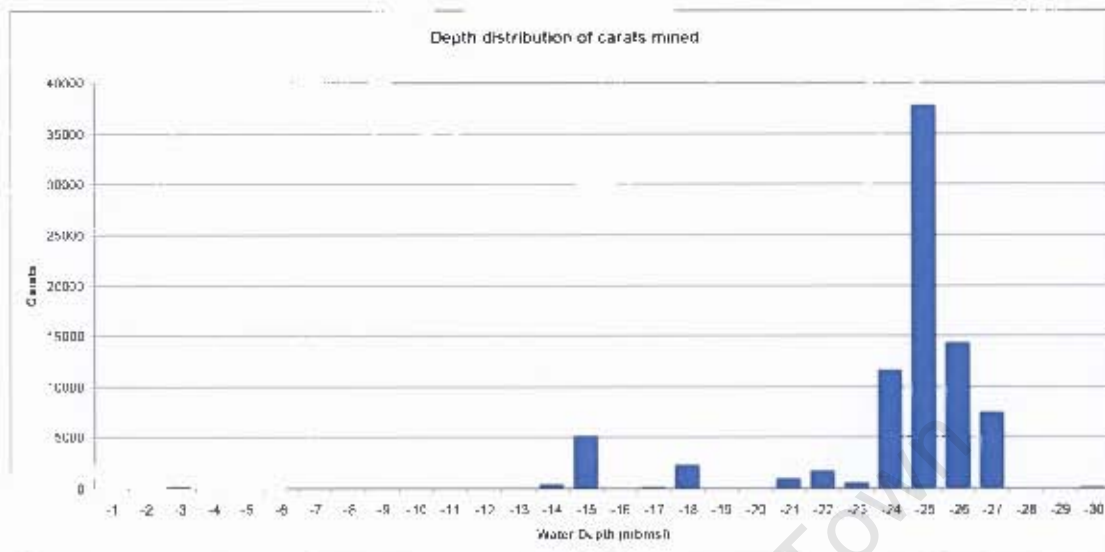


Figure 9.6: Depth distribution of diamonds mined from the sea in the Zweispitz area.

The Zweispitz dataset accounts for a total of 483 records (87,363 cts) which has been compiled from 3 sources. Historical records for shallow marine production mined between 1990-1999 accounts for 186 data points (76,972 cts). More recent production records which were recorded since 2002 account for 25 data points (537 cts). Surfzone mining activities account for 272 data points (9,854 cts). On land some 722 cts were mined from remnants of raised palaeo beach deposits about 1 km north of the headland (Figure 9.2)

Some 172 shallow marine records accounting for 74,778 cts had the screened tons mined recorded. The average screened gravel (+1.6 mm, -12 mm) grade for shallow marine mining in Zweispitz is high (> 1000 cpht) and the average stone size for the marine operations is 0.23 cts/stn, which is slightly lower than that of the entire dataset which is 0.26 cts/stn.

For the surf zone operations no tons mined were recorded. The average stone size for the surf zone mining operations was 0.28 cts/stn which is slightly higher than that of the entire dataset which is 0.26 cts/stn. However, this is most likely due to inefficient treatment processes. Limited landbased mining took place. The average headfeed grade from remnants of raised palaeo beach deposits was low (10 – 100 cpht) and the stone size was also relatively low at 0.20 cts/stn.

The mining at Zweispitz essentially took place from two areas namely the trench in the south (area A) and the northern mining area (area B), (Figure 9.7). The average grade of screened gravel (+1.6 mm, -10 mm) recovered from the area is in excess of 1000 cpht. There is however considerable variance in grade within the Zweispitz area with the highest grade encountered in

the northern portion of area **A**. The grades of screened gravel recovered in Zweispitz will be expressed as a relative percentage of the average grade of the northern portion of area **A**.

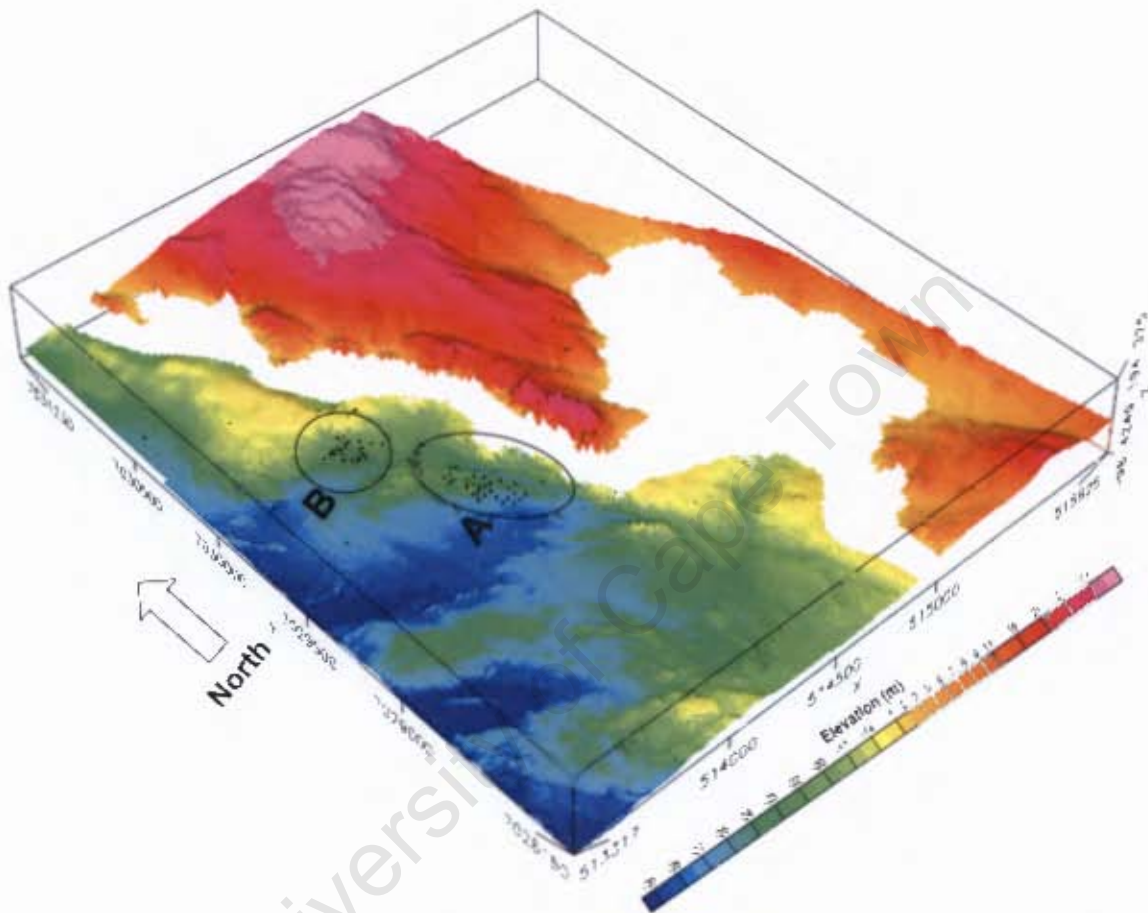


Figure 9.7: 3D Perspective of Zweispitz with the 2 respective areas of shallow marine mining focus.

Area A – the Trench

The trench can basically be divided into 3 zones based on the morphology, diamond stone size, grade and volume of diamonds recovered (Figures 9.8 & 9.9)

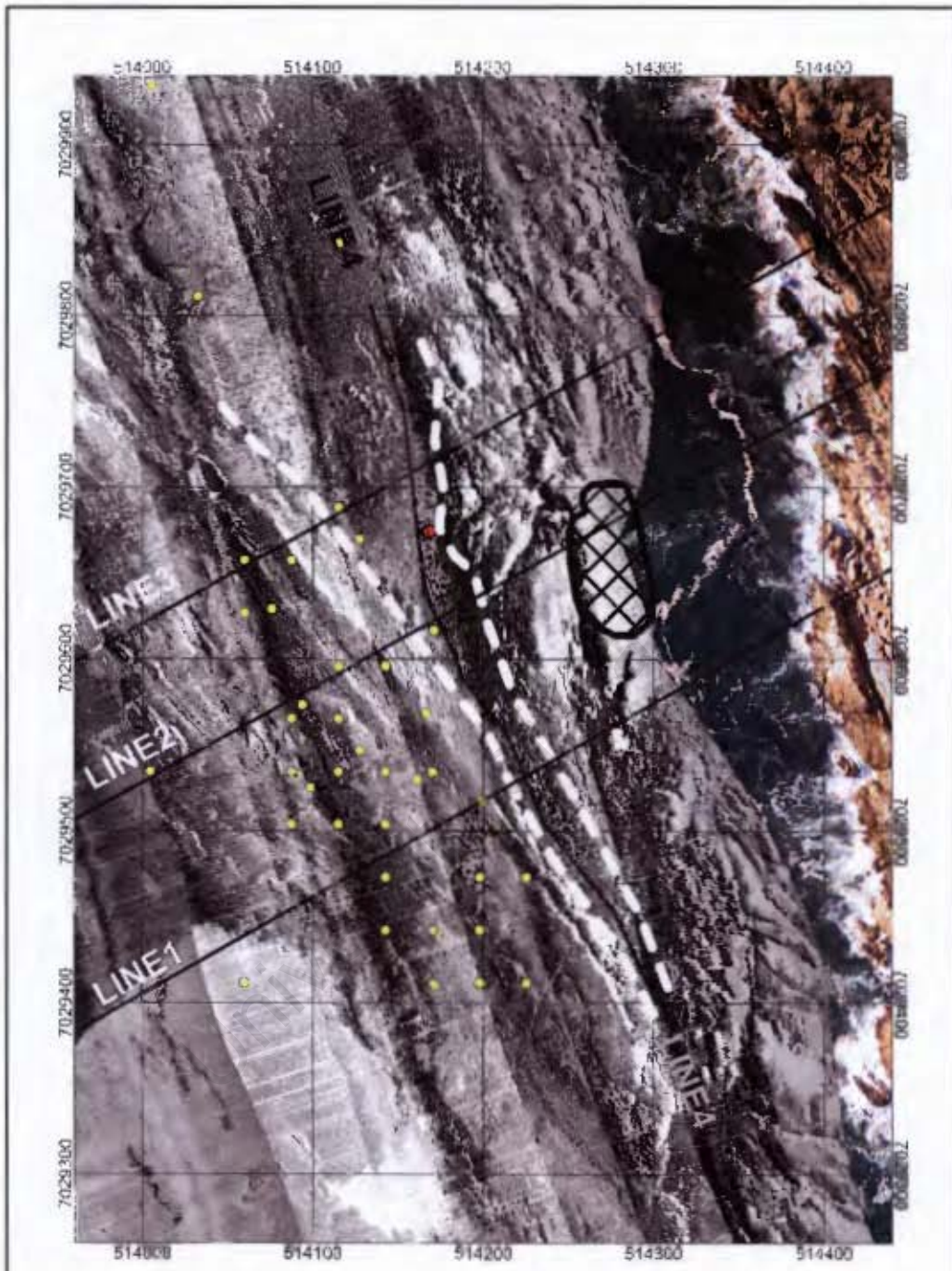



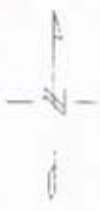
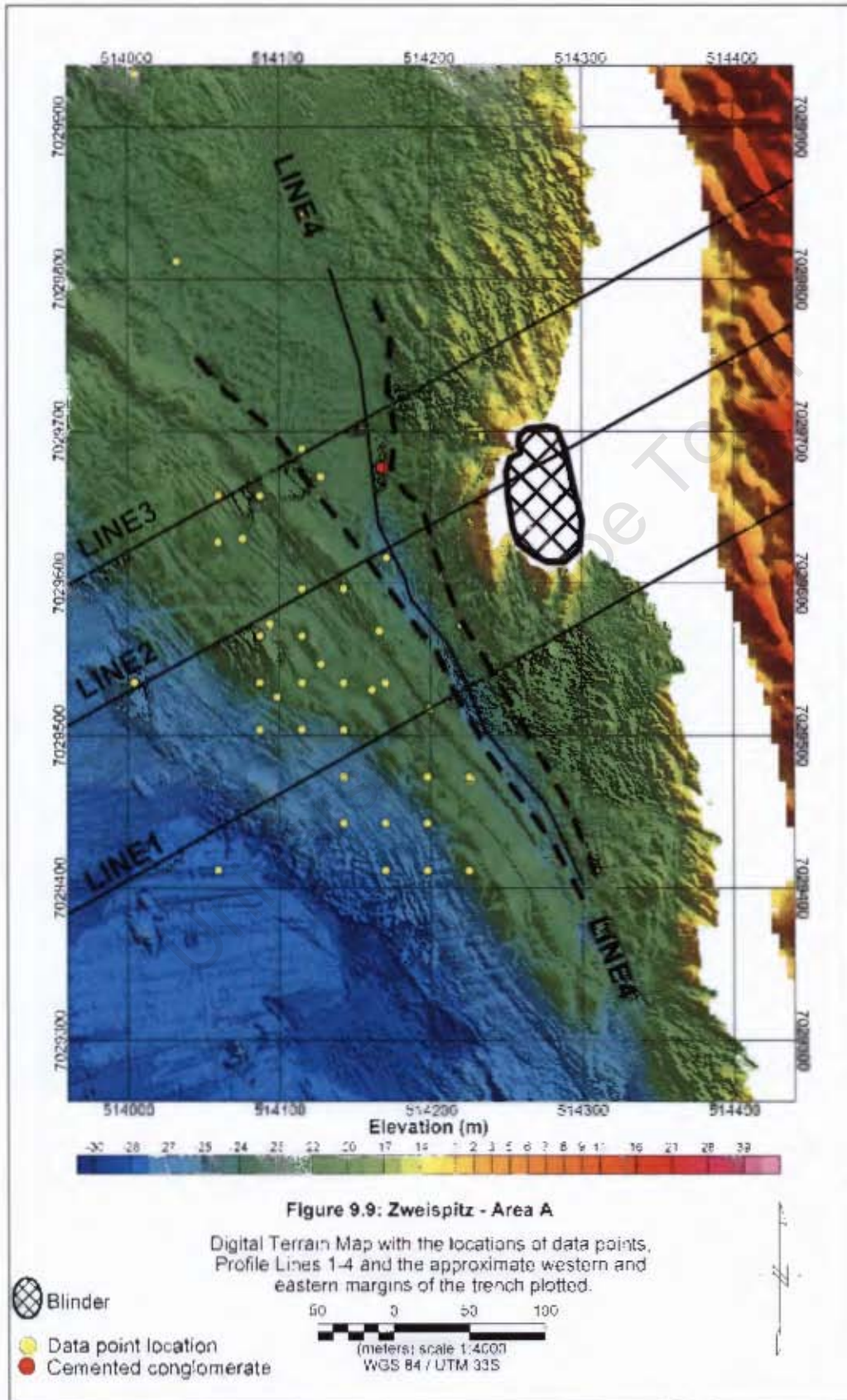


Figure 9.8: Zweispitz - Area A

Sidescan Sonar and Aerial Photograph images with the locations of data points, Profile Lines 1-4 and the approximate western and eastern margins of the trench plotted

-  Blinder
-  Data point location
-  Cemented conglomerate





In the southern portion of the trench the feature is approximately 45 m wide, 3 m deep and the floor depth at -25 m (Figures 9.8, 9.9 & 9.10). The western seaward wall of the trench is steep sided with a more gently sloping eastern landward margin. About 9,000 cts was recovered from this portion of the trench at an average stone size of 0.28 cts/stn. The relative grade was 68% of highest grade. Approximately 150 m further north along the trench, the average stone size decreased to 0.22 cts/stn and the relative grade is 44% of the highest grade. About 7,500 cts were recovered from this portion of the trench.

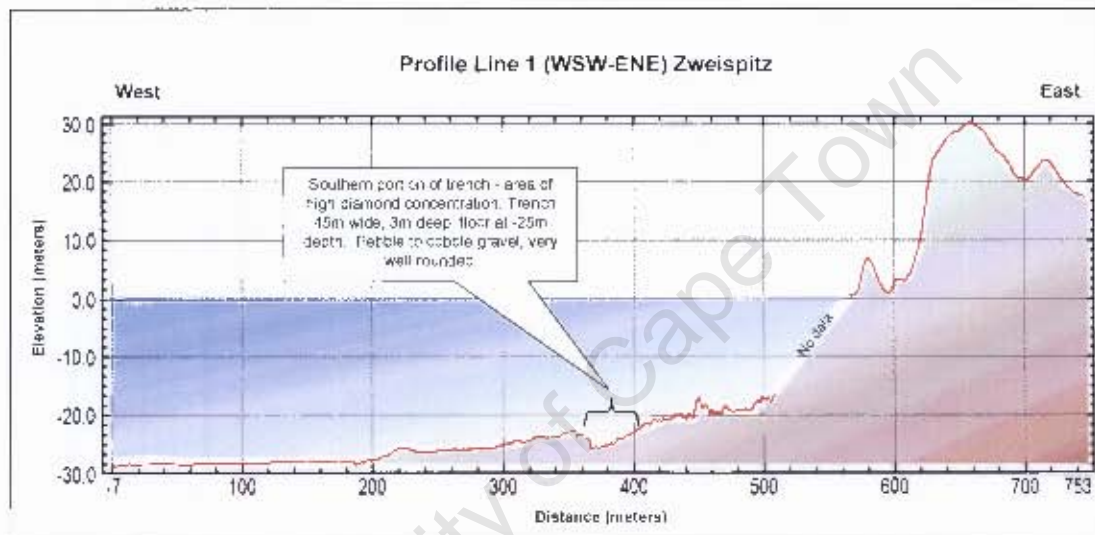


Figure 9.10: Profile Line 1 (WSW-ENE) of terrain elevation in Zweispitz.

A 1.0 m high ridge separates the southern portion, where profile line 1 is situated, from the central part of the trench where profile line 2 is located. In the central portion of the trench, adjacent to the blinder, the feature has widened to approximately 85 m. Here the side walls of the trench are 5 m high and the floor is at its deepest depth at -25.5 m (Figure 9.11). Profile line 2, perpendicular to the strike of the feature, shows that the trench has a deep, bowl shape here. About 14,500 cts was recovered from this portion of the trench at an average stone size of 0.20 cts/stn. The relative grade was 36% of the highest grade.

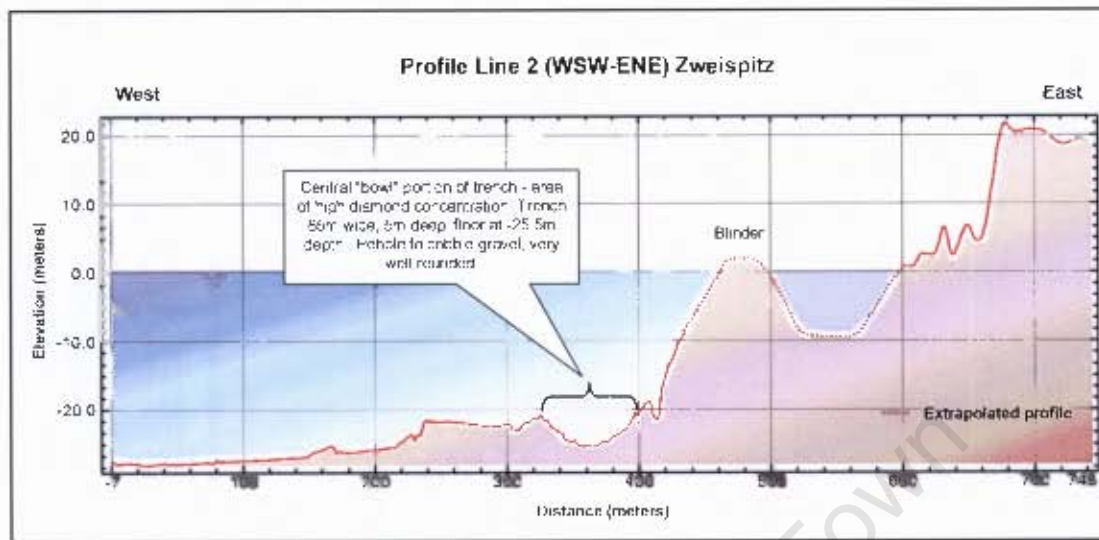


Figure 9.11: Profile Line 2 (WSW-ENE) of terrain elevation in Zweispitz.

North of the central bowl area, the trench widens further to 130 m but the trench becomes shallower and the side walls are only 2 m high. The floor of the trench starts to rise towards the north and is -23 m deep at the intersection with profile line 3 (Figure 9.12). The profile line, perpendicular to the strike of the feature, shows that the trench has widened and flattened out, no longer having the deep bowl shape here. About 17,000 cts were recovered from this portion of the trench at an average stone size of 0.21 cts/stn. The relative grade was 30% of the highest grade.

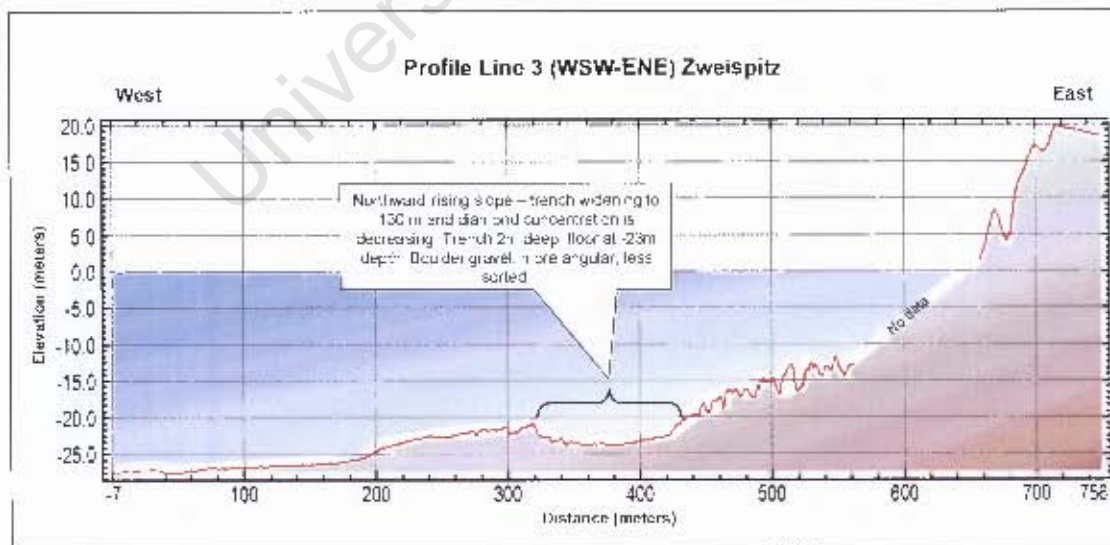


Figure 9.12: Profile Line 3 (WSW-ENE) of terrain elevation in Zweispitz.

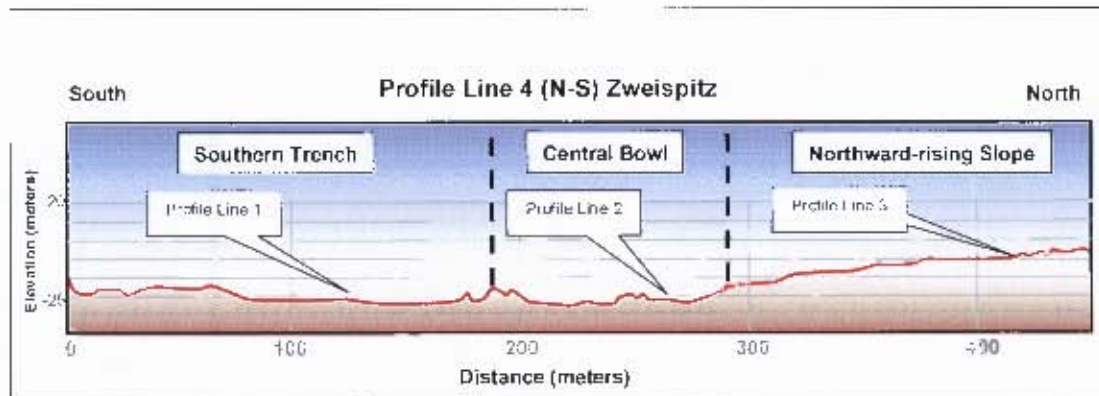


Figure 9.13: Profile Line 4 (N-S) of terrain elevation along the longitudinal axis of the trench in Zweispitz.

A profile line along the trench floor shows that the elevation of the floor of the southern portion of the trench varies between -24.5 m and -25.5 m. A 1.0 m high ridge separates the southern portion of the trench from the central bowl area. The maximum depth of the central bowl area is -25.5 m. Moving out of the central bowl towards the north the trench widens further while the elevation of the trench floor steadily rises forming a gentle northward-rising slope (Figure 9.13). As the trench widens it opens up into an area characterised by large boulders. In this area north of the trench approximately 17,500 cts was recovered at an average stone size of 0.24 cts/stn. This area had the highest grade of all of the areas in the Zweispitz feature and consequently all of the grades are expressed as a relative percentage of the screened gravel grade of this area.

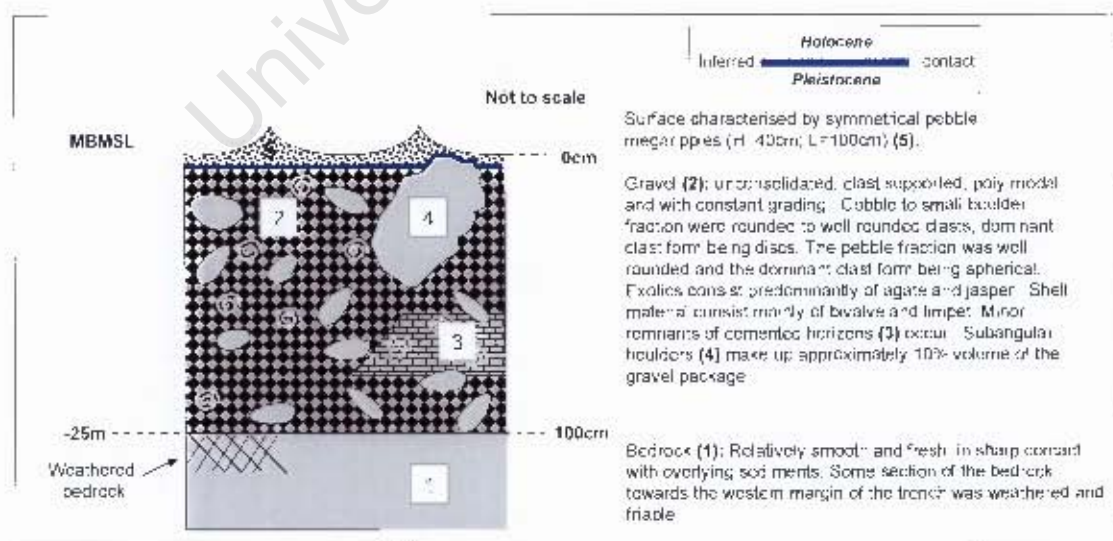


Figure 9.14: Typified stratigraphic column of gravel package encountered in the Zweispitz trench.

The Zweispitz trench contained a gravel package which was approximately one to two metres thick and developed on a fairly smooth bedrock surface (Unit 1) with which it was in sharp contact (Figure 9.14). The western sidewall of the trench comprised friable bedrock. The gravel (Unit 2) generally had a white colour due to the presence of weathered shell material and consisted of a well packed, unconsolidated, clast supported, polymodal package with a constant grading. Cobble and small boulder size fraction clasts were rounded to well rounded and the dominant clast form was discs. The pebble size fraction clasts were very well rounded and the dominant clast form was spheroidal. Exotics consisted predominantly of agate and jasper. Recent dives (June 2008) revealed rare clasts of bioturbated calcite cemented conglomerate on the north-eastern edge of the central bowl area (Unit 3), (Figures 9.14 & 9.15). These clasts are considered to be *in situ* as the gravel prospected appeared undisturbed and several slabs exceeded 0.5 m in diameter and would therefore not have been moved significantly by possible previous diver mining activities (*pers. comm.* Bjorn Basler). The matrix of the conglomerate consists of friable, chalky, fine shell fragments with fine to coarse sand. Shell clasts consist of mostly intact small gastropods and limpets with casts of bivalves including Ribbed Mussel *Aulacomya ater* evident. Lithic clasts include well rounded pebbles of quartzite and white vein quartz up to 30 mm in diameter. No exotics were present. Occasional large subangular to subround boulders of local bedrock (Unit 4) were present in the gravel. No internal bedding or other such features could be identified in sections of this gravel package. The gravel presented a competent face during mining operations which could survive a storm event. The surface of the gravel consisted of well rounded pebbles which were in symmetrical megaripples with a wave length of approximately 100 cm and a wave height of approximately 40 cm (Unit 5).

MacDonald (1997) recorded that the slimes (-1.6 mm) made up a minor portion of the package. The gravel fraction (+1.6 -10 mm) constituted approximately 60% of the gravel. The oversize fraction (+10 -250 mm) made up approximately 30% of the package and boulders (+250 mm) about 10% volume of the gravel.

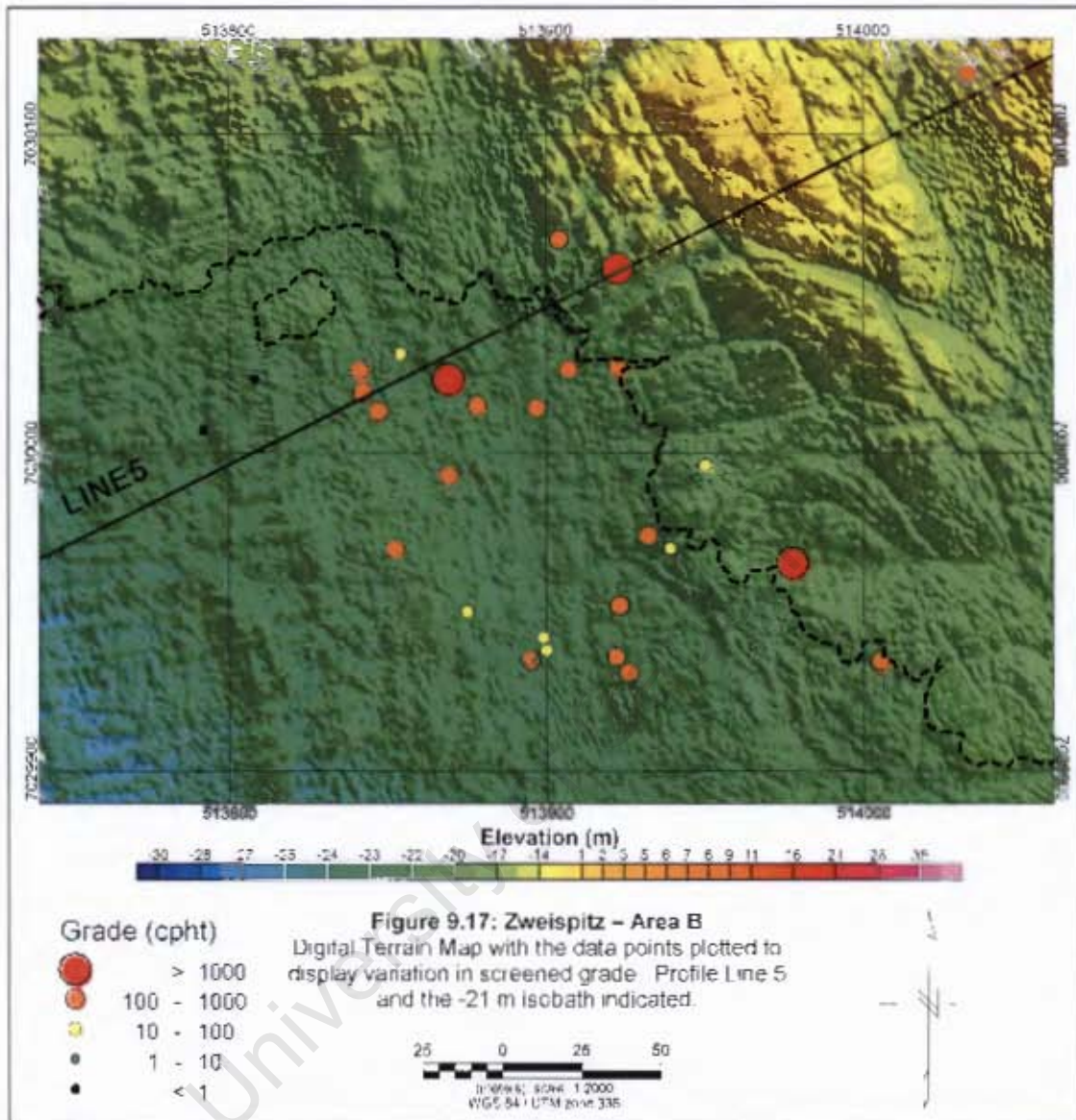


Figure 9.15: A clast of bioturbated, calcite cemented conglomerate recovered from -25.5 m water depth, on the eastern edge of the central bowl area in Zweispitz. See figure 9.9 for location.

Area B – the South Facing Embayment

Situated about 300 m northwest of the trench the northern mining area lies in an open south facing embayment at the -21 m sea still stand (Figures 9.16 & 9.17).





Situated mostly on a relatively rough bedrock surface at the base of a -21 m cliff, about 4,000 cts was recovered from this area at an average stone size of 0.20 cts/stn (Figure 9.18). The relative grade was 15% of the highest grade

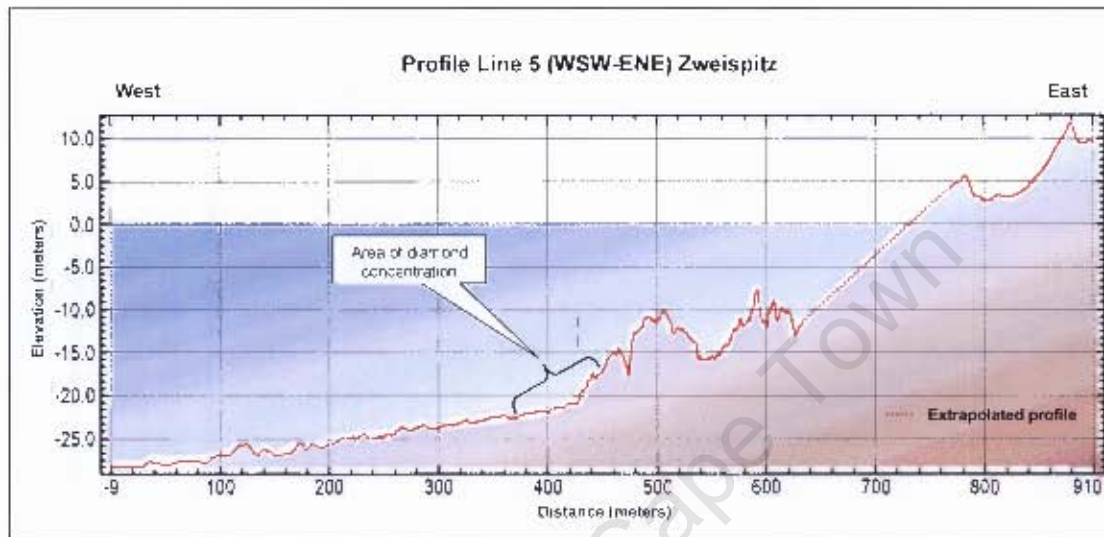


Figure 9.18: Profile Line 5 (WSW-ENE) of terrain elevation in Zweispitz.

As illustrated in Figure 9.19, the bedrock is generally rough and cut by shallow (<1m deep) gullies. The bedrock is soft and weathered in places but generally smooth and in sharp contact with the overlying sediments (Unit 1). At the base of the gravel a continuous layer of whitish coloured clay is encountered at the bedrock interface (Unit 2).

The gravel is a matrix supported package which is generally light grey in colour. The matrix consists of unconsolidated fine to coarse sand with varying amounts of decomposed shell material. The gravel is polymodal, un-graded and well sorted, consisting of local bedrock clasts which are rounded to well rounded, and ranging in size from pebble to cobble fraction with occasional subrounded local bedrock boulders present (Units 3 & 4). The sequence is topped by a layer of unconsolidated fine to coarse sand containing various amounts of shell (Unit 5).

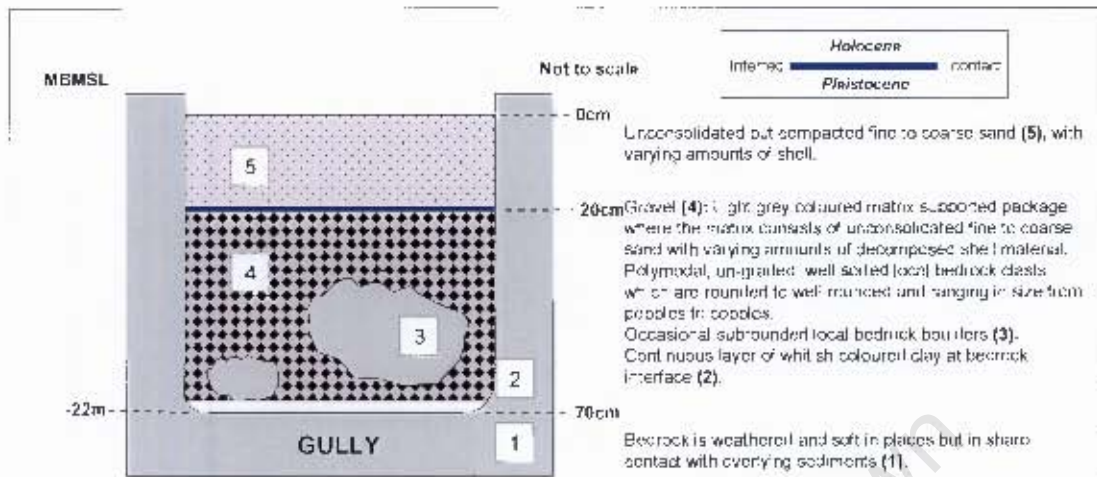


Figure 9.19: Typified stratigraphic column of sedimentary package encountered in gullies in the northern mining location at Zweispitz.

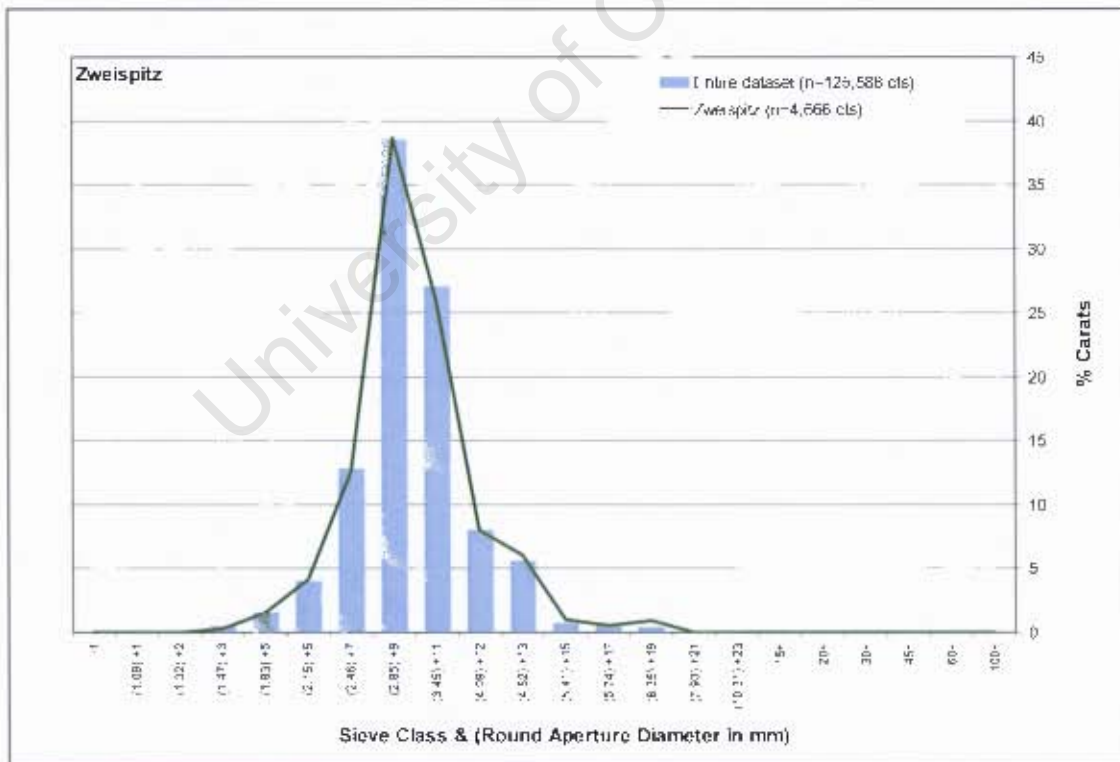


Figure 9.20: Size frequency distribution of diamond parcels which contain 79% contents from Zweispitz area plotted with the size frequency distribution of carats mined from the whole study area.

The size frequency distribution dataset for Zweispitz has been compiled from 2 diamond parcels totaling 4,666 cts. During the time when Zweispitz was actively mined, production from the various mining vessels was rolled together for valuation. The parcels making up the Zweispitz SFD dataset comprise of 79% carats from Zweispitz with the remaining 21% originating from production obtained from shallow marine vessels mining in other locations in the study area (Halifax Island to Elizabeth Bay).

The cumulative size frequency distribution (percentage carats per sieve class) of the Zweispitz data displays a uni-modal size distribution peaking in the +9 sieve class (Figure 9.20). It is a well sorted diamond population with 77% of the carats occurring in the +7 to +11 sieve classes. The Zweispitz population (n=4,666 cts) mimics the entire population plot for the whole of the study area (n=125,588 cts) perfectly.

University of Cape Town

9.2 DISCUSSION

The average stone size of diamonds mined from the Zweispitz area is 0.23 cts/stn which is similar to the average stone size of 0.26 cts/stn for the entire study area. Although the size frequency distribution of the diamond population from Zweispitz is based on a combined parcel (4,666 cts) of which 79% are from Zweispitz, it is very similar to that of the entire diamond population for the whole of the study area (Figure 9.20). Based on the similarities in stone size and size frequency distribution, it can be assumed that the diamonds mined from the Zweispitz area are part of the shallow marine diamond population encountered within the study area.

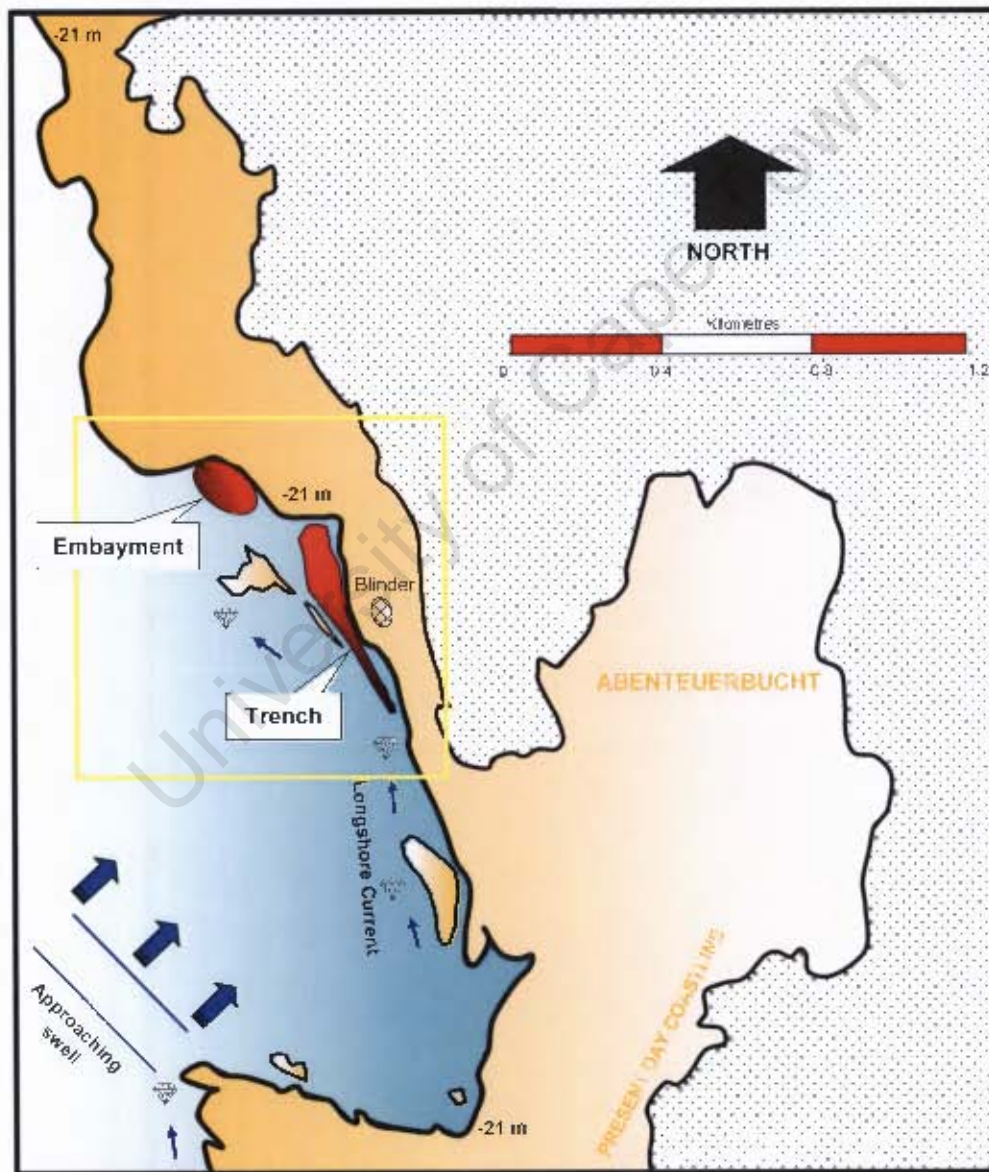


Figure 9.21: The Zweispitz area had two major mineralised zones at the -21 m sea still stand namely the trench and a south facing embayment.

The primary mineralised zone in Zweispitz consists of a trench from which the bulk of the diamonds were recovered (Figure 9.21). The trench is a funnel shaped coast parallel feature about 350 m in length oriented with its narrowest part in the south. The average diamond size peaks in the southern portion of the trench at 0.28 cts/stn which then decreases rapidly to between 0.22 cts/stn and 0.20 cts/stn. This is typical for a diamond population which has been transported, even over short distances (Sutherland, 1982). The trench floor then rises up and the feature opens up into a well packed boulder field where the stone size increases to 0.24 cts/stn and the highest grade material is encountered. A lesser amount of production was recovered from within bedrock gullies at the base of a cliff situated in a small south facing embayment on the -21 m isobath (Figure 9.21). The deposition model for the -21 m sea still stand scenario is proposed as follows (Figure 9.22):

- i. Diamondiferous gravel transported northward through wave action and longshore drift enters the southern part of the Zweispitz trench. The floor of this southern portion is characterised by a rough bedrock surface which presents a good trapsite within the trench. As a result the relative grade of screened gravel recovered from this section is very high at 68%. The average stone size is 0.28 cts/stn and 9,000 cts have been mined from this part of the feature.
- ii. For the next 100 m section of the trench the bedrock floor is smooth and flat lying between -25.0 m and -25.5 m. The average stone size has decreased to 0.22 cts/stn and only 7,500 cts has been mined from this part of the feature. This is most likely due to the smooth floor surface in this part of the trench which does not present trapsites to retain diamonds which were steadily transported northward through wave action and longshore drift. This is also evident in the relative grade which has decreased from 68% to 44%.
- iii. The central bowl area is separated from the narrow smooth bedrock portion of the trench by a 1 m high ridge. Situated adjacent to the present day blinder, the trench widens to form an elongated bowl with 5 m high sidewalls being -25.9 m at its deepest. The average stone size is 0.20 cts/stn and 14,500 cts were recovered from this part of the feature. The deepest part of the trench is found within the bowl which resulted in the increased volume of gravel and consequently diamonds which were retained here. The relative grade of material mined decreased further to 36%.
- iv. The floor of the trench rises gently from -25.5 m in the northern part of the bowl to -22.2 m, 100 m northward. Moving up against the rising slope the trench becomes shallower with sidewalls only 2 m high, simultaneously the feature opens up laterally

towards the north. The average stone size was 0.21 cts/stn and approximately 17,000 cts were recovered from this part of the feature. The gravel in this area was relatively thick presenting a mining face up to 2.0 m thick. This is also reflected in the relative grade of material mined which was 30%.

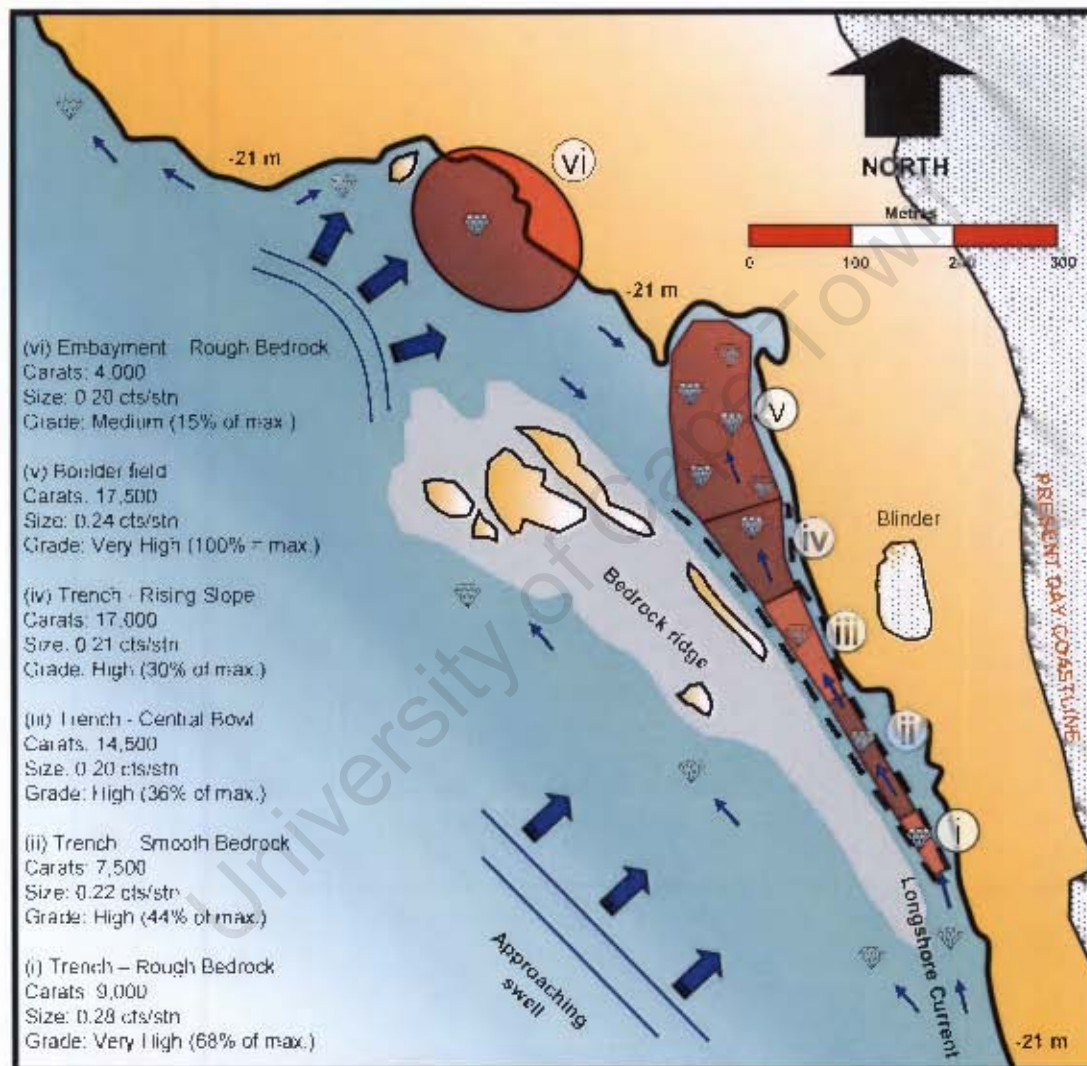


Figure 9.22: Deposition model for Zweispitz. Note the bedrock ridge which forms the western margin of the trench. Diamondiferous gravel would be transported northward via longshore drift and would be fed into the trench from the south and the gravel would be retained in the elongated trapsite. Waves refracted and diffracted around the NW edge of the bedrock ridge would assist to retain gravel in the trench and boulder field.

- v. North of the rising slope is an area characterised by boulders which were noticeably less rounded than those encountered within the trench. The gravel package of the boulder

field area had a very well-packed framework which presented difficult mining to the divers who had to 'un-pack' the gravel framework by hand. This boulder field formed a good trap site as the relative grade of material mined was the highest in the whole Zweispitz area. The average stone size of this area also increased to 0.24 cts/stn.

- vi. A small south facing embayment formed at the -21 m sea still stand is situated northwest of the trench. Here limited amounts of diamonds were trapped within bedrock gullies at the base of a cliff. The average stone size was 0.20 cts/stn and about 4,000 cts were recovered from this area. The relative grade was the lowest of mined areas in Zweispitz at 15%. The diamonds trapped here were obviously also transported northward via longshore drift. At a -21 m sea still stand a series of small islands and a bedrock ridge emerge to the south of the south facing embayment. Swells approaching from a south-southwesterly direction would have been refracted and diffracted around this bedrock high feature resulting in a southeastward flowing current during storm events. This would most likely have prevented the north westward distribution of material being transported northward along the trench. The diamondiferous gravel encountered in the south facing embayment was therefore most likely never trapped by the trench but bypassed the bedrock high and islands on the western margin.

A series of NNW-SSE coast parallel features are evident in the bedrock situated immediately west of the trench (Figure 9.10). These features probably mark the western edge of the contact between the gneisses of the Namaqua Metamorphic Complex basement rocks and the later stage amphibolite which forms the prominent Zweispitz headland (Figure 4.1). This boundary is likely on a fault which was preferentially eroded. The amphibolite is more erosion-resistant than the gneiss of the NMC. Clasts eroded from the amphibolite lying at the base of the cliff would form the abrasive agent to scour the trench at the base of the cliff. The bulk of these larger clasts were transported a few hundred metres along the trench by longshore drift. These clasts were deposited in the present day boulder field (area V) where they formed a trap site. The most significant portion of the process is likely to have occurred when the sea-level was at approximately -21 m. At this sea still stand the trench would have been situated at the base of a cliff in the breaker zone, where the highest energy would have been dispensed by breaking waves, and consequently, the most erosion would take place (Jacob, 2001).

The Zweispitz deposit contained significant amounts of white, chalky, friable shell material.

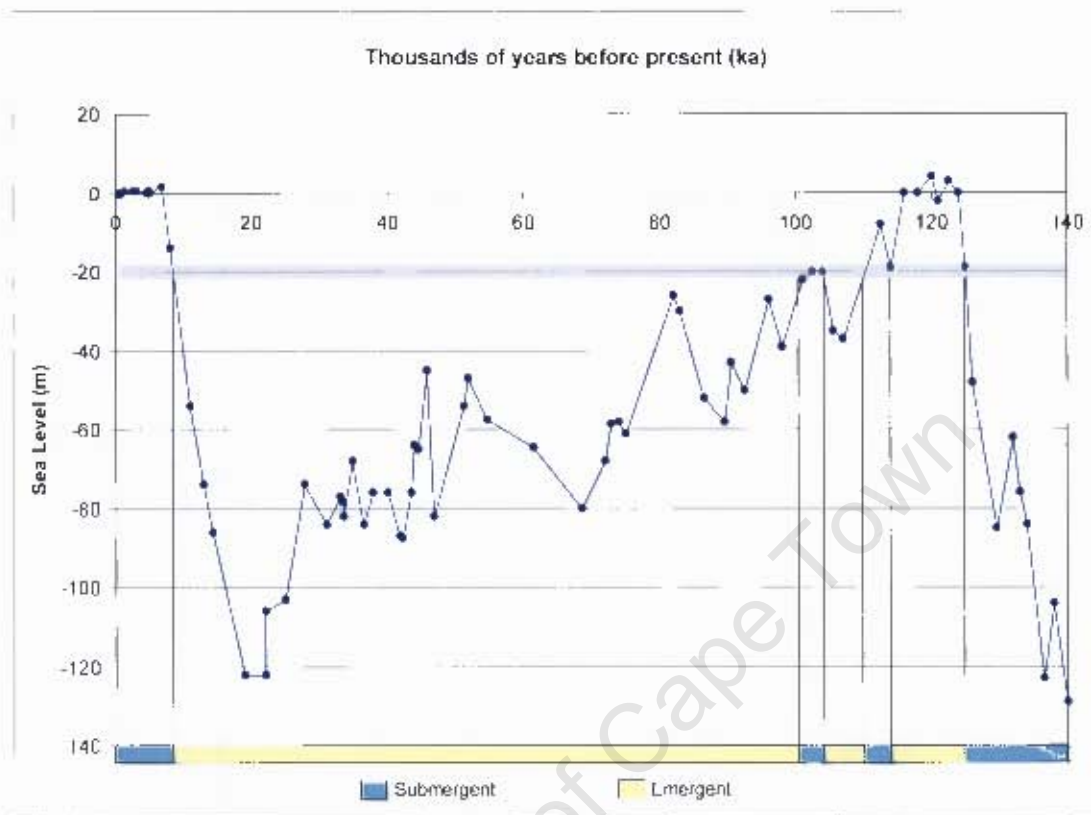


Figure 9.23: Composite sea-level curve for the last 140 ka indicating submergent and emergent periods for the -18 m to -22 m coastline (Compton, 2001; Compton *et al.*, 2002; Yokoyama *et al.*, 2000; Chappel *et al.*, 1996; Fairbanks, 1990; Shackleton, 1987).

These shells therefore have a weathered appearance which makes it likely that they were entrapped at least 100 ka ago as this was the first opportunity before the LGM where the -18 m to -22 m shoreline would have been submergent and exposed to shallow marine processes. This area would therefore have been sub-aerially exposed from 100 ka to 10 ka ago (Figure 9.23).

Although the main gravel body is not cemented, the presence of *in situ* calcite cemented conglomerate on the north-eastern edge of the central bowl area, indicate that conditions were on a previous occasion, probably since the Femia, conducive to the precipitation of calcite cement. This was most likely for a limited period of time as the sparse evidence for cementation has only been reported from the edge of the depression.

10. THE SOUTHERN AREA

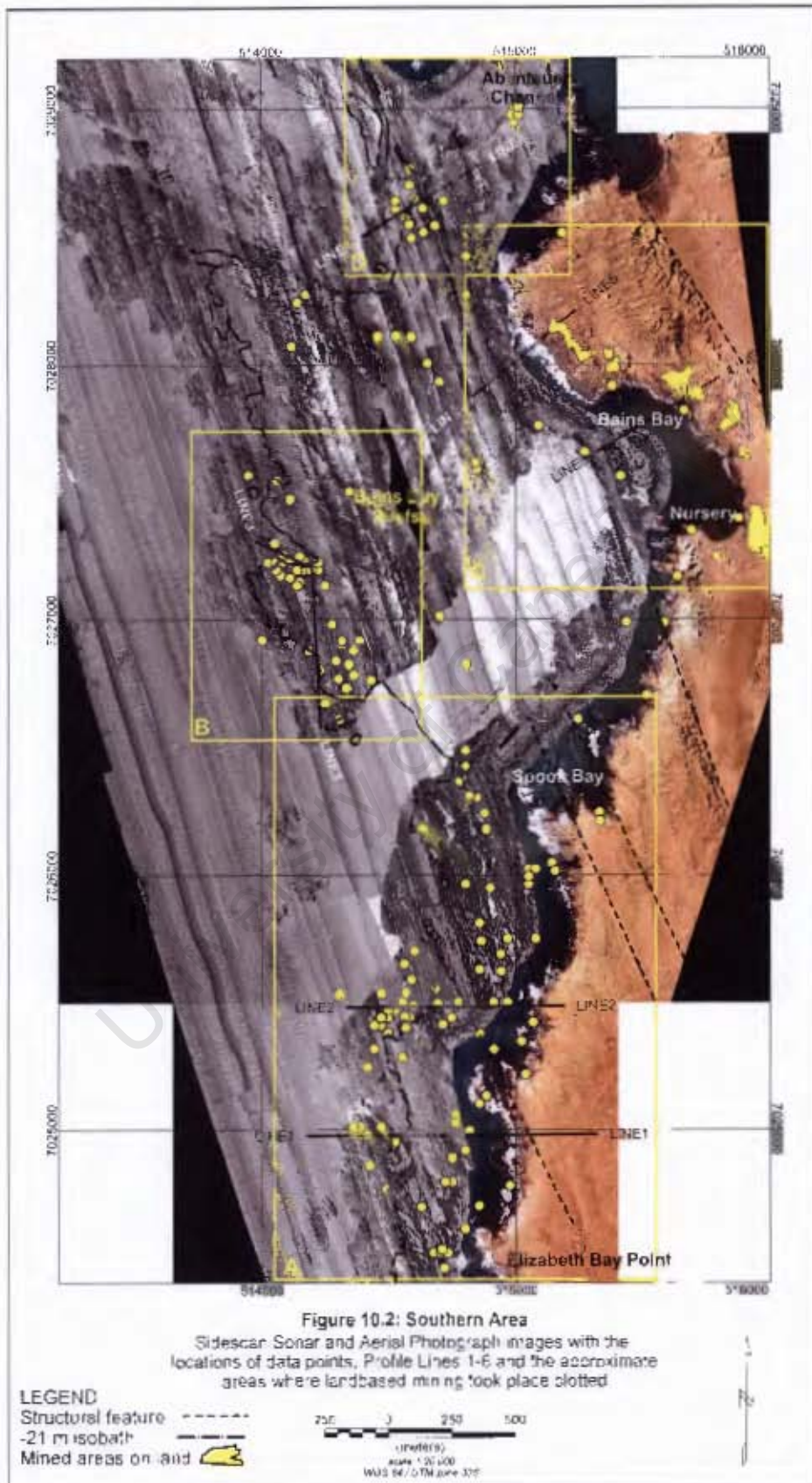
10.1 RESULTS

The "Southern Area" refers to the area between Abenteurbucht in the north and Elizabeth Bay Point in the south. It includes the areas which will be referred to individually in the text as the submarine channel flowing out of Abenteurbucht, Bains Bay Reefs, Bains Bay, Nursery and Spook Bay (Figures 1.3, 2.1 & 10.1). The area is predominantly underlain by Proterozoic aged rocks of the Namaqua Metamorphic Complex which is composed of mixed gneiss consisting of banded and more complex migmatitic material with the predominant composition of quartz diorite (Figure 4.1). Bands of quartzite and amphibolite also occur in the area (Greenman, 1966).

Elizabeth Bay Point forms the headland of the largest south facing embayment and sediment bypass systems along the southern Namibian coast. North of the Elizabeth Bay Point headland the rocky coastline is oriented in a north-easterly direction with numerous small embayment features (Figures 10.2 & 10.3). Spook Bay is a small north facing embayment situated halfway between Bains Bay and Elizabeth Bay Point (Figures 10.1 & 10.2). Bains Bay is a small southwest facing, kidney shaped embayment situated 1 km south of Abenteurbucht and approximately 3 km north of Elizabeth Bay Point. The Nursery is the southern part of this embayment. The Bains Bay Reefs are a series of blinders situated approximately 1.5 km offshore of Bains Bay.



Figure 10.1: Facing north, an oblique aerial photograph of the Southern Area.



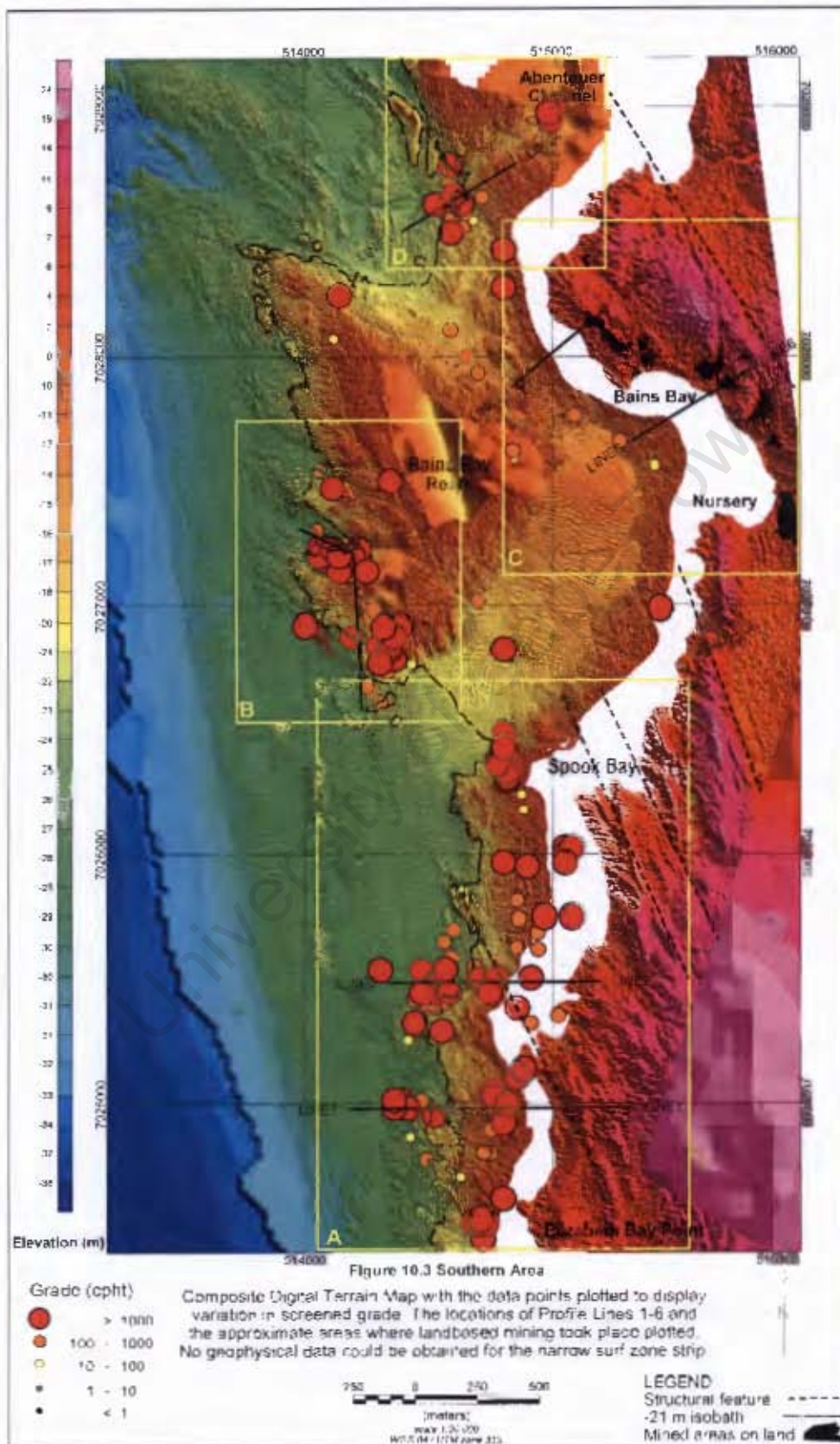


Figure 10.3 Southern Area

The seabed between Abenteuerbucht and Elizabeth Bay Point is comprised of exposed Pre-Cambrian bedrock in which a series of northwest-southeast trending parallel faults occurs. Preferential erosion along these faults has resulted in the formation of Bains Bay and Spook Bay (Figure 10.2). The area is flanked on the west by a sediment drape, the inshore margin of which lies at approximately -25 m depth. A smaller sediment drape 'tongue' or offshoot measuring approximately 1600 m X 500 m extends off the main sediment body in a northeasterly direction. The western margin of this sediment offshoot lies at -14 m depth. The ripple-like features which are clearly visible in the sediment tongue area are data artefacts and not megaripples (Figure 10.3). The sediment of the deeper and shallower portions of the drape area displays a light coloured acoustic facies which indicates unconsolidated, fine sand. Also present along the margins of the sediment drape are isolated patches of a darker coloured acoustic facies within which mega-ripples can be observed. This indicates areas of unconsolidated, rippled, pebble gravel. Apart from the sediment offshoot mentioned above, the bedrock surfaces are relatively free of unconsolidated sediment down to depths of approximately -25 m. The bedrock rises sharply from -25 m depth to surface to form the topographically proud Bains Bay Reefs. At the -21 m sea still stand, the Bains Bay Reefs would have formed the headland to a small south facing embayment (Figures 10.3 & 10.4).

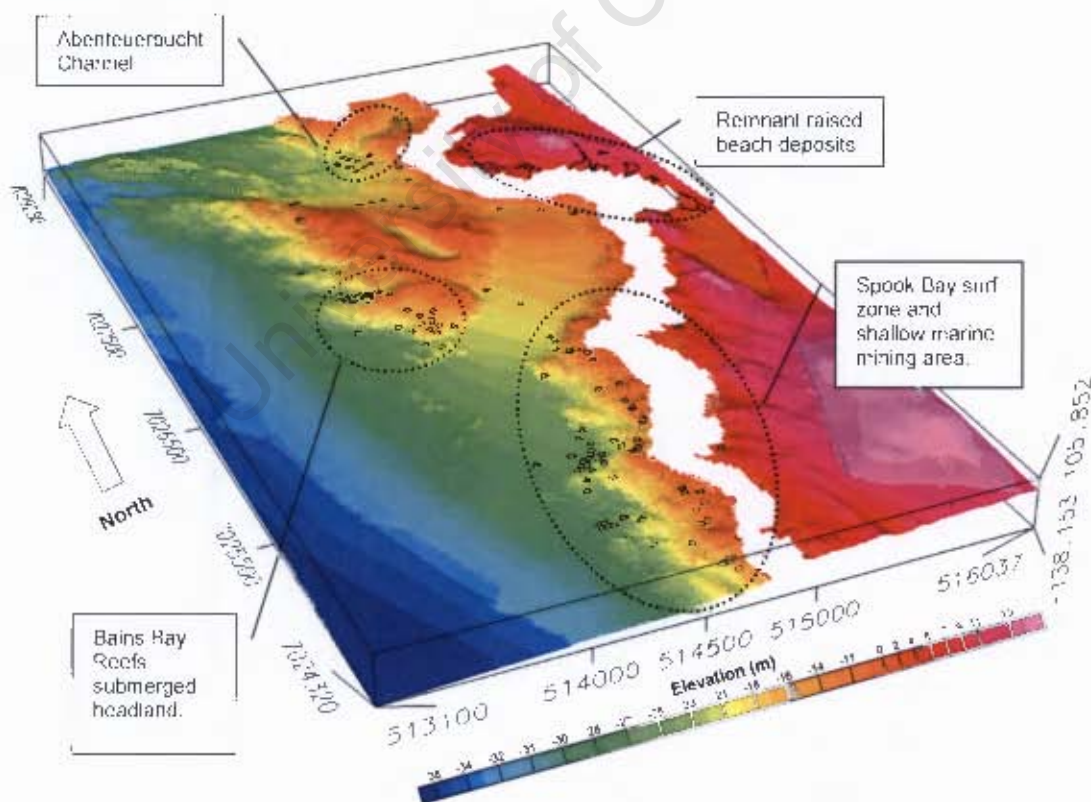


Figure 10.4: Three dimensional view of the Southern Area indicating the four areas where diamonds were concentrated and subsequently mining took place.

The dataset for the mining and sampling which have taken place between Abenteuerbucht and Elizabeth Bay Point accounts for a total of 647 records which have been compiled from 5 sources. Historical records for production mined between 1990-1999 accounts for 281 data points (38,701 cts). More recent production records which were recorded since 2002 account for 25 data points (987 cts). Diver-assisted sampling carried out between 1999 and 2003 represents 18 records (28 cts). Surf zone mining activities account for 323 data points (24,170 cts). On land some 9,336 cts were mined from remnants of raised palaeo beach deposits in the Bains Bay vicinity.

Some 586 shallow marine records accounting for 60,565 cts had the screened tons mined recorded. The average screened gravel (+1.6 mm, -12 mm) grade for shallow marine mining in the Southern Area is high to very high (> 1000 cpht) and the average stone size for the shallow marine operations is 0.29 cts/stn, which is slightly higher than that of the entire dataset which is 0.26 cts/stn. For the surf zone operations no tons mined were recorded. However, divers who mined in the area indicated that the grades recovered from this area were exceptionally high compared to recoveries from other areas within the study area. The average stone size for the surf zone mining operations was 0.30 cts/stn which are notably higher than that of the entire dataset which is 0.26 cts/stn. No tonnage data were recorded for the landbased mining in this area and the average stone size was relatively low at 0.20 cts/stn.

The carat production by depth graph indicates that the diamonds in the Southern Area were mined from a wide range of depths (Figure 10.5). The graph was compiled from 647 data points, representing 63,886 cts, which were mined from the sea in the Southern Area. There are notable peaks in production at the -12 m, -20 m and -25 m depths.

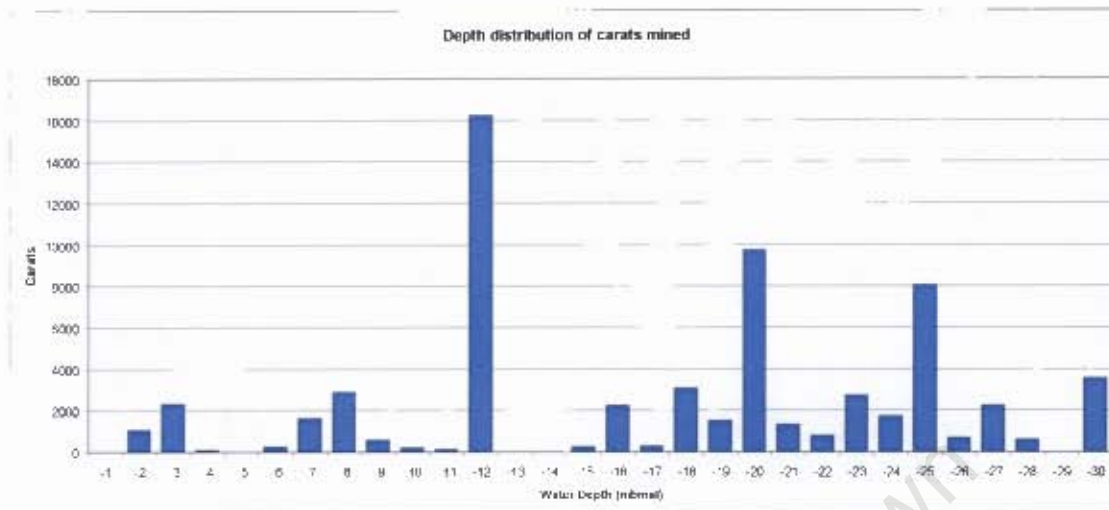
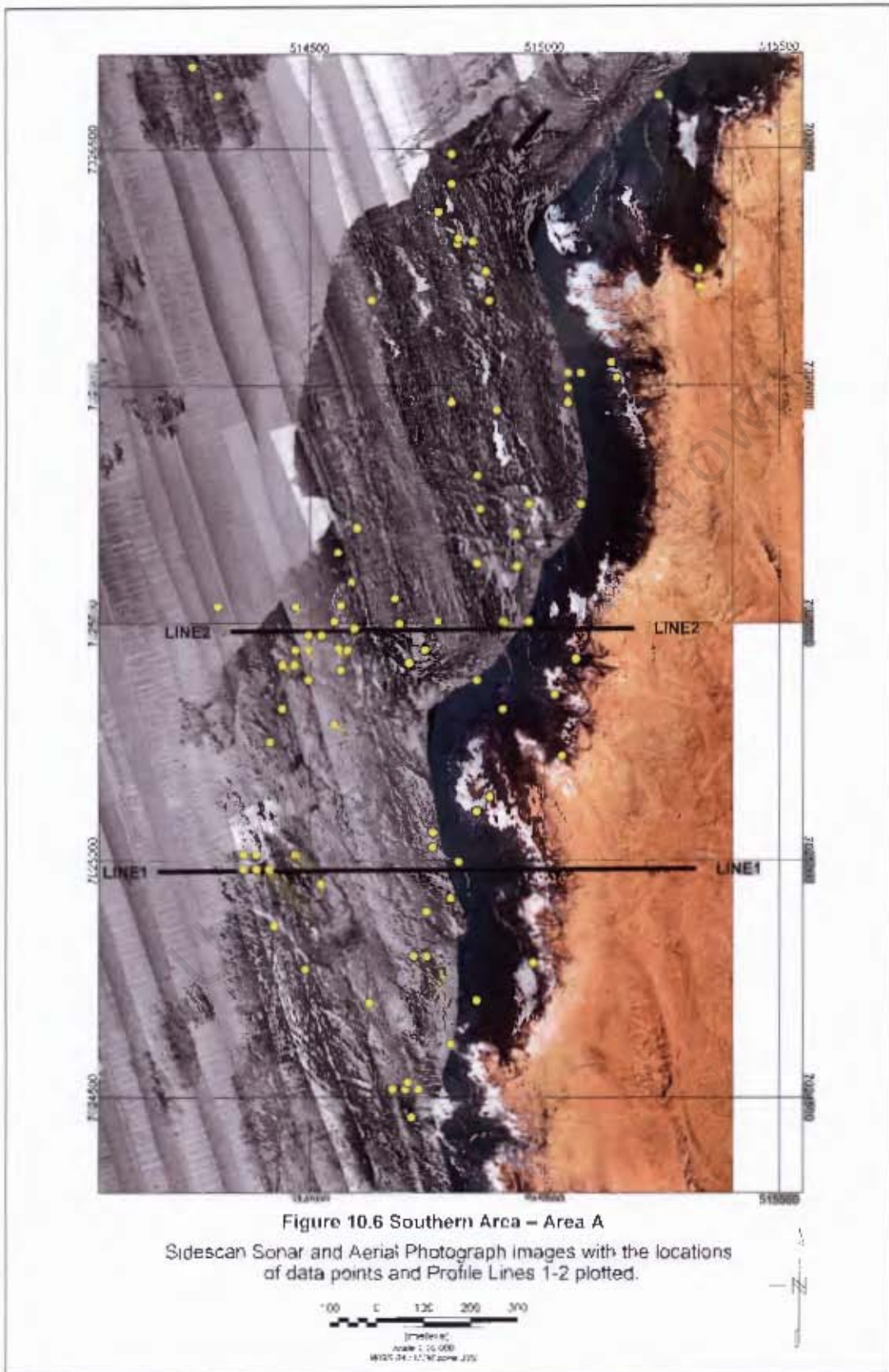


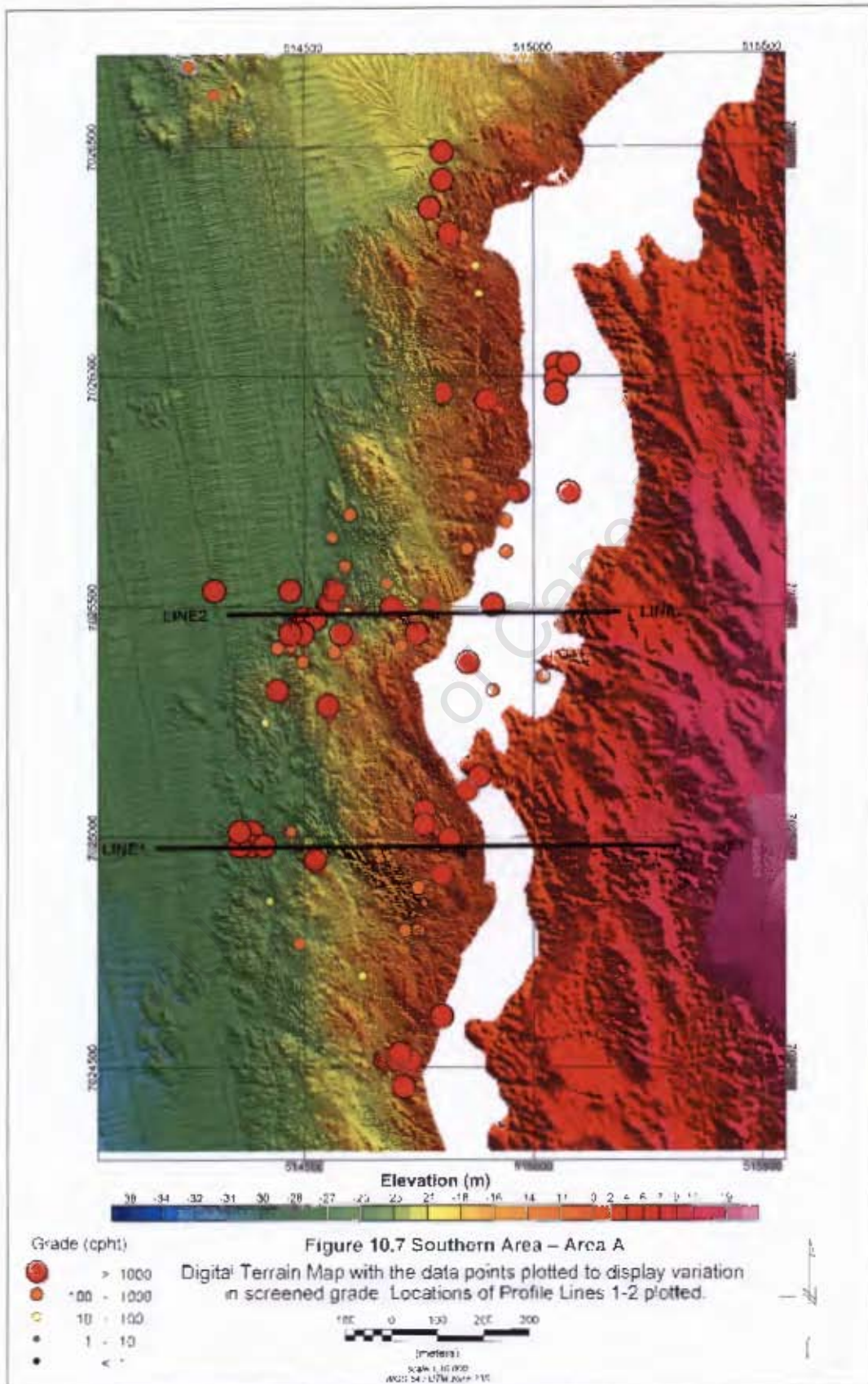
Figure 10.5: Depth distribution of diamonds mined from the sea in the area between Abenteuerbucht in the north and Elizabeth Bay Point in the south.

Mining in the Southern Area was concentrated in 4 areas namely the rough bedrock area in the south (area A), the area around Bains Bay Reefs (area B), raised palaeo beaches in Bains Bay (area C) and where Abenteuerbucht Channel cuts through a low ridge in the north (area D). The average grade of screened gravel (+1.6 mm, -10 mm) recovered from the area is in excess of 1000 cpht. There is however variance in grade within the Southern Area with the highest grade encountered in area A in the south. The grades of screened gravel recovered in the Southern Area will be expressed as a relative percentage of the average grade of screened gravel recovered from area A.

Area A

This area is situated immediately north of Elizabeth Bay Point along the coastline to Bains Bay (Figures 10.6 & 10.7). The rocky coastline is oriented in a SW-NE direction and it has several embayment features of various sizes. A rough bedrock surface is exposed to a depth of about -25 m from where it is covered by a sediment drape extending westwards. Approximately 52,000 cts were recovered from this area. Surf zone divers focused on this area and recovered over 19,000 cts from depths between -2 m and -12 m. The bulk of the surf zone production was recovered from -12m depth and the average stone size was 0.27 cts/stn. This area was also the focus of shallow marine operations who, in this area specifically, recovered 33,000 cts between depths of -15 m and -30 m with an average stone size of 0.30 cts/stn.





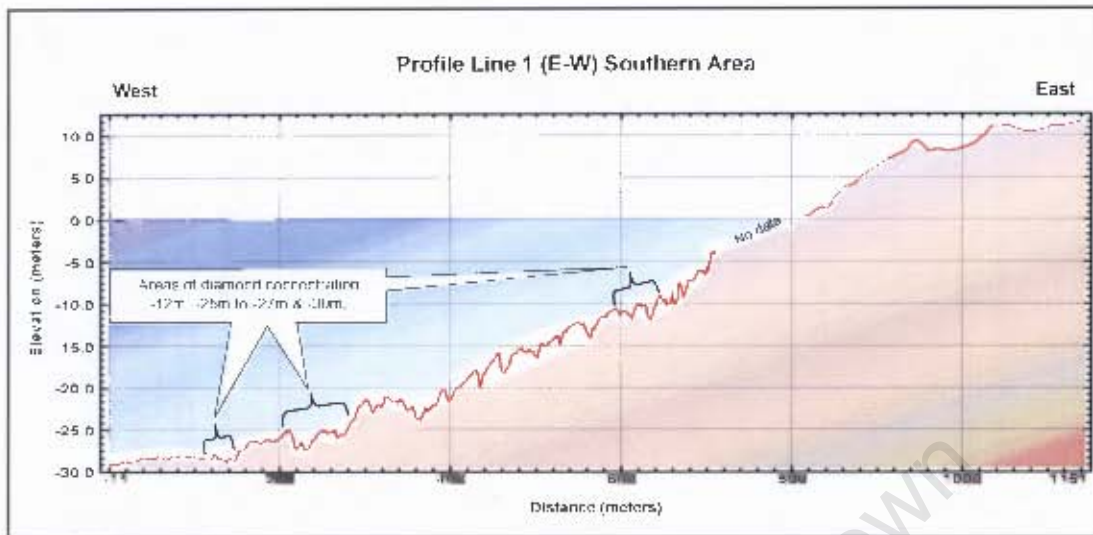


Figure 10.8: Profile Line 1 (E-W) of terrain elevation in the Southern Area (see Figure 10.7).

East-west oriented Profile Lines 1 & 2 indicates a fairly gently westward dipping coastal profile with a rough bedrock surface (Figures 10.8 & 10.9).

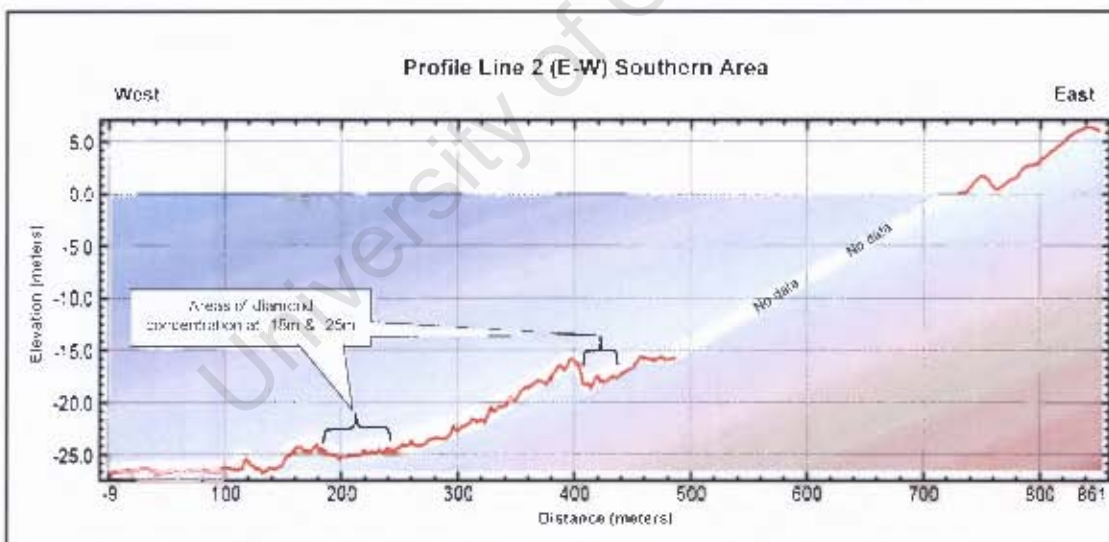
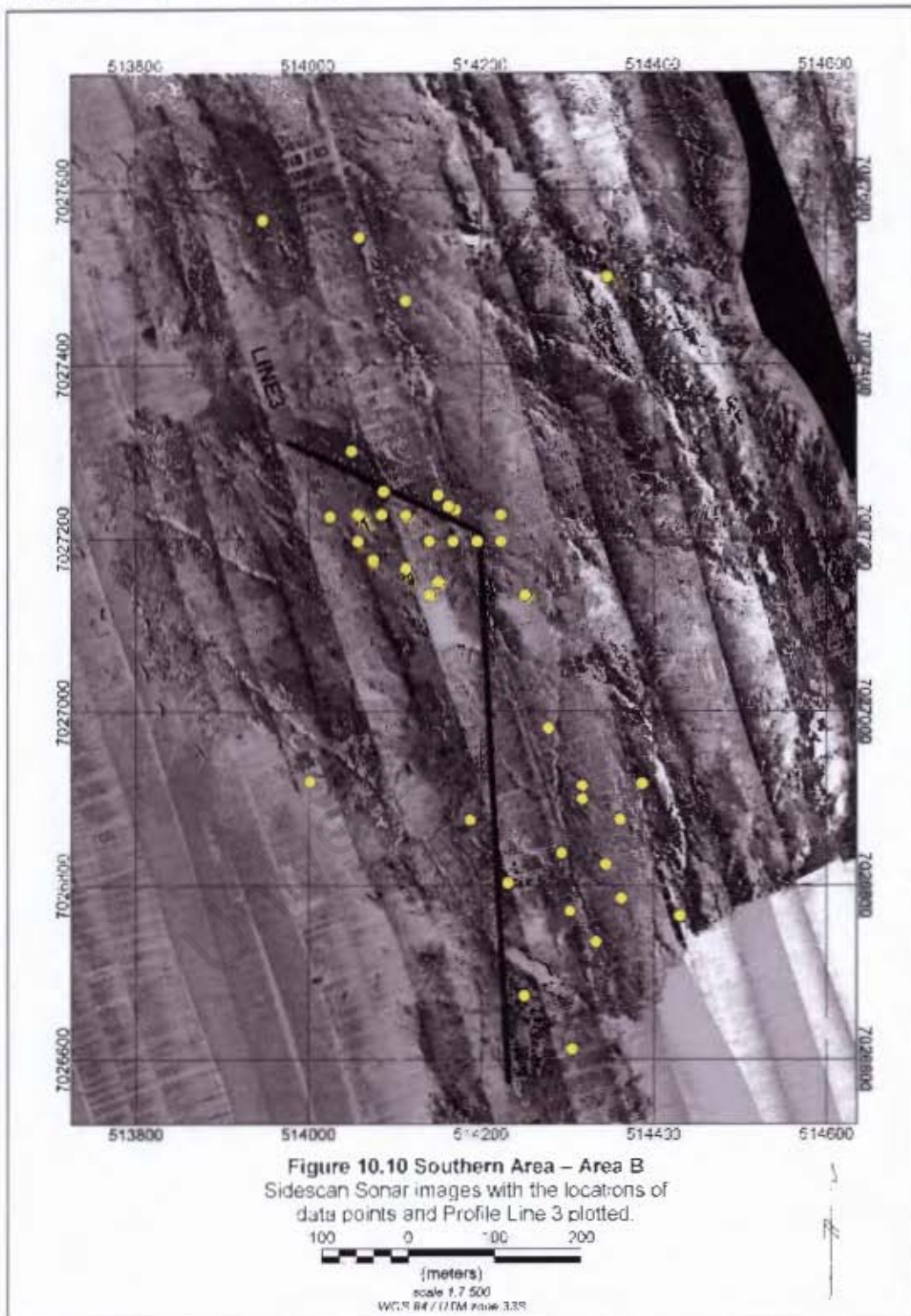


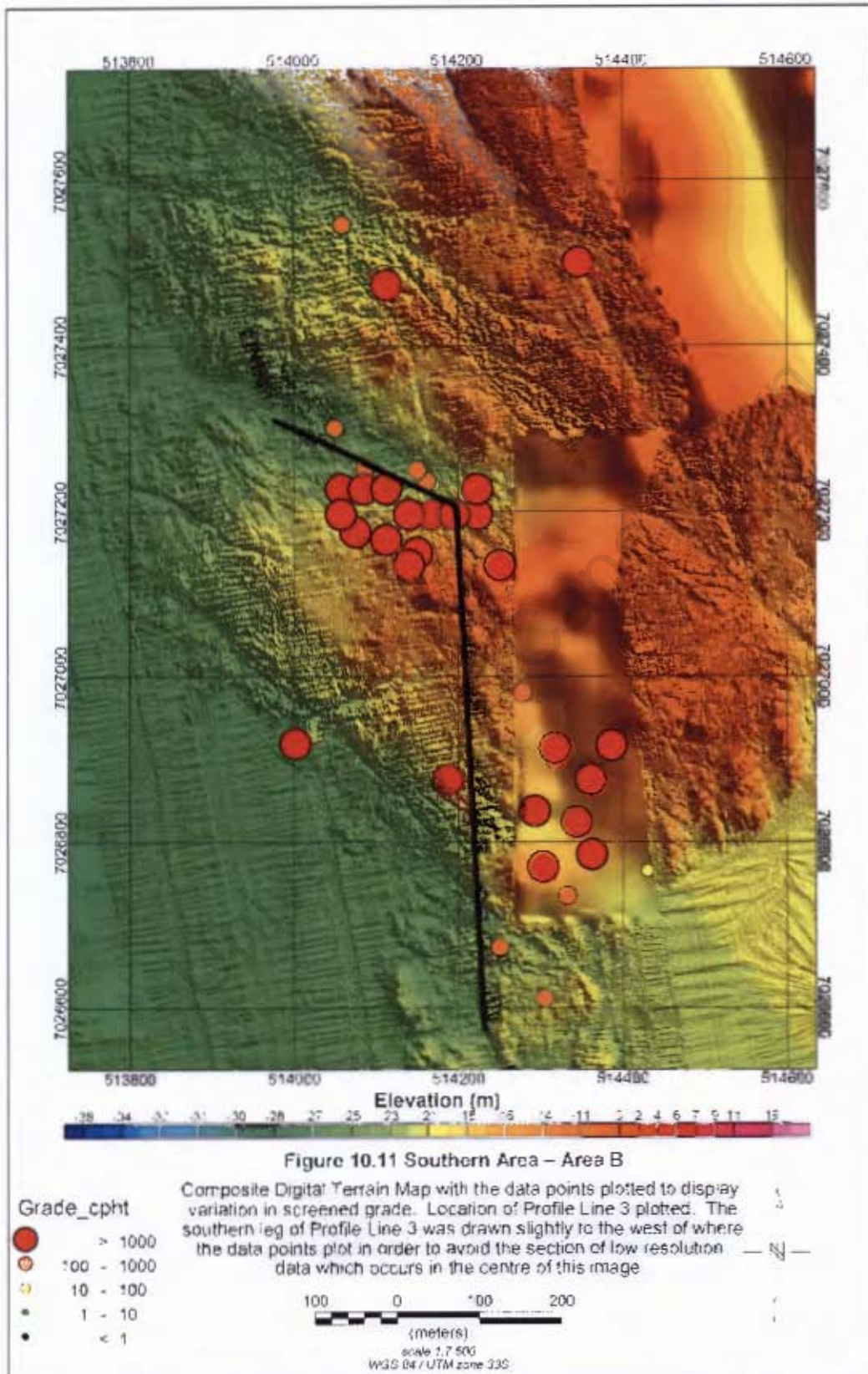
Figure 10.9: Profile Line 2 (E-W) of terrain elevation in the Southern Area (see Figure 10.7).

Area B

This area is situated on the southwestern slope of the pinnacles forming the Bains Bay Reefs where approximately 6,800 cts were recovered at a relative screened grade of 72% and an average stone size of 0.31 cts/stn (Figures 10.10 & 10.11).

Approximately 4,100 cts were recovered from the pushing south facing slope and about 2,700 cts were recovered from a wide gully on the lee slope.





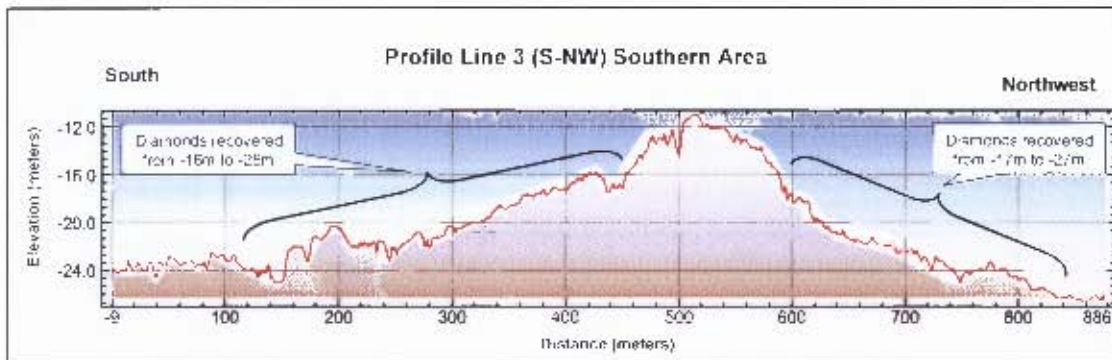
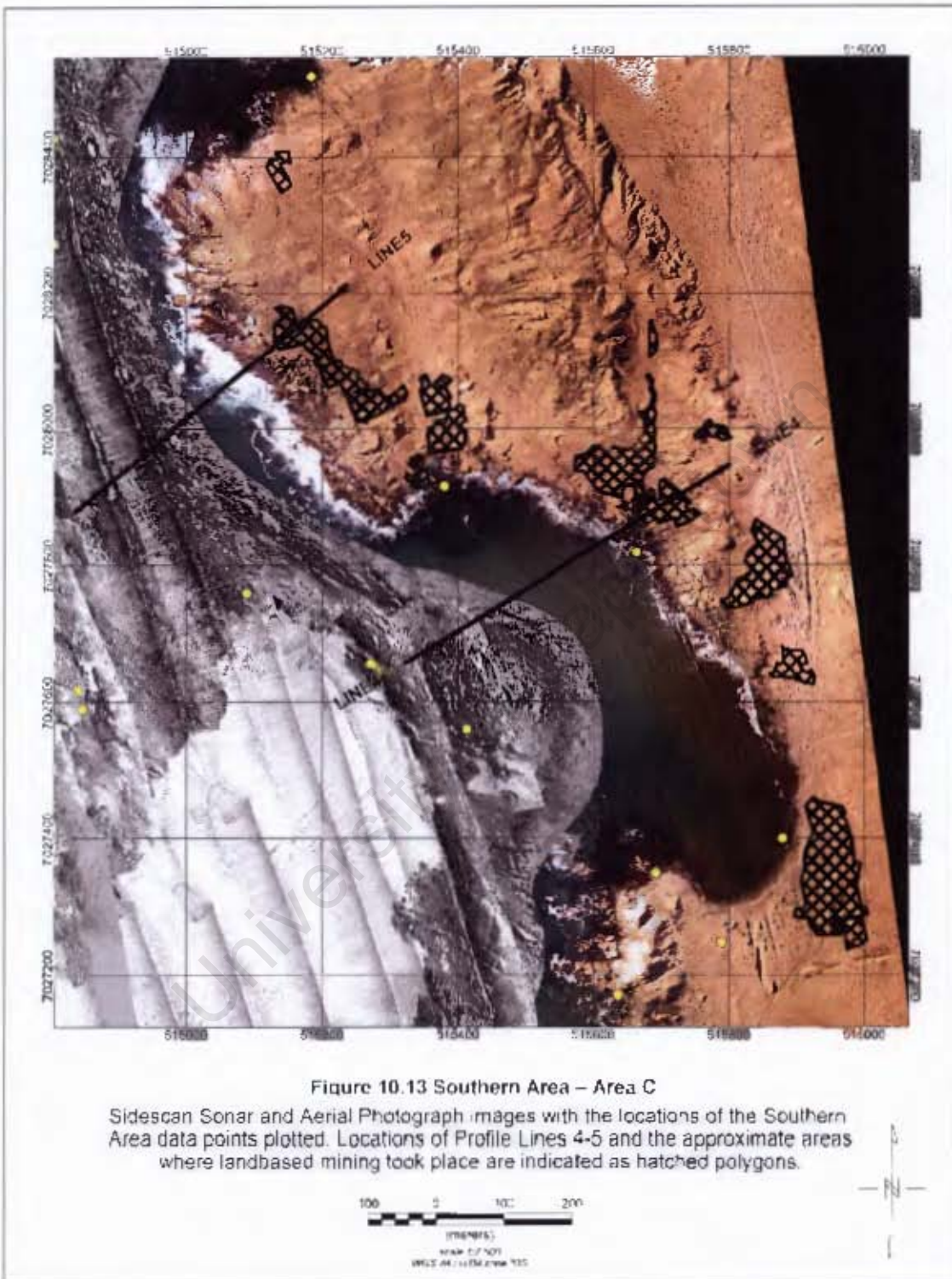


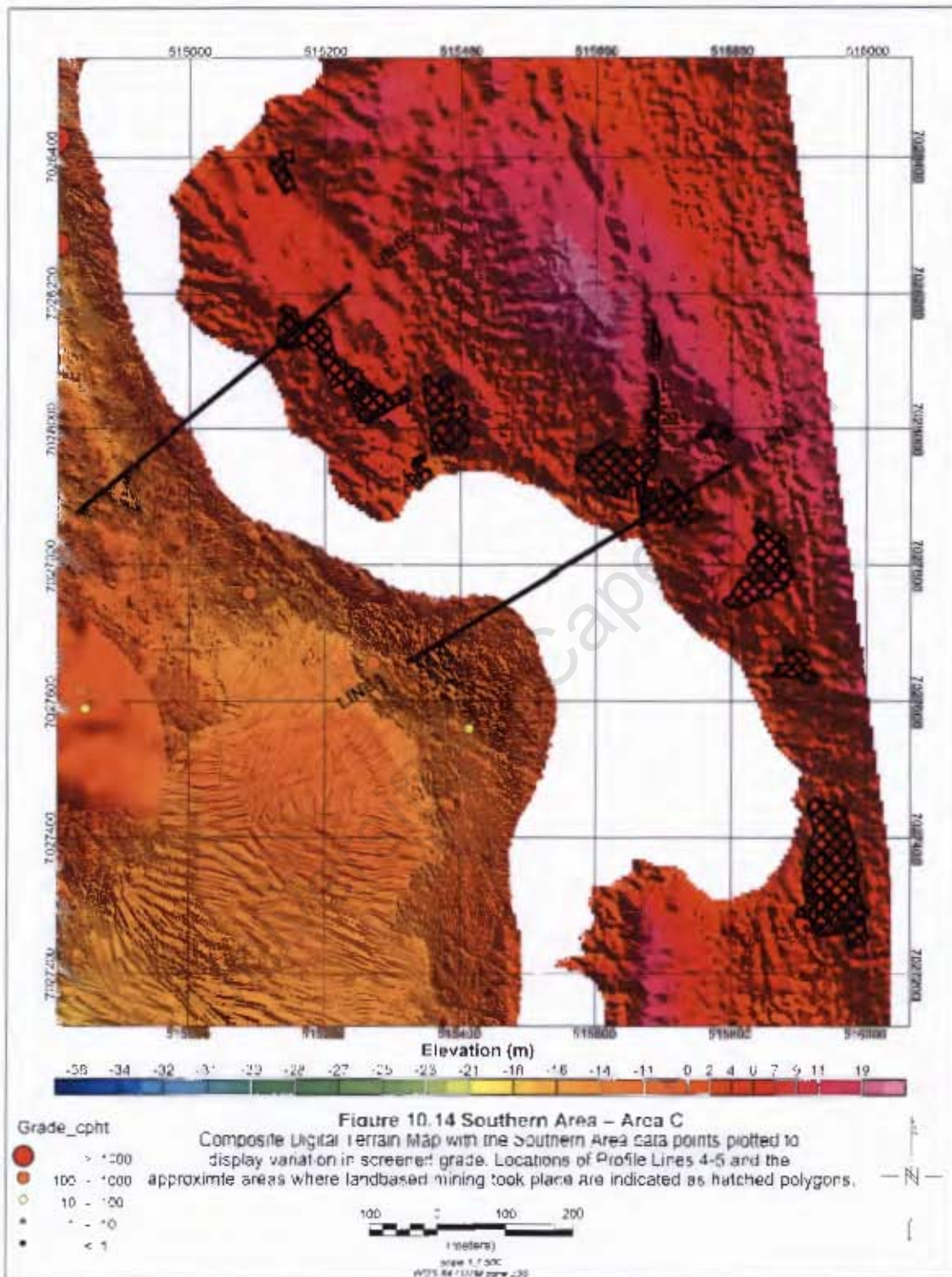
Figure 10.12: Profile Line 3 of terrain elevation over Bains Bay Reefs in the Southern Area (see Figure 10.11)

On both sides of the slope the diamond distribution was over a wide range of depths (Figure 10.12). The average screened grade did not differ significantly between the recoveries from the southern pushing slope and the northern lee slope. Likewise the average stone size was 0.31 cts/stn for both sides of the pinnacle.

Area C

This area is situated inshore from Bains Bay Reefs and covers the landbased mining which occurred in the vicinity of Bains Bay proper. Just over 9,300 cts were mined from remnant portions of palaeo raised beaches in the Bains Bay area (Figures 10.13 & 10.14). The average stone size was 0.20 cts/stn, notably smaller than the average for the study area which is 0.26 cts/stn. No tonnage data were recorded so grades could not be determined. Only the carats and stones recovered for the combined areas mined are known for this portion of the landbased mining. Most of the areas mined were situated below 7 mamsl with only a minor portion extending above this level. Both Profile Lines 4 & 5 indicates that low ridges occur on the seaward side of these small preserved pockets of gravel (Figures 10.15 & 10.16).





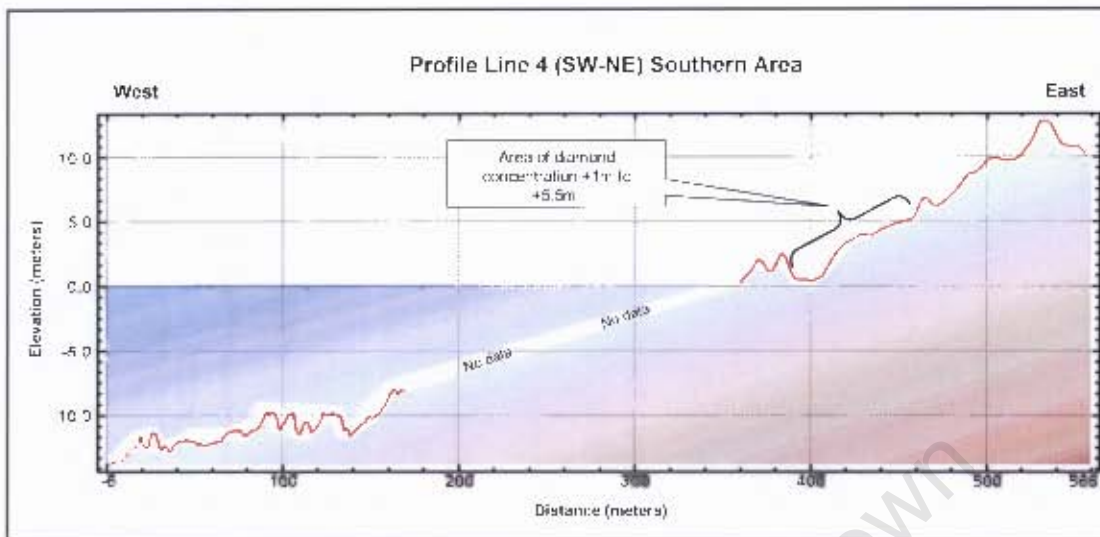


Figure 10.15: Profile Line 5 of terrain elevation at Bains Bay where raised deposits were mined (see Figure 10.14).

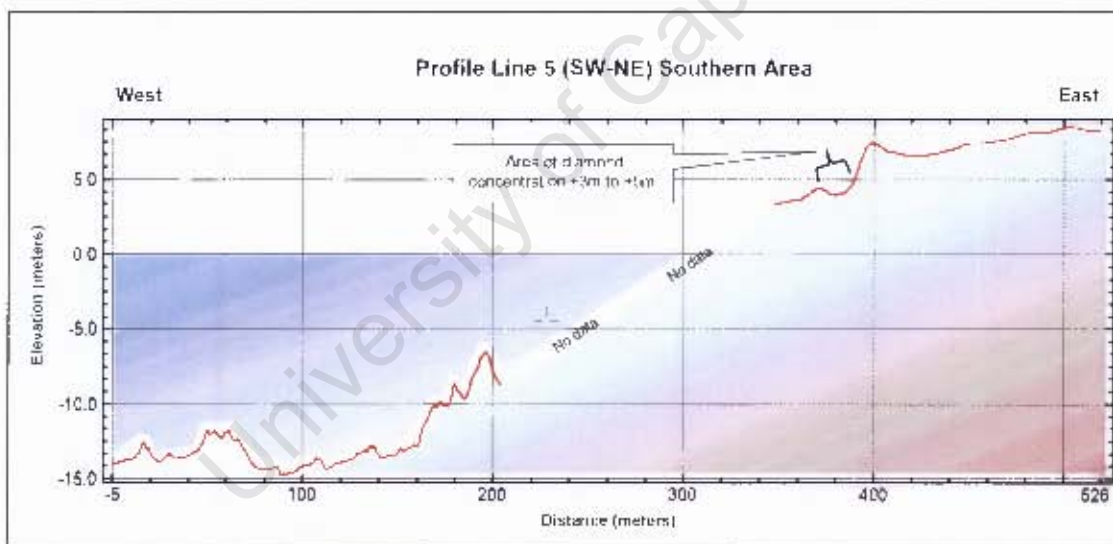
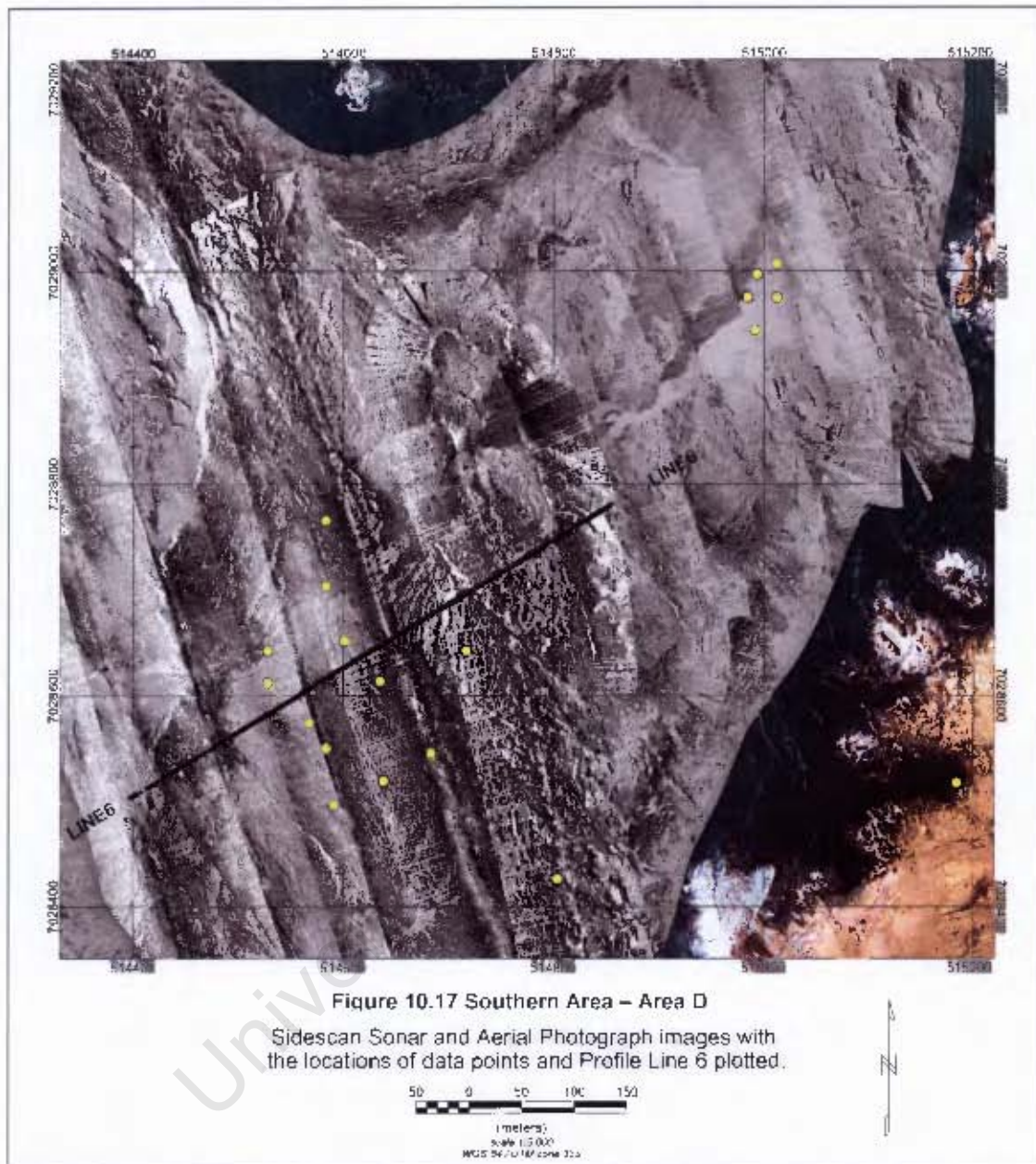
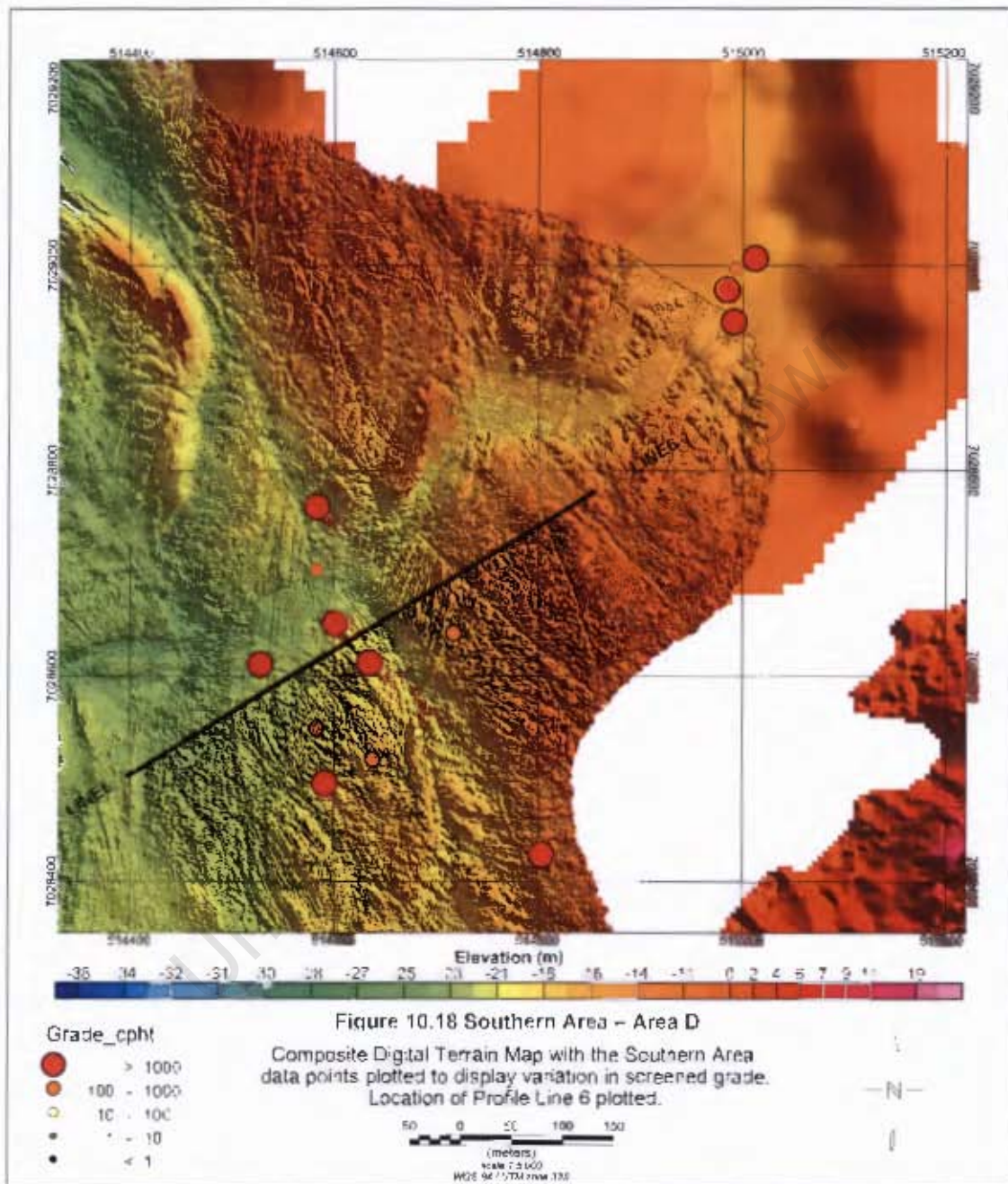


Figure 10.16: Profile Line 5 of terrain elevation at Bains Bay where raised deposits were mined (see Figure 10.14).



Area D

This area is situated to the north of the Bains Bay headland in the channel leading from Abenteurbucht (Figures 10.17 & 10.18). Nearly 2,600 cts were mined from this area at a depth of -20 m. The average stone size of 0.27 cts/stn for the area is very similar to that of the entire study area at 0.26 cts/stn. The relative screened grade in this area was very similar to that of Area A at 98%. The bulk of the diamonds were recovered from the base of a cliff in the vicinity where the Abenteurbucht channel cuts through the cliff (Figure 10.18 & 10.19).



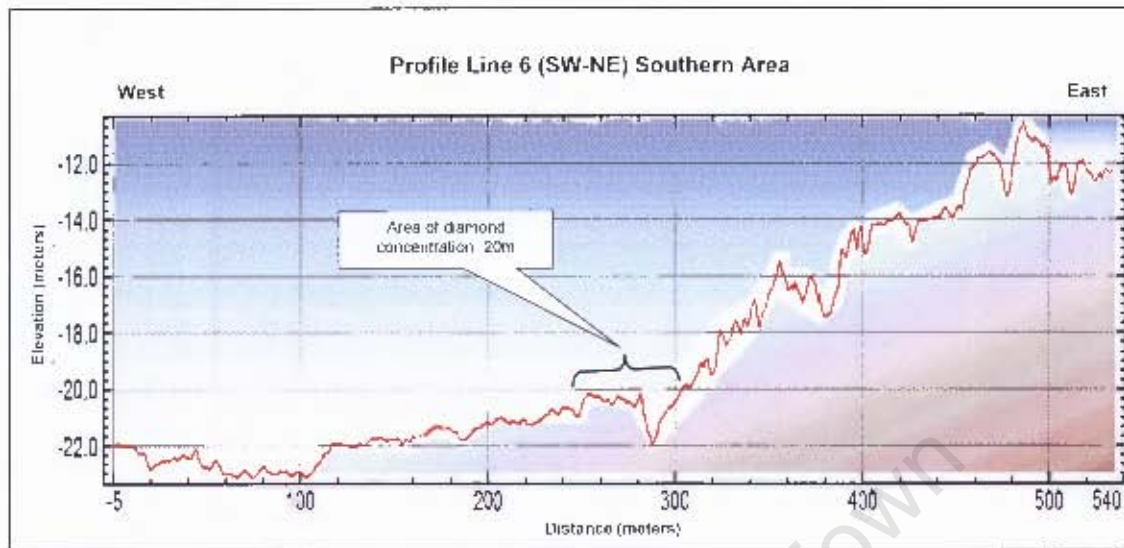


Figure 10.19. Profile Line 4 of terrain elevation at Abentourbucht Channel (see Figure 10.18).

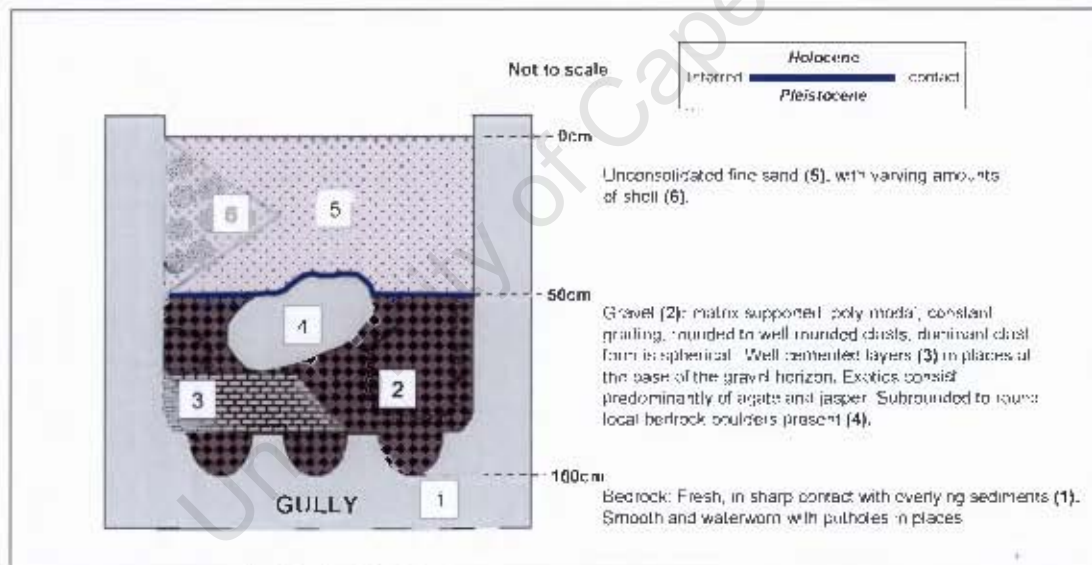


Figure 10.20: Schematic stratigraphic column of gravel package encountered in the Southern Area.

In the Southern Area the divers encountered a gravel package which was approximately one metre thick and developed on a fairly smooth bedrock surface with which it was in sharp contact (Unit 1 Figure 10.20). The gravel (Unit 2) was an unconsolidated, clast supported, polymodal package with a constant grading. Cobble and small boulder size fraction clasts were rounded to well rounded and the dominant clast form were spheres, discs and blades. The pebble size fraction clasts were very well rounded and the dominant clast form was spheroidal. Exotics consisted predominantly of agate and jasper. Clear internal bedding could be distinguished

between gravel, fine sand and shell horizons in sections of this package. The shells were generally whitish in appearance, chalky and friable. A very well cemented layer was often encountered at the base of the horizon at approximately -22 m depth (Unit 3). The cemented horizon is reportedly very hard and resistant even to pneumatic hammers in places. Occasional large subangular to subround boulders of local bedrock were present in the gravel (Unit 4). The sequence is generally topped off by a layer of unconsolidated fine sand (Unit 5) with varying amounts of fresh shell present (6). A Holocene/Pleistocene contact is inferred between the gravel package and the unconsolidated sandy shell layer above it

MacDonald (1997) recorded that the slimes (-1.6 mm) made up a major portion of the package. The gravel fraction (+1.6 -10 mm) constituted approximately 30% of the gravel. The oversize fraction (+10 -250 mm) made up approximately 50% of the package and boulders (+250 mm) about 20% volume of the gravel

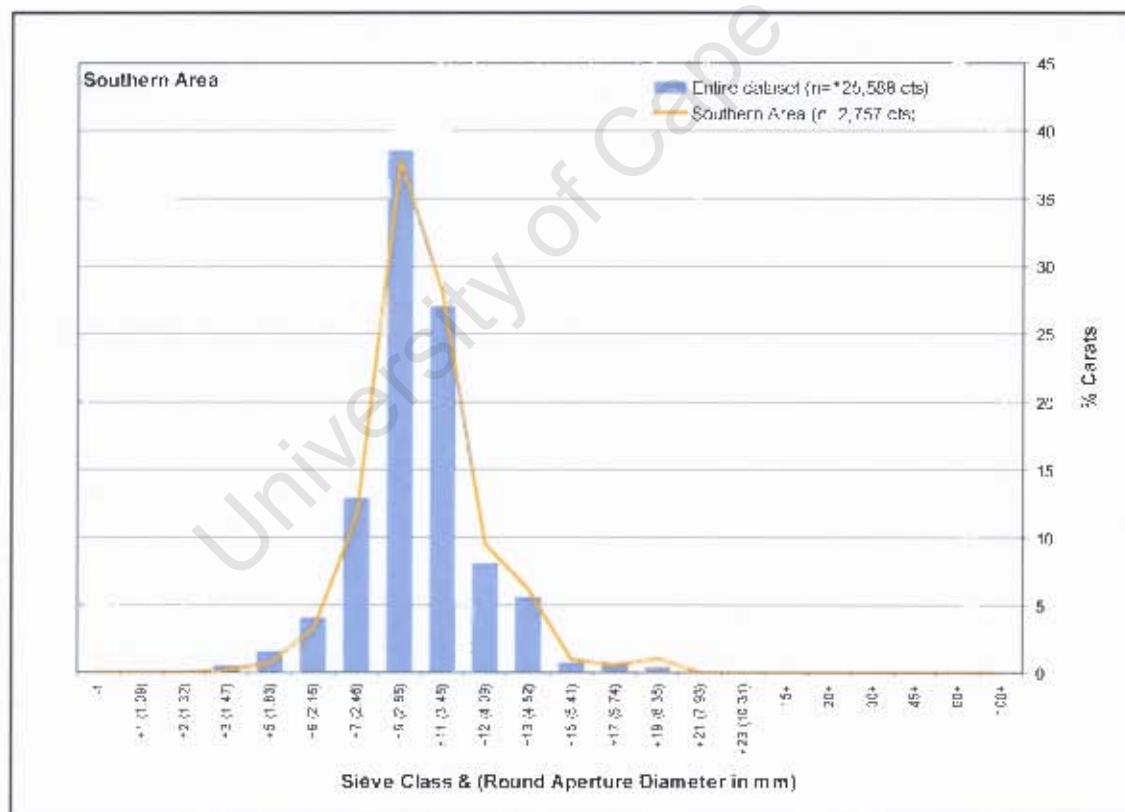


Figure 10.21: Size frequency distribution of a diamond parcel which contains 75% contents from the Southern Area plotted with the size frequency distribution of carats mined from the whole study area.

The size frequency distribution (SFD) dataset for the Southern Area consist of 1 diamond parcel totaling 2,757 cts. During the time when the area between Abenteuerbucht and Elizabeth Bay Point were actively mined, production from the various vessels was rolled together for during the monthly consignments for valuation purposes. The parcel making up the Southern Area SFD dataset comprise of 75% of the carats from the Spook Bay area with the remaining 25% originating from production obtained from shallow marine vessels mining in other locations in the study area (Halifax Island to Elizabeth Bay).

The cumulative size frequency distribution (percentage carats per sieve class) of the Southern Area data display uni-modal size distribution peaking in the +9 sieve class (Figure 10.21). It is a well sorted diamond population with 78% of the carats occurring in the +7 to +11 sieve classes. The Southern Area population (n=2,757 cts) mimics the entire population plot for the whole of the study area (n=125,588 cts).

University of Cape Town

10.2 DISCUSSION

The average stone size of diamonds mined from the marine portion of the Southern Area is 0.29 cts/stn which are slightly higher than the average stone size of 0.26 cts/stn for the entire study area. Although the size frequency distribution of the diamond population from the Southern Area is based on a single parcel (2,757 cts) of which 75% are from the Southern Area, it is almost identical to that of the entire diamond population for the whole of the study area (Figure 10.21). Based on the similarities in stone size and size frequency distribution, it can be assumed that the diamonds mined from the Southern Area are part of the shallow marine diamond population encountered within the study area.

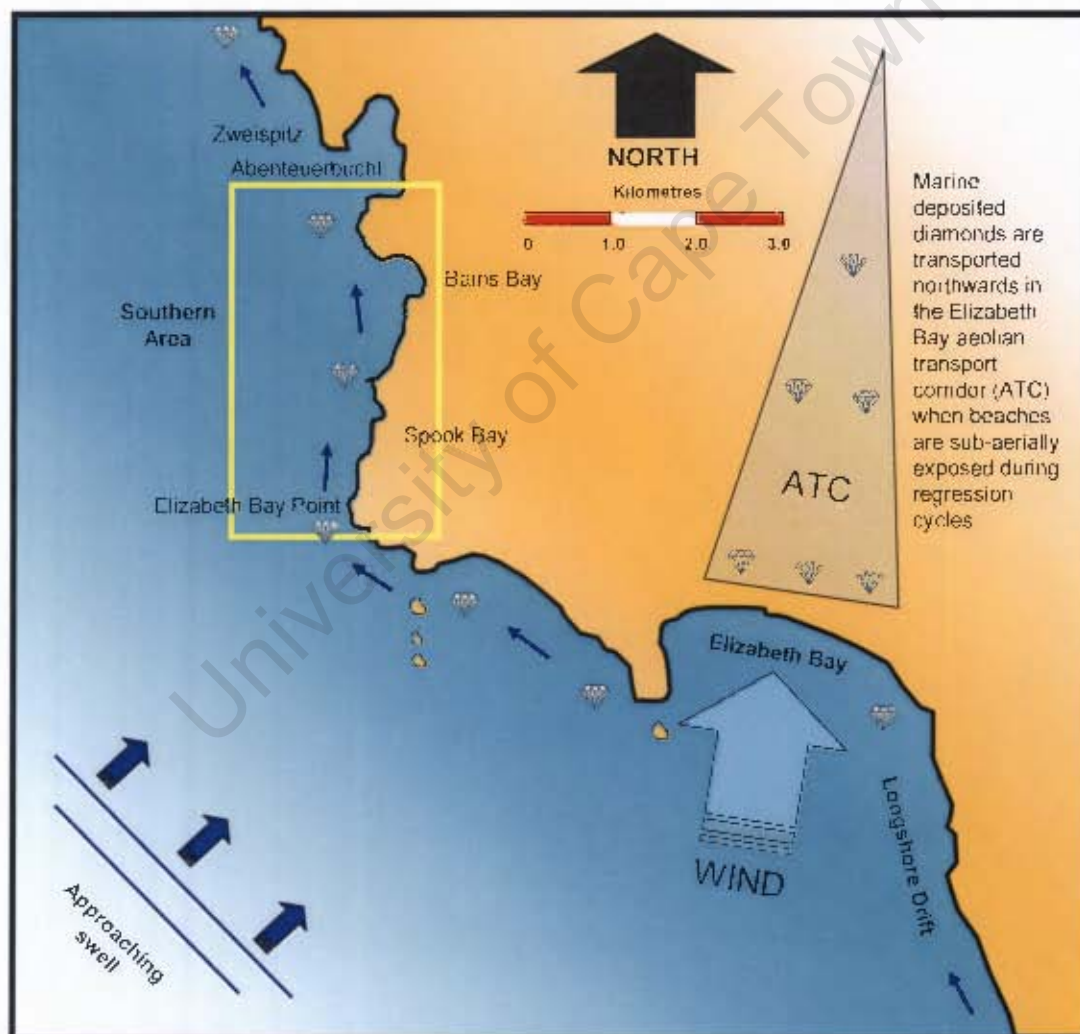


Figure 10.22: The location of the Southern Area relative to Elizabeth Bay which forms the largest south facing embayment and sediment bypass systems along the coast.

The Southern Area is situated immediately north of Elizabeth Bay Point where the coastline orientates in a roughly northeast-southwesterly direction again after the large Elizabeth Bay embayment (Figure 10.22). The Bains Bay Reefs forms the headland of a small south facing embayment at sea still stands between -24 m and -14 m. This headland would interrupt the northward flowing longshore drift.

Area A

This area is situated as the corner is turned northward after Elizabeth Bay Point (Figure 10.23; Area A). The area has a fairly gently sloping coastline with a rough bedrock surface which offers numerous bedrock controlled trapsites. As the waves approach this section northeast-southwesterly oriented section of the coast at an oblique angle, the rough "washboard" surface provides trapsites within which gravel can be retained and reworked. This resulted in the concentration of a substantial amount of diamonds at various depths between -2 m and -30 m in this area. Surf zone divers recovered approximately 19,000 cts at an average stone size of 0.27 cts/stn from depths between -2 m and -12 m. Boat based divers recovered 33,000 cts at an average stone size of 0.30 cts/stn, primarily from depths between -20 m and -25 m. The relative screened grade for gravel recovered from this area was very high at 100%.

Area B

Situated to the north of Area A are the Bains Bay Reefs which form the headland of a small south facing embayment at sea still stands between -24 m and -14 m (Figure 10.23; Area B). At shallower sea still stands it forms an island. The south facing slope of this area is slightly protected from the oncoming wave energy by two small outcrops/islands. These small islands, combined with the rough bedrock surface, provided trapsites and the environment within which gravel could be retained and subsequently reworked. Divers recovered 4,100 from the south facing slope at an average stone size of 0.31 cts/stn from depths between -16 m and -28 m. Approximately 2,700 cts were mined from the north facing slope also at an average stone size of 0.31 cts/stn between depths of -17 m and -27 m. The slightly larger stone size of 0.31 cts/stn of Area B compared to the 0.30 cts/stn recovered from the deeper sections in Area A, may be a reflection of the higher energy environment within which reworking took place. The exposure to oncoming waves, especially during storm events, are not conducive for sediment accumulation and that is most likely the reason why more diamonds were not concentrated in this specific area.

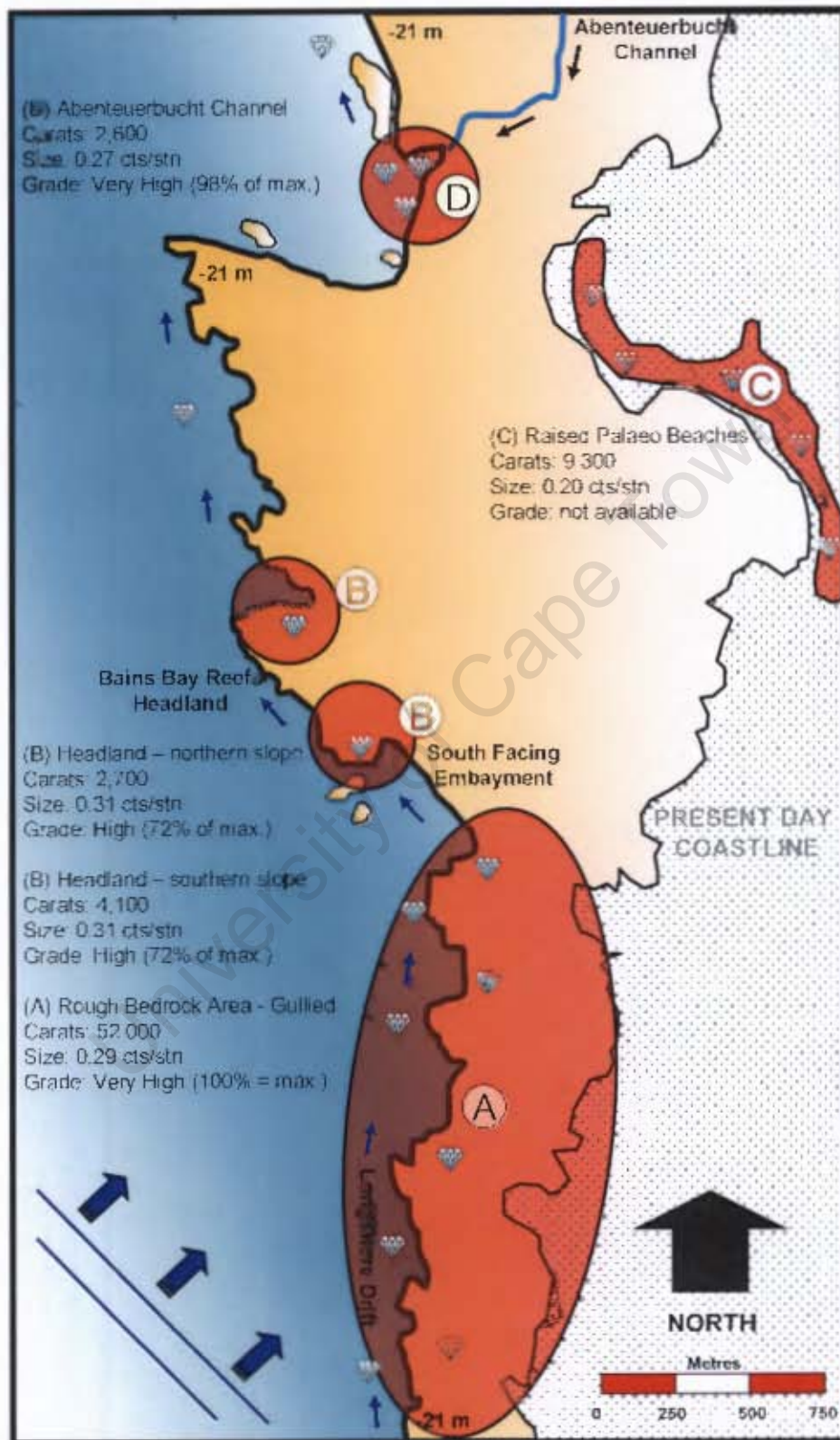


Figure 10.23: Schematic representation of the -21 m sea still stand scenario and diamond occurrence within the Southern Area.

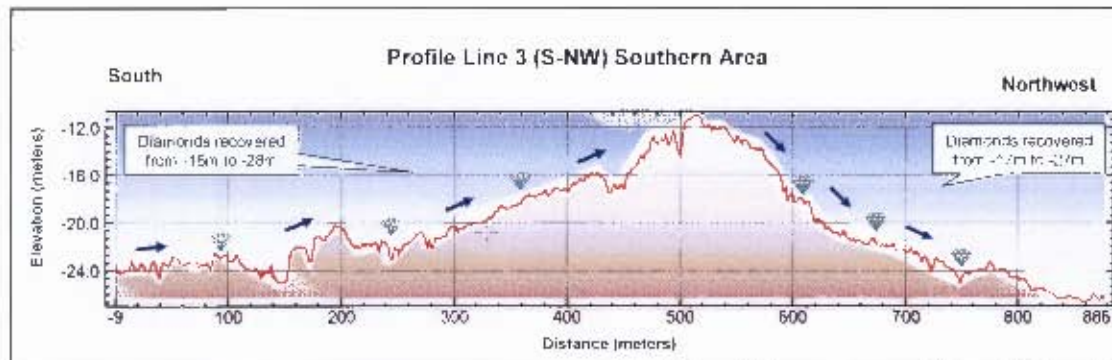


Figure 10.24: Profile Line 3 of terrain elevation over Bains Bay Reefs indicating the possible transport of diamonds over the reef (see Figure 10.13).

It is feasible that some of the diamonds concentrated on the south facing slope area were transported over the reef during storm events and came to rest in the gullies on the north facing lee slope (Figure 10.24). This would explain the relatively wide range of depths over which diamonds occur on both sides of the reef.

Area C

Area C is situated onshore in Bains Bay and covers the landbased mining of raised palaeo beaches which took place here (Figure 10.23). Approximately 9,300 cts were recovered at an average stone size of 0.20 cts/stn which is significantly smaller than the average for the study area which is 0.26 cts/stn. However, the 0.20 cts/stn is consistent with other raised beach deposits mined in the area. No tonnage data were recorded for the landbased operations in the Southern Area so the grade of the deposit is not known. The low ridges found on the seaward side of the small raised beach deposits would most likely have assisted in the preservation of these remnants (Figures 10.15 & 10.16)

Approximately half of the mined areas occur below 5 mamsl and practically all of the areas are situated at elevations below 9 mamsl. Compton (2006) showed that at Bogenfels Pan, situated approximately 70 km southeast of the study area, the sea-level did not exceed 5 mamsl during the Mid-Holocene highstand from 7,300 to 5,900 years ago. The portions of the remnant beaches situated below 5 mamsl were therefore most likely deposited during the last 7,300 years (Figure 5.3), (Compton, 2006). The portion of the remnant beaches situated at elevations between 5 and 9 mamsl were formed at least 120 ka ago, as this was the first submergent period for these elevations of the coastline (Figure 10.25).

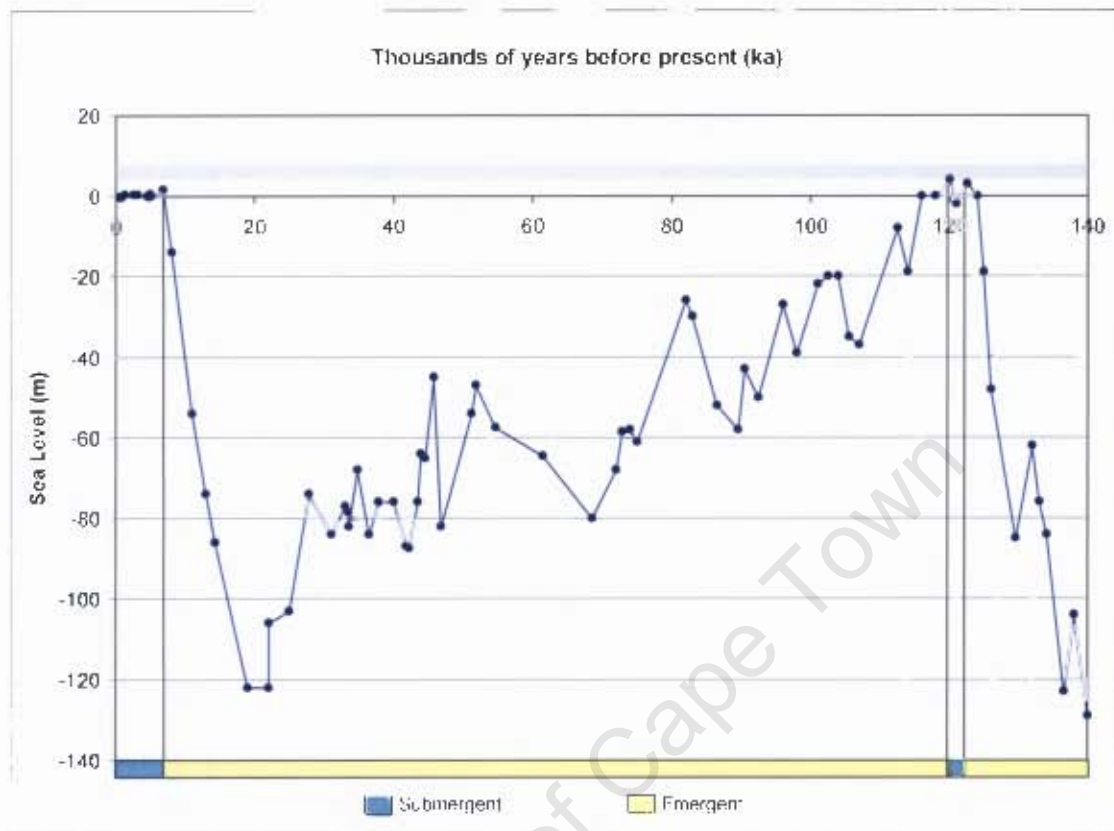


Figure 10.25: Composite sea-level curve for the last 140 ka indicating submergent and emergent periods for the +5 m to +10 m coastline (Compton, 2001, Compton *et al.*, 2002; Yokoyama *et al.*, 2000; Chappel *et al.*, 1996; Fairbanks, 1990; Shackleton, 1987).

Area D

The Abenteuerbucht Channel is the 3rd area where diamonds were concentrated in the present day marine environment of the Southern Area (Figure 10.25: Area D). At Abenteuerbucht Channel the diamonds were recovered from an area close to where the drainage channel cuts through a NW-SE trending ridge. This ridge formed a cliff at lower sea still stands and it is at the base of this cliff where the most of the diamonds were recovered in this area at the -20 m (Figure 10.21). At this sea still stand any material washing out of Abenteuerbucht would also be reworked in this high energy surf zone environment at the base of the cliff. Clastic material introduced to this -20 m shoreline would increase bedrock roughness and enhance this areas ability to retain diamonds. About 2,600 cts were recovered from this area at an average stone size of 0.27 cts/stn. The relative screened gravel grade was very high at 98%. This suggests that area where fluvial and marine processes interact forms an environment conducive to the concentration of diamonds. However, this is a small feature and subsequently only relatively small amounts of diamonds were retained.

The diamonds recovered versus depth profile indicate that diamond deposits were spread over a wide range of depths in this area. The profile of the coast along this stretch of coast is less steep and therefore offers space for a wider range of sea still stands, especially at -12 m, to deposit and rework gravel deposits. The consistently high to very high grades recovered in this area gives an indication to the degree of reworking and concentration which took place. The cementation and presence of large boulders assisted with the preservation of these deposits.

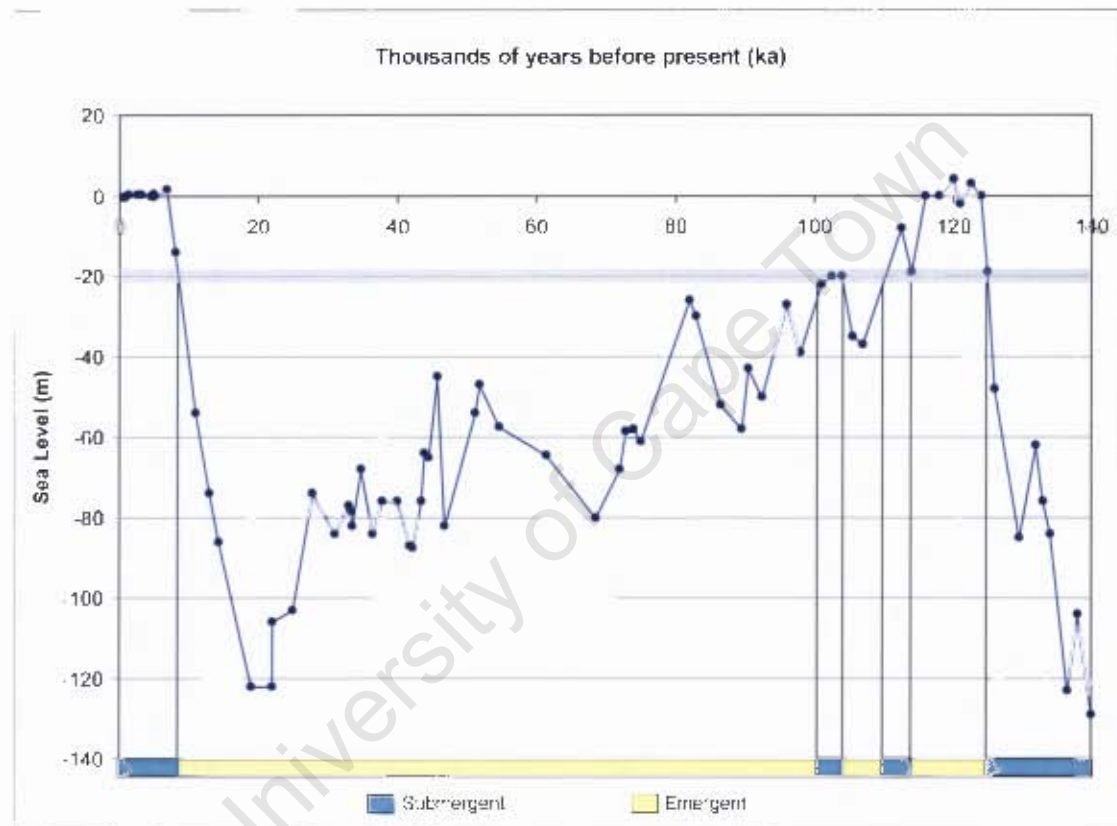


Figure 10.26: Composite sea-level curve for the last 140 ka indicating submergent and emergent periods for the -20 m to -24 m coastline (Compton, 2001; Compton *et al.*, 2002; Yokoyama *et al.*, 2000; Chappel *et al.*, 1996; Fairbanks, 1990; Shackleton, 1987).

The cemented horizons which were encountered by the divers in various areas at depths of approximately -22 m, indicate that the gravel was most likely sub-aerially exposed and calcite cementation took place during this emergent period. As the shells encountered in this gravel package had a weathered, white and chalky appearance – it is most likely that deposition occurred at least 100 ka ago. This was the first submergent period for the -22 m shoreline before the Last Glacial Maximum (Figure 10.26). Cementation would have taken place during sub-aerial exposure subsequent to deposition.

11. SUMMARY

11.1 Diamond Size Frequency Distributions

There is very little sediment accumulation along the coastal strip in the study area. Onshore, the rare pockets of accumulated sediments consist almost entirely of locally derived clasts. A negligible portion by volume consists of erosion-resistant exotic clasts transported by fluvial, marine and aeolian processes from the hinterland of Southern Africa. In the study area, these exotics are generally smaller than 25 mm in diameter (pebbles) with the most noticeable lithologies being agate, jasper, banded ironstone and diamond. From observation, the offshore accumulations of gravel within the shallow marine portions of the study area reflect the same as the onshore scenario. The overall drop in sea-level since the Palaeogene and asymmetrical uplift of the continent has resulted in poor sediment preservation in the coastal plain of the West Coast (Wigley & Compton, 2006).

The diamonds in the study area were mostly recovered from water depths <30 m by divers. This diamond population, mined from a relatively narrow coastal zone, displays notable consistency in terms of particle size frequency distribution (SFD). Despite a mean decrease in stone size from south (0.29 cts/stn) to north (0.25 cts/stn), the SFDs for each of the 4 areas discussed deviated very little from the composite SFD for the whole study area (Figure 11.1).

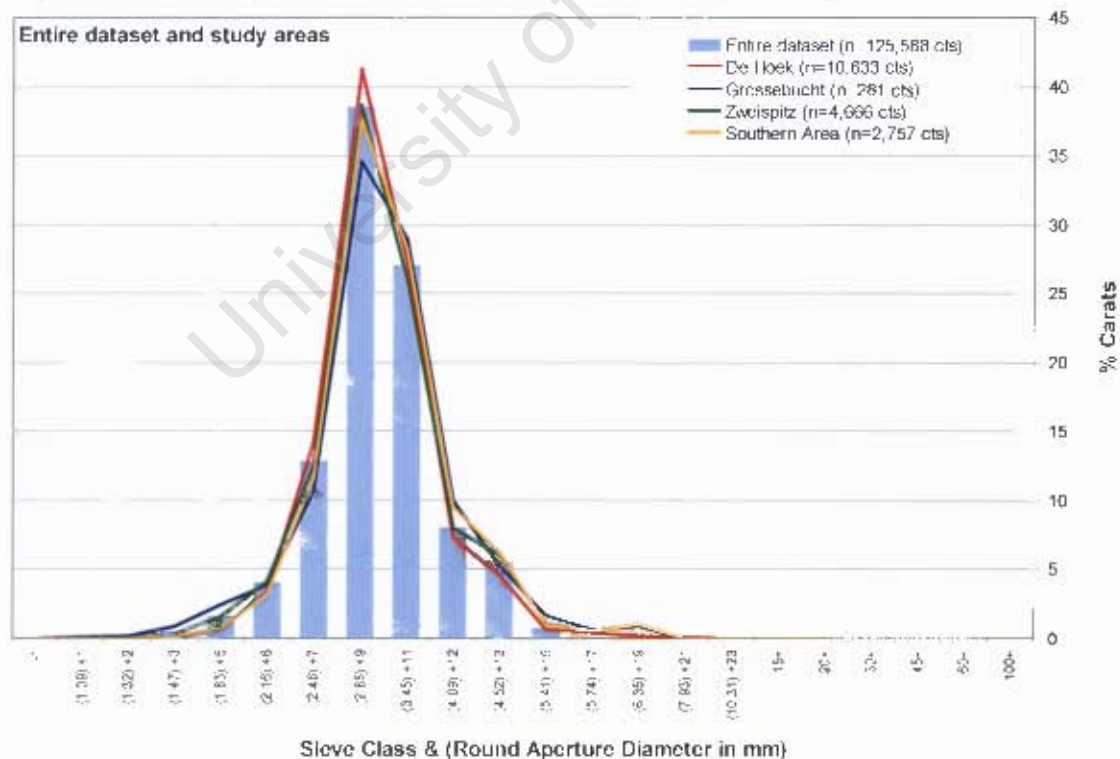


Figure 11.1: Size frequency distribution of the 4 study areas plotted with the size frequency distribution of carats mined from the whole study area.

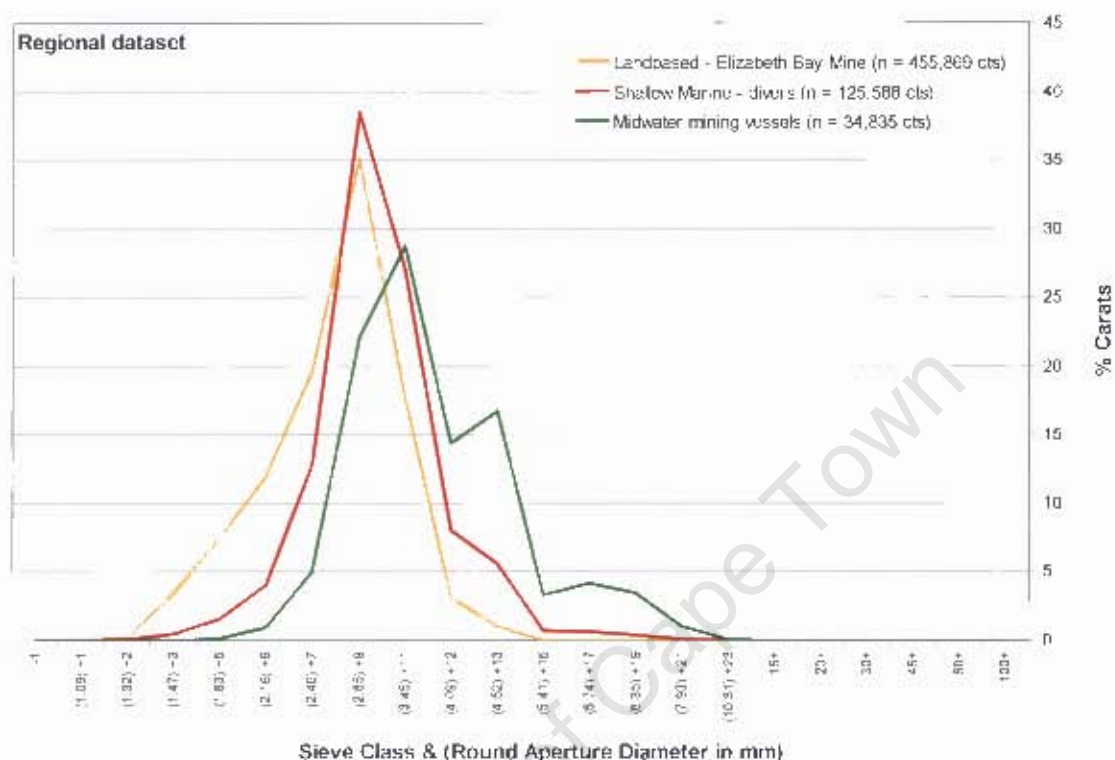


Figure 11.2: Size frequency distribution for 3 deposits occurring at various elevations within close proximity of another (Figure 11.3). On land the SFD for Elizabeth Bay Mine the Shallow Marine (0 to -30 m) dataset compiled for this study and the Midwater (-30 to -70 m) data from the Peninsula/Channel deposit situated immediately SW of the study area are plotted.

Situated east of the study area is the Elizabeth Bay aeolian diamond deposit and to the west of the study area is the Midwater (-30 to -70 m) deposit. Although occurring on different elevations, these three distinct deposits are in close geographical proximity to each other (Figure 11.3). The SFDs for the three deposits display variations (Figure 11.2). The SFD of Elizabeth Bay Mine peaks in the +9 sieve class and has a greater relative percentage of stones in the smaller sieve classes compared to the Shallow Marine and Midwater datasets. This is due to the smaller stones being preferentially transported and removed from the marine beach setting by wind action in the Elizabeth Bay aeolian transport corridor (ATC) during regressions. The Midwater SFD shows larger stones with peaks in the +11 and +13 sieve classes. This is a different population of diamonds, which were transported and distributed northward along the coast when the sea-level was lower.

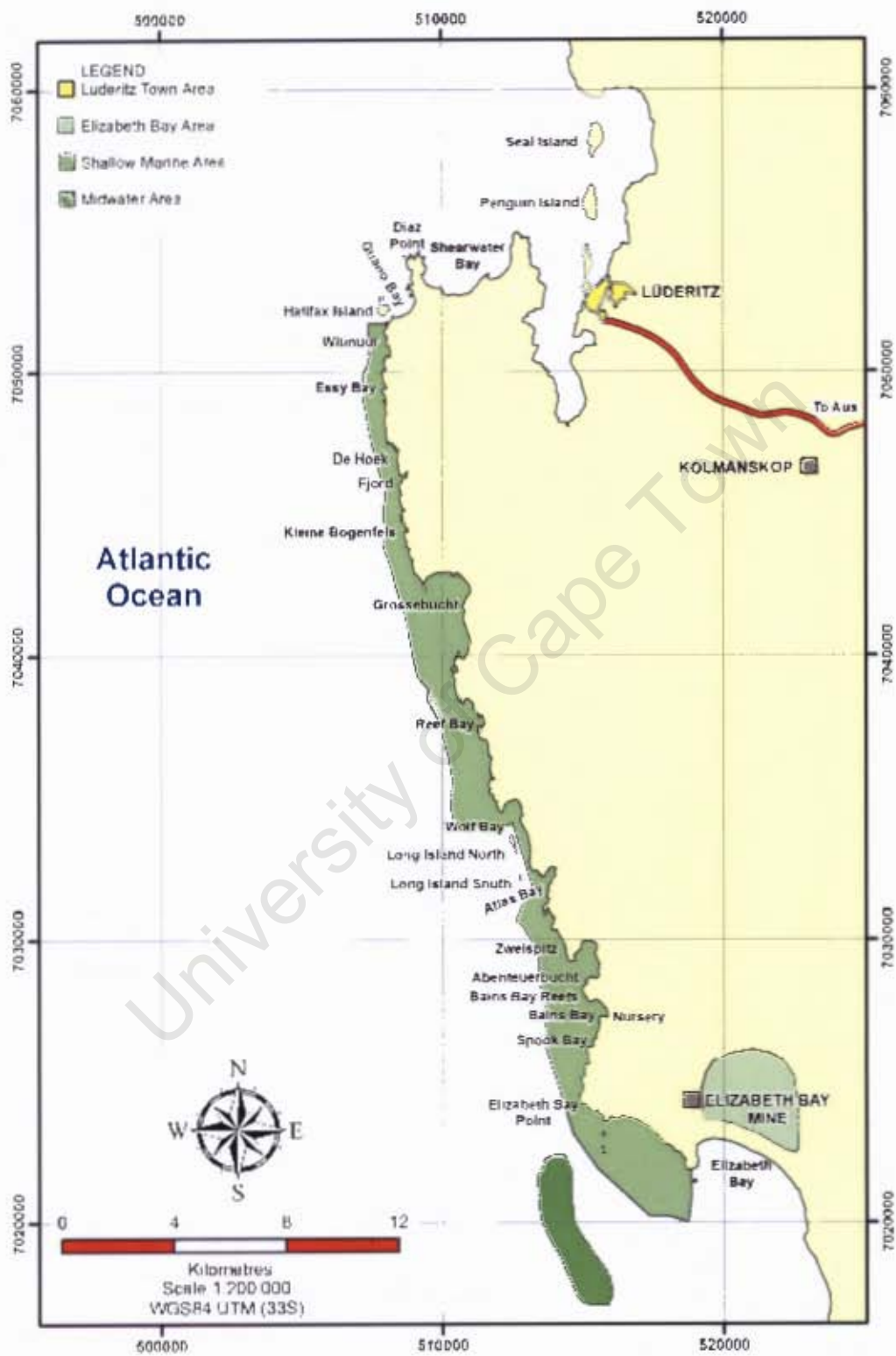


Figure 11.3: Map indicating the approximate locations of the Elizabeth Bay, Shallow Marine and Midwater areas from where the production were mined which were used for the diamond size frequency comparison (see Figure 11.2).

11.2 Sea-level

The marine placers were formed along palaeo-strandlines at various elevations subject to cycles of transgression and regression. No evidence of aeolian upgrading (presence of ventifacts in gravel) of the shallow marine and surf zone deposits has been reported historically or recently. The nearest palaeo and present-day ATC is situated to the east of the study area at Elizabeth Bay (Figure 4.20), (Corbett, 1993). Furthermore the drainage channels are relatively short and only occasionally mobilised during rare flash floods. Although even small drainage channels provided some essential clastic material to trapsites in the study area, there is no evidence to suggest that a significant amount of fluvial upgrading took place. The drainage channels themselves most probably played a bigger role by trapping windblown diamonds on their northward journey (Rau, 2003). However, due to the lack of ATCs in the study area, the streams themselves probably contributed a negligible portion of the trapped diamonds.

The highest amount of energy is dispersed in the breaker zone, which is where erosional forces and reworking processes are therefore concentrated (Martinez & Harbaugh, 1993; Jacob, 2001). We can therefore assume that the elevations at which diamond deposits are encountered in the study area were the approximate elevations of the sea-level at the time of deposition. Within the study area, diamonds were more concentrated at -12 m, between -18 m and -21 m and between -24 m and -27 m depths (Figure 11.4). These depths generally coincide with nick points identified by Rau (2003) working in the Hottentots Bay Grant and Saddle Hill Prospect areas to the north of Lüdentz.

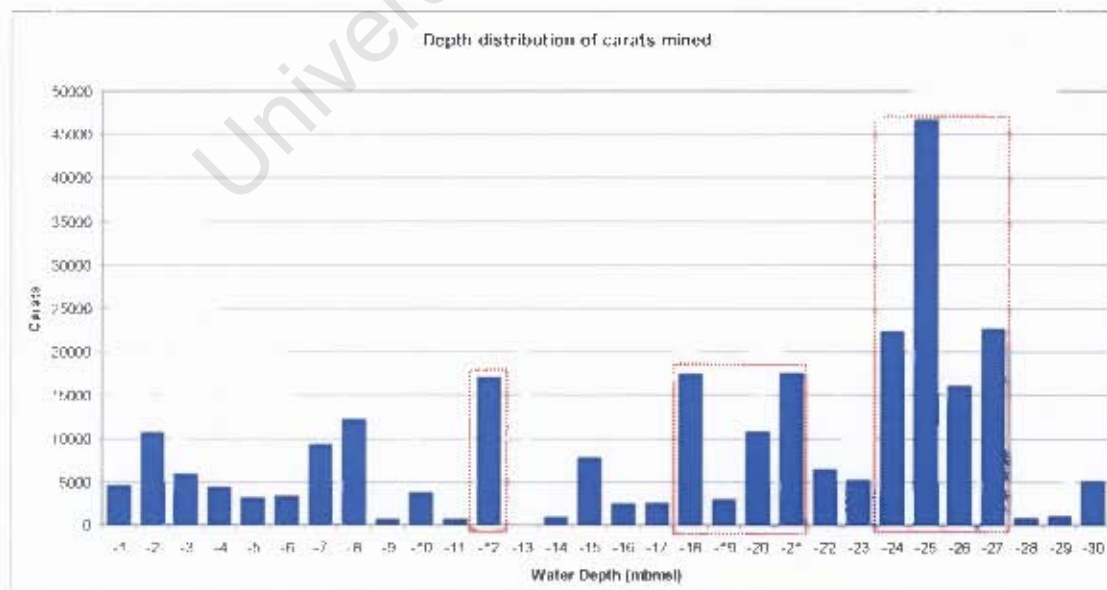


Figure 11.4: Within the study area, increased concentrations of diamonds were encountered at -12 m, between -18 m and -21 m and between -24 m and -27 m depths.

11.3 Bedrock and Boulders

Bedrock lithology and competence combined with the presence of lithic clasts plays an important role in the formation of trapsites both in the fluvial as well as the marine setting (De Wit, 1996, Jacob *et al.*, 1999; Jacob, 2001, Rau, 2003).

The dominant underlying bedrock in the southern part of the study area, between Wolf Bay in the north and Elizabeth Bay in the south, is Namaqua Metamorphic Complex gneiss. The gneiss is cut by a regional series of parallel normal faults and preferential erosion along these features has resulted in the formation of numerous inlets and embayments along the coastal strip of the study area. This preferential weathering and erosion has assisted greatly in shaping the morphology of the present day coastline by creating numerous inlets.

The amphibolite which forms the topographically proud Zweispitz headland seems to be more resistant to weathering than the NMC gneiss which it intruded. The weathering-resistant clasts would have contributed significantly to the mechanical erosion of the structural feature which marks the inferred contact between the amphibolite and the NMC gneiss when sea-level was at or about -21 m. The exploitation of this structural feature resulted in the formation of the Zweispitz trench.

At Grossebucht Area D, the Diaz Point Formation (Unit 3) consists of quartzite overlain by diamictite. Coarse-grained leucogranite, gneiss, quartzite boulders, and occasional retrograded amphibolite clasts from the diamictite are more resistant to weathering than the matrix, which is composed of fine-grained quartz, feldspar and chlorite. Once released from the matrix these clasts act as abrasive agents and contribute to the mechanical erosion of the bedrock, especially in the surf zone (Figure 11.5). Like the underlying bedrock of the NMC gneiss, the rocks of the Diaz Point Formation are cut by a regional series of parallel normal faults trending $\sim 300^{\circ}$ and an intersecting set of faults trending $\sim 210^{\circ}$ also occurs in places. At Grossebucht Area D the preferential weathering and erosion of these features has resulted in the formation of gullies that acted as effective heavy mineral trapsites.



Figure 11.5: Facing west at De Hoek, the deformed pinkish coloured leucogranite boulder clasts in the Diaz Point Formation Unit 3 are released from the diamictite through weathering and erosion and then act as abrasive agents in the surf zone environment to form gullies and other trapsites.

The combination of faulting and weathering-resistant boulders would also have contributed to the formation of the caves in De Hoek *Shallow* (Figure 7.9). In the De Hoek *Deep* feature it would have assisted in the incision of the gullies in the zone of terrestrial and marine interaction along the -24 m palaeo-shoreline (Figure 7.18).

The presence of boulders therefore enhances the quality of the trap site in several ways:

- It causes surface roughness which is required to trap and concentrate diamonds (De Wit, 1996; Jacob *et al.*, 1999; Jacob, 2001).
- When the clastics are more resistant to weathering than the surrounding bedrock on which it rests, the clasts will act as abrasive agents which greatly assist in the incision of wave-cut platforms and trap site features in the bedrock (Jacob, 2001).
- Large boulders form a protective armour over the gravel it covers and which occurs within the framework, protecting it from post depositional erosion during subsequent transgression/regression cycles i.e. it is a preservation factor.

11.4 Geomorphology

The morphology of the coastline, and how it changes with various sea level stands, plays a key role in the formation of trap sites (Corbett, 1989; Jacob, 2001; Rau, 2003). It is thought that the southerly wind and swell regime has been driving the northward transport of sediments from the mouth of the Orange River since the Eocene, although this transport system strengthened during the Neogene (Spaggiari *et al.*, 2002; Pether *et al.*, 2000; Ward & Jacob, 1999; Ward & Corbett, 1990). Headlands and subsequent embayments, islands and other topographical features emerge at various sea-levels. As the waves approach the coast from a south-southwesterly direction (Rossouw, 2002), they enter progressively shallowing water and depending on the bottom profile and the shape of the coastline in relation to the approaching waves, the wave energy will be focused in some areas and dispersed in others (Brown *et al.*, 1989). The areas where wave energy is focused will be areas where active erosion takes place. The predominantly rocky coastline in the study area is an indication that it is a high energy coast subject to erosional forces. However, in areas where features like headlands offer shelter, the wave energy is dispersed and deposition of sediments takes place i.e. Abenteurbucht, Atlas Bay & Grossebucht (Figure 4.1). The ideal geomorphological feature, in terms of forming a trap site, would offer some degree of shelter in order to retain gravel on its northward journey. Too much shelter would result in the accumulation of fine sediments and the formation of sandy beaches, such as at Abenteurbucht, Atlas Bay & Grossebucht. A degree of exposure to energy is therefore required to rework the gravels without removing them from the site. Ideally the site would be effective as a trap through a range of depths as that would increase the amount of time that the gravels would be exposed to reworking processes. Examples are the Southern Area A – rough gullied bedrock (Figure 10.23), and the Zweispitz trench, northward-rising slope and boulder field (Figure 9.22). South facing embayments often provide a favourable coastal profile in order to retain gravel to form a good trap site, such as at De Hoek Shallow, Grossebucht Basin, Zweispitz North Cliff and

the Southern Area A - rough gullied bedrock. The most significant island which occurs in the study area is Long Island North (Figure 11.3). It forms a barrier against the approaching waves and therefore creates a low-energy leeward shore. This does not seem to have influenced diamond concentration significantly as the leeward side of the island was reportedly not economically mineralised. This situation is similar to that encountered at Possession Island (Figure 1.3), which is also a north-south elongated island. At Possession Island only one small embayment on the leeward side in the southern part of the island was mineralised. This small mineralised pocket was in very shallow water (<2m) and formed due to an accumulation of wash-over gravel.

11.5 Cementation

Cementation of sediments in the northern Sperrgebiet is common in the terrestrial setting and has been widely reported and documented in production logsheets by divers operating in the shallow waters and by the large mining vessels operating in the deeper waters off the coast (Corbett, 1993; Jamieson & Talbot, 1983; Milne, 1985). During sea-level low stands it is likely that a variable mixture of seawater and groundwater accumulated in emergent local depressions. Evaporation concentrated the resultant brine. The precipitation of dolomite is dependant on the brine being Mg-enriched relative to Ca. When the solution is relatively Ca-enriched, calcite is likely to precipitate as cement. The depletion of Ca, relative to Mg, by the precipitation of CaCO_3 from the evaporating waters can then be followed by dolomite precipitation from the resultant Mg-enriched brine (Pettijohn *et al.*, 1987). It is therefore possible to encounter calcite and dolomite cementation within the same cemented horizon. All of the cemented conglomerate samples obtained from the shallow marine portions of the study area were tested with a standard 10% HCl solution. These acid tests indicated calcite cementation within all of the samples. The calcite cementation process, as described by Pettijohn *et al.* (1987), was most likely responsible for the variable cementation of trapsite-filled sediments in the study area.

About 55% of the carats of the 4 areas discussed in this study were mined from features where significant cemented horizons were present. The cemented horizons generally formed a protective capping which assisted in preserving the reworked deposits during post depositional cycles of transgression and regression. Although preservation factors assist greatly in preserving the gravel in trapsites – they are not always present. They are noticeably absent from Zweispitz, for example. There, an anomalously large volume of diamonds was accumulated within series of trapsites conveniently arranged along the axes of transport. Although the gravel package is thought to be at least 80 ka in age and was therefore sub-aerially exposed for a considerable period of time during the LGM, there were no significant signs of cementation.

11.6 Size of trapsite

The size of the trapsite plays an important role in the search for prospecting targets. Large features are easier to identify than small. The larger the area, the more material can be accommodated and reworked. With the increased volume of material being reworked there is a greater opportunity for more diamonds to be accumulated in a large trapsite. However, being large and accommodating more material, the gravel in the large features tends to be more diluted and of lower average grade, as in the Grossebucht Basin. Although they can retain large volumes of material, they are generally exposed to low to medium intensity wave energy which reworks the gravel over a longer period of time.

Referring to the gully systems encountered along the coast between Oranjemund and Chameis, Jacob (2001) stated that the quality of a bedrock controlled trapsite increased correspondingly with the depth to which it was incised into the platform, as long as it remained a closed system. An example of a high quality trapsite would be the De Hoek Shallow Caves. These caves are situated 2 m below present sea-level and are exposed to high wave energy levels. They produced the highest average grade of screened gravel from the features studied. The condition of the shells in the gravel indicated that the gravels are not older than 8.0 ka. The reworking and concentration of diamonds in the gravel most likely took place within the cave in a time period not exceeding 8.0 ka. The presence of large boulders and the cementation of the gravel undoubtedly served to preserve this small extremely high grade deposit. It is therefore possible to concentrate gravel to a high degree over a short period of time with high energy levels in a good trapsite. These isolated and rarely encountered small, high grade jackpots are what every diver is searching for.

12. CONCLUSIONS

For the purpose of this study data were collected from various sources which range from informal discussions with divers to a formal and structured sampling programme and geophysical surveys. The bulk of the historical mining records have relatively lower associated level of confidence and must be viewed in conjunction with geographically proximal records and higher confidence sampling and mining records. However, keeping the limitations in mind, using the combined dataset in conjunction with geophysical survey data made it possible to make sound observations and to display the available data of diver-assisted mining in the study area in meaningful context.

The diamond size frequency distribution (SFD) of the Shallow Marine (0 to -30 m) deposit in the study area is similar to the proximal aeolian deposit mined on land at Elizabeth Bay and the deeper Midwater (-30 to -70 m depth) deposit situated southwest of the study area. Although similar, the three deposits have distinct SFD signatures. The shallow marine deposit SFD is notably consistent over the 4 areas studied along the 30 km section of coastline. The Elizabeth Bay, Shallow Marine and Midwater diamonds were deposited at different times and sea-level varied for each event. It is very likely that each deposit is comprised of a series of complicated overlapping smaller pulses of emplacement. However, continuous reworking over a considerable period of time smoothed out most of the anomalies in each deposit.

Within the study area, diamonds were widely distributed down to -30 m, which is the practical depth limit for diver-assisted operations. Significant concentrations of diamonds were encountered at -12 m, between -18 m and -21 m and between -24 m and -27 m depths. These depths indicate that sea-level was most likely at, or about these depths for a significant period of time, allowing reworking processes to concentrate diamonds.

The geomorphology of the coastline at a particular sea still stand provides the opportunity for the accumulation, retention and reworking of northward travelling diamondiferous gravel. Although south facing embayments play a significant role, additional factors are required for the accumulation of discrete pockets of anomalously high grade diamondiferous gravel i.e. "Jackpots". Surface roughness provided by the bedrock and/or boulders was a significant additional factor attributing to the formation of the majority of trapsites in the study area.

The accumulations of gravel mined by the divers were generally thin (<3.0 m in thickness). Such surficial deposits are prone to erosional processes and likely to be broken down and re-introduced to the shallow marine conveyor during subsequent re- and transgressional cycles. Factors assisting with the preservation of the gravel include:

- **Morphology of the trapsite:** The bedrock controlled trapsite provides protection from erosional processes when emergent and shallow marine processes during submergent periods. The Zweispitz Trench and Bowl and the Grossebucht Basin are examples of such bedrock controlled trapsites in which gravel was accumulated and was retained, reworked and preserved without assistance from additional preservation factors.
- **The presence of boulders** provides surface roughness which not only enhances the quality of the trapsite but it also forms an armoured lag, protecting the gravel body from erosional and shallow marine reworking processes.
- **Cementation** provides a protective capping which preserves the underlying sediments. This is an important preservation factor as about 55% of the carats of the 4 areas discussed in this study were mined from features where cemented horizons were present.

The gravel mined from the caves in the shallows at De Hoek, where fresh blue/black coloured *Choromytilus meridionalis* shells were present, are inferred to have been deposited between 8.0 ka and 4.5 ka ago i.e. after the Last Glacial Maximum (LGM). Deposition of gravels for the rest of the areas studied are inferred to have taken place at least 80 ka ago, i.e. before the LGM, as the gravel contained weathered, chalky, friable shells. In the instance of deeper gullies in De Hoek, some brown discoloured *Choromytilus meridionalis* shells were also present. As these deposits are generally thin (<3.0 m in thickness), it is unlikely that they could have survived several millions of years and the numerous re- and transgressional cycles which occurred in that period. It does seem more feasible that these gravels were deposited during the Late Quaternary. This aligns with work by previous authors as summarised by De Decker (1987): the prominent wave-cut cliff and the palaeostrandline at about -20 m depth encountered along the West Coast of southern Africa (Murray *et al.*, 1970; O'Shea, 1971), is thought to have formed since the last interglacial.

Extremely high grade gravel (even by diver-assisted mining standards) was mined from the caves in the shallows at De Hoek. This shows that diamonds can be concentrated to a very high degree over a relatively short period (8.0 ka) of time. This would only be possible as long as there is a regular supply of diamondiferous gravel, a high quality trapsite and a high energy environment. These small high grade features or jackpots are not regularly distributed and are virtually impossible to identify using geophysical data.

Due to limitations of survey data collected in the shallow marine environment and as gullies and small basins are often covered by a thin layer of fine sand, it is usually not possible to observe the presence of boulders within a target feature. The presence and extent of preservation factors can

only be determined after prospecting and or mining of a target has commenced and a face has been opened up by the divers.

The normal tools available to the geologist to assist in selection of targets for the divers are sidescan sonar and high resolution multibeam bathymetry data. Using these tools it is proposed that target selection for diver-assisted mining along the southern Namibian coast be done in the following manner:

1. Focus on -18 to -21 m depth and -24 m and -27 m depths.
2. Focus on areas where the geomorphology of the coastline provides an opportunity to trap and retain gravel being moved northward by wave action and the longshore drift.
3. Find areas which provide space to accommodate a reasonable volume of gravel.
4. Preferentially select areas displaying rough gullied bedrock and which are proximal to fluvial drainages i.e. a supply of coarse clastic material.

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13. REFERENCES

- Aizawa, M., Bluck, B.J., Cartwright, J., Milner, S., Swart, R. and Ward, J.D. (2000). Constraints on the geomorphological evolution of Namibia from the offshore stratigraphic record. *In: Miller, R.M. (Editor), Communications of the Geological Survey of Namibia, 12*, 337-346.
- Anderson, R.S., Densmore, A.L. and Ellis, M.A. (1999). The generation and degradation of marine terraces. *Basin Research, 11* (1), 7-19.
- Apollus, L. (1995). The distribution of diamonds on a late Cainozoic gravel beach, Southwestern Namibia. *Unpublished M.Sc. Thesis, University of Glasgow, Glasgow, Scotland*. 170pp.
- Brown, J., Colling, A., Park, D., Phillips, J., Rothery, D. and Wright, J. (1989). Waves, tides and shallow-water processes. *In: Bearman, G. (Editor), The Open University, Oceanography Course Team*, ISBN-0-08-036371-7. 187pp.
- Bluck, B.J., Ward, J.D. and De Witt, M.C.J. (2005). Diamond mega-placers: southern Africa and the Kaapvaal craton in global context. *In: McDonald, I.; Boyce, A.J.; Butler, I.B.; Herrington, I.J. and Polya, D.A. (Editors), Mineral deposits and earth evolution*. Geological Society, London, Special Publications, **248**, 213-245.
- Bluck, B.J., Ward, J.D. and Spaggiari, R. (2001). Gravel beaches of southern Namibia. *In: Packham, J.R., Randall, R.E., Barnes, R.S.K. and Neal, A. (Editors), Ecology and geomorphology of coastal shingle*. Westbury Academic and Scientific Publishing. 56-75.
- Bluck, B.J., Ward, J.D., Cartwright, J. and Swart, R. (2007). The Orange River, southern Africa: an extreme example of a wave-dominated sediment dispersal system in the South Atlantic Ocean. *Journal of the Geological Society, London, 164*, 341-351.
- Bremner, J.M.; Rogers, J. and Willis, J.P. (1990). Sedimentological aspects of the 1988 Orange River floods. *Transactions of the Royal Society of South Africa, 47*, 247-294.
- Chappel, J., Omura, A., Esat, T., McCulloch, M., Pandolfi, J., Ota, J. and Pillans, B. (1996). Reconciliation of late Quaternary sea levels derived from coral terraces at Huon Peninsula with deep sea oxygen isotope records. *Earth and Planetary Science Letters, 141*, 227-236.

Collina-Girard, J. (2002). Underwater mapping of late Quaternary submerged shorelines in the Western Mediterranean Sea and the Caribbean Sea. *Quaternary International*, **92**, 63-72.

Compton, J.S. (2001). Holocene sea-level fluctuations inferred from the evolution of depositional environments of the southern Langebaan Lagoon salt marsh, South Africa. *The Holocene*, **11**, 4, 395-405.

Compton, J.S. (2006). The mid-Holocene sea-level highstand at Bogenfels Pan on the southwest coast of Namibia. *Quaternary Research*, **66**, 303-310.

Compton, J.S. (2007). Holocene evolution of the Anichab Pan on the southwest coast of Namibia. *Sedimentology*, **54**, 55-70.

Compton, J.S., Harris, C. and Thompson, S. (2001). Pleistocene dolomite from the Namibian shelf: High $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and $\delta^{18}\text{O}$ values indicate an evaporative mixed water origin. *Journal of Sedimentary Research*, **71**, 5, 800-808.

Compton, J.S., Mulabisani, J. and McMillan, I.K. (2002). Origin and age of phosphorite from the Last Glacial Maximum to Holocene transgressive succession off the Orange River, South Africa. *Marine Geology*, **186**, 43-261.

Corbett, A. (2002). Diamond beaches, a history of Oranjemund. 2nd Edition, Namdeb Diamond Corporation (PTY) Ltd. Oranjemund, Namibia. ISBN 0-620-28288-6. 144pp.

Corbett, I.B. (1989). The sedimentology of diamondiferous deflation deposits within the Sperrgebiet, Namibia. *Unpublished PhD thesis, Geology Department, University of Cape Town*, 430pp.

Corbett, I.B. (1993). The modern and ancient pattern of sandflow through the southern Namib deflation basin. *Special Publication of the International Association Sedimentologists*. **16**, 45-60.

Corbett, I.B. (1996). A review of diamondiferous marine deposits of western southern Africa. *Africa Geoscience Review*. **3**, 2, 157-174.

Corbett, I.B.; Ward, J.D. and Hockney, A.P. (1993). Northern Areas Exploration Programme 1993: Aeolian deposits between Elizabeth Bay and Schmidfeld North and implications for

Northern on/offshore placers. *Namdeb Mineral Resource Department internal report, Namdeb Diamond Corporation (Pty) Ltd., Oranjemund, Namibia, 19pp.*

De Beer, J.H. and Meyer, R. (1983). Geoelectrical and Gravitational Characteristics of the Namaqua-Natal Mobile Belt and its Boundaries. *In Botha, B.J.V. (Editor), Special Publication of the Geological Society of South Africa, Namaqualand Metamorphic Complex, 10, 91-100.*

De Decker, R.H. (1987). The geological setting of diamondiferous deposits on the inner shelf between the Orange River and Wreck Point, Namaqualand. *Bulletin of the Geological Survey of South Africa, 86, 99pp.*

De Decker, R.H. (1988). The wave regime on the inner shelf south of the Orange River and its implications for sediment transport. *Suid Afrikaanse Tydskrif vir Geologie, 91 (3), 358-373.*

De Wit, M.C.J. (1996). The distribution and stratigraphy of inland alluvial diamond deposits in South Africa. *Africa Geoscience Review, 3, 2, 175-189.*

De Wit, M.C.J. (1999). Post-Gondwana drainage and the development of diamond placers in western South Africa. *Economic Geology, 94, 721-740.*

Dingle, R.V. and Scrutton, R.A. (1974). Continental breakup and the development of Post-Palaeozoic sedimentary basins around southern Africa. *Geological Society of America Bulletin, 85, 1467-1474.*

Dingle, R.V. and Hendey, Q.B. (1984) Late Mesozoic and Tertiary sediment supply to the Eastern Cape Basin (SE Atlantic) and palaeo-drainage systems in southwestern Africa. *Marine Geology, 56, 13-26.*

Fairbanks, R. G. (1990). A 17 000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. *Nature, 342., 637-642.*

Frimmel, H.E. (2000). The Pan-African Gariep Belt in southwestern Namibia and western South Africa. *In: Miller, R.M. (Ed), Communications of the Geological Survey of Namibia, Special Issue: Henno Martin commemorative volume, 12, 197-209.*

Greenman, L. (1966). The geology of area 2615 Luderitz, South West Africa. *Unpublished MSc thesis, University of Cape Town, South Africa, 105pp.*

Gurney, J.J., Levinson, A.A. and Smith, H.S. (1991). Marine mining of diamonds off the west coast of Southern Africa. *Gems & Gemology*, **27**, 4, 206-219.

Hallam, C.D. (1964). The geology of the coastal diamond deposits of southern Africa (1959). *The geology from some ore deposits of Southern Africa*. Geological Society of South Africa, **2**, 671-728.

Haq, B.U., Hardenbol, J. and Vail, P.R. (1987). Chronology of fluctuating sea-levels since the Triassic. *Science*, **235**, 1156-1166.

Hay, W.W. and Brock, J.C. (1992). Temporal variations in intensity of upwelling off southwest Africa. In: Prell, C.P. and Emeis, K.C. (Editors), *Upwelling systems: Evolution since the early Miocene*. Geological Society, London. *Special Publications*, **63**, 63-497.

Jacob, .J. (2001). Late Proterozoic bedrock geology and its influence on Neogene marine diamondiferous trapsites, MA1 – Sperrgebiet, Namibia. *Unpublished MSc Thesis, University of Cape Town, South Africa*, 134pp.

Jacob, R.J., Bluck, B.J. and Ward, J.D. (1999). Tertiary-age diamondiferous fluvial deposits of the lower Orange River valley, Southwestern Africa. *Economic Geology*, **94**, 749-758.

Jamieson, B.H.D. and Talbot, C.S.E. (1983). Luderitz area geological investigations. Report: Map sheet 2615 CAd Kolmanskop. *CDM Geological Department internal report. Namdeb Diamond Corporation (Pty) Ltd., Oranjemund, Namibia*, 63pp.

Jasper, M.J.U., Stanistreet, I.G. and Charlesworth, I.G. (2000). Neoproterozoic inversion tectonics, half-graben depositories and glacial controversies, Gariep fold-thrust belt, southern Namibia. *Communications of the Geological Survey of Namibia*, **12**, 187-196.

Joynt, R.H., Greenshields, R. and Hodgen, R. (1972). Advances in sea and beach diamond mining techniques. *International Oceanic Commission – Engineering Committee on Oceanic Resources, from De Beers Marine Archive, Cape Town*, 25pp.

Joynt, R.H. (1979). Evaluation of the gullied bedrock area between Mittag and Chameis Bay. *CDM Geological Department internal report. Namdeb Diamond Corporation (Pty) Ltd., Oranjemund, Namibia*, 23pp.

Kaiser, E. (1926). Die Diamantwüste Sudwestafrikas, Volumes 1 & 2. *Dietrich Reimer (Ernst Vohsen), Berlin*, 321pp & 256pp.

Kuhns, R. (1995). Sedimentological and Geomorphological Environment of the South African Continental Shelf and its Control on Distribution of Alluvial, Fluvial and Marine Diamonds. *Society for Mining, Metallurgy and Exploration, Proceedings of Annual Meeting, Denver, Colorado*. 6pp.

Kröner, A. and Jackson, M.P.A. (1974). Geological reconnaissance of the coast between Luderitz and Marble Point, South West Africa, *In: Kröner, A. (Editor), Contributions to the Precambrian Geology of Southern Africa: A volume in honour of John de Villiers, South Africa, Chamber of Mines, Precambrian Research Unit*, **15**, 79-103.

Levinson, O. (1983). Diamonds in the desert – the story of August Stauch and his times. *Tafelberg Publishers Ltd, Cape Town, ISBN 0624019217*, 172pp.

Macdonald, W. (1997). Some observations of diamond distribution and gravel characteristics in the 0 to -30 m zone: Elizabeth Bay Licence Area. *Unpublished presentation, Bi-annual De Beers West Coast Conference, Cape Town*.

Martinez, P.A. and Harbaugh, J.W. (1993). Simulating nearshore environments. *Pergamon Press Limited, Headyton Hill Hall, Oxford*. 265pp.

McCarthy, T. and Rubidge, B. (2005). The story of earth and life – a southern African perspective on a 4.6-billion-year journey. *Struik Publishers, Cape Town, ISBN 1770071482*, 333pp.

McDaid, J.A. (1975). Preliminary report on the geology of the northern part of Diamond Area No. 1, South West Africa. *Chamber of Mines, Precambrian Research Unit, University of Cape Town*, **13**, 89-96.

Milne, G.C. (1985). Lüderitz area geological investigations. Report: Map sheet 2615 CCa Marburg and CCb Wetzlar. *CDM Geological Department internal report. Namdeb Diamond Corporation (Pty) Ltd., Oranjemund, Namibia*. 67pp.

Moore, J.M. and Moore, A.E. (2003). The roles of primary kimberlitic and secondary Dwyka glacial sources in the development of alluvial and marine diamond deposits in Southern Africa. *Journal of African Earth Sciences*, **38**, 2, 115-134.

Murray, L.G., Joynt, R.H., O'Shea, D. O'C., Foster, R.W. and Kleinjan, L. (1970). The Geological environment of some diamond deposits off the coast of South West Africa. *In: Delany, F.M. (Editor), ICSU/SCOR Working Party 31 Symposium, Cambridge: The geology of the East Atlantic Continental Margin. Institute of Geological Sciences, 70/3, 110-141.*

Oppenheimer, E. and Williams, A. (1914). Diamond deposits of German South West Africa. *Unpublished report to the chairman and directors of De Beers Consolidated Mines, Limited, Kimberley, D.F.A. Ltd. Printers, Kimberley, 58pp.*

O'Shea, D.O'C. (1971). An outline of the inshore submarine geology of southern South West Africa and Namaqualand. *Unpublished MSc Thesis, University of Cape Town, Rondebosch, South Africa, 101pp.*

O'Shea, D.O'C. (1985). A review of marine prospecting for diamonds off the West coast of Southern Africa. *Unpublished report, De Beers Marine (Pty) Ltd., Cape Town, 13pp.*

Pallet, J. (1995). The Sperrgebiet: Namibia's least known Wilderness. *Desert Research Foundation of Namibia and NAMDEB, Windhoek, Namibia, ISBN 9991670939, 84pp.*

Partridge, T.C. and Maud, R.R. (1987). Geomorphic evolution of southern Africa since the Mesozoic. *South African Journal of Geology, 90, 2, 197-208.*

Pether, J., Roberts, D.L. and Ward, J.D. (2000). Deposits of the west coast. *In: Partridge, T.C. and Maud, R.R. (Editors), The Cenozoic of Southern Africa. Oxford Monograph on Geology and Geophysics, 40, 33-54.*

Pether, J. (1994). The sedimentology, palaeontology and stratigraphy of coastal plain deposits at Hondeklip Bay, Namaqualand, South Africa. *Unpublished MSc Thesis, University of Cape Town, Rondebosch, South Africa, 313pp.*

Pether, J. (2008). Palaeontological Mitigation and Geoheritage: De Beers Namaqualand Mines. *Unpublished Initial Draft Report, De Beers Namaqualand Mines, 28pp.*

Pettijohn, F.J., Potter, P.E. and Siever, R. (1987). Sand and Sandstone, 2nd Edition. *Springer, ISBN 0387963502, 9780387963501. 553pp.*

Pickford, M. and Senut, B. (2002). The fossil record of Namibia. *Geological Survey of Namibia*, Windhoek, 39pp.

Rau, G. (2003). The intergrated use of detailed geophysical, geological and oceanographic techniques to delineate and prioritize marine diamond placer deposits on the inner shelf, west coast, Central Namibia: EPL 1950 (Hottentot Bay) – a case study. *Unpublished MSc Thesis, Rhodes University, Grahamstown, South Africa*, 139pp.

Rispel, C. (2004). The geology of the area east and south-east of Grossebucht, Luderitz, Namibia. *Unpublished BSc Honours Report, Rhodes University, Grahamstown, South Africa*, 52pp.

Rogers, J. (1977). Sedimentation on the continental margin off the Orange River and the Namib Desert. *Unpublished PhD thesis, Geology Department, University of Cape Town*, 212pp.

Rogers, J., Pether, J., Molyneux, R., Genis, G., Kilham, J.L.C., Cooper, G and Corbett, I.B. (1990). Cenozoic geology and mineral deposits along the west coast of South Africa and the Sperrgebiet. *Guidebook, Geocongress '90, Geological Society of South Africa*, PR1,111pp.

Rossouw, M. (2002). Metocean data summary: Offshore of Oranjemund. *CSIR Report ENV-S-C-2002-028 prepared for De Beers Marine (Pty) Ltd, Cape Town*, 40pp.

Schneider, G.I.C. (2004). The roadside geology of Namibia. *Gebruder Borntraeger, Berlin-Stuttgart, ISBN 3443150802*, 294pp.

Schneider, G.I.C. and Miller, R. McG. (1992). Diamonds In: *The mineral resources of Namibia, Ministry of Mines and Energy, Geological Survey, ISBN 0-86976-258-3*, 5.1-5.32.

Shackleton, N.J. (1987). Oxygen isotopes, ice volume and sea level. *Quaternary Science Review* 6. 183-190.

Shannon, L.V. and O'Toole, M.J., (1999). Integrated overview of the oceanography and environmental variability of the Benguela Current region. *United Nations Development Programme, BCLME Thematic Report, 2*, Windhoek, Namibia, 57pp.

Siegfried, P.R. (1993). Report: Results of preliminary investigations into the geology of the Diaz Point Formation, Lüderitzbucht, Namibia. *Communications of the Geological Survey of Namibia*, **8**, 119-126.

South African Committee for Stratigraphy. (1980). Stratigraphy of South Africa. *Compiled by Kent, L.E., Part 1. Lithostratigraphy of the Republic of South Africa, South West Africa/Namibia, and the Republics of Bophuthatswana, Transkei and Venda. Handbook of Geological Survey of South Africa*, **8**, 690pp.

SAN HO-21. (1994). South African Sailing Directions, **1**, *General information - Hydrographic office of the South African Navy, Cape Town, South Africa, ISBN 095832395X*. 3.3-3.48.

Spaggiari, R.I., Ward, J.D. and Bluck, B.J. (2002). Quaternary diamond bearing beaches of southern Namibia. IAS 16th *International Sedimentological Congress, Rand Afrikaans University, Johannesburg, July 2002, Abstract Volume*, 341pp.

Stocken, C.G. (1978). A review of the Later Mesozoic and Cenozoic deposits of the Sperrgebiet. *CDM Geological Department internal report. Namdeb Diamond Corporation (Pty) Ltd., Oranjemund, Namibia*, 33pp.

Sutherland, D.G. (1982). The transport and sorting of diamonds by fluvial and marine processes. *Economic Geology*, **77**, 7, 1613-1620.

Tankard, A.J., Jackson, M.P.A., Eriksson, K.A., Hobday, D.K., Hunter, D.R. and Minter, W.E.L., (1982). Crustal Evolution of Southern Africa – 3.8 Billion Years of Earth History. *ISBN 0387906088, New York, Heidelberg, Berlin. Springer-Verlag*, 523pp.

Tucker, E.T. (1996). *Sedimentary rocks in the field*, 2nd Edition. *John Wiley & Sons, ISBN 0-471-96215-5*. 15-16.

United States Naval Research Laboratory, Stennis Space Center. (2002). *Satellite Image - Sea Surface Temperature (°C) 08-01-2002*.

Van der Wateren, F.M. and Dunai, T.J. (2001). Late Neogene passive margin denudation history – cosmogenic isotope measurements from the central Namib desert. *Global and Planetary Change*, **30**, 271-307.

Van Staden, A., Naidoo, T., Zimmerman, U. and Germs, G.J.B. (2006). Provenance analysis of selected clastic rocks in Neoproterozoic to lower Paleozoic successions of southern Africa from the Gariiep Belt and the Kango Inlier. *South African Journal of Geology*, **109**, 215-232.

Walker, C.H. and Gurney, J.J. (1985). The recovery of diamonds from the surf zone of the south Atlantic near the Olifants River, R.S.A. *Proclamation of the Joint International Diving Symposium, La Jolla*, 315-333.

Ward, J.D. and Bluck, B.J. (1997). The Orange River: 100 million years of fluvial evolution in southern Africa. *Sixth International Conference of Fluvial Sedimentology, University of Cape Town, South Africa, September 1997*. Abstract volume, 222pp.

Ward, J. D. and Corbett, I.B. (1990). Towards an age for the Namib. In: Seely, M.K. (Editor), *Namib Ecology: 25 Years of Namib research. Transvaal Museum Monograph, 7, Transvaal Museum, Pretoria*, 17-26.

Ward, J. D. and Jacob, R.J. (1999). The large-scale sediment transport system of southwestern Africa: Examples from Cainozoic deposits in the lower Orange valley, the Sperrgebiet and Namaqualand. *XV International Union for Quaternary Research Conference Field Guide*. 37pp.

Wigley, R.A. and Compton, J.S. (2006). Late Cenozoic evolution of the outer continental shelf at the head of the Cape Canyon, South Africa. *Marine Geology*, **226**, 1-23.

Williams, R. (1996). King of sea diamonds – the saga of Sam Collins. *W.J. Flesch & Partners (PTY) Ltd, P.O. Box 3473, Cape Town. ISBN 094998969X*, 176pp.

Wright, J. A. (1964). Gully pattern and development in wave-cut bedrock shelves north of the Orange River mouth, South West Africa. *Transactions of the Geological Society of South Africa*, **117**, 163-171.

Yokoyama, Y., Lambeck, K., De Dekker, P., Johnston, P. and Fifield, L.K. (2000). Timing of the Last Glacial Maximum from observed sea-level minima. *Nature*, **406**, 713-716.