Seismic stratigraphy of the northern KwaZulu-Natal upper continental margin

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ABSTRACT

This study presents the interpretation of Edo-Western and Sparker seismic geophysical data acquired on the northern KwaZulu-Natal upper continental margin by various organisations since 1981.

Five seismic sequences are recognised and these are traceable across the entire length of the study area. The oldest is interpreted as a late Cretaceous marine sequence (Sequence A), probably the offshore equivalent of the St. Lucia Formation exposed onshore. This sequence is overlain by a progradational, probable late Tertiary shelf sequence (Sequence B) onlapping in places against the underlying marine sequence. The outer portion of this sequence on the upper continental slope is characterised by complicated reflection termination patterns indicating the possible presence of discreet sequences within this shelf and slope unit. These shelf and slope sediments are overlain by a thin (less than 20m) reworked and eroded Pleistocene shelf unit (Sequence C), itself overlain by linear Pleistocene aeolianites (Sequence D) in places. The youngest sequence observed is the Holocene unconsolidated sediment wedge (Sequence E) on the inner shelf, attaining thicknesses of greater than 20m in places. The various sequences were mapped out and sediment isopach maps were produced (wherever possible) as well as an overall geological subcrop map of the study area.

150 kilometres of shallow penetration Edo Western seismic records acquired off the Sodwana Bay continental shelf were interpreted. Two sediment types are recognised, namely consolidated beach rock/aeolianite and unconsolidated Quaternary shelf sand/bioclastic reef derived sediment. In places, accumulations of bioclastic sediment in subaqueous dune troughs which have been subsequently buried by migrating bedforms manifest themselves on seismic records as dark semi-continuous reflectors beneath the migrating bedform. Close inshore, seismic records show prominent reflectors interpreted as consolidated sediment beneath varying thicknesses of unconsolidated sediment. Close to the shelf break (occurring at approximately –60m), seismic interpretation indicates that thin beach rock developments perch directly upon unconsolidated shelf sand, with the beach rock

having been eroded through in places to expose unconsolidated sediment beneath. A sediment thickness map for this area was compiled from the seismic data. The limited penetration of the Pinger system necessitated "greater-than" values being used in many areas. Greatest sediment thicknesses occur in subaqueous dune fields where unconsolidated sediment thickness is at least 11m. In inshore areas absent of subaqueous dune fields, sediment thicknesses are typically low, varying between 1 and 3m. A prominent submerged dune ridge close inshore limits substantial unconsolidated sediment build-up to landward of this feature. On the seaward side substantial build-up is limited by the action of the Agulhas Current which is actively transporting sediment into the head of submarine canyons which incise the continental shelf at Sodwana Bay. This study shows that on the northern KwaZulu-Natal continental shelf where there is a dearth of unconsolidated Quaternary sediment, the Edo Western seismic system is a useful tool for discerning thin veneers of unconsolidated sediment less than 4m thick. When considering the overall low volumes of unconsolidated sediment present on the shelf, this hitherto unconsidered volume of sediment constitutes an important part of the shelf sediment budget.

Submarine landslide features observed on sparker seismic records are described and discussed. Submarine landslides are present which affect a) Sequences A and B, b) Sequence B only and c) Sequence A only, ages of these sediment failures can thus be inferred as being either post- Late Cretaceous or post- Late Tertiary. Offshore Kosi Bay, submarine landslide features affecting Sequence A are buried by unaffected Sequence B sediments, indicating a post- Late Cretaceous to pre- Late Tertiary age of occurrence. Style of failure tends towards mass flow in those submarine landslides in which Sequence B only sediments are affected, while those in which Sequence A is affected exhibit some slide features indicating a greater degree of internal coherency of these sediments compared to Sequence B. Slope stability analysis of a submarine landslide feature offshore St. Lucia Estuary Mouth indicates the failed sediment mass would have been stable under static conditions and that external dynamic forces such as storm waves or seismic activity would have been necessary to induce failure. It is demonstrated that the Zululand earthquake of 1932 would have exceeded the intensity necessary to induce

sediment failure and this event should therefore be considered as a possible cause.

Seismic evidence of fluvial incision/subaerial exposure at the boundaries between Sequences A and B and C and E are further evidence of lowered sea-levels probably during the Oligocene and Late Pleistocene. The position of the incision into Sequence C relative the present course of the Mkuze River indicates the possibility that this incision could represent the palaeo-outlet of this river.

Seismic expression of 3 submarine canyons in the study area indicate that they are currently undergoing active headward erosion, independent of any direct modern fluvial influence. In the case of Ntabende Canyon, a nearby continental shelf incision postulated to be the palaeo-Mkuze outlet indicates that provision of terrigenous material to this portion of the continental shelf could well have accelerated mass wasting processes within the canyon itself. This submarine canyon could therefore have progressed more rapidly to a relatively mature phase of development. Subsurface structure indicates the lack of any post- Late Tertiary fault features beneath the canyons, thus excluding faults active in post- Late Tertiary times as a developmental factor.

It is shown that the overall, external morphology of the KwaZulu-Natal upper continental margin is strongly influenced by seismic stratigraphic relationships, with the main influencing factors being outcrop position of the various sequences and depositional angle of sediments of which a sequence is comprised. External morphology has also been greatly modified in places by mass-wasting processes. It is demonstrated also that relating the observed seismic stratigraphy to onshore geological cross sections is problematic due to the distances involved and lack of confident offshore dates for the seismic sequences observed.

Seismic relationships observed contribute to an understanding of relative sea-level movements since the Late Cretaceous and the overall geological evolution of the northern KwaZulu-Natal upper continental margin, details of which are discussed.

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CHAPTER 1

INTRODUCTION

1.1 Project outline

The geology of the northern KwaZulu-Natal upper continental margin is not well understood. Several localised studies have contributed towards a better understanding, but a single study dealing with the broad geological structure has not been undertaken even though a substantial amount of geophysical data exists. These data however have not been fully interpreted or presented in a form which would clarify the broad geological structure.

This study rectifies this situation by presenting the results of the interpretation of Edo-Western and sparker seismic geophysical data acquired by various organisations since 1981. Findings are presented within a seismic stratigraphy framework applicable to the entire northern KwaZulu-Natal upper continental margin and the onshore geology of the Maputaland coastal plain.

Geophysical data used in this study were acquired by the Council for Scientific and Industrial Research (CSIR) and Geological Survey. Sparker seismic data were acquired by the CSIR in 1981 and 1983 while the Geological Survey (now called the Council for Geoscience) acquired shallow penetration Edo-Western seismic data in the late 1980s and early 1990s. Reference is also made to Geological Survey side-scan-sonar data acquired during the same period, detailed studies of which have been completed by other workers.

In this chapter, the locality of the study area is discussed in terms of continental margin physiography, climate, oceanography and onshore geology. In Chapter 2, findings of previous geophysical studies on the northern KwaZulu-Natal continental margin are reviewed. Chapter 3 presents the results of the interpretation of sparker seismic data in the study area and develops a seismic stratigraphy for the northern KwaZulu-Natal upper continental margin. Chapter 4 presents the results of the interpretation of Edo-

Western seismic data acquired on the Sodwana Bay continental shelf area. Chapter 5 discusses morphology and possible mechanisms of submarine landslides recognised on sparker seismic records. Chapter 6 discusses sparker seismic data acquired in submarine canyons in the study area and possible indications as to the development of these features. Chapter 7 discusses evidence on sparker seismic records of fluvial incision into the continental shelf during periods of sea-level regression. This evidence is discussed in relation to sea-level curve data. Chapter 8 summarises the findings of this study and attempts to relate the seismic stratigraphy of the continental margin of the study area to the stratigraphy of the Maputaland Coastal Plain as postulated by other workers.

1.2 Locality

The study area is the northern KwaZulu-Natal upper continental margin, between Mtunzini in the south, and Kosi Bay in the north (Fig. 1.1). Continental margins constitute continental shelf and slope (Shepard, 1963). Although the KwaZulu-Natal continental slope descends to depths greater than 2000m, seismic data to a depth of only 400m below sea-level were considered. The length of the continental margin studied is 240km while the average width is approximately 6km. An area of approximately 1440km^2 was therefore studied.

1.3 Continental Margin Physiography

Bathymetry of the northern KwaZulu-Natal continental margin is shown in Fig. 1.2. The KwaZulu-Natal continental shelf is very narrow compared to world-wide averages (Ramsay, 1994). The shelf width averages approximately 5km with the shelf break situated at a depth varying between 60m and 100m (Goodlad, 1986). World-wide averages for shelf width and shelf break depth are 75km and 130m respectively (Shepard,1963).

The continental shelf is widest in the study area south of Richards Bay where the coastline orientation changes from NNE trending to NE trending. South of the study area, lateral outbuilding of the Tugela cone (Goodlad, 1986) has led to the development of a 45km wide continental shelf in this area. North of Richards Bay the

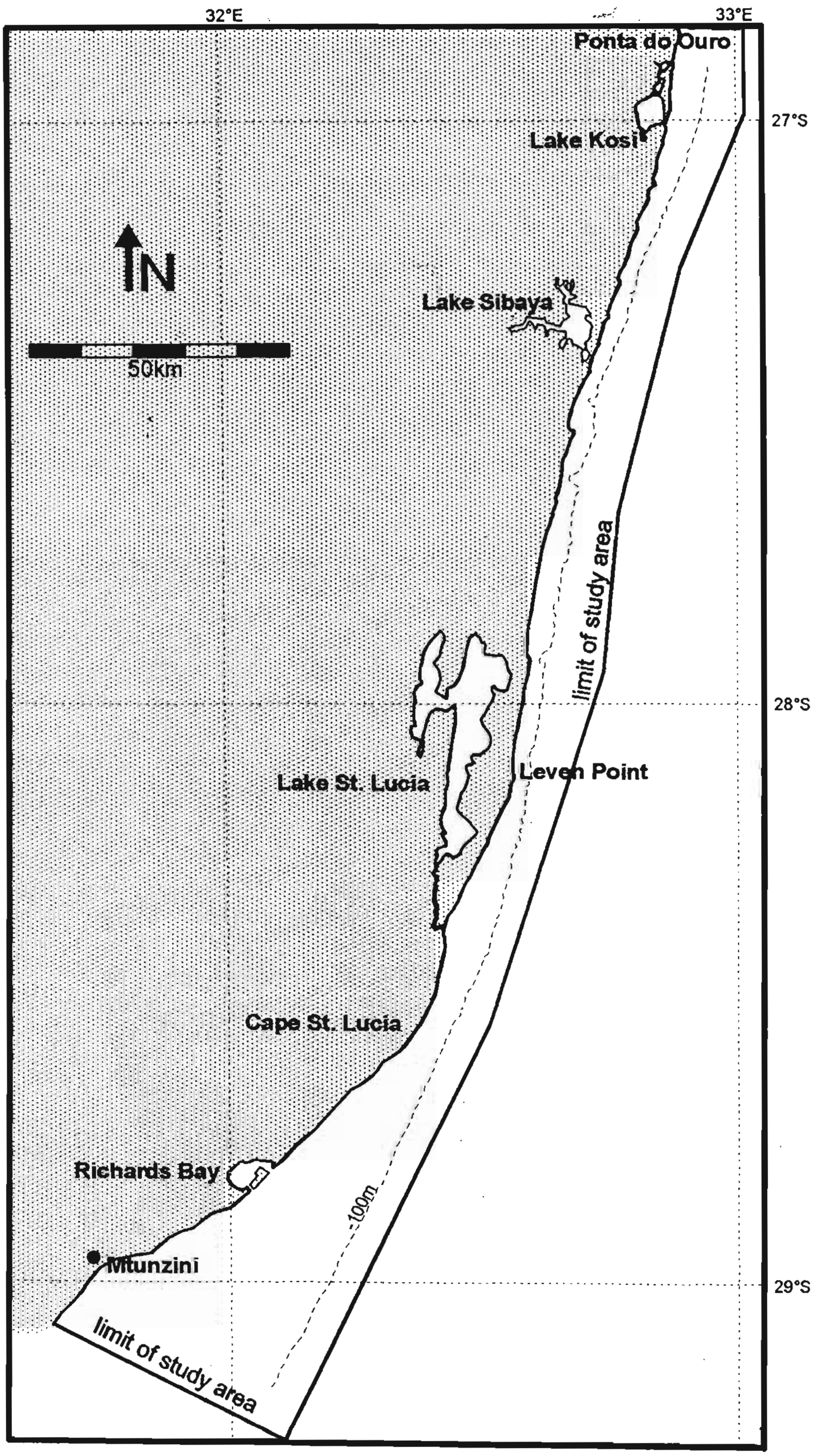


Fig. 1.1: Locality of study area

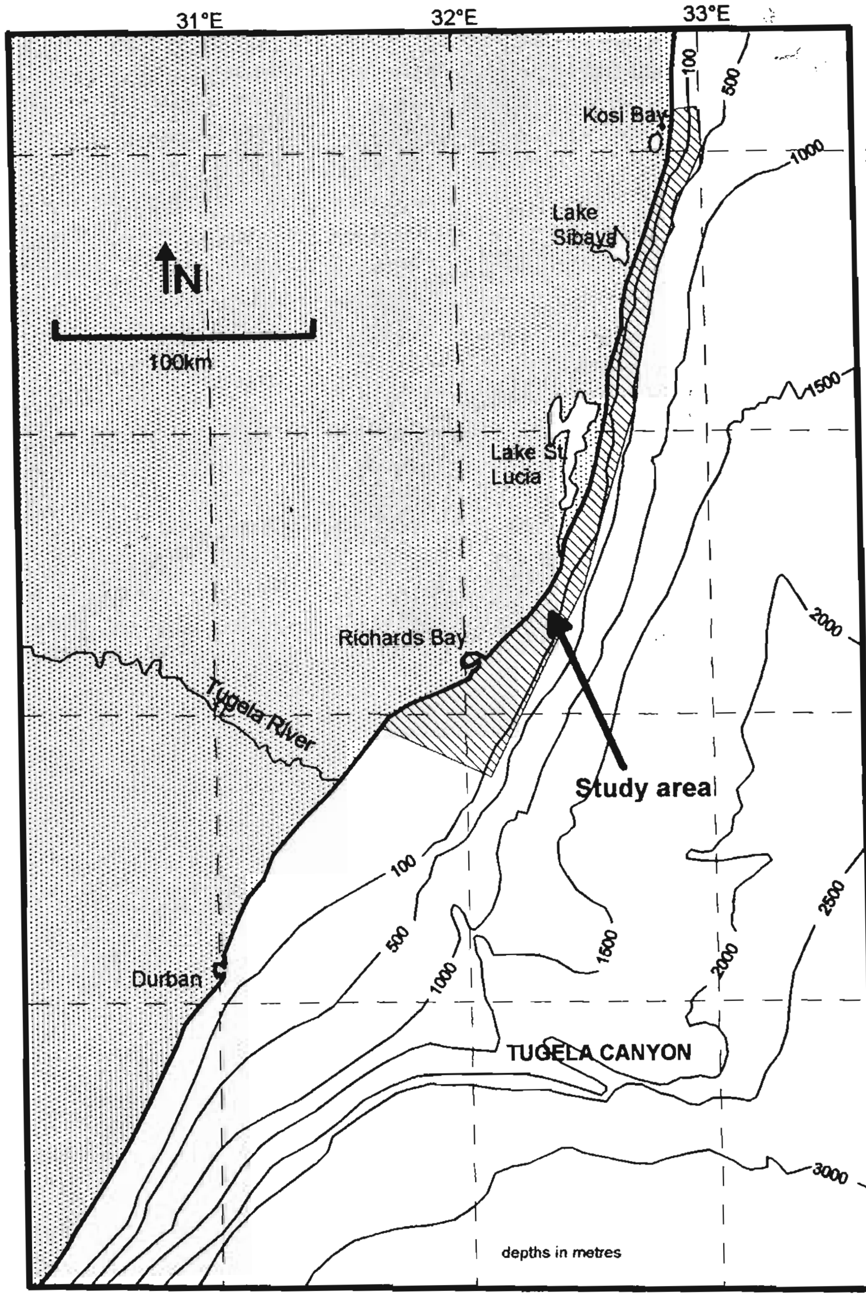


Fig. 1.2: Bathymetry of the Kwa-Zulu-Natal continental margin (simplified after Martin and Flemming, 1988)

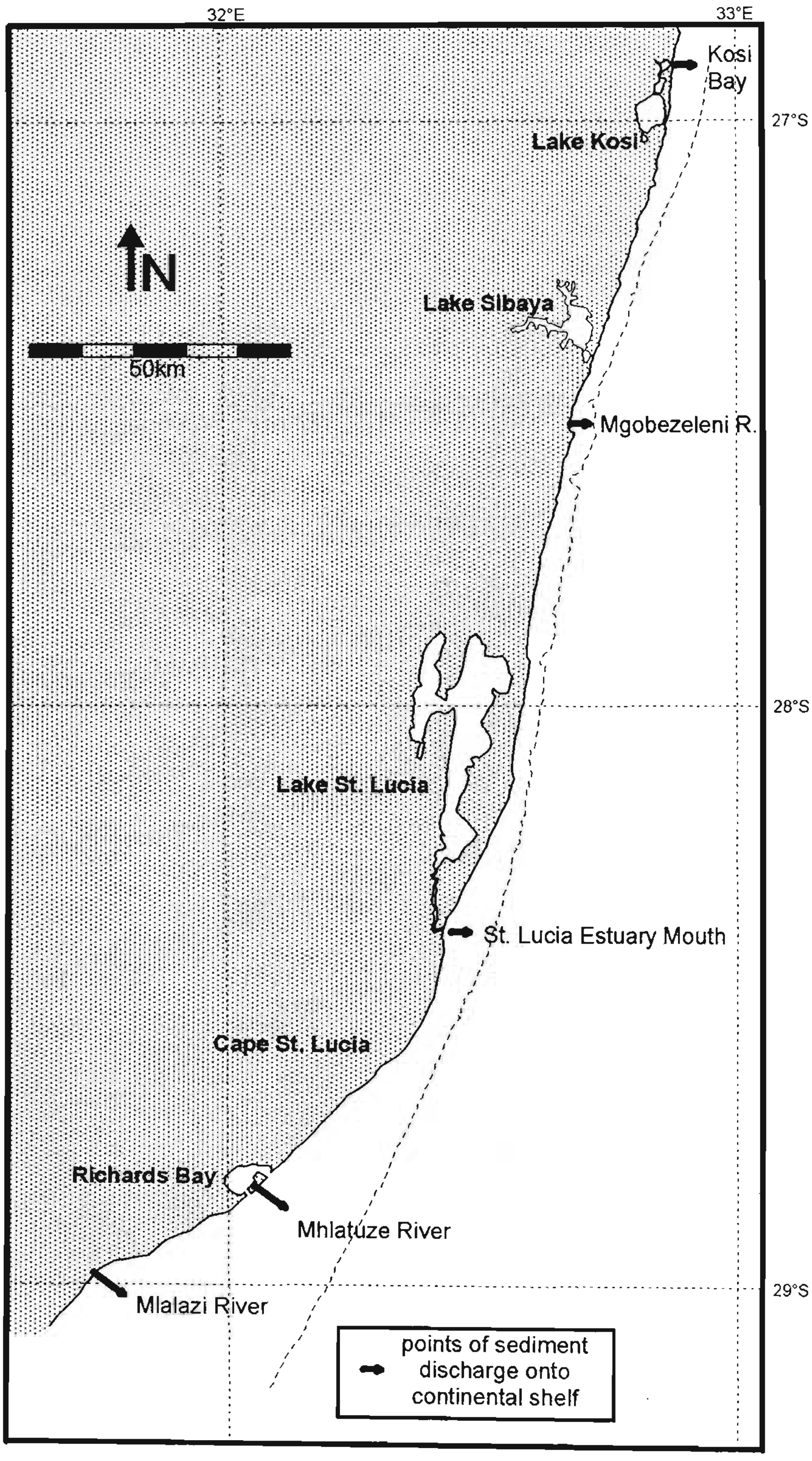


Fig. 1.3: Sediment dicharge points in the study area

width of the shelf is less than 6km in most places.

The KwaZulu-Natal coastline and continental shelf as far north as Durban has a transform fault origin, having formed during the shearing away in a south westerly direction of the Falkland Plateau 138-132Ma ago (Goodlad, 1986, pers. comm., MK Watkeys). Martin (1984) interprets this transform fault origin of the coastline as being responsible for the narrow continental shelf width of the SE African margin. Further north however the offshore submerged crust between Maputaland and the Mozambique Ridge is continental in origin (Watkeys and Sokoutis, 1998) and the narrow nature of the continental margin north of Durban must therefore be ascribed to some other phenomenon.

The continental shelf in the study area is distinguished by the incision of several submarine canyons (Bang, 1968). Although not easily discernible in Fig. 1.2 due to the inappropriate scale, these submarine canyons have a marked effect on continental margin bathymetry. In some cases submarine canyons incise the shelf to as close as 1km to the shoreline (Botes, 1988; Ramsay, 1991, 1994). Submarine canyons are common features of most continental margins (May *et al.*, 1983), although seldom are they located so close the coast. Submarine canyons are important with respect to sediment transport dynamics on the KwaZulu-Natal continental shelf, acting as conduits for terrigenous sediment movement from the continental shelf to the deep oceanic basins (Ramsay, 1991; 1994; Sydow, 1988).

Sediment discharge onto the continental shelf in the study area takes place at the outlets of the Kosi Lake system, Mgobozeleni River, St. Lucia estuary system, Mhlatuze River at Richards Bay and the Mlalazi River near Mtunzini (Fig. 1.3). In the northern part of the study area between St. Lucia Estuary mouth and Kosi Bay (a distance of approximately 170km) the only terrigenous discharge is from the minor Mgobozeleni River at Sodwana Bay.

The coast in the study area has a linear clastic, sandy shoreline (Cooper, 1991).

1.4 Climate

The study area experiences a humid, sub-tropical climate with warm summers (Schulze, 1982). The prevalent wind direction in summer is north to north-easterly while in winter there is balance between southerly and northerly winds (Schulze, 1982). Winds are therefore predominantly coast parallel. Rainfall in the study area is 1000-1100mm/annum (Schulze, 1982). Important with regard to sedimentary processes on the KwaZulu-Natal continental shelf are tropical cyclones which, when they occur are responsible for extensive wave and flood damage onshore and redistribution of unconsolidated sediment offshore (Ramsay, 1991).

1.5 Oceanography

The north-south flowing Agulhas Current which dominates sedimentary processes on the KwaZulu-Natal continental shelf, flows close inshore as a result of the narrow continental shelf off the KwaZulu-Natal coast (Ramsay, 1991). Martin (1984) states that the current can attain velocities up to $3ms^{-1}$. Work by Flemming (1978; 1980; and 1981) and Flemming and Hay (1988) and Ramsay (1991, 1994) has shown that giant subaqueous dunes migrate southwards in the direction of the Agulhas Current. Where eddies from the Agulhas Current system migrate inshore, bedload parting zones exist which changes bedform migration direction from southward to northward. Average tidal range in the area is 2m (Schumann and Orren, 1980), the coast can therefore be classified as low-mesotidal (Hayes, 1979). Dominant swell direction is from the south-east. These waves are of persistently high energy and of large amplitude (Ramsay, 1991).

1.6 Onshore Geology (Fig. 1.4)

The study area is directly offshore the Maputaland coastal plain, a flat area broadening in a northward direction from Mtunzini, bordered in the west by the Jurassic basalts and rhyolites of the Lebombo Group (Martin and Flemming, 1988; Geological Survey of South Africa, 1985a and b; Watkeys *et al.*, 1993). The coastal plain attains a width of 60km at Ponta do Ouro and is underlain by a succession of Cretaceous to Recent rocks and unconsolidated sediments (SACS, 1980). The lower-most sedimentary rocks

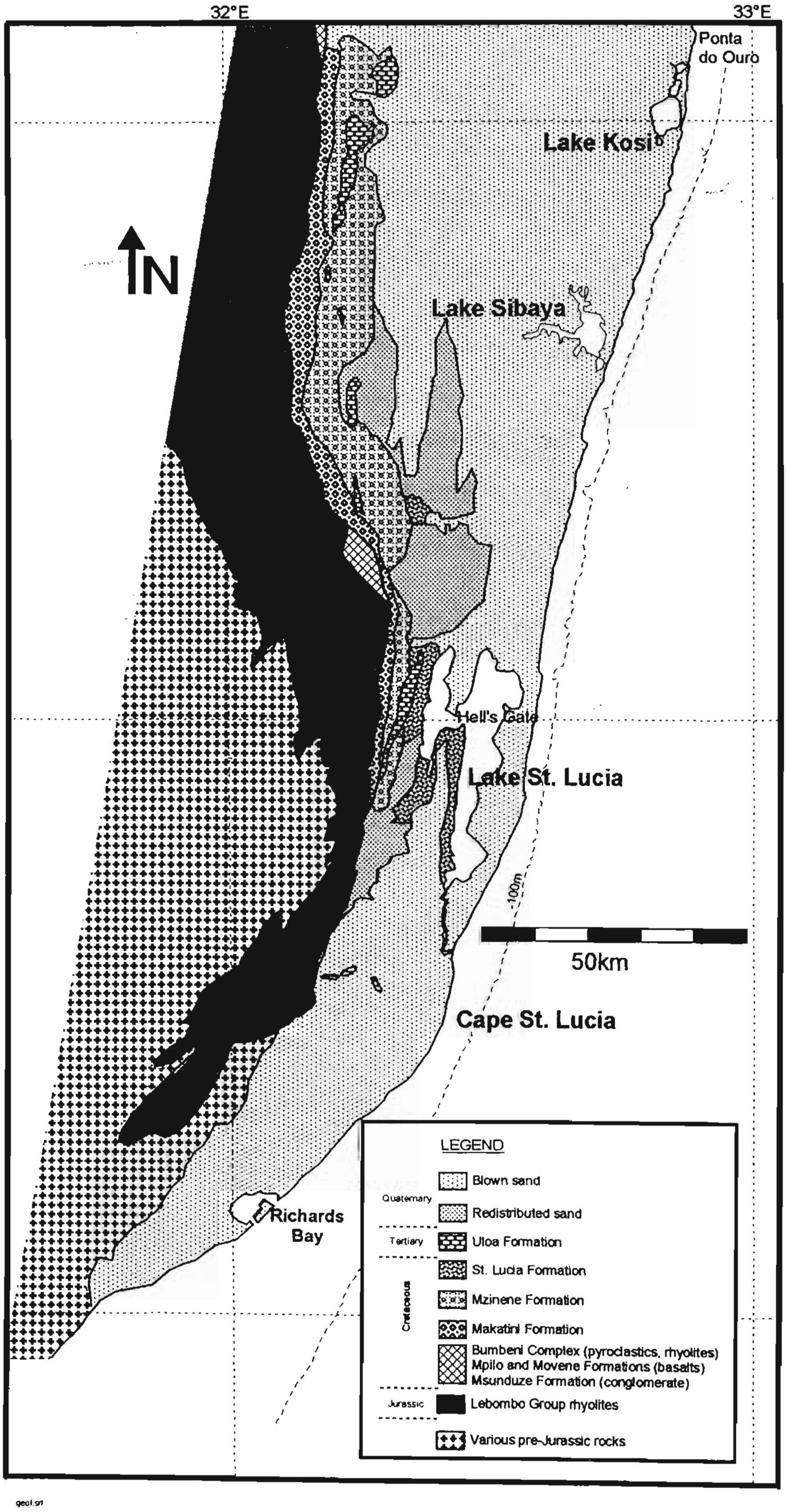


Fig. 1.4: Onshore geology of the study area (simplified after Geological Survey of South Africa, 1985a and b and Watkeys et al., 1993)

abutting against the Lebombo volcanics are the Lower Cretaceous conglomerates of the Msunduze Formation (Watkeys *et al.* 1993) overlain by the sandstones and siltstones of the Makatini and Mzinene Formations. These are overlain by the Upper Cretaceous marine sandstones and siltstones of the St. Lucia Formation. Outcrop on the Maputaland coastal plain is mostly obscured by redistributed Pleistocene to Recent unconsolidated sediments. The coastal plain profile is interrupted in places by linear Pleistocene dune ridges, as far as 53km from the present coastline (Martin and Flemming, 1988). These were formed during elevated sea-levels as coastal dune cordons similar to the present day cordons, found along much of the KwaZulu-Natal coast. It is important to realise that the Maputaland coastal plain and adjacent continental shelf represent emerged and submerged portions of a continuous feature, their separation at any time depending on sea-level (Martin and Flemming, 1988). It follows therefore, that this geophysical study of the continental margin could contribute towards the clarification of the relatively poorly understood geology of the Maputaland coastal plain, its emergent counterpart.

CHAPTER 2

PREVIOUS WORK

Offshore geophysical research into the geological evolution of the KwaZulu-Natal continental margin has been carried out by various workers since the 1960's. Organisations such as the CSIR's National Research Institute for Oceanology (NRIO) and the Geological Survey of South Africa have acquired most of the available geophysical data in the area. The Zululand coastal plain and continental margin were also the subject of intense oil exploration in the 1960's and 1970's. Substantial low-resolution, deep penetration seismic and borehole data therefore exist for the area, but generally as confidential information.

2.1 Seismic stratigraphy studies

The most significant work that has contributed towards the present understanding of the seismic stratigraphy of the northern KwaZulu-Natal upper continental margin is by Sydow (1988) and Birch (published in 1996, but in press for nearly 20 years). Birch can be credited with being the first to describe a generalised seismic stratigraphy for the southeast African upper-most continental margin. Although his study concentrated mainly on the distribution and nature of unconsolidated Quaternary sediments on the southeast African continental shelf, he also considered underlying features. Sydow (1988) developed the first detailed seismic stratigraphy of the KwaZulu-Natal continental margin. Although based on a very localised study, concentrating on the Leven Point area, his stratigraphic framework formed an important basis from which the seismic stratigraphy described in this work was developed.

2.1.1 Sydow's seismic stratigraphy

Sydow interpreted high-resolution continuous seismic reflection profiles acquired during a detailed survey of the Leven Point area (Fig. 2.1). These records were acquired during cruise number 86-05 of the CSIR Research Vessel *Meiring Naude*. He investigated stratigraphic controls of mass wasting and canyon development in the

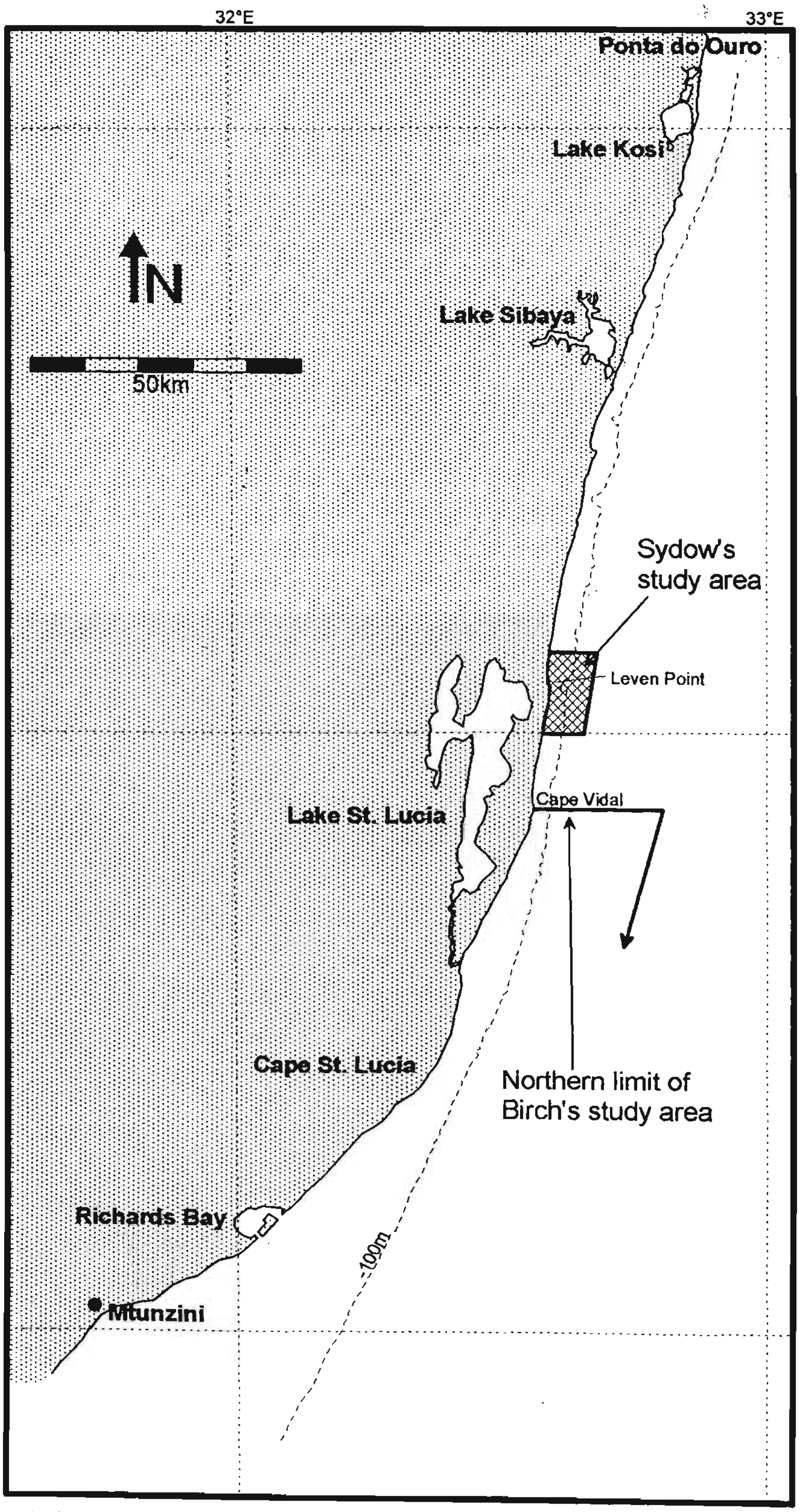


Fig. 2.1: Locality of Sydow's (1988) study area and the northern limit of Birch's (1996) study area

area. Seismic profiles were acquired using a 700 Joule multiple electrode sparker energy source. Resolution of this Sparker system is 3.2 to 4.8m and penetration of approximately 160m was achieved in places.

Sydow (1988) produced an idealised seismic stratigraphy of the continental margin in the Leven Point area as compiled from his interpretations of coast perpendicular seismic sections (Fig. 2.2). A coast-perpendicular line drawing interpretation of a sparker seismic section is shown in Figure 2.3. Sydow recognises seven distinct seismic sequences (A to F) each separated by prominent reflectors.

The continuous, sub-parallel and gently seaward dipping strata of Sequence A, the deepest unit resolved by the sparker system, is interpreted as being the marine Upper Cretaceous St. Lucia Formation. This assumption is supported by gravity core studies in Leven Canyon (Siesser, 1977).

The onlapping, continuous reflection configuration of Sequence B suggests a marine environment and is tentatively interpreted as a Lower Tertiary (Mid to Upper Palaeocene) marine clay, based on reflection configuration and studies of gravity cores (Siesser, 1977).

Sequence C is interpreted as a progradational unit deposited during a period of high terrigenous influx. Within Sequence C, a nearshore shallow marine shelf facies grades seawards into a progradational facies on the upper slope, interpreted as material which has been deposited seaward of the shelf break. The age of Sequence C is taken to be Upper Tertiary (Miocene or Pliocene) based on stratigraphic evidence further offshore.

The thin Sequence D, comprising a poorly continuous, channelled internal reflection configuration is also interpreted as representing shallow marine nearshore facies although this unit, where present, thins towards the shelf edge. It is not associated with prograding sediments on the upper slope as is the case with Sequence C. This sequence is interpreted as the eroded remnants of sediments deposited on the outer shelf during a period of decreased terrigenous influx in the Pleistocene. Sequence E is interpreted as sediments of the same age which were transported to form subaerially exposed coastal sand dune cordons during a glacially induced regressive period.

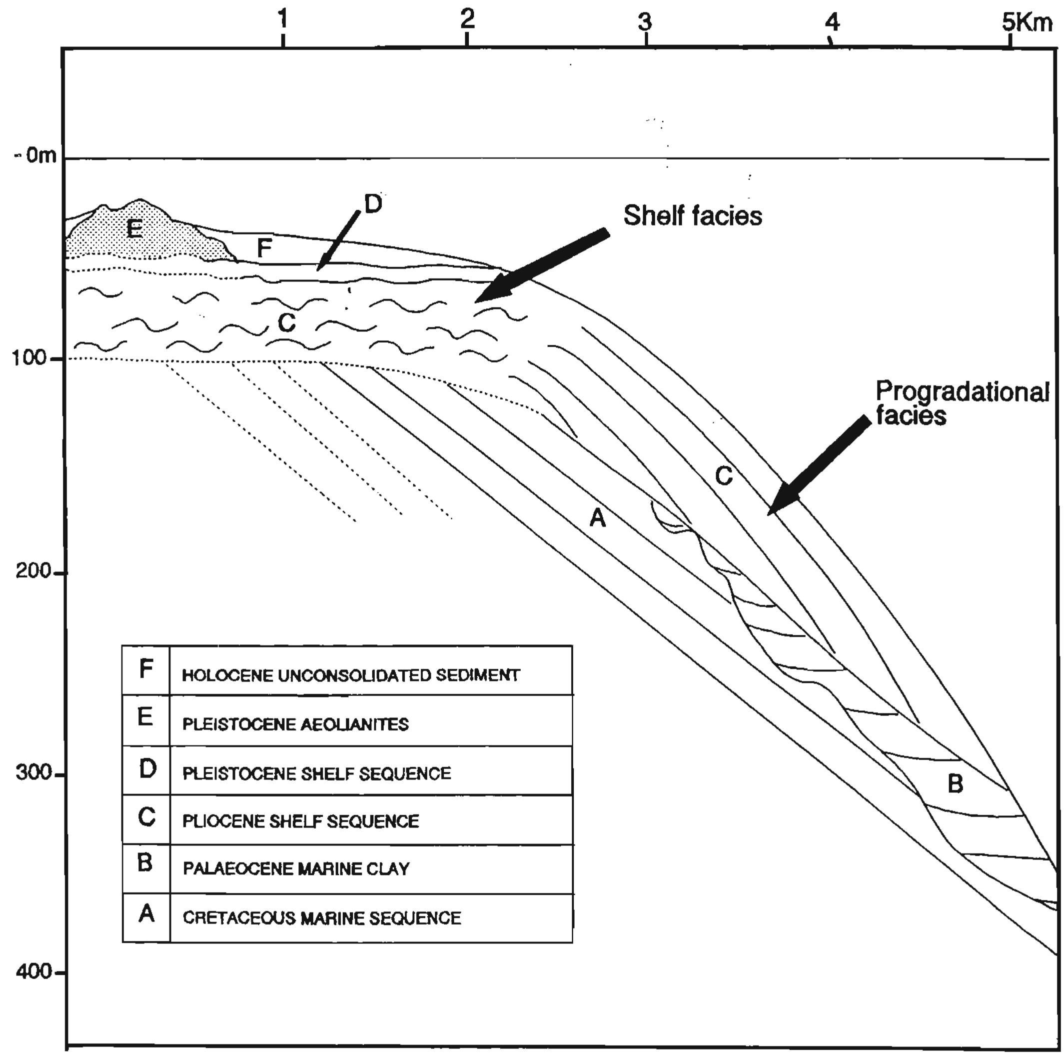


Fig. 2.2: Idealised seismic stratigraphy of Sydow (1988)

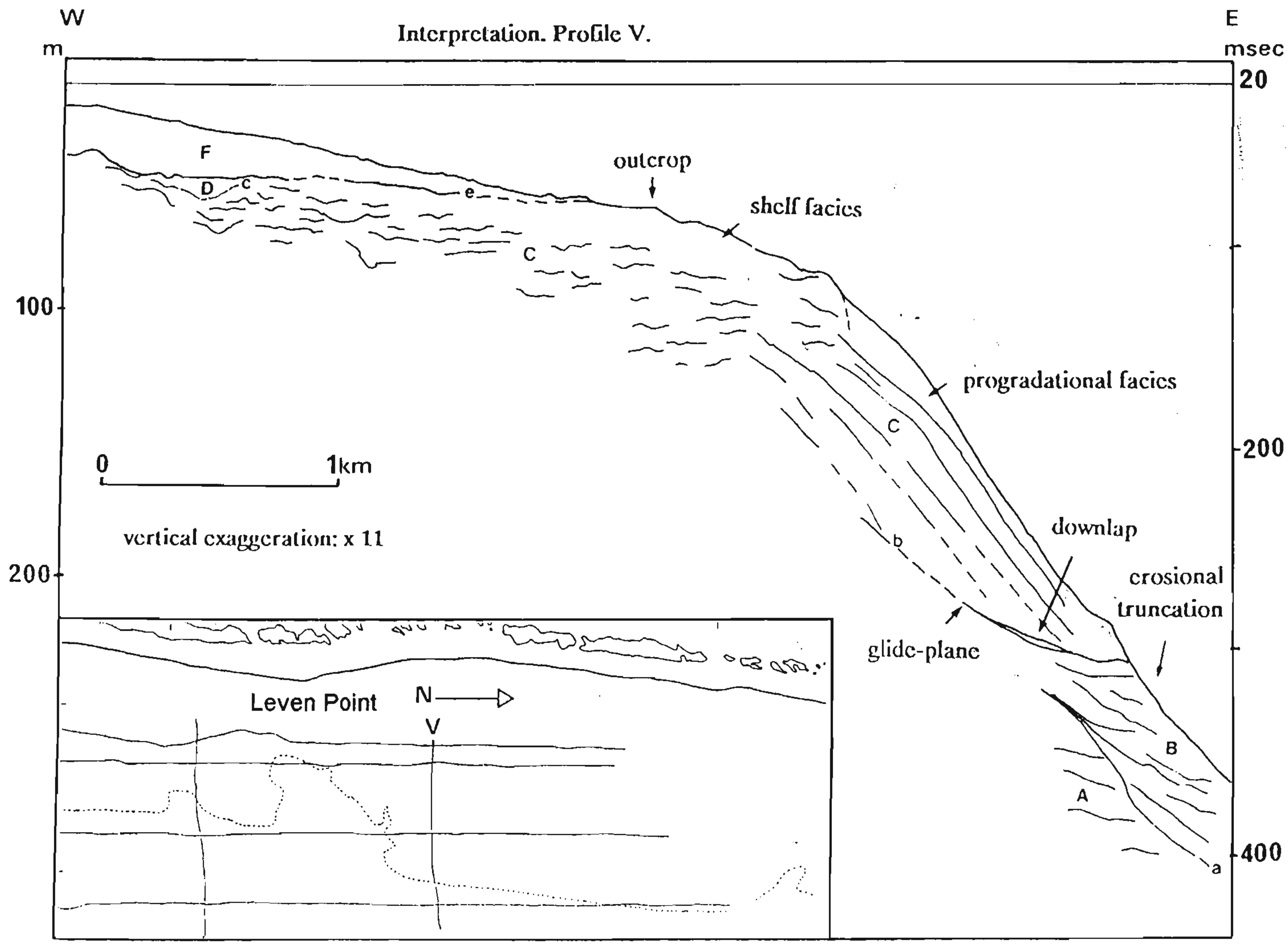


Fig. 2.3: Line drawing interpretation of coast perpendicular sparker seismic section acquired at Leven Point (from Sydow, 1988).

Sydow (1988) interprets the acoustically semi-transparent Sequence F as an unconsolidated inner-shelf Holocene sand prism. These sediments are up to 25m thick in places and are thought to have been deposited on the continental shelf during catastrophic flood discharges from fluvial outlets at St. Lucia Estuary mouth and Leven Point. The Palaeo-outlet from Lake St. Lucia at Leven Point has been closed for the last 5000 years (Van Heerden, 1987). This palaeo-outlet is inferred from the presence of a buried channel 40m below present sea-level, visible on seismic sections acquired in Lake St. Lucia (Van Heerden, 1987).

2.1.2 Birch's seismic stratigraphy

Birch (1996) interpreted continuous airgun seismic reflection profiles acquired during a survey of the southeast African continental shelf between Cape Vidal and Cape Padrone, near East London (Fig. 2.1). These seismic records were acquired during cruise numbers. 392 and 382 of RV *Thomas B. Davie*. This was part of a study of Quaternary near-shore sedimentation on the continental shelf of southern Africa. Seismic records were obtained using an $82cm^3$ Bolt airgun energy source. The resolution of this system is listed as approximately 4m and the maximum penetration achieved was approximately 60m, substantially less than the 160m achieved by the sparker tool used to produce the data studied by Sydow (1988).

Birch's line drawing interpretations of seismic sections acquired between Cape Vidal and Durnford Point are shown in Figure 2.4. Figure 2.5 is an idealised representation of Birch's seismic stratigraphy based on his descriptions. Although Birch has not rigidly subdivided several sedimentary sequences, the following can be inferred from his observations:

Clearly recognisable on the inner-shelf is an unconsolidated Quaternary sediment prism more than 15m thick in places. This nearshore sand prism lies unconformably upon seaward inclined sediments interpreted as being of Tertiary or Cretaceous age. These seaward dipping reflectors are not very clear in sections 124; 127 and 130 between Cape St. Lucia and Cape Vidal (Fig. 2.4) but are easily recognisable further south. In section 114, acquired just south of Durnford Point, these seaward dipping

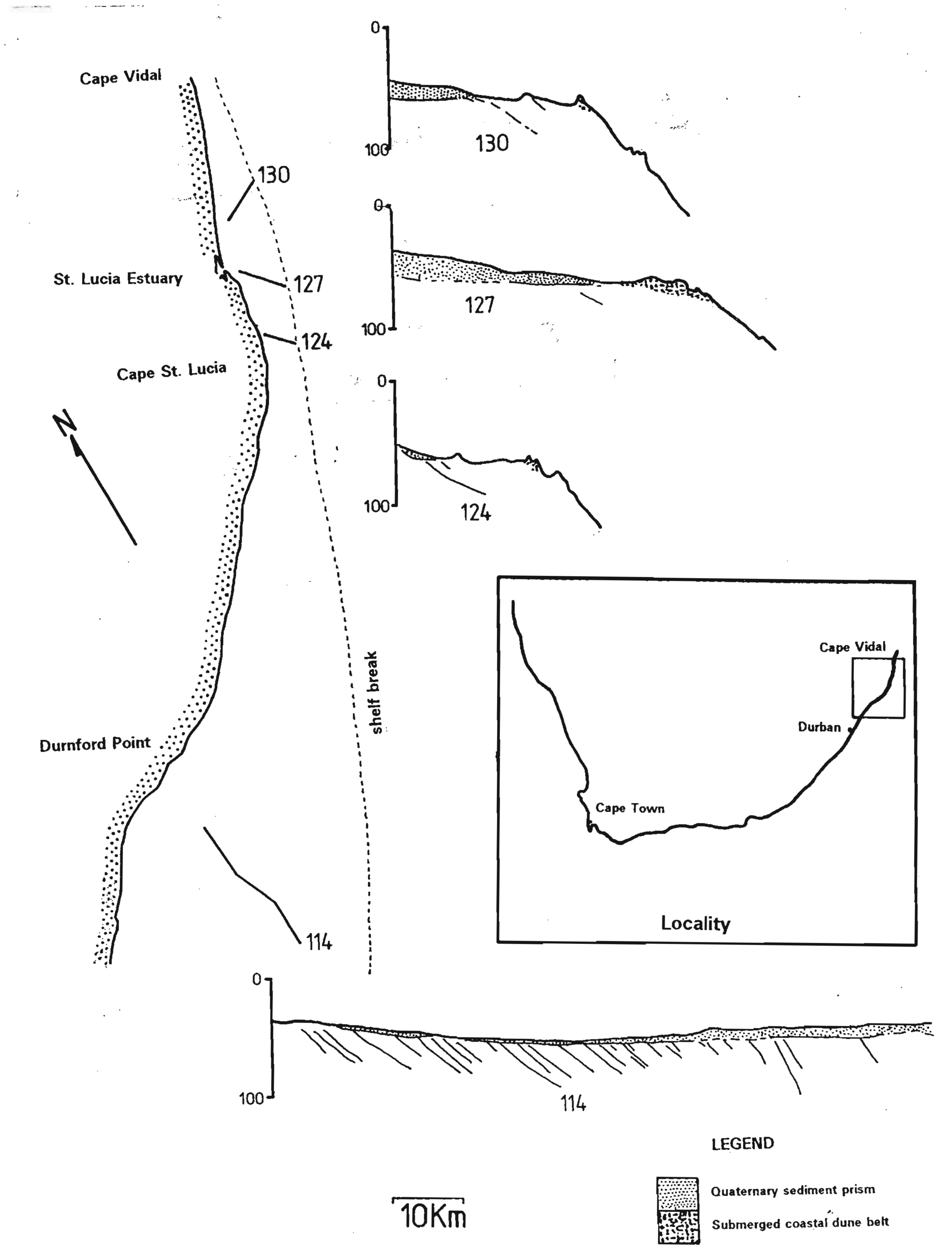


Fig. 2.4: Line drawing interpretations of airgun seismic sections acquired between Cape Vidal and Durnford Point

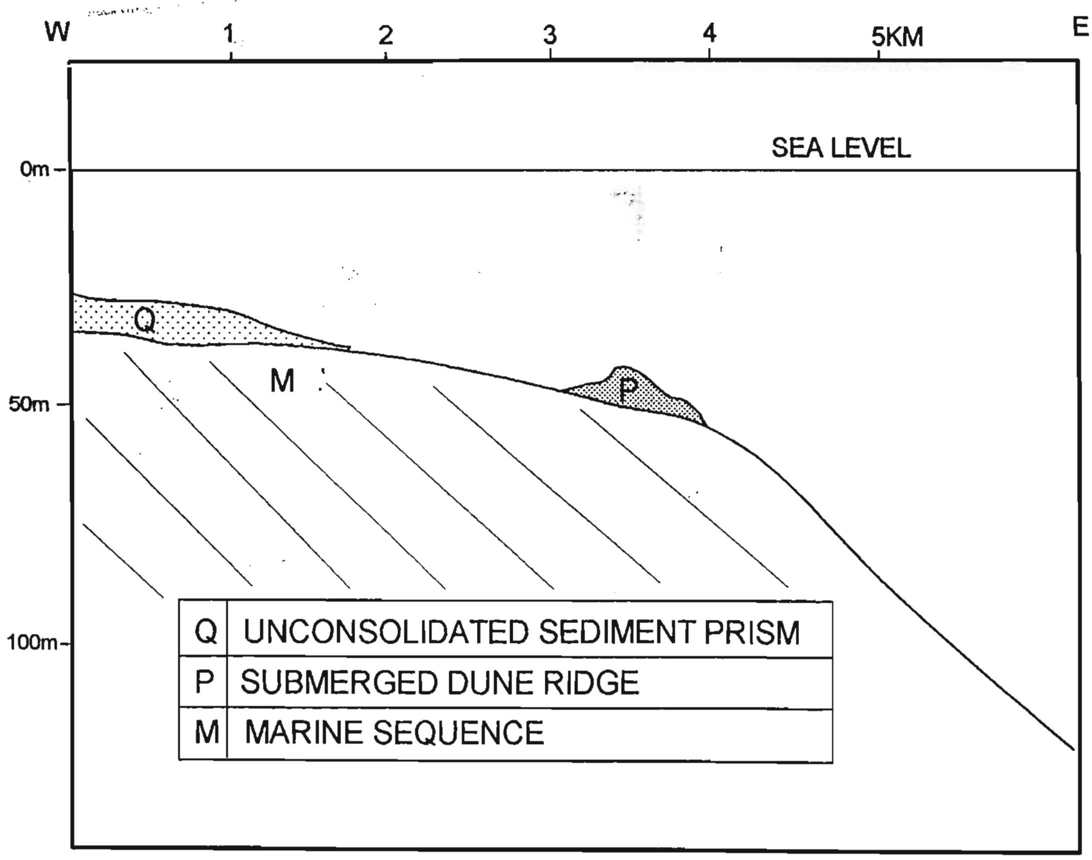


Fig. 2.5: Diagrammatic representation of seismic stratigraphy of the northern KwaZulu-Natal upper continental margin, described by Birch (1996)

reflectors are clearly visible.

On the seaward edge of the continental shelf, submerged Pleistocene aeolianites form a distinct ridge. In places the Quaternary unconsolidated sediment wedge is banked up against it. The base of the unconsolidated sediment is often not discernible and has been extrapolated from areas where the base is clearly visible.

2.1.3 Comparison between seismic stratigraphies of Sydow and Birch

Both workers clearly recognise and delineate the inshore unconsolidated (Holocene) sediment prism. The thickness of this prism is fairly constant across the two areas, Sydow noting up to 25m at Leven Point and Birch noting up to 20m at the St. Lucia estuary mouth. Both workers recognise the existence of submerged Pleistocene aeolianites (Sydow's Sequence E). South of Cape Vidal in Birch's study area, the submerged dune ridge is located close to the edge of the continental shelf whereas north of Cape Vidal in Sydow's study area the ridge is located closer inshore. This trend continues northwards and at Sodwana Bay this submerged dune ridge is located approximately 1.5km offshore forming the substrate for various coral reefs (Ramsay, 1991).

Due to the low-resolution of the airgun seismic tool, Birch does not recognise Sydow's Sequence D (eroded Pleistocene near-shore marine facies). He draws no distinction between Holocene and Pleistocene sediments referring to the unconsolidated sediment prism as "Quaternary".

Birch's seismic sections do not extend sufficiently onto the continental slope to detect the existence of Sydow's Sequence B (Upper Palaeocene marine clay).

Both workers were able to recognise seaward dipping marine strata which Sydow interpreted as being Late Cretaceous St. Lucia Formation sediments (Sequence A). Birch describes them simply as being inclined Tertiary and Cretaceous sediments.

The most startling contrast between the two seismic stratigraphic interpretations is the absence of Sydow's shelf facies and progradational unit (Sequence C) south of Cape

Vidal. Sydow's interpretations show this unit to be up to 50m thick. In Sydow's sections the seaward dipping marine sediments are unconformably overlain by a substantial shelf and prograding wedge. This is overlain unconformably by Pleistocene and Holocene sediments, whilst in Birch's interpretation, Quaternary unconsolidated sediments rest directly upon seaward dipping Tertiary and Cretaceous sediments. The fact that Birch lists the seaward dipping marine sediments as either Tertiary, (i.e. including Pliocene and Miocene), or Cretaceous age does not solve the problem. Even if Birch's seaward dipping marine sediments are of Tertiary age they have distinctly different internal reflection configuration to Sydow's sequence C. While Sydow's Tertiary sediments have reflections of variable amplitude, poor continuity and channelled internal reflection configuration grading regressively into steeply dipping, continuous downlapping reflections on the shelf edge, Birch's possible Tertiary sediments are simply continuous dipping reflectors of approximately constant amplitude. These discrepancies are addressed later in this study.

2.1.4 Seismic studies in adjacent deep ocean basins

Detailed seismic studies by Martin (1984), Goodlad (1986) and Dingle *et al.* (1978) described the plate tectonic and sedimentary history of the deep ocean basin areas adjacent to this study area in the northern Natal Valley (Fig. 2.6). Since these studies outline sedimentation rates of the basin areas they also provide an insight into rates of onshore erosion and consequent shelf sedimentation history. These workers recognised several seismic sequences separated by four regional stratigraphic horizons (Fig. 2.6). These horizons were given the somewhat whimsical and as yet, unmodified names of MacDuff, Jimmy, Angus and L. The lowermost Horizon Mac-Duff is thought to represent a Mid-Cretaceous (Cenomanian/Turonian) non-depositional hiatus (Goodlad, 1986). Horizon Angus is estimated to be early Oligocene in age. Horizon Jimmy is situated near the Miocene/Pliocene boundary while Horizon L lies near the top of the Pliocene/Quaternary sequence. Horizons Angus, Jimmy and L were correlated with significant events in the development of the Agulhas Current (Goodlad, 1986). Invigorated deep current action is invoked to explain the Angus and Jimmy erosive hiatuses (Goodlad, 1986) while Horizon L is related to the development of the cyclonic eddy in Delagoa Bay (Martin, 1984).

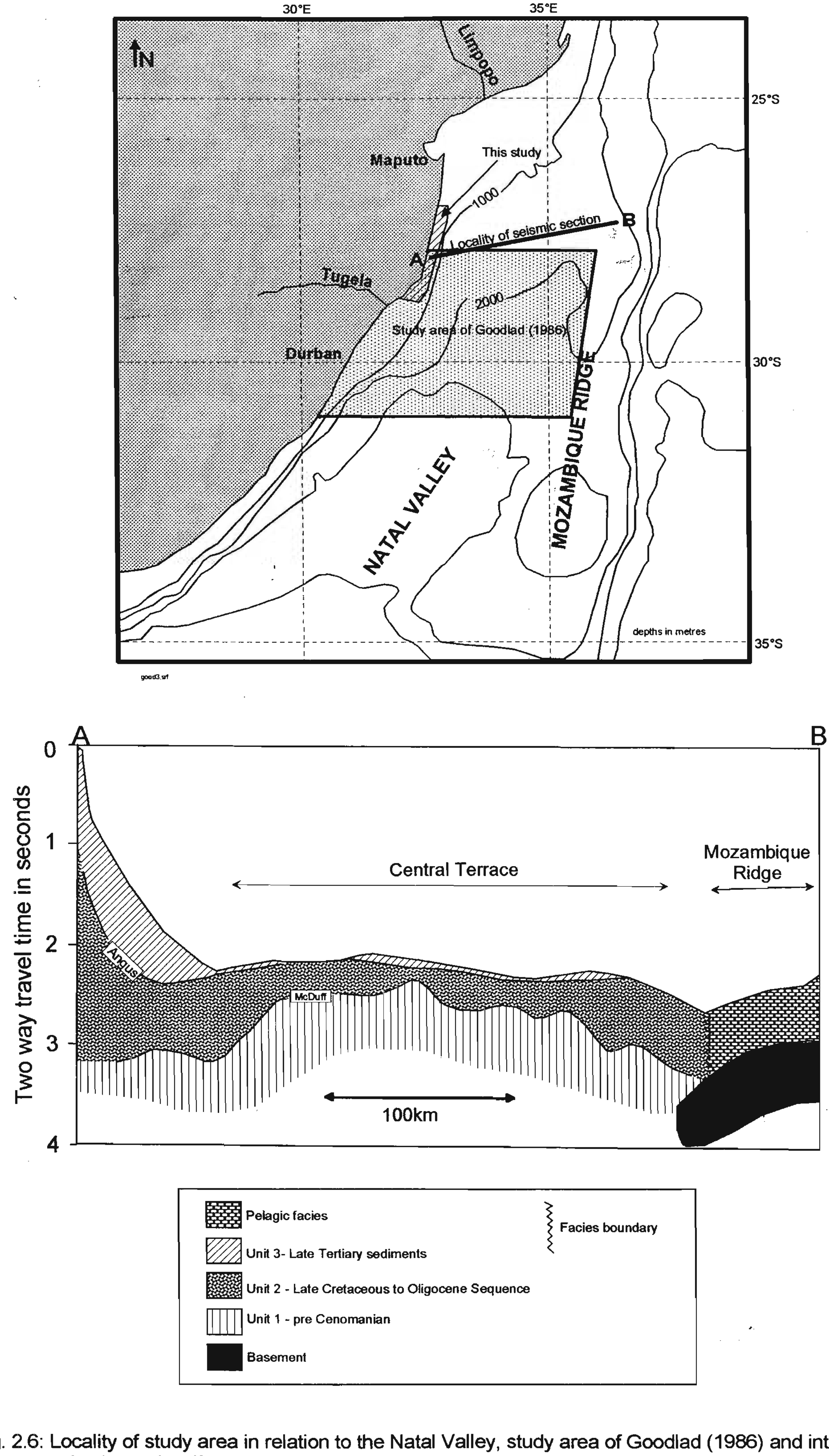


Fig. 2.6: Locality of study area in relation to the Natal Valley, study area of Goodlad (1986) and interpre
seismic section (from Dingle et al., 1978)

2.2 Continental shelf sedimentation studies

Substantial work has been carried out on the sediment dynamics of the modern KwaZulu-Natal continental shelf. Detailed studies of shelf sediment dynamics have contributed towards an understanding of the present-day processes operating on the KwaZulu-Natal continental shelf. Publications by Birch (1996) and Martin (1985) and Martin and Flemming (1986) have delineated unconsolidated Quaternary sediment depocentres. Martin's (1985) study concentrated on the shelf between Leven Point and Mtunzini (Fig. 1.1) while Birch's (1996) study included the entire east coast continental shelf between Ponta do Ouro and East London. Martin and Flemming's (1986) study included the southeast and southern coast of Africa. These seismic and sedimentological studies provided detailed maps of sediment thicknesses as well as spatial variations in sediment texture.

Flemming (1978 & 1981) describes sand transport dynamics along the southeast African continental margin while Ramsay (1991& 1994) describes the sedimentology of the Sodwana Bay continental shelf. These workers provided detailed descriptions of bedform patterns in their respective study areas.

CHAPTER 3

SPARKER SEISMIC STRATIGRAPHY

Despite the fact that the length of the study area is greater than 240km, the seismic sequences observed on sparker seismic records can be traced continuously from the northern to the southern extremes of the study area. Where possible "Sequence Stratigraphy" principles were used when developing the seismic stratigraphic framework for the study area. At the beginning of this chapter, data acquisition methods are briefly described. Principles used to delineate seismic sequences and facies are outlined. Some of the interpretation and sequence stratigraphy application problems are briefly described. Individual seismic sequences and facies observed throughout the study area are described in terms of their diagnostic characteristics. Some seismic profiles clearly showing the delineated seismic sequences and facies are included to complement the descriptions. Later in the chapter, the study area is subdivided and spatial variations of sequence characteristics, thicknesses and relationships of sequences to one another are described. These are explained in terms of local continental shelf morphology, current processes and geological history in Chapter 8.

3.1 Data Acquisition

All data interpreted in this chapter were acquired aboard the Research Vessel *Meiring Naude* by the CSIR. Data were collected during January 1981 and June/July 1983 (cruise nos. 81-01 and 83-10). Data acquisition formed part of NRIO's Sediment Current Interaction programme. A "sparker" system of continuous seismic reflection profiling was used. Technical aspects of data acquisition and interpretation are described in Appendix A. Overall sparker seismic data coverage on the northern KwaZulu-Natal continental shelf of these two cruises is shown in Fig 3.1. Not all of the data acquired during these two cruises were interpreted during this study since much of it was acquired in deeper water outside the study area. Only good quality, clear seismic data acquired on the upper continental margin were interpreted.

3.2 Seismic sequence stratigraphy

Seismic Sequence Stratigraphy methods were initially developed in the mid-1970's by

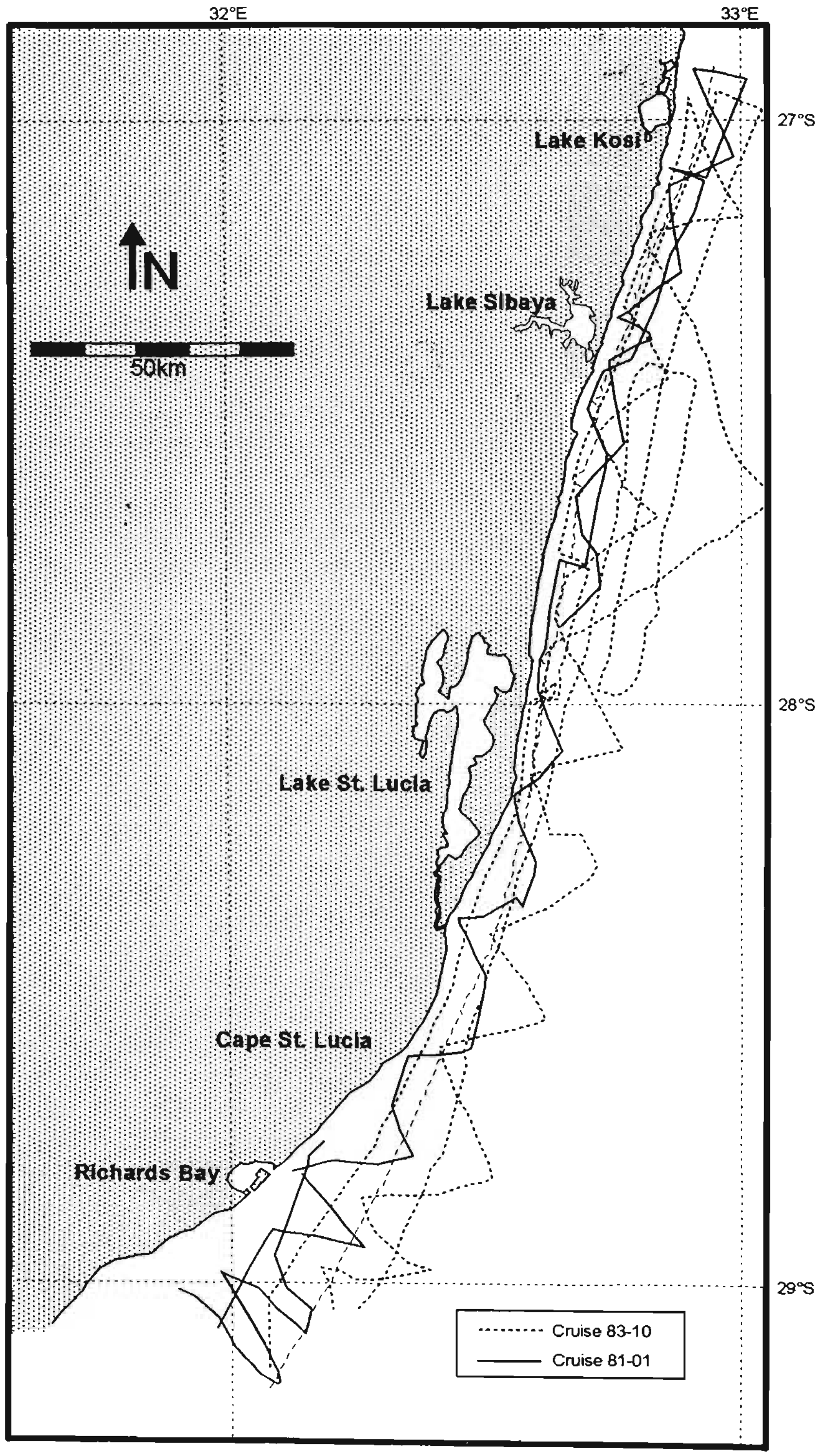


Fig. 3.1: Seismic data coverage acquired during cruises 8101 and 83-10 of the Research Vessel Meiring Naude

petroleum geologists as a tool for hydrocarbon exploration and research. The concept has since developed beyond its original intended purpose to the extent where it is now utilised by a wide variety of earth scientists in many diverse spheres of research. While still essentially used to analyse sedimentary basins, its application has widened from it being used only to interpret low resolution, deep penetration seismic data to it being used to interpret high resolution seismic data acquired using a wide variety of seismic tools, each of varying resolution and penetration. Although continuous seismic reflection profiling methods were developed years before principles of sequence stratigraphy, nowadays few seismic studies are undertaken which do not utilise sequence stratigraphy principles in some way. As with any popular method of analysis or philosophy, there are and have been many critics (for example Miall, 1986; Tipper, 1993) of sequence stratigraphy methods. These have led to developments and refinements since the late 1970's and while problems still remain, sequence stratigraphy stands as a tool which has been successfully applied in the past, and is sure to be successfully applied in the future to various aspects of sedimentary basin analysis.

Sequence stratigraphy is the study of rock relationships within a chronostratigraphic framework of repetitive, genetically related strata bounded by surfaces of erosion or non-deposition, or their correlative conformities (Van Wagoner *et al.*, 1988). Sequence stratigraphic analysis begins with the delineation of **sequences**. Seismic sequences are recognised on seismic records by identifying discontinuities caused by reflection terminations representing unconformities. Depending on the geometry of these reflection terminations, they are either termed **onlap**, **downlap**, **toplap**, and **truncation** (Fig. 3.2). Sequences can be further subdivided into **systems tracts** which are deposited at specific times during a cycle of relative sea-level movement (Van Wagoner *et al.*, 1988). Only seismic sequences and seismic facies were recognised in this study. Systems tracts within seismic sequences were not recognised and are therefore not dealt with further.

Seismic facies analysis constitutes the delineation and interpretation of characteristics such as reflection geometry, continuity and amplitude, as well as the external form and associations of seismic facies units (Van Wagoner *et al.*, 1988). Delineation of seismic facies allows interpretation of sedimentary processes and environmental settings and

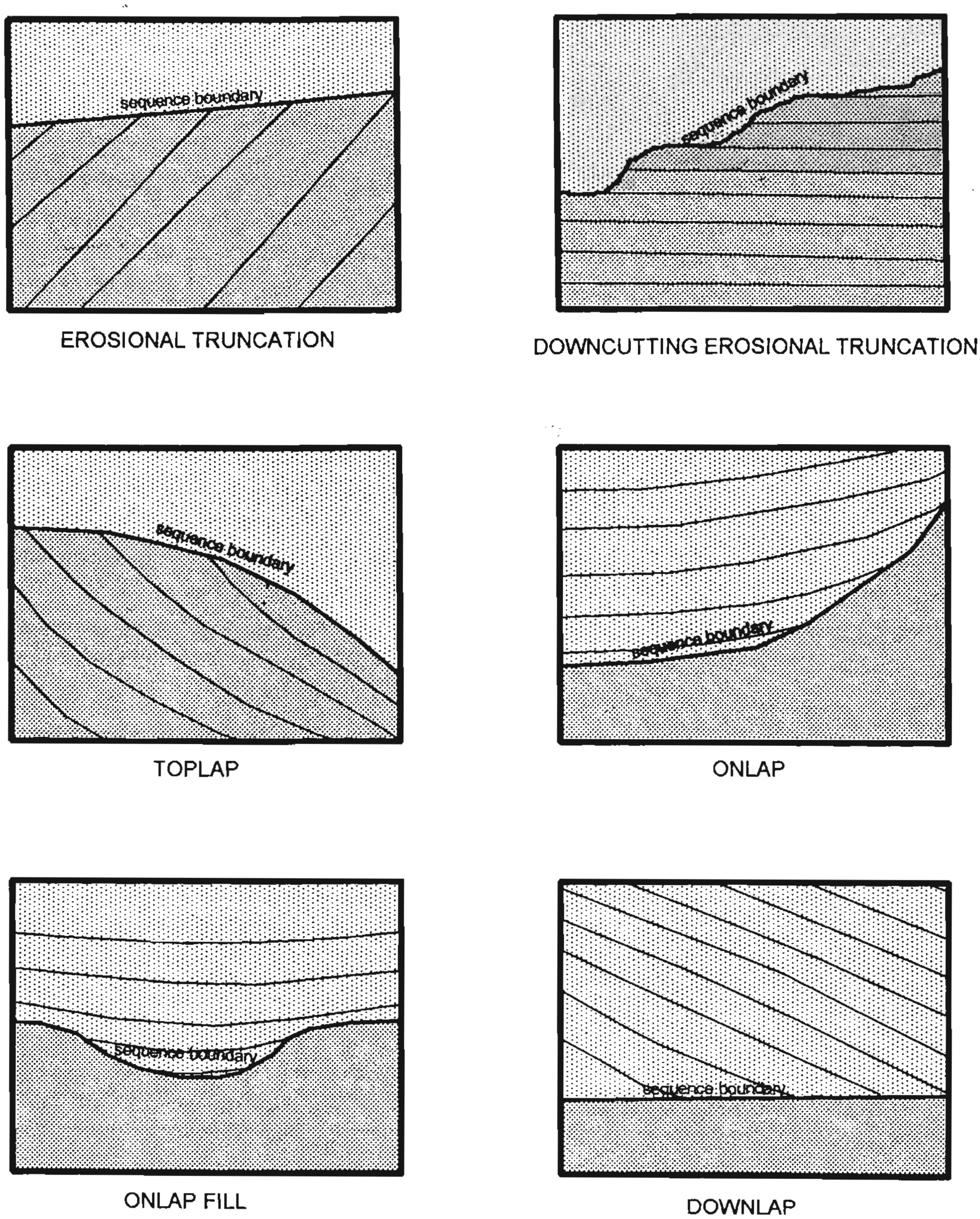


Fig. 3.2: Schematic represenation of seismic reflection termination patterns and sequence boundaries (fro
Van Wagoner et al. 1988)

thus the lithology of the seismic facies under consideration (Van Wagoner *et al.*, 1988).

3.3 Problems with sequence stratigraphy application

The concept of sequence stratigraphy developed on continental shelves as a process related methodology which relates deposition of sediments to changes in sea-level. It has been very successfully applied in the study of sedimentary basins which have experienced/are experiencing rapid rates of sedimentation. Although sequence stratigraphy principles have been successfully applied in many other sedimentary geological environments, application of these principles in this study has proved difficult due to various factors.

As mentioned in Chapter 1, the northern KwaZulu-Natal continental margin is globally unique in terms of its narrowness and shallow shelf break. Due to the outbuilding of the Tugela Cone the continental shelf south of Richards Bay is up to 45km wide. North of Mtunzini however the shelf narrows rapidly to approximately 5km wide (Fig. 1.2.). The length compared to the width of this study area is therefore extremely high. The Zululand coastal plain can effectively be considered as a subaerially exposed continental shelf. This study is therefore concerned mainly with the outer edge of the continental shelf. At present, accumulation of large volumes of sediment on most parts of the northern KwaZulu-Natal continental shelf is limited. This is because fluvial sediment discharge to this narrow outer continental shelf finds its way rapidly to the adjacent oceanic basins due to the close proximity of the shelf break and the presence of numerous submarine canyons. These incise the already narrow continental shelf, and unconsolidated sediments are funnelled into them as a result of transport of sediment by the Agulhas Current (Flemming, 1978 and 1981).

Due to the physiography of the northern KwaZulu-Natal upper continental margin described above, only the outer, upper tip of a feature which extends much further inland is being studied. Coupled with the relatively shallow penetration (160m) of the sparker seismic tool (compared to the airgun tool as utilised by oil companies), this hinders the successful application of seismic sequence stratigraphy principles.

Seismic sequence stratigraphic interpretation of shallow penetration, high resolution

Pinger and Edo-Western seismic records has been successfully carried out in the studies of Quaternary sediments (e.g. Stevenson, 1992;) thereby showing that the principles developed on a much larger scale can be equally well applied on a much smaller scale. On the northern KwaZulu-Natal continental shelf however, the dearth of unconsolidated Quaternary sediments once again means that sequence stratigraphic principles could not be applied with complete success since the several isolated unconsolidated sediment depocentres present on the shelf are constantly being reworked and redistributed, principally by the action of the Agulhas Current (Flemming, 1978 and 1981).

3.4 Seismic Stratigraphy

A simplified representation of the external sequence geometry, reflection termination patterns and internal reflection characteristics of seismic sequences recognised on the northern KwaZulu-Natal upper continental margin is shown in Figure 3.3. The seismic stratigraphy described is very similar to that described by Sydow (1988). Despite limitations of the seismic tool and the physical structure of the northern KwaZulu-Natal continental margin, five seismic sequences were recognised on the basis of reflection termination patterns, internal reflection configuration and geometry and shelf profile morphology. Although seismic sequence characteristics vary from area to area, in the following section some general sequence characteristics are described as they appear throughout the study area.

The most complete sequence stratigraphy is visible on the wider continental shelf south of Richards Bay (Fig. 1.1). The simplified seismic stratigraphy (Fig. 3.3) is therefore best applied to this area of the continental margin. Seismic sequences recognised were assigned a letter **A** to **E** (**A** the oldest and **E** the youngest). Seismic facies recognised within seismic sequences were assigned numbers e.g. Facies 2 of Sequence B etc. Distinct reflectors interpreted as unconformities separating individual seismic sequences were assigned a lowercase letter (e.g. a or c) based on the name of the underlying sequence. These reflectors are the sequence boundaries. Although distinct in some areas, they are not always visible due to poor record quality and shallow penetration. In some cases where these erosive reflectors were visible, it was not clear exactly which seismic sequence is present underneath. These reflectors therefore

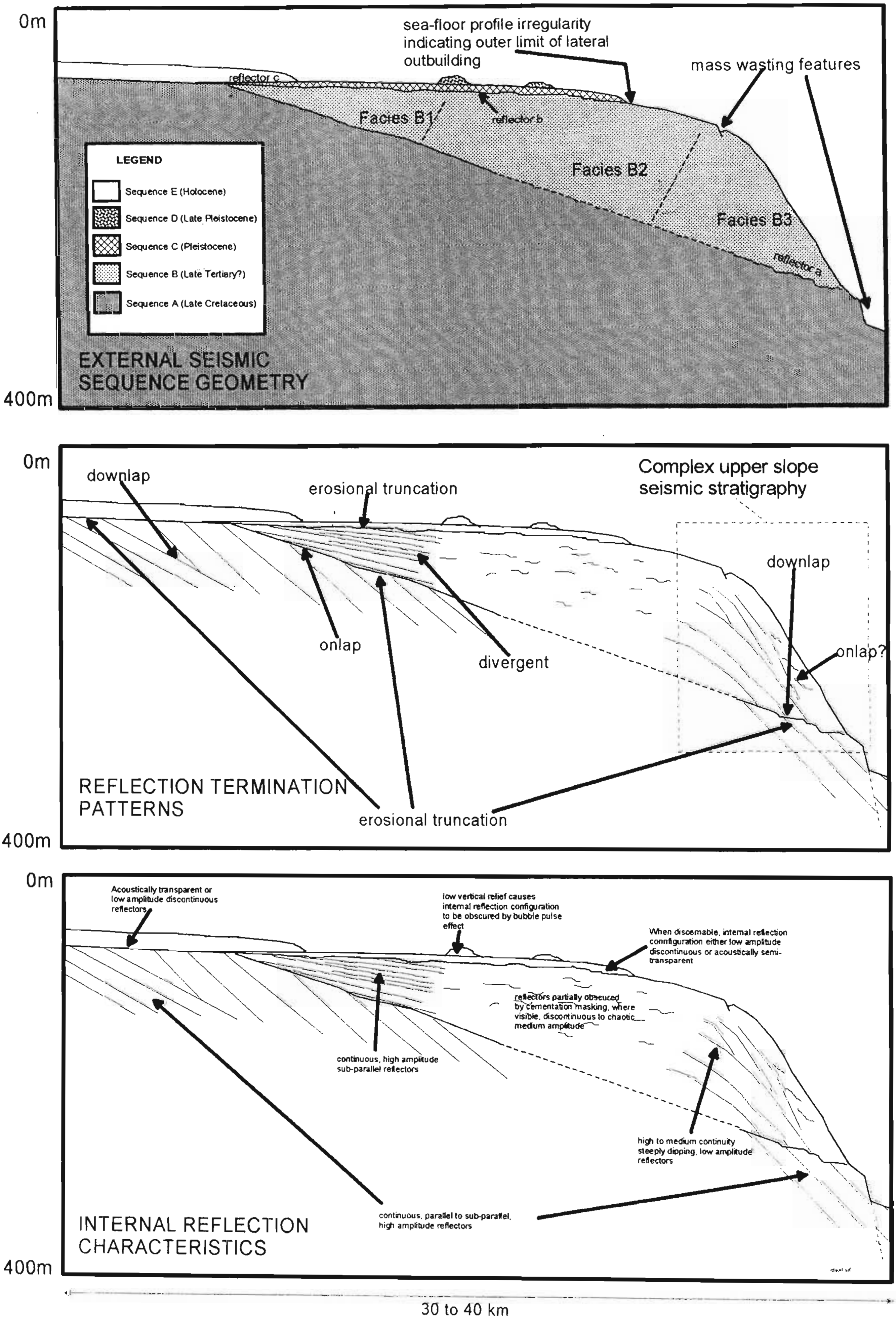


Fig. 3.3: Schematic representation of seismic stratigraphic variables on the northern KwaZulu-Natal upper continental margin

proved more reliable bottom, than top sequence boundary indicators.

Unfortunately, sequence stratigraphy interpretation in this study could not be aided by boreholes and sediment samples. Age control on the northern KwaZulu-Natal upper continental margin and shelf is poor (Sydow, 1988). Some degree of conjecture is therefore required when assigning or correlating observed seismic sequences to specific stratigraphic units documented onshore. As mentioned, Sydow was the first to develop a generalised offshore seismic stratigraphic framework of any part of the northern KwaZulu-Natal continental margin from the interpretation of sparker seismic records acquired in a localised study of the Leven Point area (see Fig. 2.2). Sydow did not have the benefit of direct age control methods. Instead, he inferred age constraints by comparison with published sea-level curves, deep sea depositional events, local onshore geology, onshore geomorphological studies and studies of the few gravity cores available. Before seismic stratigraphic frameworks as described in this and previous studies are to be confidently believed, especially with regard to inferred ages, confirmatory borehole data are needed.

3.4.1 Sequence A

The deepest sequence observed on sparker seismic profiles consists of parallel to sub-parallel, high amplitude seaward dipping reflectors of high continuity. Although these seaward dipping reflectors are generally of high amplitude, some reflectors clearly are more distinct than others. On seismic profiles south of Mtunzini, the Sequence A reflectors are clearly erosionally truncated by the present sea-water/sediment interface close inshore. Farther offshore, the top of Sequence A is marked by Reflector a, an undulating, seaward dipping reflector, which erosionally truncates Sequence A reflectors. Beneath the shelf break and continental slope where Sequence A is buried by younger material, Reflector a is recognisable by its erosional truncation of underlying Sequence A reflectors. When it is apparently concordant to the underlying Sequence A reflectors it is recognisable by the downlap of overlying reflectors. The bottom of Sequence A is beyond the penetration depth of the sparker seismic system. The overall thickness of the sequence can therefore not be calculated, but is greater than 160m.

On some seismic sections in the south of the study area, a downlap surface is present within sediments assigned to Sequence A, indicating the possible existence of a separate sequence within this unit.

Parallel reflection configuration usually indicates uniform rates of deposition on a uniformly subsiding shelf or basin (Van Wagoner *et al.*, 1988). Continuity of seismic reflections is closely related to sedimentary strata continuity. Thus, the relatively high continuity of Sequence A reflectors suggests this sequence consists of widespread uniform stratiform deposits (Van Wagoner *et al.*, 1988). The relatively high amplitude reflectors of Sequence A indicates significant acoustic impedance contrasts between intraformational strata. This indicates the presence of intraformational disconformities or local unconformities (unconformity nomenclature of Van Wagoner *et al.* 1988 is used), i.e. sharp acoustic impedance contrasts representing sharp lithofacies contrasts. The reflection configuration of Sequence A, and its depth of occurrence indicate that it is the same as Sydow's (1988) Sequence A recognised off Leven Point. Sydow correlates this sequence with the marine Upper Cretaceous St. Lucia Formation on the basis of extrapolation to onshore successions. Onshore extrapolation by Sydow (1988) of the contact between Sequence A and the overlying sequence shows that Sequence A sediments would crop out landward of the coastal dune cordon. The St. Lucia Formation crops out onshore north and south of Hell's Gate in Lake St. Lucia (Sydow, 1988). Sydow's (1988) assumption is by virtue of the fact that a gravity core retrieved in Leven Canyon (Siesser, 1977) from a depth of 380m where Sequence A crops out, contained Late Cretaceous age sediments as dated by Siesser (1977). In the case of Sequence A, the high amplitude reflectors probably represent interbedded silts, sands and calcareous concretions of which the St. Lucia Formation is constituted (Kennedy and Klinger, 1975; Dingle *et al.*, 1983).

3.4.2 Sequence B

Sequence B directly overlies Sequence A on the outer shelf and upper continental slope. Sequence B has a more complex internal reflection configuration and external geometry. By marking boundaries between gradational changes in seismic reflection characteristics, three **seismic facies** were recognised (although they are not always discernible on all seismic sections). **Facies 1**, consisting of high continuity, sub-parallel and sometimes divergent reflectors of high amplitude, grades laterally into discontinuous to chaotic reflectors of low amplitude (**Facies 2**) on the outer shelf. These in turn grade seawards into more steeply dipping sub-parallel, low amplitude reflectors of high to medium continuity (**Facies 3**) on the continental slope. Where the seismic stratigraphic relationships are well developed (e.g. in the Richards Bay area), Facies 1 reflectors onlap against Reflector **a** beneath the continental shelf. Erosional truncation of inshore Facies 1 reflectors by Reflector **b** also occurs in places. An unknown thickness of Sequence B sediments has therefore been eroded during sea-level regressions. On the continental shelf, Sequence B sediments are buried by younger sediments. On the shelf edge and continental slope however Sequence B sediments crop out. Steeply dipping Facies 3 reflectors downlap against the underlying Reflector **a** in places. Sequence B sediments generally attain a maximum thickness on the upper slope and pinch out in both onshore and offshore directions where Sequence A crops out.

On some seismic sections, there is evidence of a downlap surface within Facies 3, as well as an onlap surface within the outer-most upper slope sediments. This indicates that Sequence B could be further sub-divided into other sequences indicating a more complicated structure and history than is outlined in this study.

The overall geometry of Sequence B suggests a prograding reflection configuration (Mitchum *et al.*, 1977) indicative of a complex pattern of outbuilding and upbuilding. Previous workers (Sydow, 1988; Martin and Flemming, 1988) have been more specific when describing reflection configuration of continental shelf and slope sediments, describing them as complex sigmoid-oblique progradational clinoforms. The present study is less specific because the author does not believe the resolution and overall quality of the sparker seismic profiles is sufficiently high to observe specific variations of prograding reflection configuration. The internal reflection configuration of Sequence B is described simply as prograding, and is interpreted as representing strata deposited during significant lateral outbuilding or progradation.

Spatial relationships between the recognised seismic facies can be interpreted in terms of environmental setting, depositional processes and estimates of lithology. Divergent reflection configuration of Facies 1 could indicate progressive tilting of the depositional surface. High lateral continuity of Facies 1 reflectors indicates high lateral continuity of strata. The discontinuous to chaotic low amplitude reflectors of Facies 2 are indicative of poorly stratified sediments possibly rapidly deposited during a period of high sedimentation. Poor stratification could also be due to the reworking effect of the Agulhas current or reworking due to deposition above wavebase during Pleistocene transgressions and regressions. In some seismic sections, the chaotic nature of Facies 2 is due to the high sonic velocity and poor penetration through cemented overlying lithologies. The subparallel, more steeply dipping, low amplitude Facies 3 reflectors of greater continuity on the upper continental slope represent sediments deposited over the shelf break below wave-base. The fact that Facies 1 reflectors are more continuous than Facies 2 reflectors could signify lateral lithofacies contrasts, perhaps a gradual offshore decrease in grain size. It is also possible that the Agulhas Current, which may be responsible for Facies 2 reflector disruption was not as effective further inshore during the shallower water deposition of Facies 1. Overall characteristics of Sequence B indicate a period of high terrigenous influx.

Onlap of Facies 1 reflectors against Reflector a indicates deposition of Sequence B sediments during a period of sea-level rise.

As mentioned, shelf-edge prograding sequences have been documented on the east coast by previous workers (Martin and Flemming, 1988; Sydow, 1988). Martin and Flemming (1988) recognised prograding units overlying deformed Pliocene strata on sparker seismic records east of Durban. Martin and Flemming therefore favour a Late Pliocene or Pleistocene age for these sediment bodies. Sydow recognised complex sigmoid oblique prograding clinoforms on the continental shelf adjacent to Leven Point (his Sequence C). Sydow interpreted his Sequence C as a manifestation of increased terrigenous supply to the continental margin towards the end of the Tertiary. This is interpreted on the basis of information from other studies. Martin (1984) has calculated that sediments above his Miocene/Pliocene age (approximately 5Ma) Horizon Jimmy in the Limpopo cone were deposited at a very high rate (approximately 234m per million years). Geomorphological studies by Partridge and Maud (1987) correlated these high offshore sedimentation rates with major erosional cycles initiated by hinterland uplift which began in mid-Miocene times and was accentuated during the Pliocene (Sydow, 1988).

The position of Sequence B on the continental shelf and slope and its similar internal reflection configuration led to the interpretation of this sequence as the age and genetic equivalent of Sydow's Sequence C. Thus, it represents a sequence of high terrigenous influx deposited during the Miocene and Pliocene periods. It is stressed that this is an assumption based broadly on conjecture without the benefit of borehole data.

3.4.3 Sequence C

Sequence C is thinly developed, often close to the resolution of the sparker tool. Recognition was therefore not straightforward. Unlike Sequence B, Sequence C was not defined in terms of an overall distinguishable internal reflection configuration and reflection termination geometry, but rather by its relative position on the continental shelf and by the presence of Reflector **a** or **b**, an underlying erosive reflector. The bottom of Sequence C is marked by Reflector **b**, an undulating reflector of high continuity visible on some sections on the outer continental shelf. Internal reflection configuration of Sequence C varies between discontinuous low amplitude reflections to an acoustically semi-transparent unit. Sequence C sediments could also be delineated by recognising subtle sea-floor profile irregularities on the outer continental shelf. Where the normally smooth and flat continental shelf sea-floor exhibited local concave downward trends up to 8m in vertical relief, these features were interpreted as palaeo-shelf lateral outbuilding limits during a decreased terrigenous influx (relative to conditions prevalent during Sequence B deposition). The base of Sequence B could therefore be inferred as being present at the inflection point on the shelf, and could be extrapolated shorewards on the section at a shallow angle approximately parallel to the shelf profile. In places the intersection of Reflector b extrapolations and outer shelf profile inflection points coincide thereby strengthening the assumption.

The position in the stratigraphy and morphology of Sequence C suggests that it is the equivalent of Sydow's (1988) Sequence D. Sydow interprets this Sequence as the eroded remnants of a shallow-marine nearshore facies deposited above wavebase during a period of decreased terrigenous influx. Sydow assigns a probable Pleistocene age to these sediments. During the Pleistocene, numerous glacially induced sea-level fluctuations took place. Sequence C sediments would therefore have been intermittently exposed and eroded during this period.

3.4.4 Sequence D

Sequence D sediments manifest themselves as isolated irregular ridges on the continental shelf profile, usually less than 1km wide. In some sections, Sequence D sediments are recognisable where they have been buried by younger material, on the basis of a similar external geometry. Vertical relief of these ridge features varies but for the most part it is less than 8m although in places, vertical relief can be as high as 20m. Due to the bubble pulse effect (see Appendix A) and low relief of these features, internal reflection configuration of these sediments is mostly obscured by the multiple reflection package at the sediment/sea water interface unless substantial thicknesses are present. A continuous outcrop pattern could be inferred between some adjacent seismic profiles where ridge features occur at the same depth below sea-level and in a similar position relative to the continental shelf edge.

The external geometry and outcrop pattern suggests that Sequence D sediments are submerged aeolianite ridges. Submerged aeolianite ridges have been documented on the southeast African continental shelf by various workers (McCarthy, 1967; Birch, 1996; Martin and Flemming, 1986; Ramsay, 1991, 1994). Some of these submerged aeolianite ridges form the substrate for various species of coral and have therefore become popular SCUBA diving localities. These ridges are thought to have formed during glacially induced sea-level lows, when sea-level was lowered such that the presently submerged shelf was exposed (Ramsay, 1991). Sandy deposits on the shelf were transported by the prevailing northeasterly (oblique-onshore) winds to form coast parallel dune ridges similar to the present day dune cordons adjacent to, and inland from the present day coastline (Ramsay, 1991; Wright, 1995).

3.4.5 Sequence E

This sequence is mainly acoustically semi-transparent or consists of low amplitude, discontinuous reflectors. Since Sequence E is the youngest unit resolved, the top of this sequence is the present sea-floor. Sequence E is not continuous over the whole study area: rather it occurs as localised depocentres up to 30m thick on the inner shelf.

Due to the bubble pulse effect, thin Sequence E deposits up to 12m thick are obscured by the multiple reflection package.

Sequence E sediments are interpreted to be unconsolidated Holocene shelf sediments based on the previous interpretations of similar seismic sequences by Sydow (1988) and Birch (1996),. Unconsolidated shelf sediments have been described on the east coast of southern Africa in detail by such workers as Martin and Flemming (1986), Martin (1985) and Birch (1996). In a detailed seismic study, Birch (1996) noted that while there is a general dearth of unconsolidated Quaternary sediment on the eastern continental shelf, localised depocentres occur where the effect of the Agulhas Current is reduced. Depocentres are therefore found in the lee of major structural offsets of the coastline, in zones of bedload parting, behind protective headlands and embayments, in areas where the current is forced offshore due to the widening shelf. Birch (1996) and Martin and Flemming (1986) note that accumulations also occur landwards of linear Pleistocene aeolianite ridges (Sequence D) where these positive relief features have a damming effect.

3.4.6 Comparison with Sydow's seismic stratigraphy

As mentioned there are many similarities between the seismic stratigraphy outlined above, and that described by Sydow (1988) in his Leven Point area study. All of the seismic sequences described in this study can be correlated with seismic sequences recognised by Sydow. Sydow's interpretation differs however, in that his Sequence B was not positively identified in any of the seismic profiles interpreted during this study. Failure to recognise Sydow's Sequence B in this study does not necessarily infer doubt of its existence. In Sydow's study, Sequence B was not as clearly defined as Sequences A and C. It is therefore possible that minor Sequence B material was overlooked because of the inferior resolution of the Sparker systems used or that it is only well developed in the Leven Point area (for a description and interpretation of Sydow's Sequence B see section 2.1.1).

3.4.7 Detailed Sparker Seismic Stratigraphy

In the following sections, the study area was subdivided into five smaller areas and detailed descriptions of local seismic stratigraphic and sedimentological features and variations between these areas are described. Area subdivision is shown in Figure 3.4. The study area was subdivided at Cape St. Lucia, Leven Point, Lake Bhangazi and Lala Nek. Some representative sections and interpretations illustrating general seismic stratigraphy for each area are included.

3.4.7.1 Mtunzini to Cape St. Lucia

Some representative seismic sections and line drawing interpretations are shown in Figures 3.5a to 3.5i. The 36km wide continental shelf at Mtunzini is the widest shelf in the study area. This wide continental shelf is situated in the lee of a structural offset of the coastline where it changes in orientation from NNE to NE. The shelf narrows rapidly to 6km at Cape St. Lucia. The shelf break occurs at a depth varying between 80m and 120m. Coast perpendicular sparker seismic sections in this area exhibit broad flat continental shelf profiles. The sediment/water interface is generally smooth except where it is interrupted by the presence of aeolianite dune ridges (Sequence D). Subaqueous dunefields on the northern KwaZulu-Natal continental shelf are usually north or south migrating (Flemming, 1978) depending on the local current conditions and are therefore not easily recognised on coast-perpendicular seismic sections. Sidescan sonography studies by Flemming (1978) show that subaqueous sand dunes are present on the continental shelf directly offshore Richards Bay at a depth of approximately 90m. Although not obvious, low relief undulations on the outer shelf profile (Fig. 3.5f) at this point could possibly be subaqueous dunes.

Apparent dips observed on seismic sections are vertically exaggerated. Only an approximate angle of dip could be calculated by assuming that the strike directions of the sedimentary units are approximately parallel to the present -100m isobath, and then using trigonometry to calculate real dip. Sequence A reflectors dip seawards at an angle of approximately 2.8° to 3°. These seaward dipping reflectors are truncated inshore by the sea-floor (with a thin veneer of Sequence E sediments). The truncation surface at the top of this sequence on the continental shelf (Reflector a) exhibits possible erosional morphology in places (Figs. 3.5f and i) Further offshore, Sequence A reflectors are truncated by Reflector a, a gently undulating reflector dipping seaward at an angle of approximately 0.5°. Beneath the continental slope however on two seismic

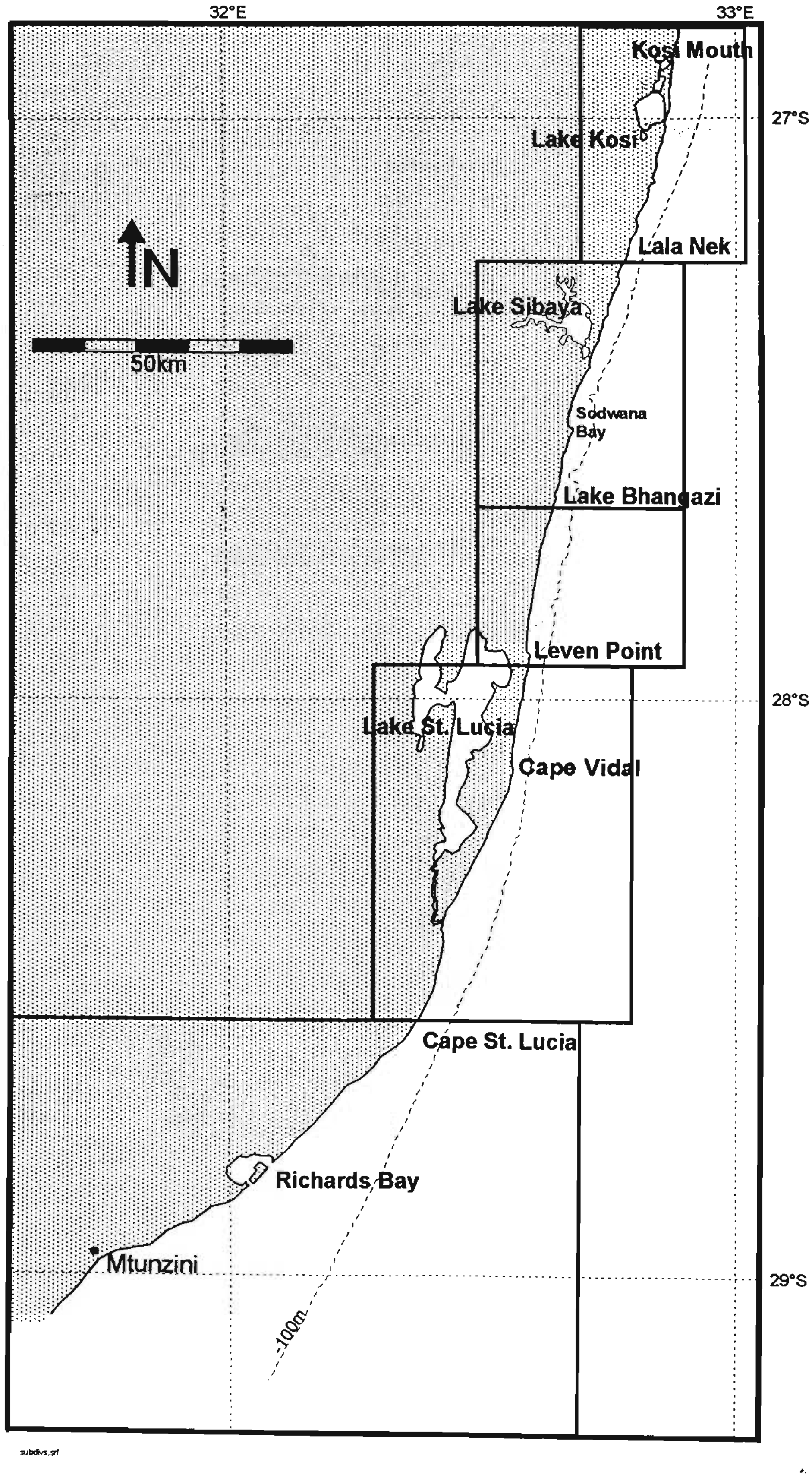


Fig. 3.4: Study area subdivision

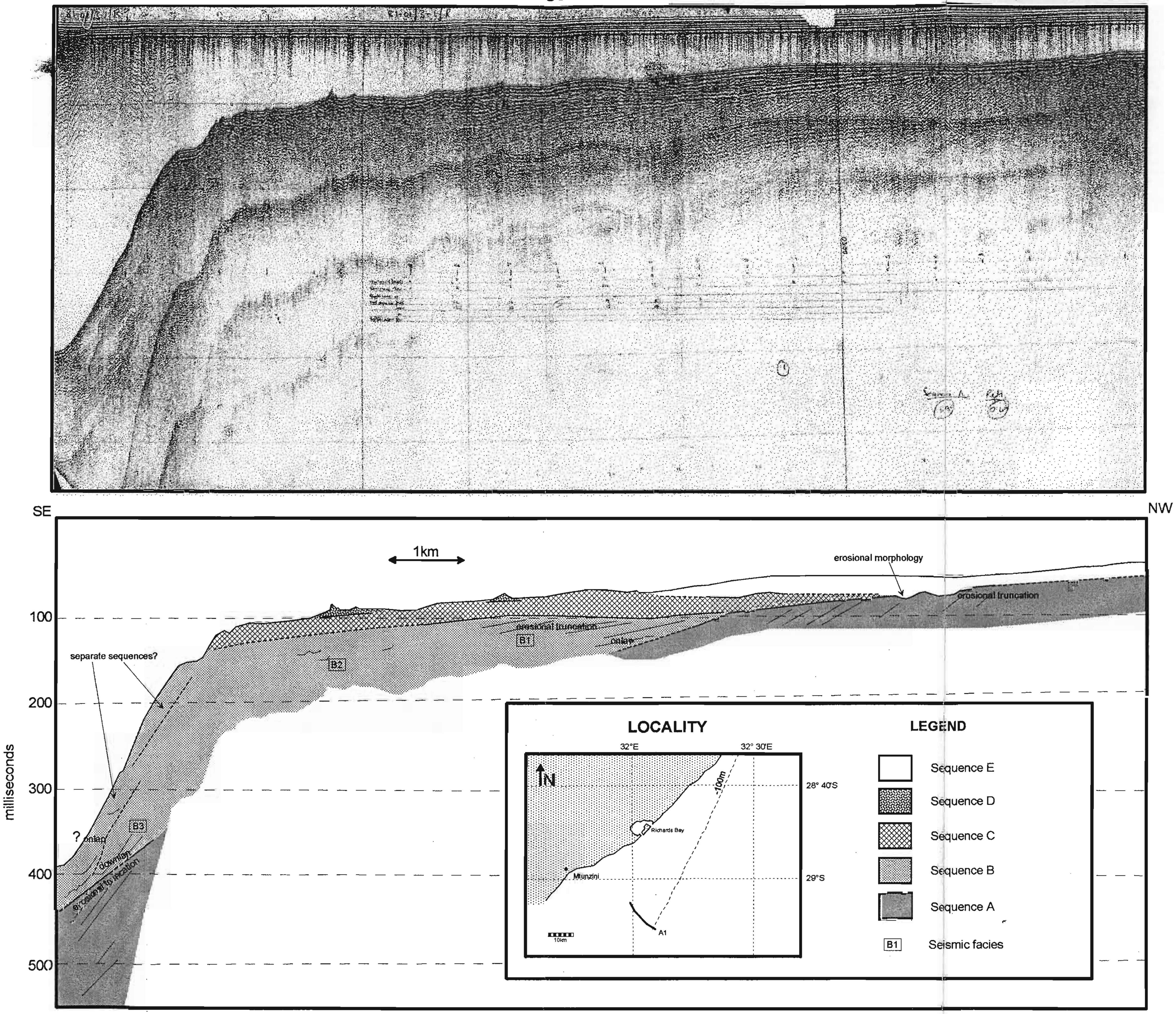


Fig. 3.5a: Sparker seismic section and interpretation of profile A1, offshore of Mtunzini

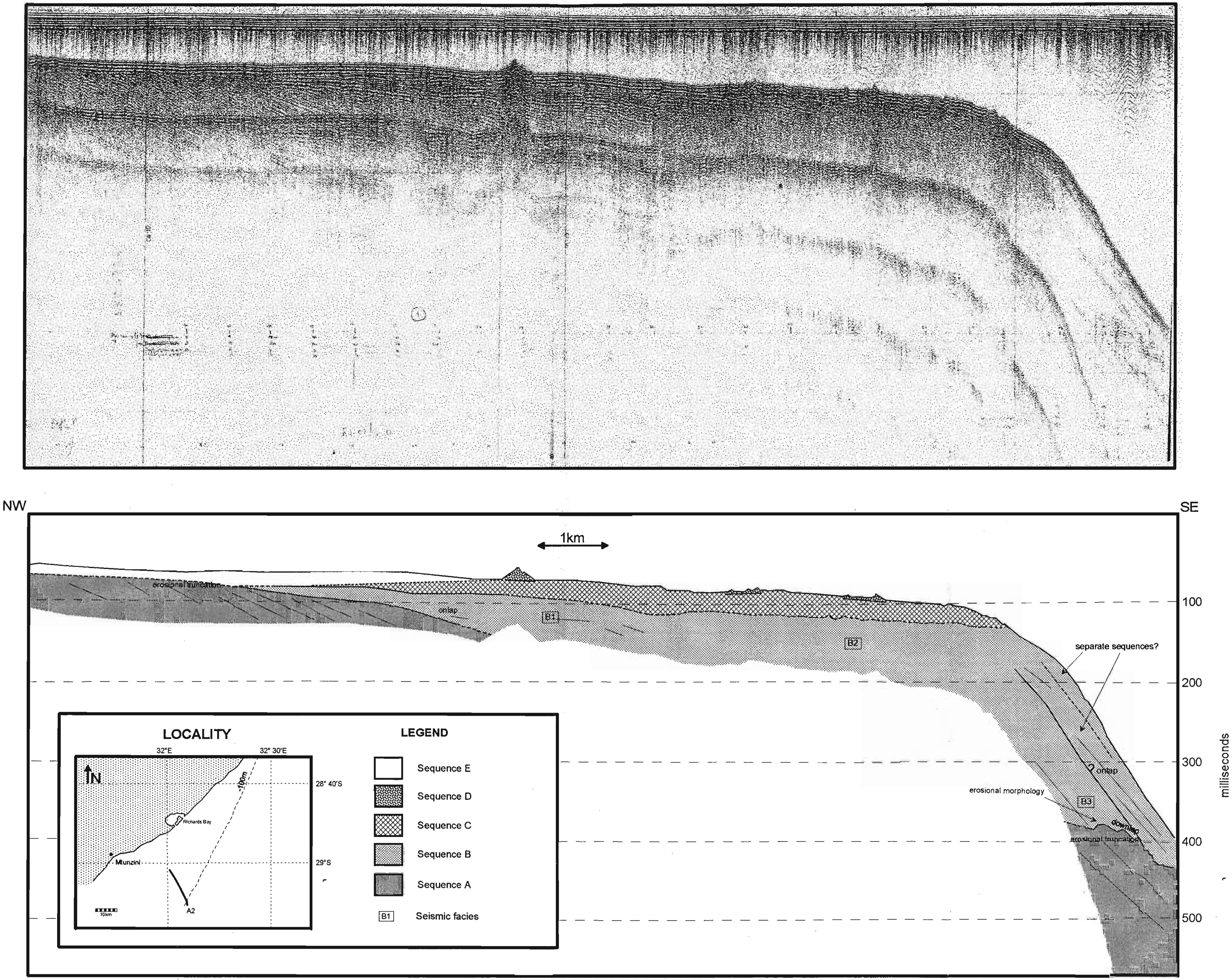


Fig. 3.5b: Sparker seismic section and interpretation of profile A2, offshore of Mtunzini

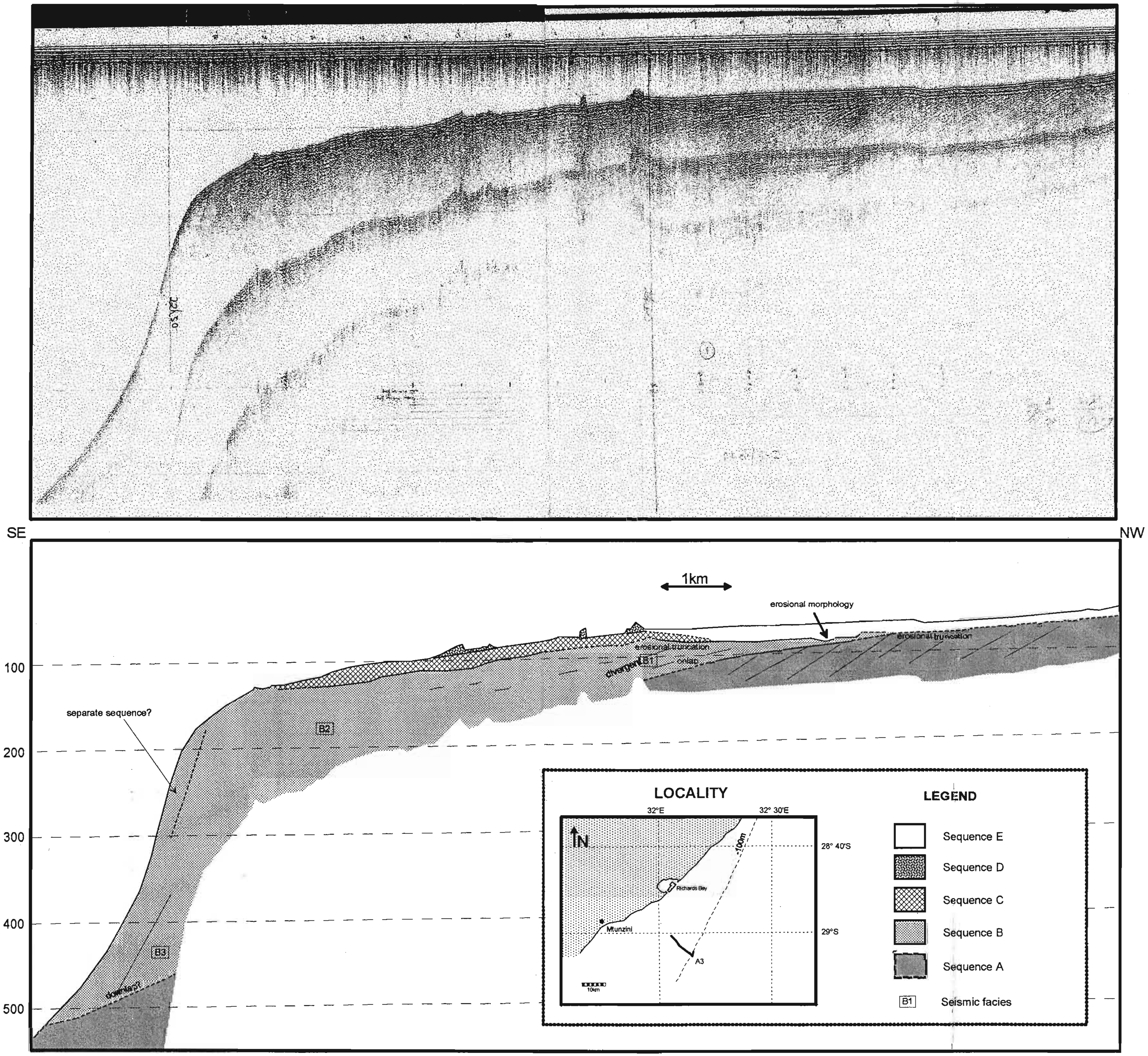


Fig. 3.5c: Sparker seismic section and interpretation of profile A3, between Mtunzini and Richards Bay

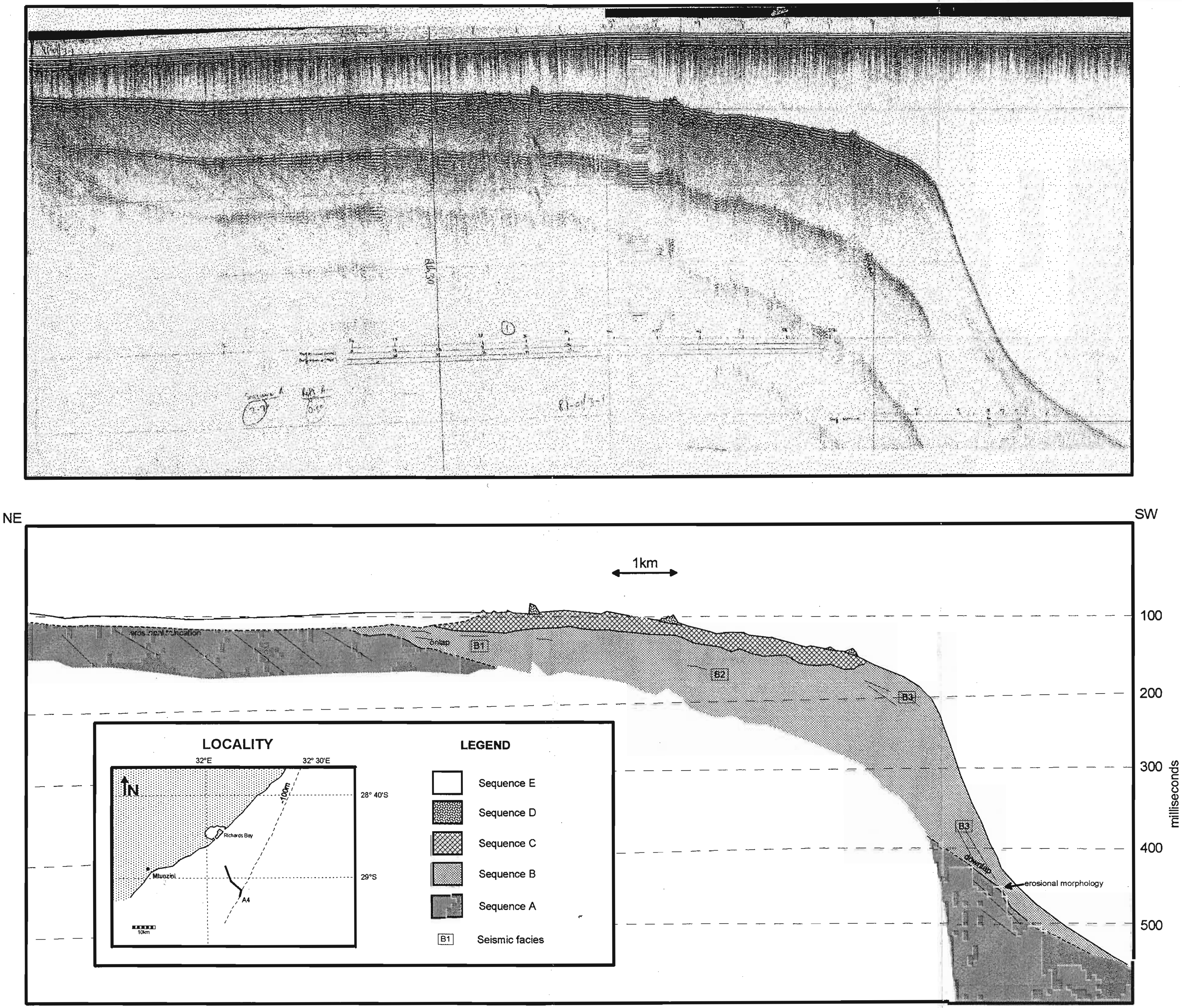


Fig. 3.5d: Sparker seismic section and interpretation of profile A4, between Mtunzini and Richards Bay

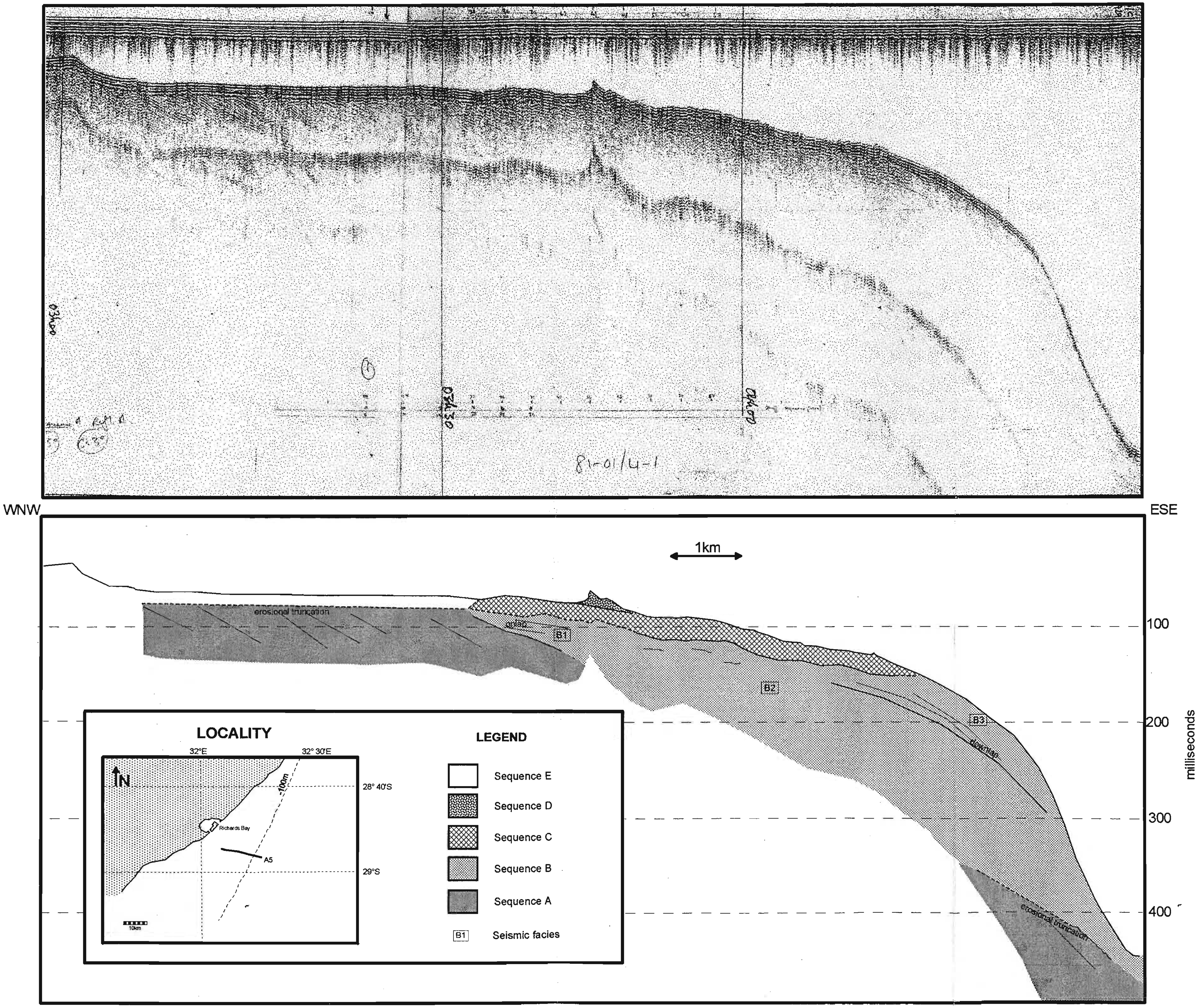


Fig. 3.5e: Sparker seismic section and interpretation of profile A5, south of Richards Bay

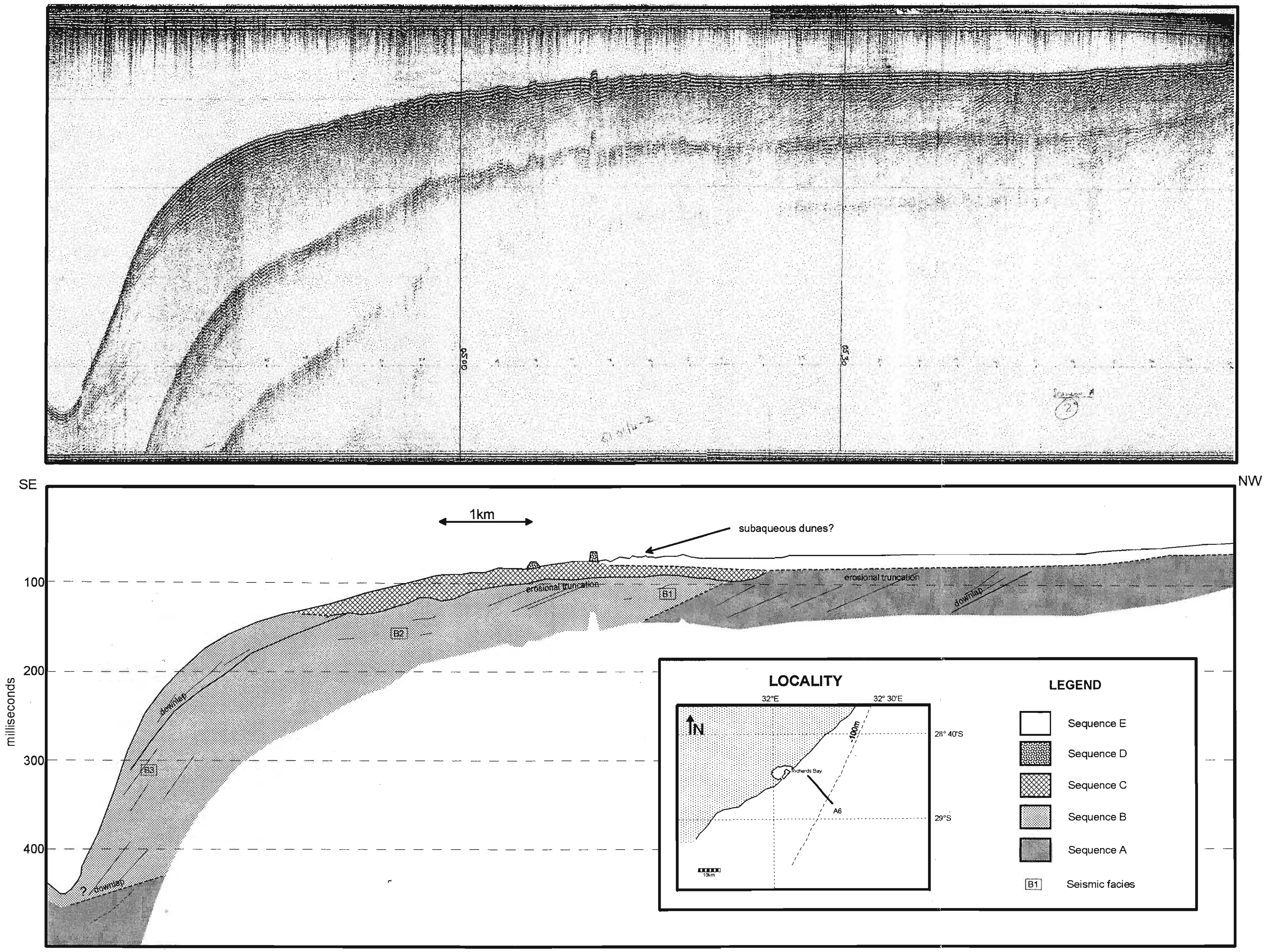


Fig. 3.5f: Sparker seismic section and interpretation of prfile A6, offshore of Richards Bay

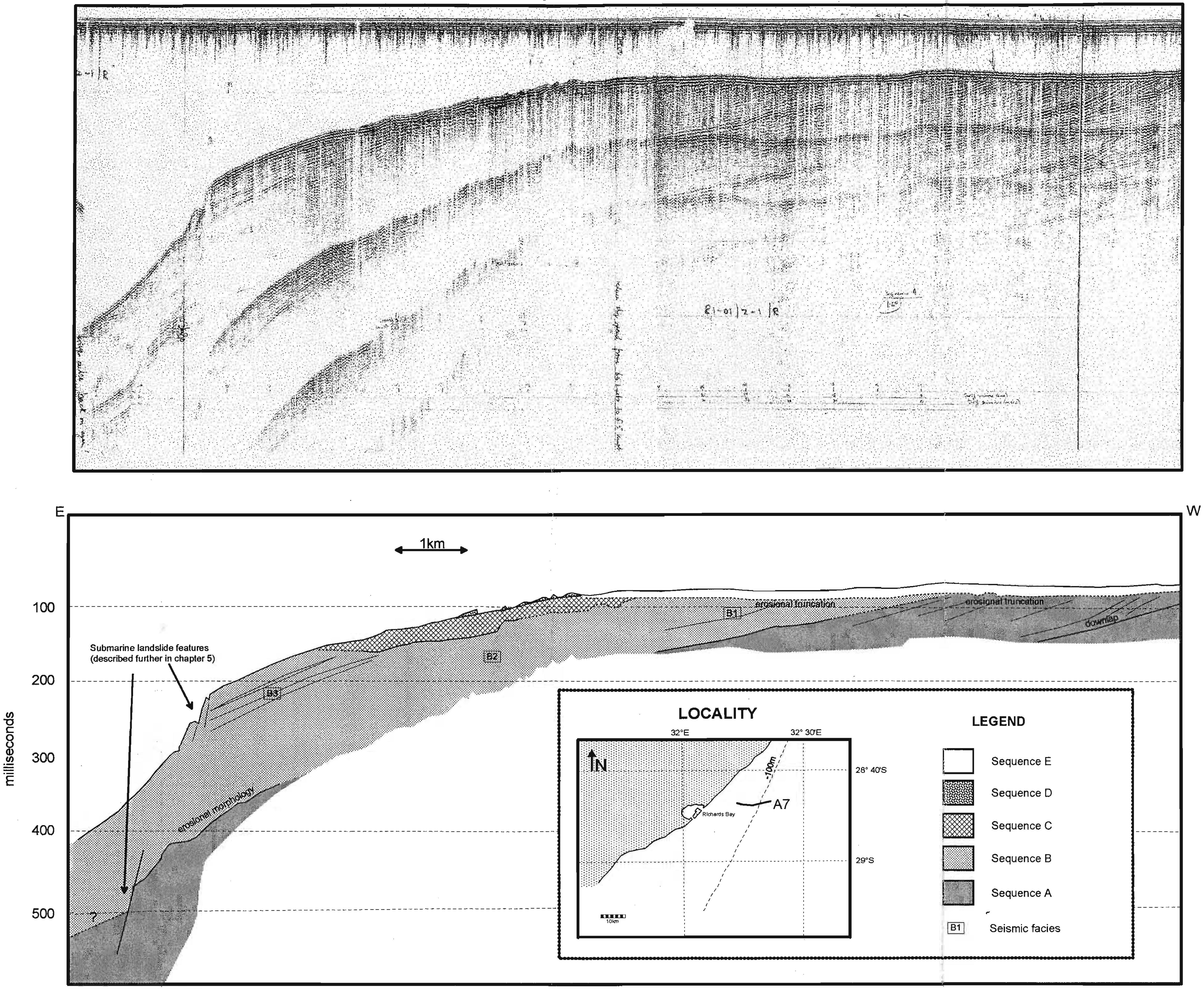
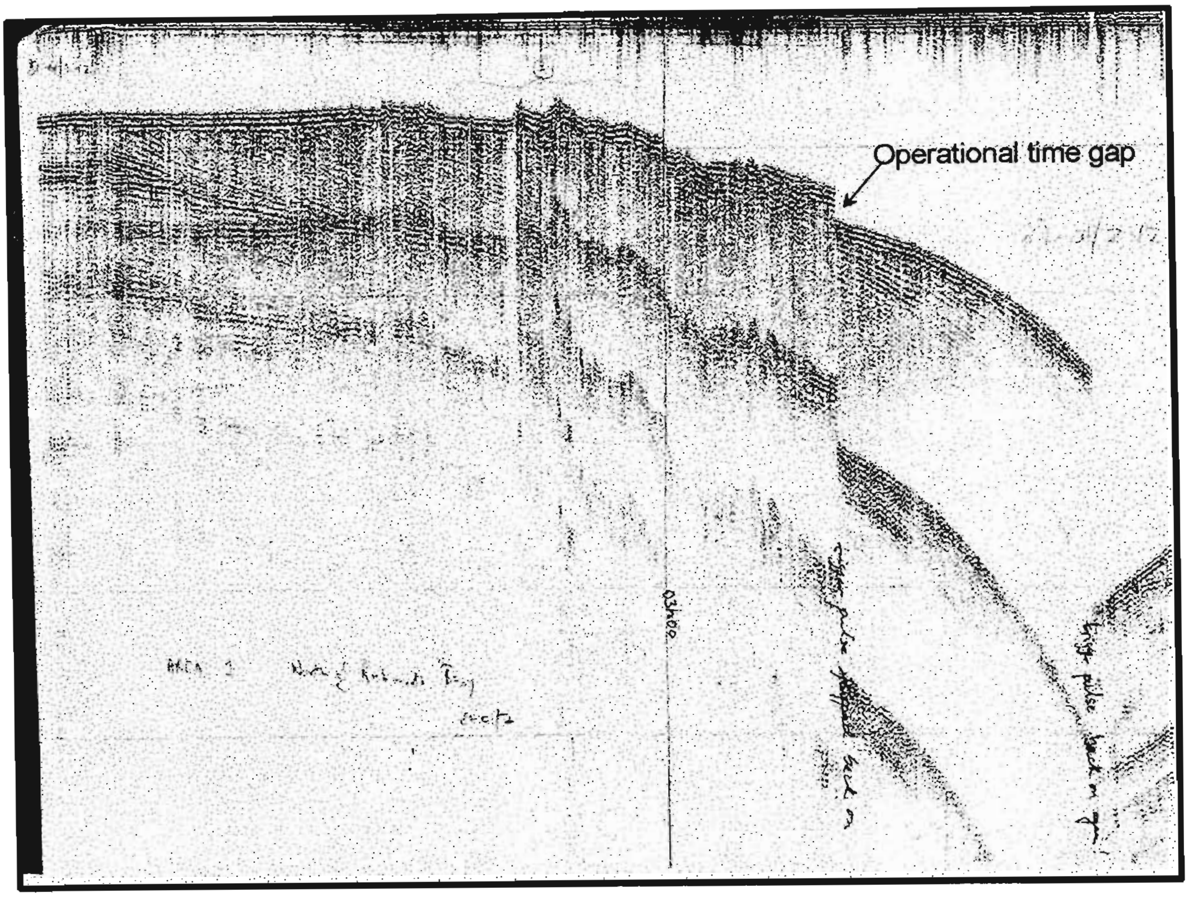


Fig. 3.5g: Sparker seismic section and interpretation of profile A7, north of Richards Bay



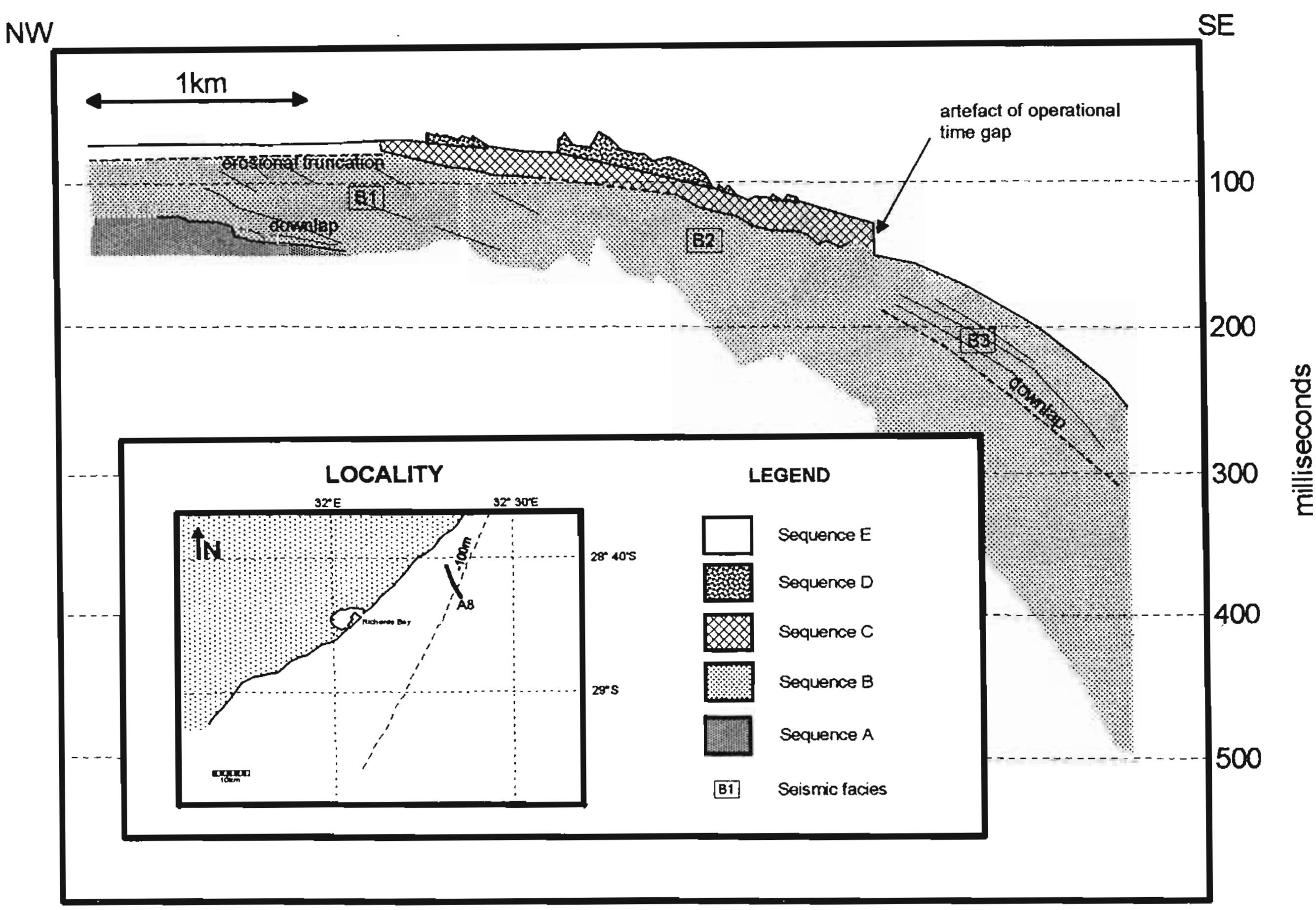


Fig. 3.5h: Sparker seismic section and interpretation of profile A8, north of Richards Bay

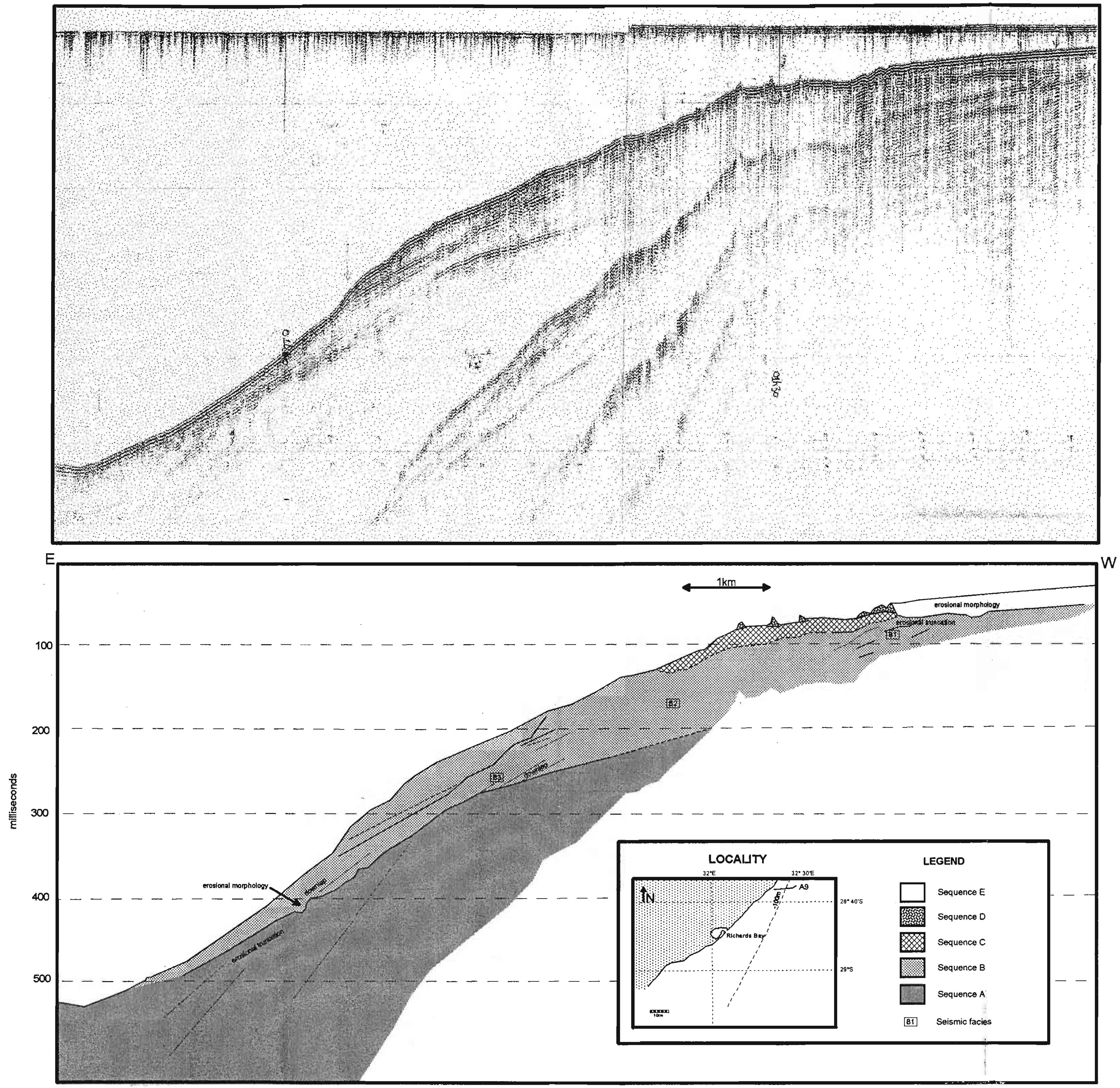


Fig. 3.5i: Sparker seismic section and interpretation of profile A9, north of Richards Bay

sections (Figs. 3.5b and i), Reflector a exhibits an erosive morphology to a depth of approximately 400msec (i.e. approximately 320m). This could either be subaerial exposure morphology or even a buried glide plane of a mass-wasting feature (mass wasting features are described further in Chapter 5). A downlapping unconformity within Sequence A is visible in the inshore portions of Figures 3.5f and h. This testifies towards a more complex sequence stratigraphy of the incompletely exposed Sequence A.

Sequence B is best exposed on the continental shelf off Richards Bay since all three seismic facies which constitute Sequence B are discernible. Discontinuous to chaotic Facies 2 reflectors on the outer shelf grade landwards into more continuous, sub-parallel Facies 1 reflectors of higher amplitude and seawards into continuous, steeply-dipping Facies 3 reflectors. Divergent reflection configuration is evident within landward extremes of this sequence whereby lateral reflection terminations occur within the sediment wedge, in the direction of convergence of the reflectors (Fig. 3.5c). This is probably due to the landward thinning of these strata beyond the resolution of the sparker seismic tool. On the continental slope, Facies 3 reflectors downlap against Reflector a in places. The upper-slope is characterised by the possible presence of a discrete sequence within sediments marked as Sequence B, marked by external geometry slope irregularities with chaotic to acoustically transparent internal reflection characteristics (Figs. 3.5 a, b and c). Further north this package thickens and is marked in places by downlap surface (Figs. 3.5e, f, g and h). Although not very clear there is also possible evidence of a downlap surface within the lower, outer portion of sediments marked as Sequence B, Facies 3 (Figs. 3.5a and b).

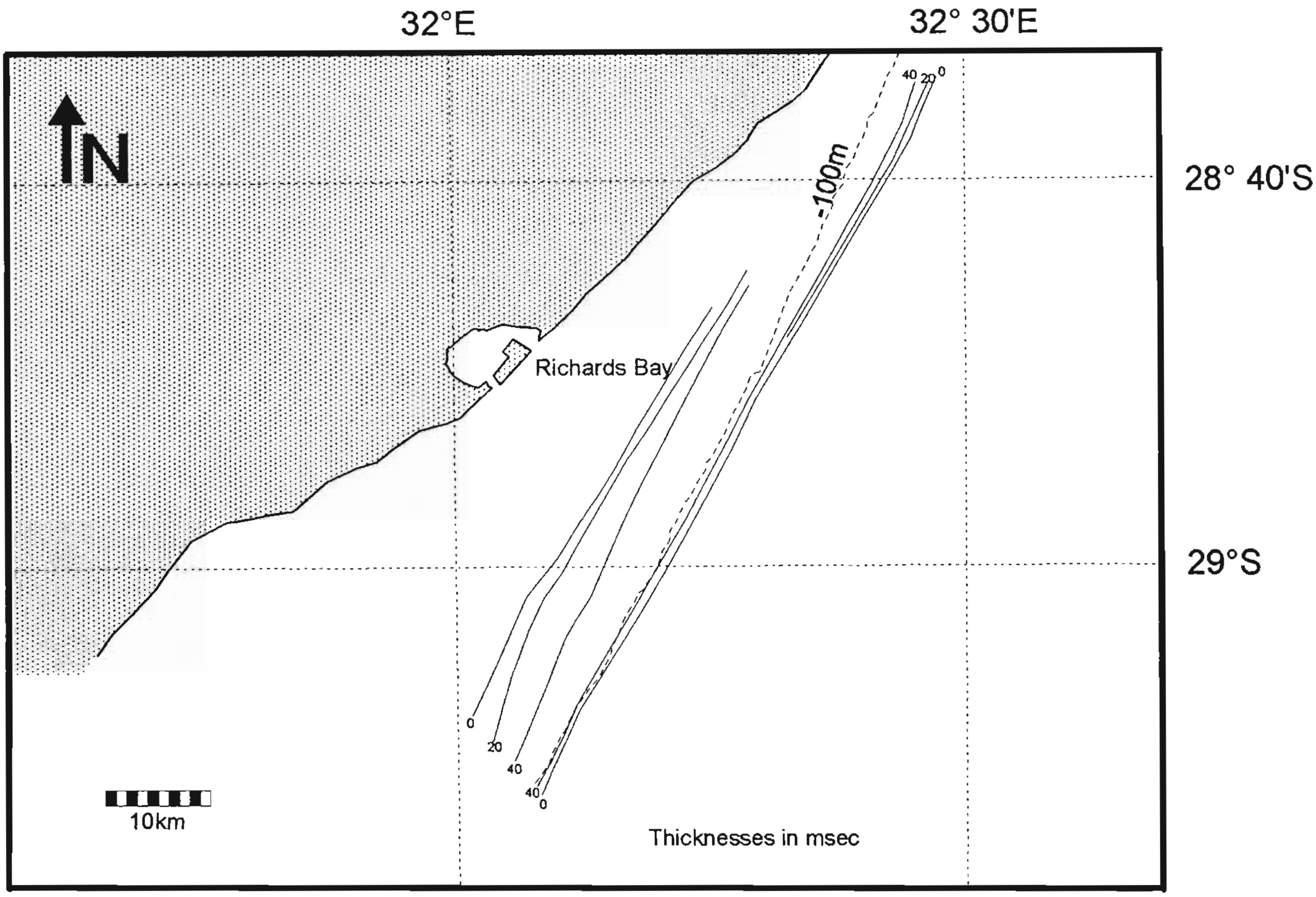
Figure 3.6 shows contoured thicknesses of Sequence B in msec. (thickness determination methods are described in Appendix A). Sequence B rapidly thickens seawards from a point of zero thickness on the mid-continental shelf to a maximum thickness of approximately 150m at the outer continental shelf, whereafter it thins rapidly and eventually pinches out, exposing Reflector a, on the continental slope. In most seismic sections the maximum thickness can not be calculated on the outer continental shelf due to the fact that Reflector a is obscured by the multiple reflection package of the sea-floor. The trend of the Sequence B isopachs shows that the inshore outcrop of the contact between Sequence A and Sequence B is not coast parallel, but moves steadily towards the shore in a northward direction. Extrapolation shows that this contact crosses the shore in the Cape St. Lucia area. Furthermore Sequence B isopachs for thicknesses of 0, 20 and 40 msec, converge in a northerly direction indicating a more gradual thickening in the south compared to in the north.

Sequence B is covered completely by Sequence C sediments on the continental shelf south of Richards Bay but crops out on the continental slope. The depth at which Sequence B pinches out (i.e. the depth at which Reflector a crops out on the continental slope) varies between 250msec and 470msec.

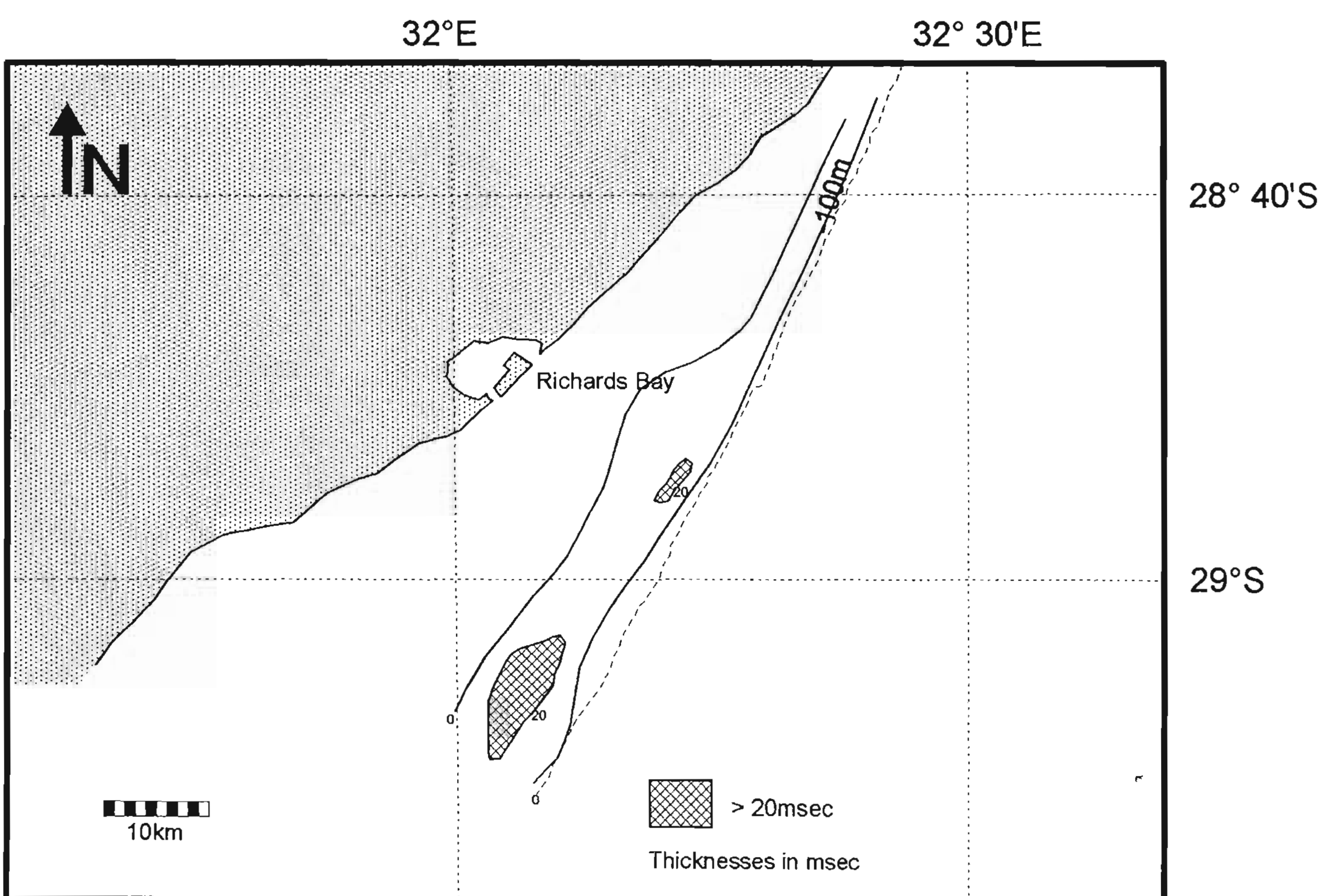
The continental slope in this area is smooth and concave except on one section just north of Richards Bay (Fig. 3.5g) in which the smooth profile is interrupted by a submarine landslide (submarine landslides features observed on sparker records are discussed further in Chapter 5).

Sequence C was delineated, and thicknesses calculated in this area either by recognising the underlying irregular Reflector b or by recognising subtle irregularities on the shelf profiles. Where the normally smooth seaward deepening shelf profile exhibited sudden downward profile irregularities up to 8m in vertical relief, these features were interpreted as palaeo-shelf edges i.e. the limit of lateral outbuilding during a decreased terrigenous influx (compared to high terrigenous influx conditions during deposition of Sequence B). The base of Sequence B could therefore be inferred as being present at the inflection point on the shelf, and could be extrapolated shorewards on the section at a shallow angle. Figure 3.6 shows approximate thickness of Sequence C sediments between Mtunzini and Cape St. Lucia. It shows that Sequence C sediments reach a maximum thickness of 24msec thinning progressively towards the shelf edge, usually pinching out on the extreme continental shelf edge.

On the continental shelf south of Richards Bay, 4 southwest-northeast trending continuous Sequence D outcrops (aeolianite dune ridges) are present (Fig. 3.7). These occur at depths of approximately 70, 74, 84, 96 and 138msec (measured at seaward base). From Richards Bay northwards these outcrops are not as continuous but were observed on various seismic sections at depths of approximately 74 and 84msec.



SEQUENCE B



SEQUENCE C

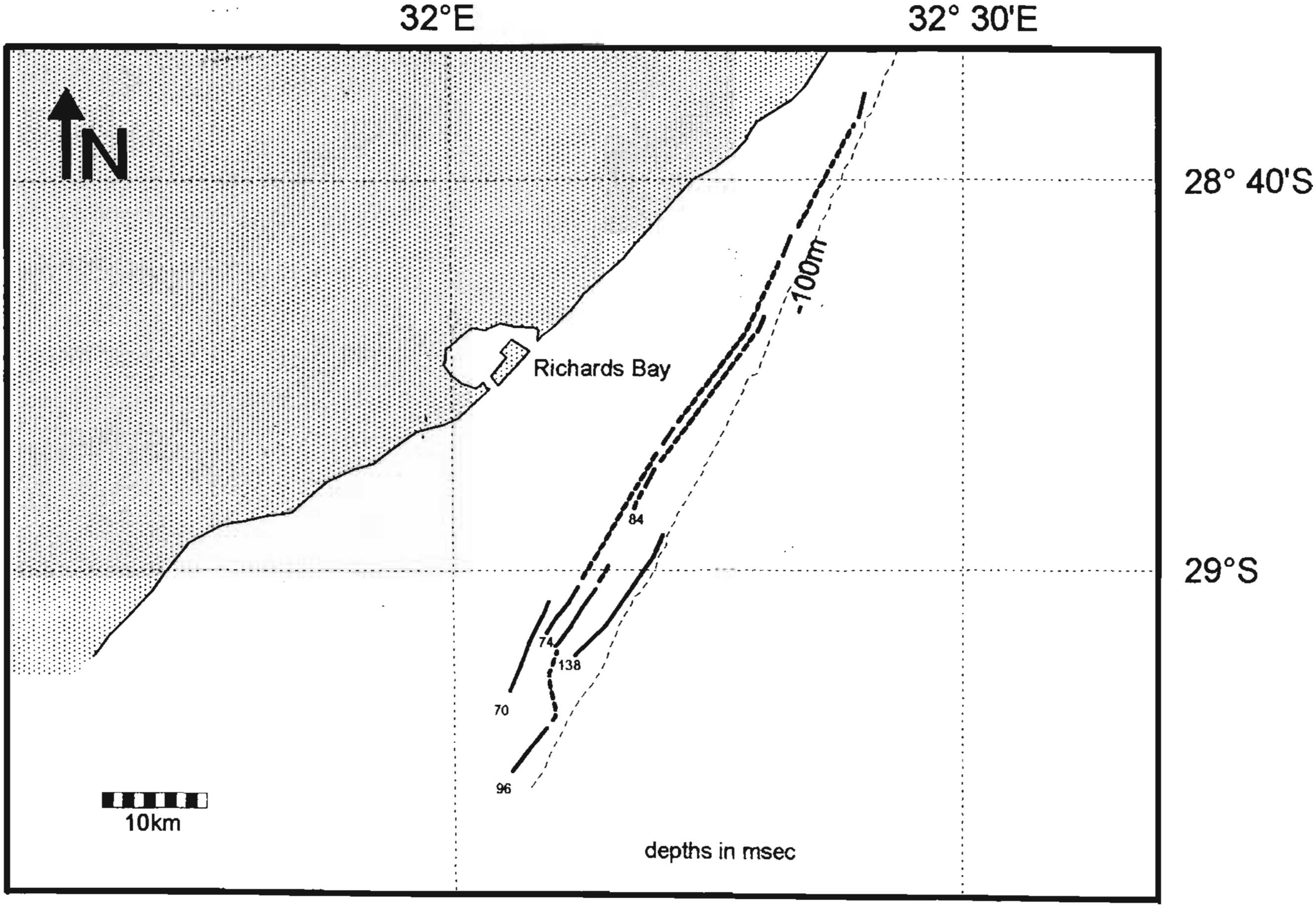


Fig. 3.7: Occurrence of Sequence D between Mtunzini and Cape St. Lucia

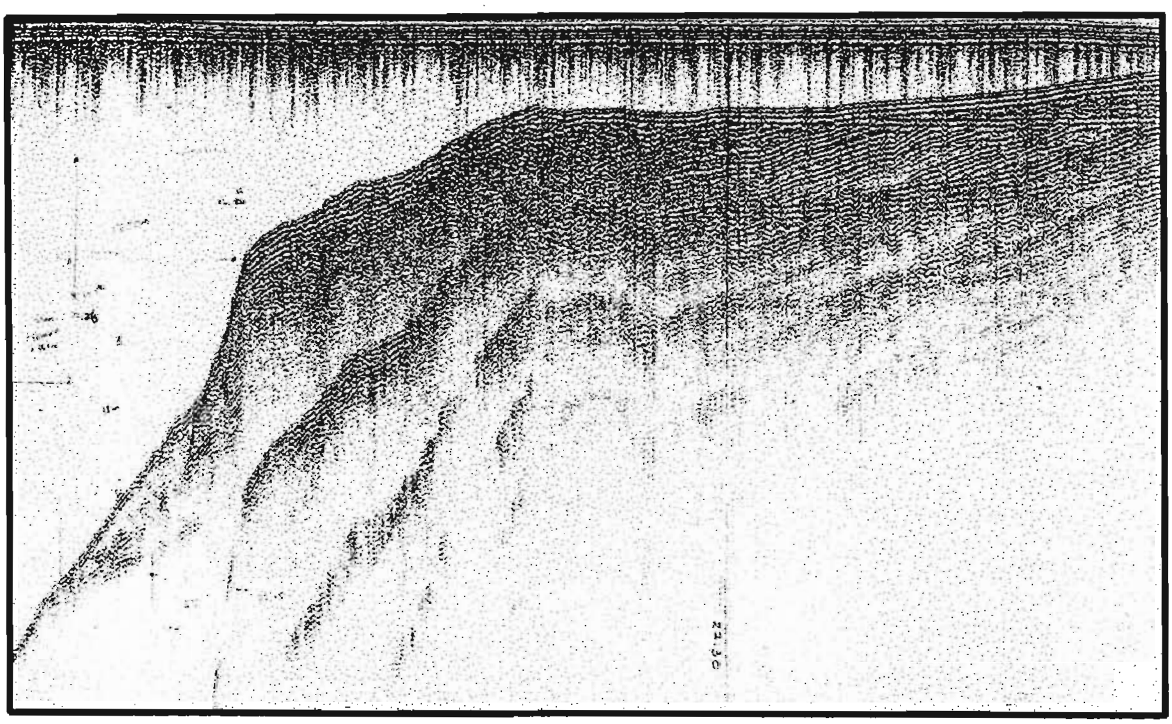
3.4.7.2 Cape St. Lucia to Leven Point

Some representative seismic sections and line drawing interpretations are shown in Figures 3.8 a to d. Some of the seismic sections are at an oblique angle to the coast. External geometry and form of seismic sequences and facies varies with the orientation of the seismic section. The oblique nature of the seismic sections in this area must therefore be borne in mind when observing seismic section interpretations. The Sequence B boundary on the continental slope is mostly delineated by recognising downlap of reflectors against the underlying Sequence A. Since downlap becomes less pronounced, the more oblique the section, Sequence B delineation proved more difficult in these seismic sections.

In the first area subdivision between Mtunzini and Cape St. Lucia, the slope profile is mostly smooth and concave downwards, between Cape St. Lucia and Leven Point the upper continental profile is characterised by complex slope angle changes due to submarine landslide processes and incipient submarine canyon development (submarine landslides and canyons are dealt with in more detail in Chapters 5 and 6). The upper continental slope in this area is therefore characterised by local topographic highs and minor submarine valleys.

Sequence A reflectors were not observed beneath the continental shelf on seismic sections in this area. This is because Sequence B sediments are present directly beneath the continental shelf to a depth greater than the first multiple reflection package of the sea-floor. Therefore, while Sequence A reflectors are present at an unknown depth beneath the continental shelf, they are obscured by the multiple reflection package. Apparent dip of Sequence A reflectors beneath the continental slope at St. Lucia Estuary Mouth is approximately 2.8° (Fig. 3.8a). In this profile, the top of Sequence A is bounded by Reflector a, a high amplitude continuous reflector dipping seaward at an apparent angle of 2.2°. Although not as clear as on some seismic sections between Mtunzini and Cape St. Lucia, Sequence A reflectors are erosionally truncated by Reflector a. Reflector a, defining the upper limit of Sequence A is not as distinct in this area.

Of the interpreted seismic sections, Reflector a is visible in Figures 3.8 a and b, directly



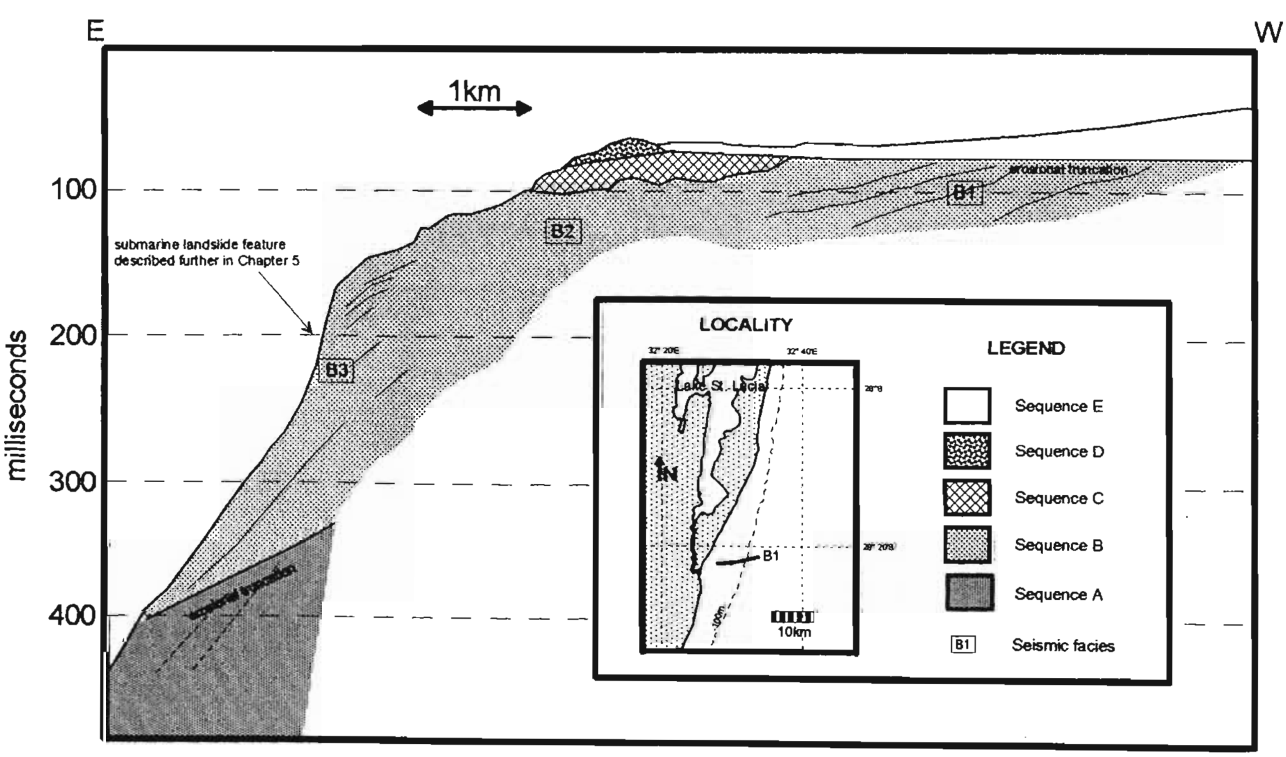
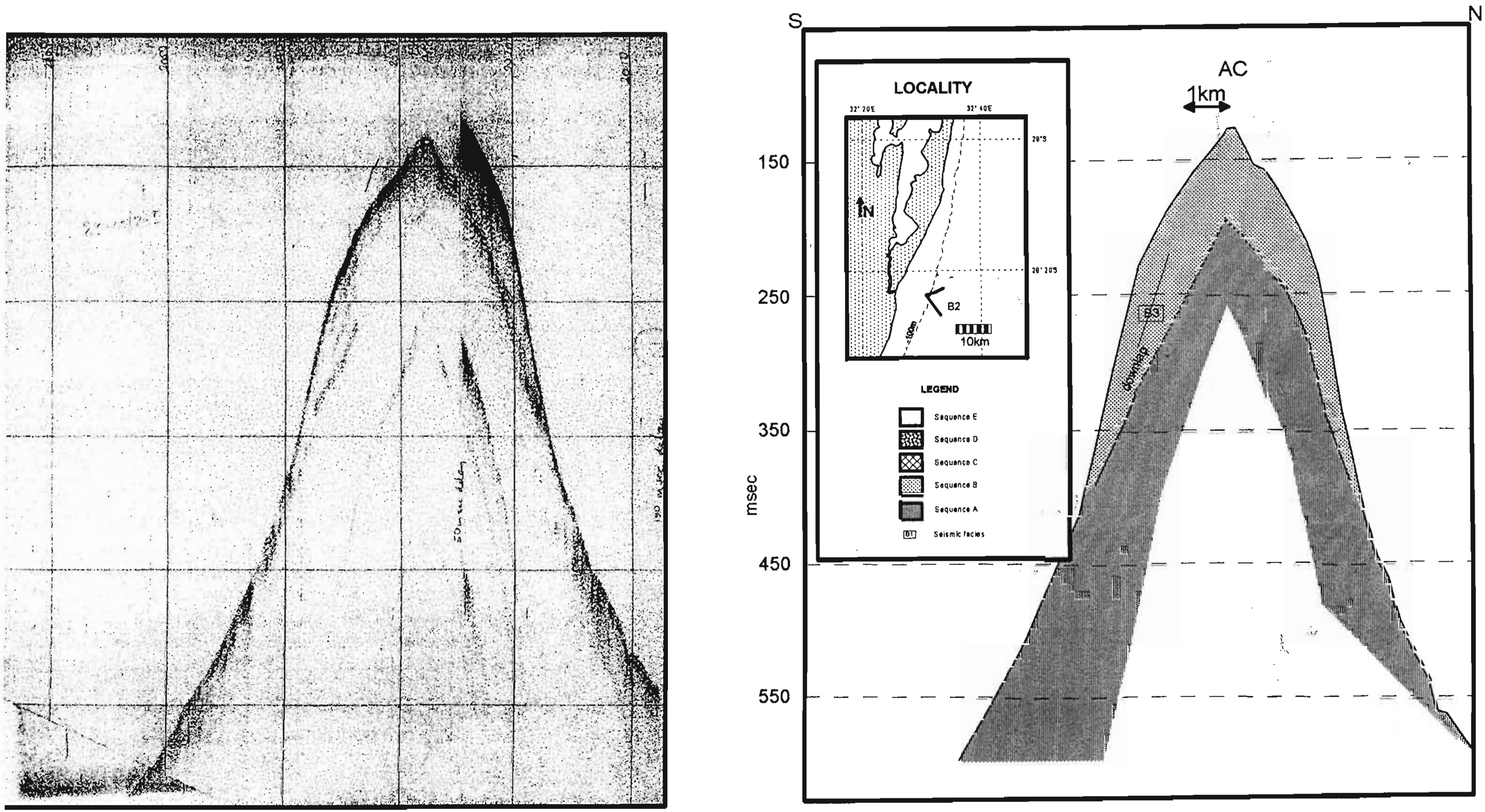


Fig. 3.8a: Sparker seismic section and interpretation of profile B1, offshore St. Lucia Estuary Mouth



ig. 3.8b: Sparker seismic section and interpretation of profile B2, offshore St. Lucia Estuary Mouth. Interpretation corrected for delay change

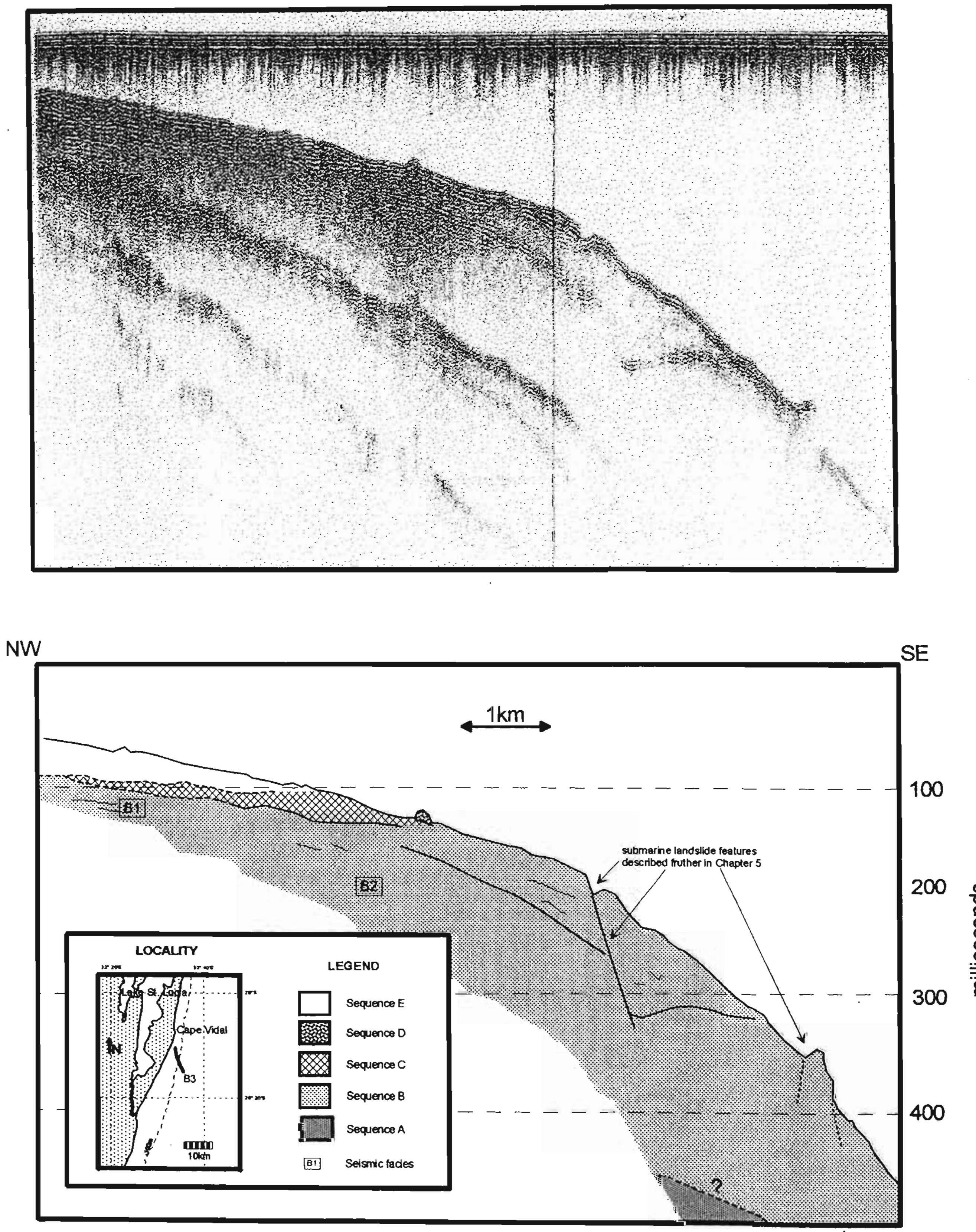


Fig. 3.8c: Sparker seismic section and interpretation of profile B3, south of Cape Vidal

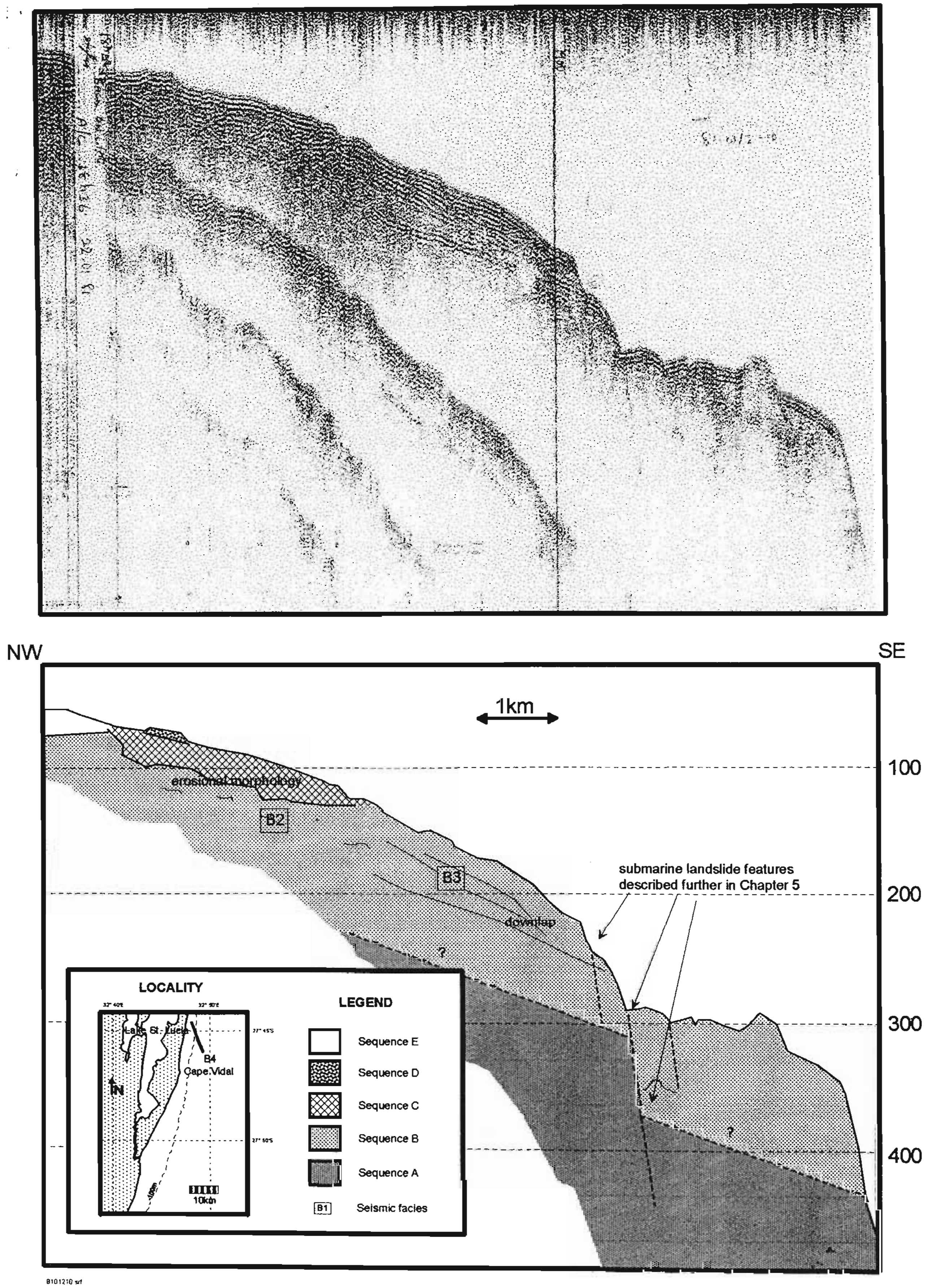


Fig. 3.8d: Sparker seismic section and interpretation of profile B4, north of Cape Vidal

offshore the St. Lucia Estuary mouth in which it is a distinct, continuous reflector showing little vertical relief, steeply dipping reflectors of Sequence B Facies 3 downlap against it beneath the continental slope. Since this reflector defines the bottom of Sequence B, the thickness of this sequence could not be determined throughout most of this study area subdivision. Sequence B thicknesses are shown in Figure 3.9. Sequence B attains an approximate maximum thickness of 160msec (128m) beneath the outer continental shelf. Beneath the continental shelf continuous reflectors of Facies 1 dipping seawards at an approximate angle of 1.6° grade seawards into chaotic, discontinuous reflectors of Facies 2 on the outer shelf. These in turn grade seawards into the more steeply dipping, continuous reflectors of the slope facies (Facies 3). Facies 1 reflectors are erosionally truncated inshore by Reflector b. As already mentioned, the inshore outcrop of the contact between Sequence A and Sequence B moves steadily onshore in a northward direction from the Richards Bay area. Extrapolation shows this contact to occur some distance onshore in the St. Lucia Estuary mouth area. On the narrow coastline north of Cape St. Lucia, Sequence B is therefore incompletely exposed. Since Reflector a (the lower limit of Sequence B) was not observed beneath the continental shelf in this area, the thickness of Sequence B sediments on the landward extremes of coast perpendicular sections is not known. Assuming similar geological relationships to those observed further south on the Richards Bay continental shelf, it is expected that Sequence B thins in a landward direction, eventually pinching out landward of the present coastline.

North of the St. Lucia Estuary mouth in Figure 3.8d, Sequence B contains a continuous, high amplitude reflector against which more steeply dipping slope facies reflectors downlap. As is the case in the area subdivision further south, this suggests a more complex Sequence B depositional history in this area, indicating a hiatus during lateral outbuilding. This reflector dips seawards at an apparent angle of approximately 1.5°.

Figure 3.9 shows the occurrence of Sequence C sediments between Cape St. Lucia and Leven Point. Except for in the St. Lucia Estuary Mouth area, the inshore limit of Sequence C is obscured by the first multiple reflection package of the sea-floor. North of this area therefore the inshore limit is inferred to trend approximately coast parallel in similar fashion to its inshore trend in the Richards Bay area. This sequence reaches a

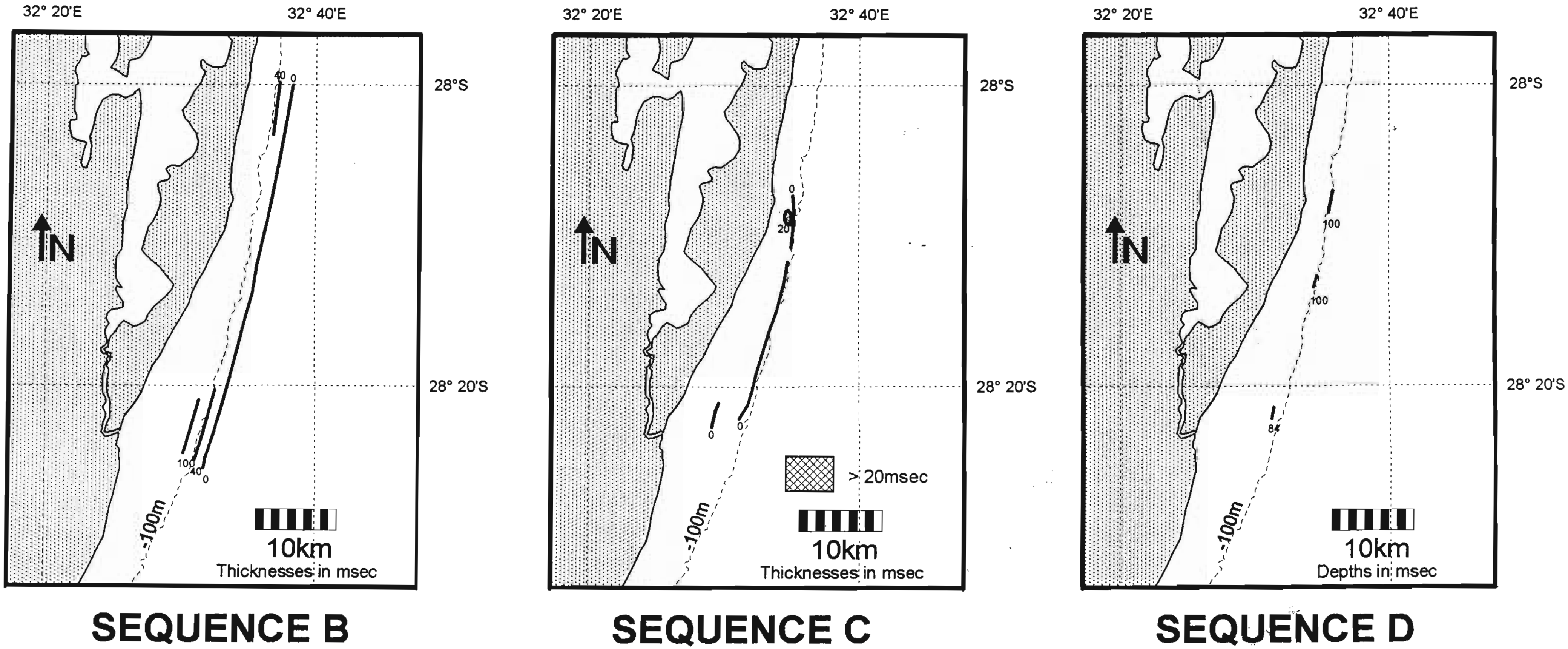


Fig. 3.9: Occurrence and thickness of Sequences B, C and D between Cape St. Lucia and Leven Point

maximum thickness of approximately 28msec (22m) and pinches out on the shelf edge.

Sequence D (aeolianite dune ridges) outcrops are not as common on the more narrow continental shelf north of Cape St. Lucia as they are on the wider shelf further south. Figure 3.9 shows the occurrence of this sequence. Two linear ridges are recognised occurring at depths of 53m and 100m respectively. As is the case on the Richards Bay continental shelf the thin nature of these deposits and obscuring effect of the bubble pulse necessitated identification on the basis of their positive relief and consequent interruption of the shelf profile rather than their internal reflection configuration or identification of underlying sequence boundary reflector.

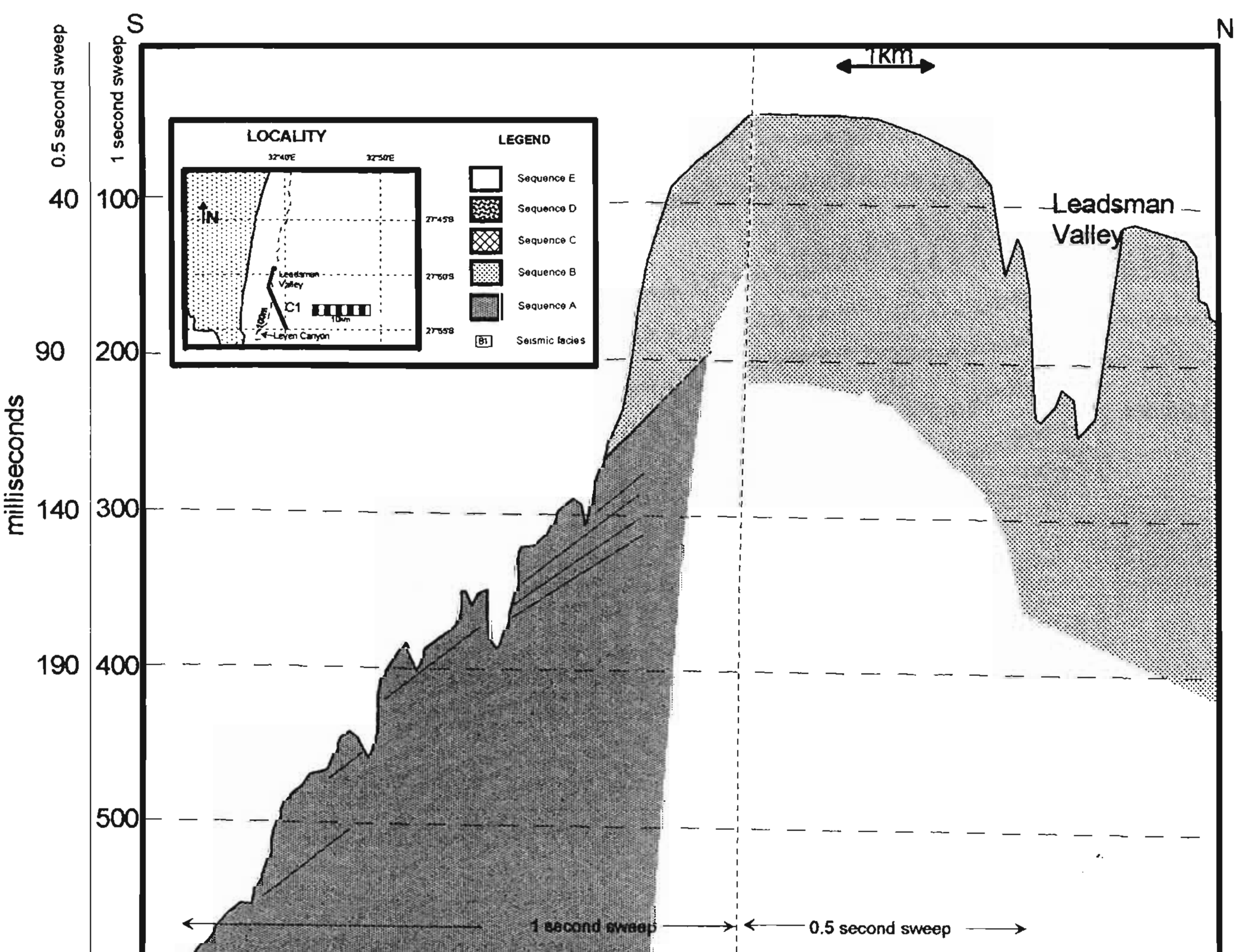
Acoustically transparent to chaotic unconsolidated shelf sediments (Sequence E) are clearly visible on inshore seismic profiles. A large unconsolidated sediment depocentre directly opposite the St. Lucia Estuary Mouth known as the St. Lucia Spit Bar is well documented by Martin (1985) and Birch (1996) and detailed unconsolidated sediment thickness maps have been compiled by these workers (see also Chapter 4).

3.4.7.3 Leven Point to Lake Bhangazi

Some representative seismic sections and line drawing interpretations are shown in Figures 3.10 a to d. Seismic data coverage in this area is concentrated in deeper water further offshore. Fewer continental shelf and upper slope profiles are available than is the case further south.

Numerous submarine canyons incise the continental shelf, the most significant being Leven Canyon directly offshore Leven Point, which incises the continental shelf to within 600m of the coast (submarine canyons are discussed in Chapter 6). Between Leven Point and Red Sands Cliffs the shelf attains a maximum width of 4.8km. This width remains constant except where the continental shelf has been incised by Leven Canyon. On coast perpendicular seismic sections the continental shelf is flat due to the absence of submerged linear Pleistocene aeolianites. The continental slope where it is not affected by the development of submarine canyons is smooth and concave.

Trigonometric restoration of a coast perpendicular seismic section directly offshore Red



... of profile C1, north of Leven Point. Interpreta

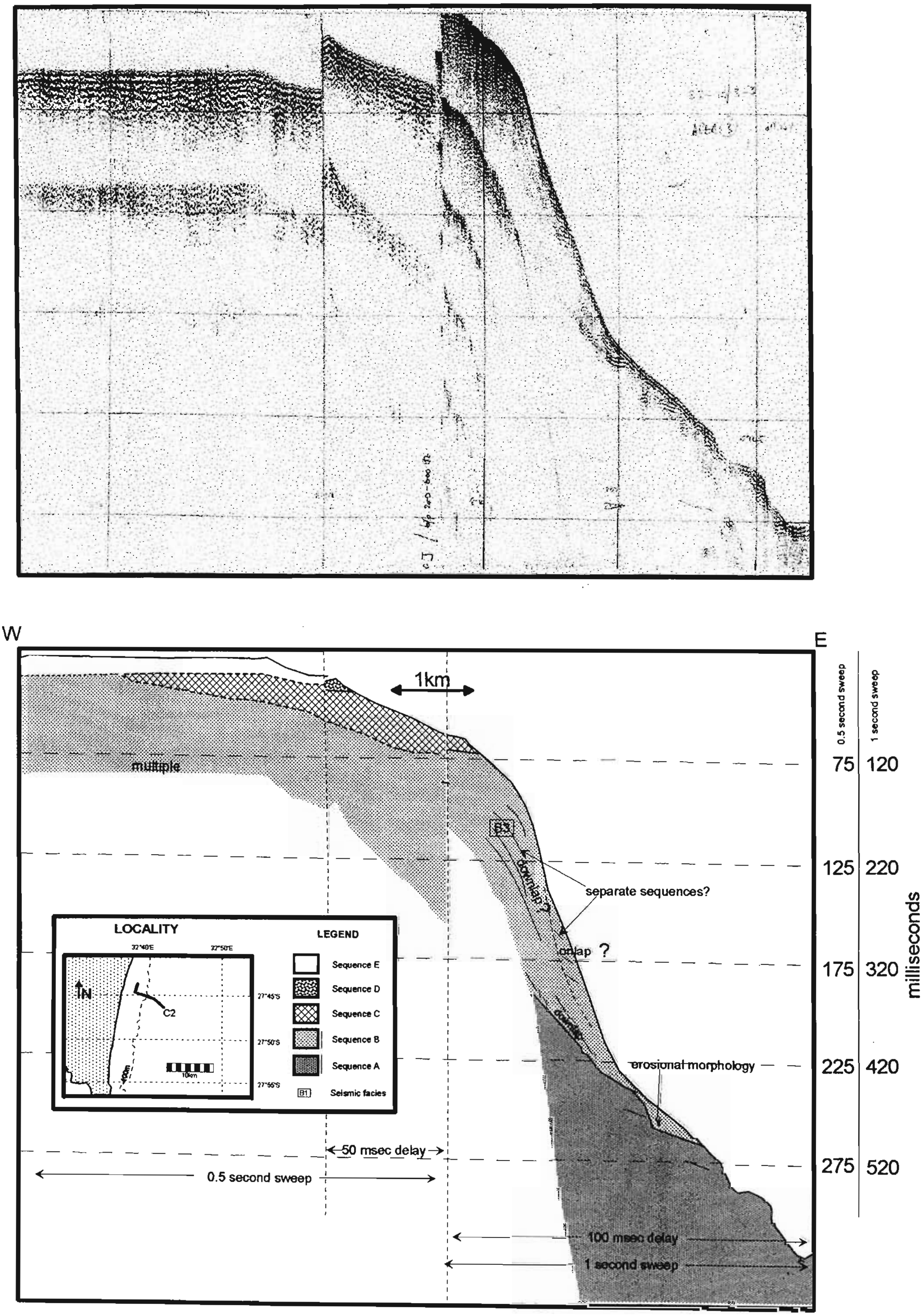


Fig. 3.10b: Sparker seismic section and interpretation of profile C2, north of Leven Point. Interpretation adjusted for delay

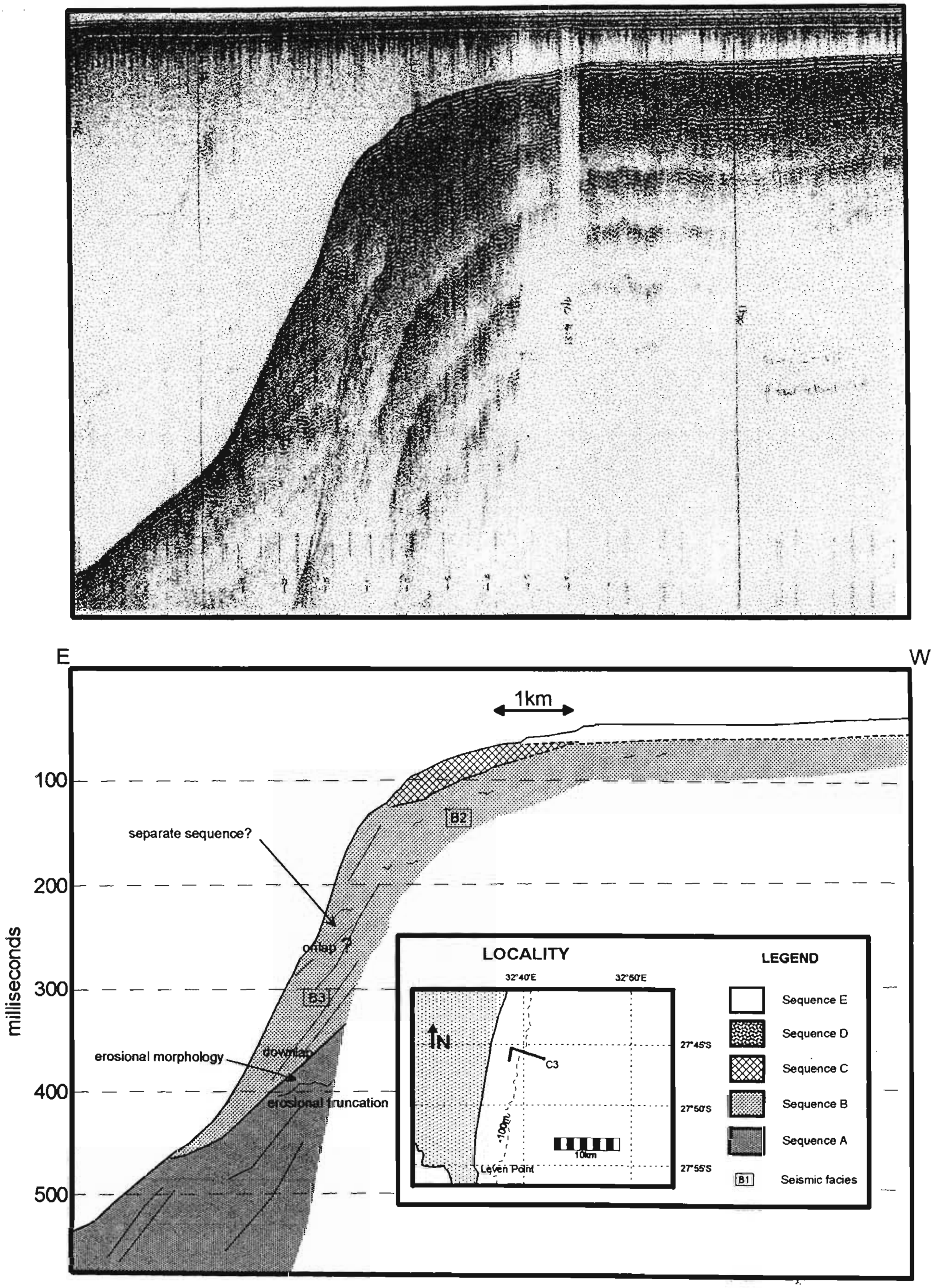


Fig. 3.10c: Sparker seismic section and interpretation of profile C3, north of Leven Point

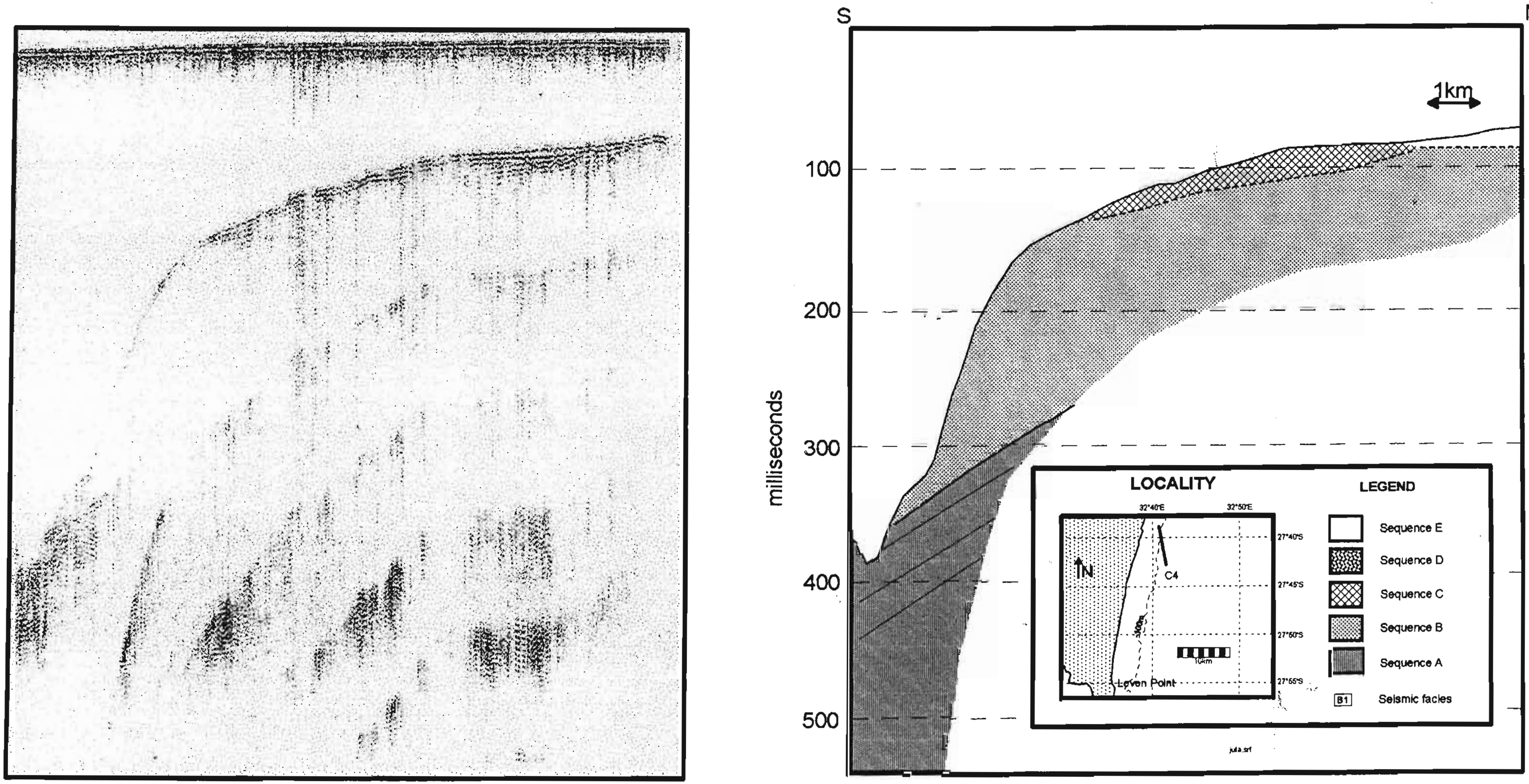


Fig. 3.10d: Sparker seismic section and interpretation of profile C4, north of Leven Point

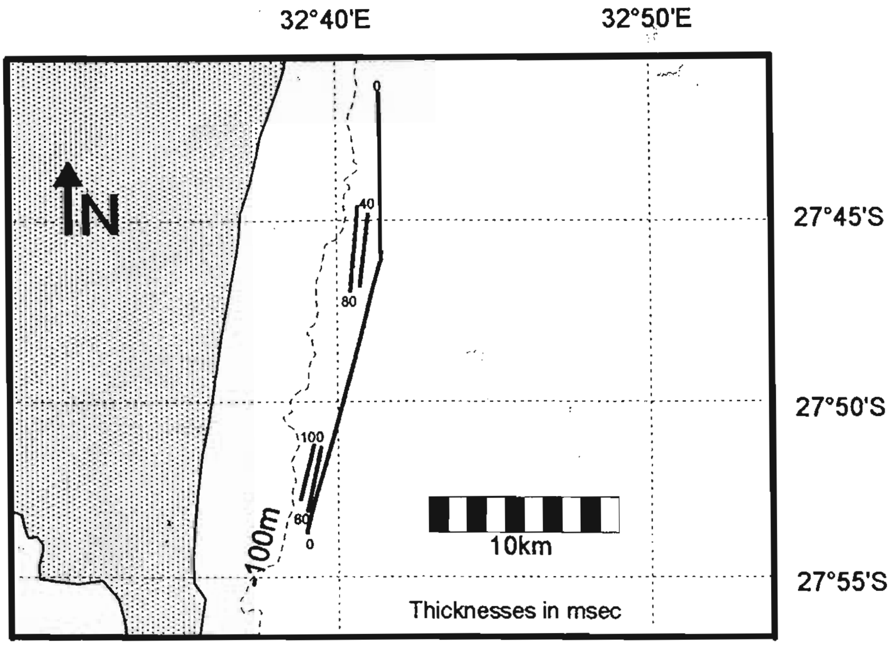
Sands Cliffs (Figs. 3.10b and c) shows the upper continental slope angle in this area to be approximately 8.3°.

Sequence A reflectors are not visible on seismic sections beneath the continental shelf due to the obscuring effect of the first multiple reflection of the sea-water/sediment interface which occurs at a depth shallower than Sequence A due to the shallow water depth. Beneath the continental slope, Sequence A reflectors range from low amplitude discontinuous to continuous high amplitude reflectors dipping seawards at an angle of approximately 2.1°. Reflector a in this area is continuous and distinct and dips in a seaward direction at approximately the same angle as the underlying Sequence A reflectors in oblique seismic sections (Figs. 3.10a and d). Erosional truncation of Sequence A reflectors beneath the continental slope is visible in the approximately coast-parallel seismic section (Fig. 3.10c). Reflector a is quite distinct compared to the continental margin between Cape St. Lucia and Leven Point.

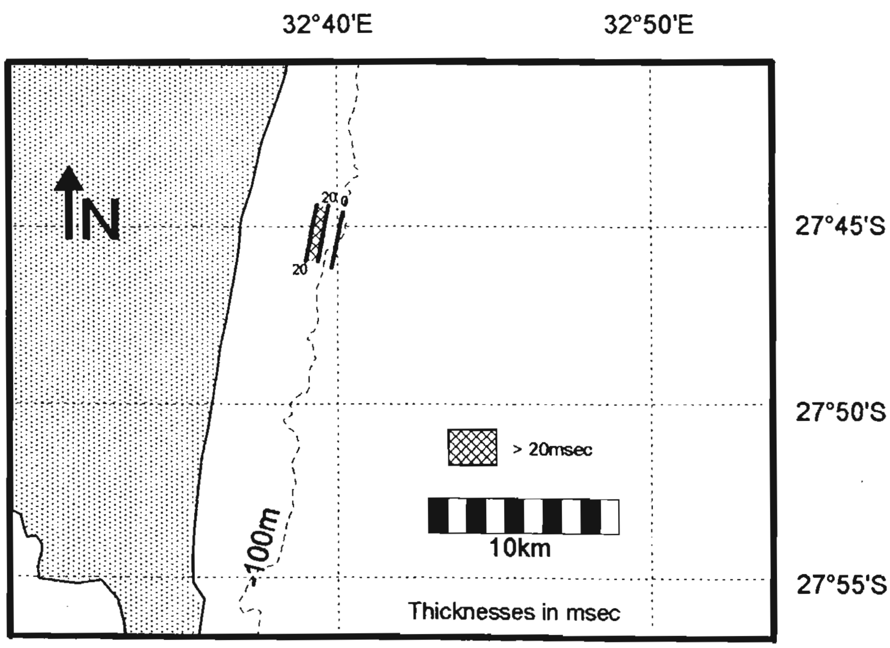
Beneath the continental shelf, chaotic, discontinuous Facies 2 reflectors grade seawards into steeply dipping semi-continuous low amplitude Facies 3 reflectors of Sequence B. The angle of dip of these slope sediments is approximately the same as that of the continental slope in this area, i.e. approximately 8°. Lower down the continental slope, the angle of apparent dip decreases to become approximately the same as the underlying Reflector a.

The outer portion of Sequence B on the continental slope is characterised by a downlap surface similar to those described in seismic sections between Cape St. Lucia and Leven Point), and a possible onlap surface is visible in the outer-most portion of Sequence B.

Thickness of Sequence B between Leven Point and Lake Bhangazi is shown in Figure 3.11. Sequence B attains a maximum thickness of approximately 160msec beneath the shelf break and thins to 0m at distances of between 4.2km and 7.8km offshore where Reflector a crops out on the continental slope. Figure 3.18 shows a distinct bulge in the outcrop pattern of Sequence B offshore Red Sands Cliffs. This area subdivision is characterised by sequence outcrop controlled slope angle changes. On oblique seismic sections and to a lesser degree on coast perpendicular seismic sections, continental



SEQUENCE B



SEQUENCE C

slope angle decreases markedly where Sequence B pinches out and Sequence A crops out. In each case, continental slope angle is approximately equal to depositional dip angle of the outcropping sequence.

Sequence C sediments are not clearly discernible on coast-perpendicular seismic sections acquired between Leven Point and Lake Bhangazi. Where present they manifest themselves as discontinuous high amplitude reflectors beneath the continental shelf. They can be distinguished from shelf facies (Facies 2) reflectors of Sequence B on the basis of their high amplitude nature (Fig. 3.10c). Reflector b, occurring at the base of Sequence C has similar characteristics as reflectors within Sequence C and it has an irregular, erosive appearance. Occurrence of Sequence C sediments is illustrated in Figure 3.11.

Sequence D sediments were not visible in seismic sections in this area. Although none were observed, submerged Pleistocene dunes have been observed on seismic sections in the Leven Point area by Sydow (1988). Side-scan-sonar records recently acquired by the Council for Geoscience also show the presence of Pleistocene aeolianites colonised by corals. In this area there are no coast perpendicular sparker seismic records acquired where linear Pleistocene aeolianites are present.

Sequence E reflectors are not discernible on coast perpendicular seismic sections due to their thin development and low resolution of the sparker seismic tool, although a thin veneer is inferred. When visible on coast parallel seismic sections, internal reflection characteristics are acoustically transparent to low amplitude and discontinuous. The upper sequence limit (i.e. sediment/sea-water interface) is smooth. Thickness of Sequence E sediments is controlled primarily by the vertical relief of the underlying Reflector c. While the upper boundary of Sequence E remains smooth, the underlying sequence boundary (Reflector d) exhibits a high degree of vertical relief. North of Red Sands Cliff, Reflector d exhibits vertical relief changes of up to 10m over a horizontal distance of approximately 1.2Km (see Chapter 7, Fig. 7.3). Relief changes of this magnitude is thought to be caused by fluvial incision during subaerial exposure (evidence of fluvial incision during subaerial exposure of the northern KwaZulu-Natal continental shelf is discussed in Chapter 7).

3.4.7.4 Lake Bhangazi to Lala Nek

Some representative seismic sections and line drawing interpretations are shown in Figures 3.12a to e. As is the case with data coverage between Leven Point and Lake Bhangazi, in this area much of the seismic data was acquired in deeper water further offshore below the upper continental slope. Unless disrupted by Pleistocene aeolianite dunes and submarine canyons, the continental shelf is smooth.

Continental shelf width ranges between 3km at Lake Bhangazi and 4km at Sodwana Bay and Hulley Point. The continental shelf is narrower where submarine canyons incise the continental shelf. Between Lake Banghazi and Jesser Point, Diepgat canyon and directly offshore White Sands, a complex of three submarine canyons namely White Sands, Wright and Beacon canyons incise the continental shelf to a distance of 1.5km from the coastline (Submarine canyons are discussed in more detail in a Chapter 6). The -100m isobath in this area is more continuous than between Leven Point and Lake Bhangazi indicating lesser influence of submarine canyon development. Since there are no coast-perpendicular seismic sections available for this area, slope angles and dip of sequence reflector angles could not be calculated.

Sequence A reflectors are not visible beneath the continental shelf on any seismic records in this area due to the obscuring effect of the first multiple reflection of the sea-floor. Beneath the continental slope they are continuous and have a high amplitude. On coast-near-perpendicular profiles (Figs. 3.12b and c), they dip offshore at an angle greater than the continental slope angle and are therefore proximally truncated by the sea-water sediment interface and Reflector a. The upper boundary of Sequence A, Reflector a is quite distinct in this area (Figs.3.12a, b, c and d). In Figure 3.12b, high degree of vertical relief of Reflector a indicates either subaerial exposure morphology or glide plane scar morphology.

Sequence B sediments are clearly discernible on most seismic profiles between Lake Bhangazi and Lala Nek. While the individual reflectors which constitute the Sequence B are not clearly visible on some of the poorer quality seismic sections, the extent of Sequence B can be inferred on the basis of the position of Reflector a or by continental slope morphology. In Figures 3.12b and c, slope facies (Facies 3) reflectors downlap

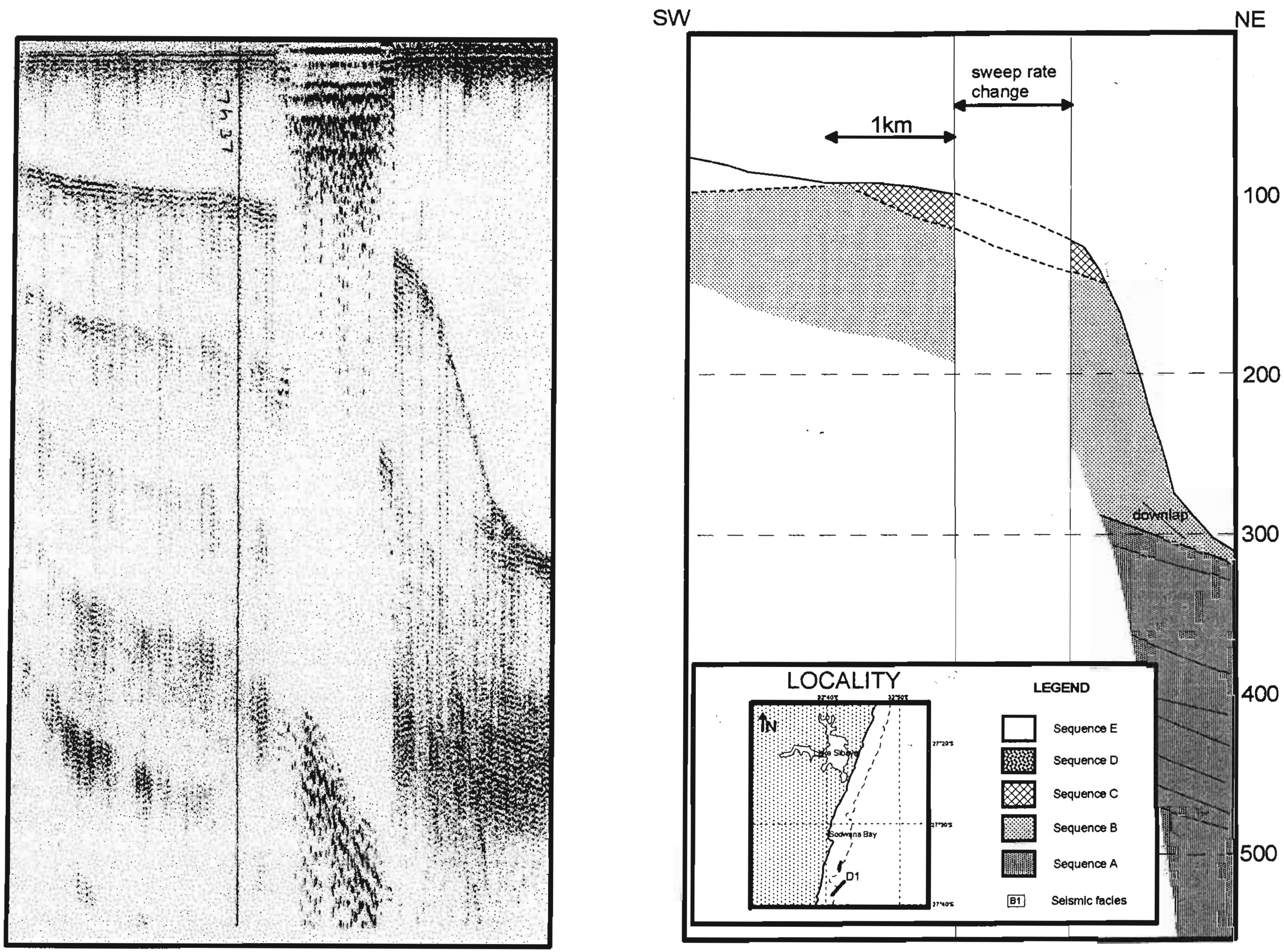


Fig. 3.12a: Sparker seismic section and interpretation of profile D1, south of Sodwana Bay

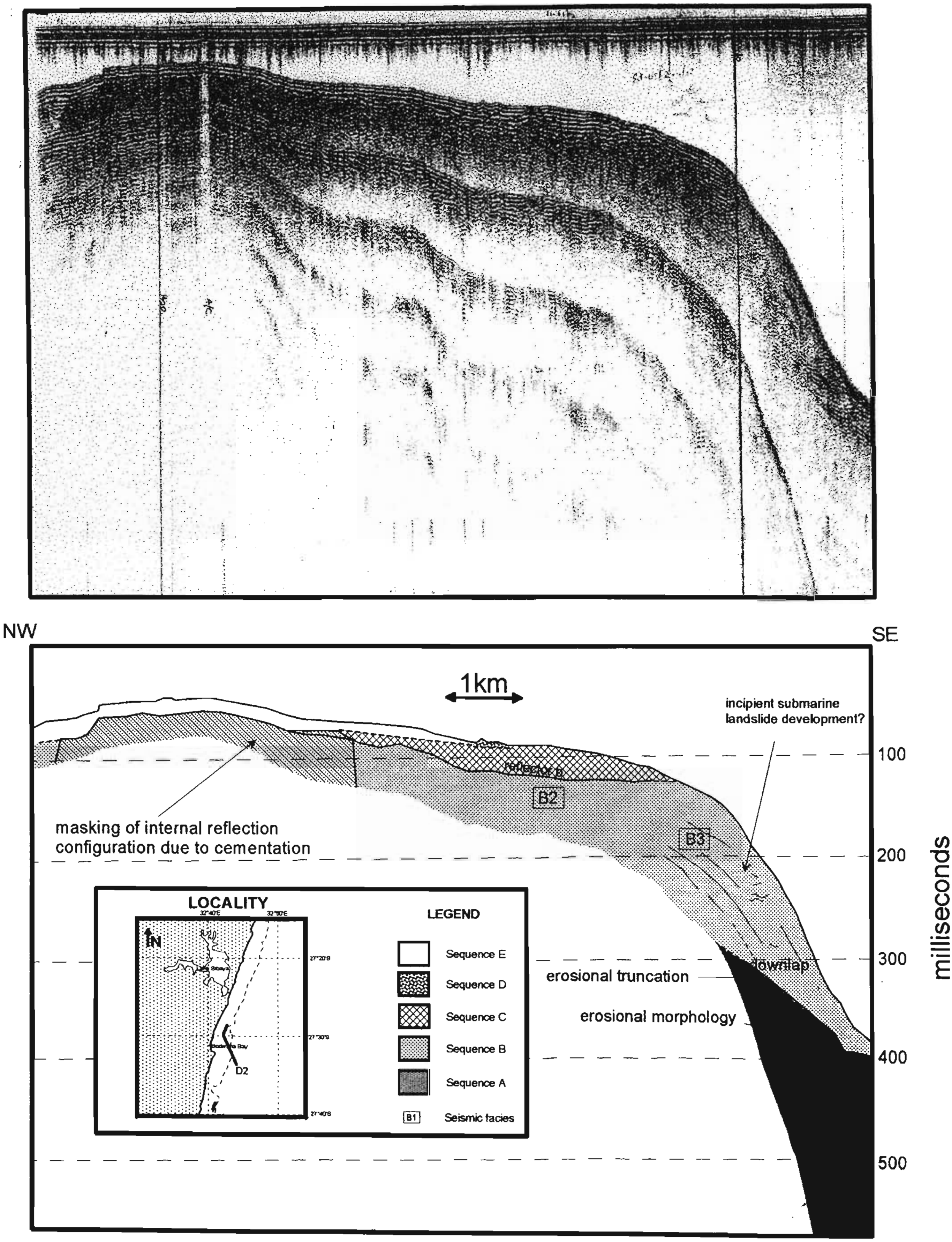


Fig. 3.12b: Sparker seismic section and interpretation of profile D2, offshore of Sodwana Bay

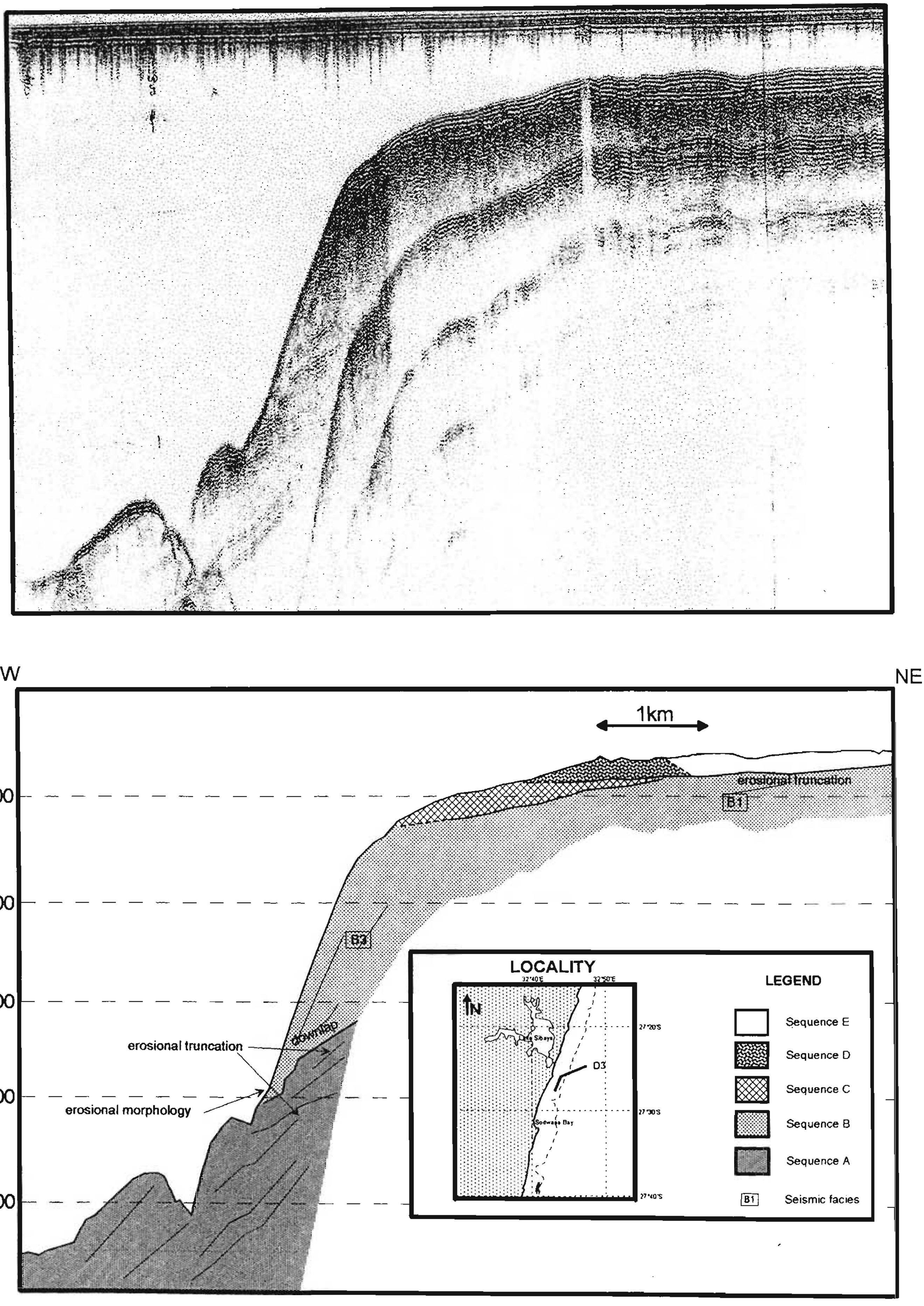
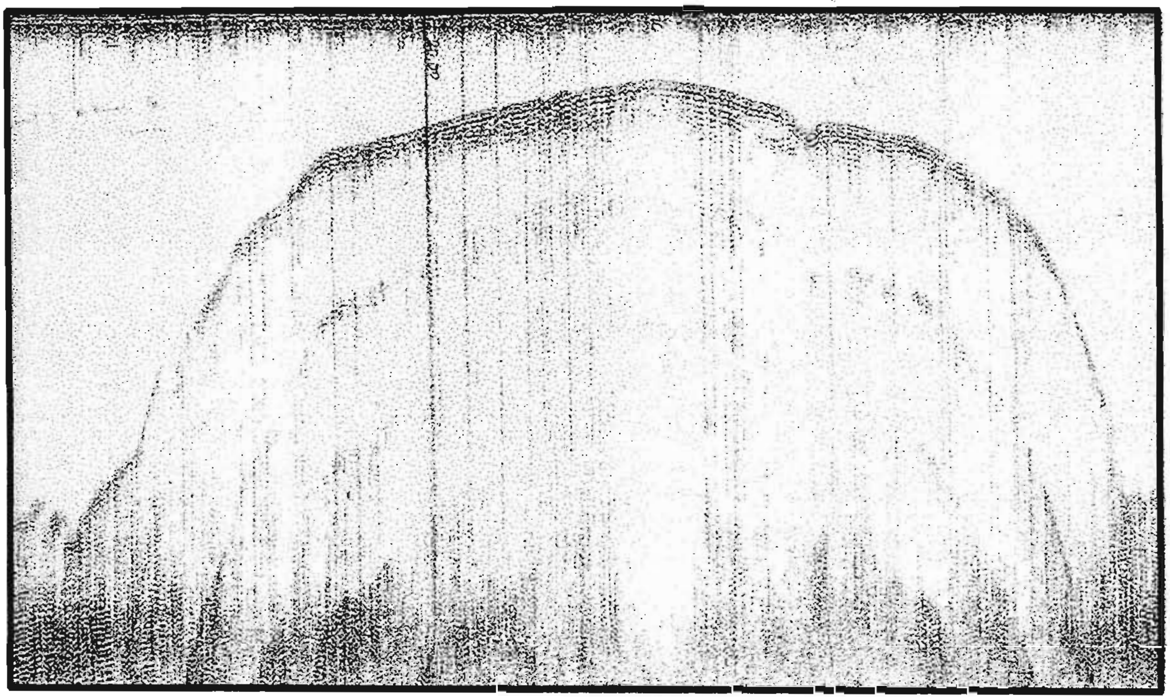


Fig. 3.12c: Sparker seismic section and interpretation of profile D3, offshore of Lake Sibaya



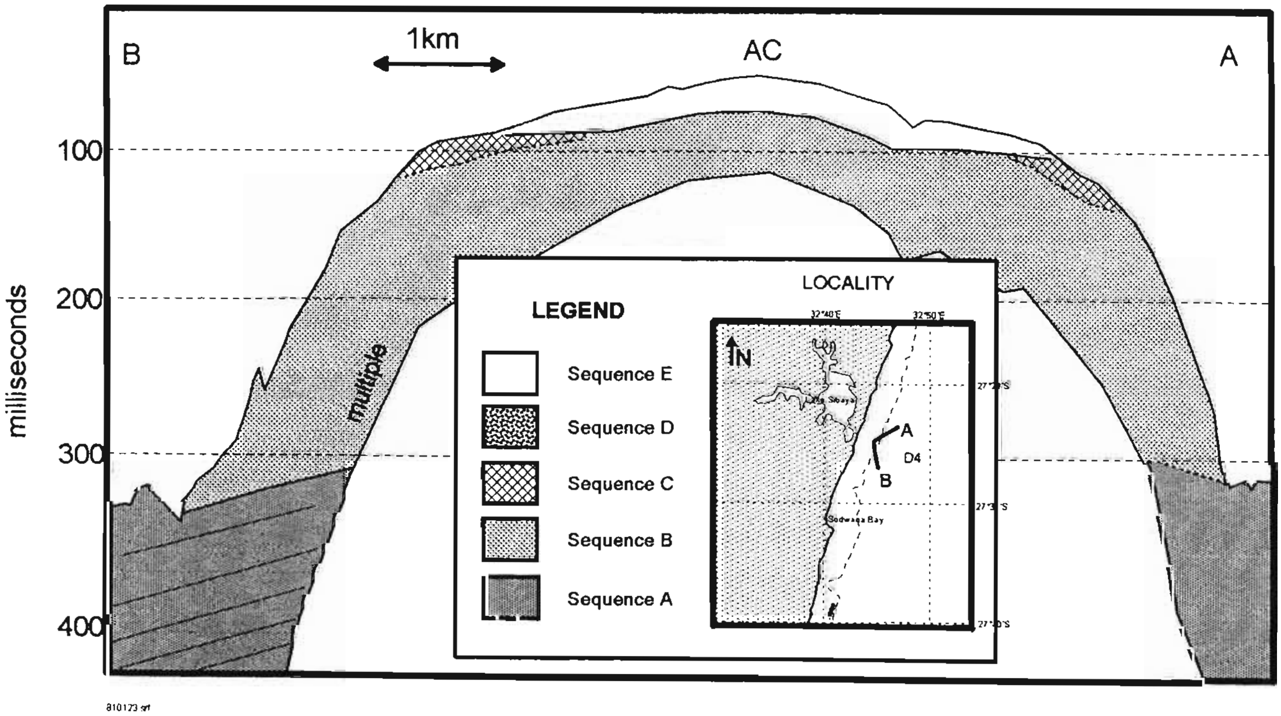


Fig. 3.12d: Sparker seismic section and interpretation, of profile D4, offshore of lake Sibaya

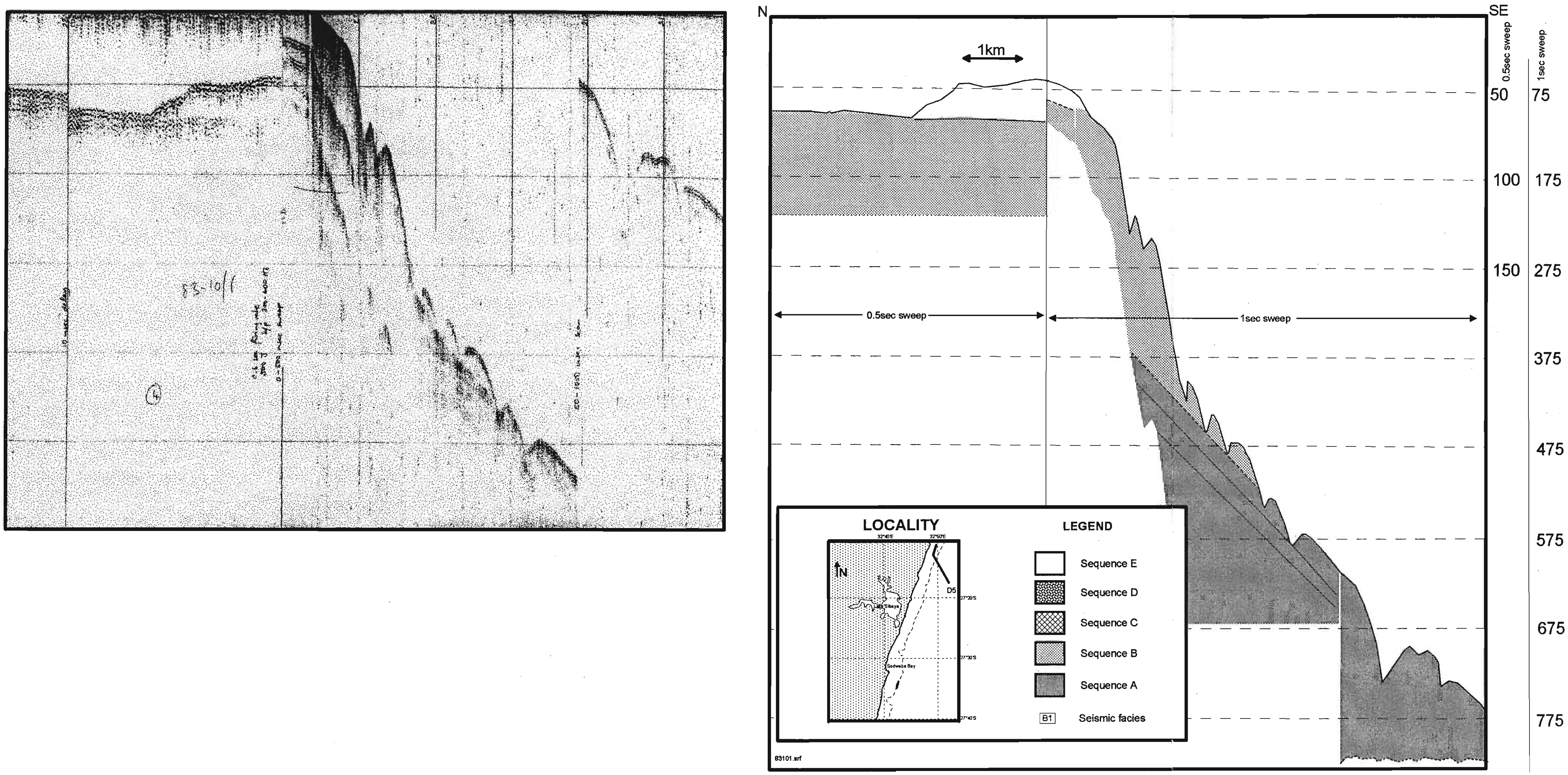


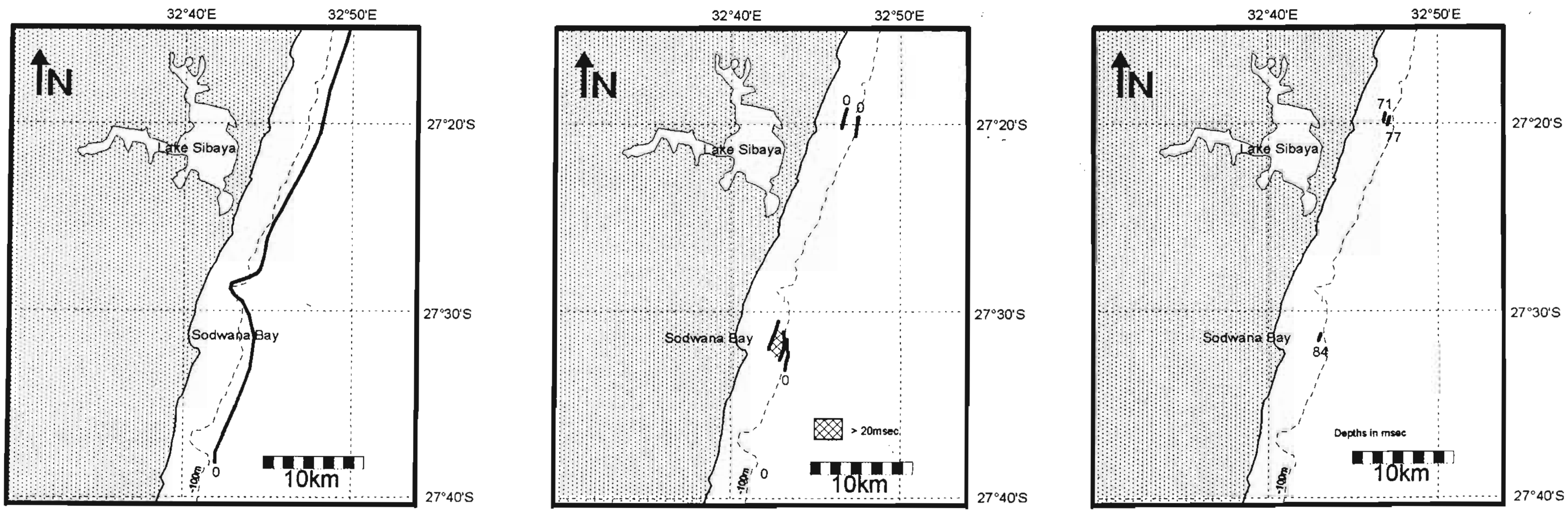
Fig. 3.12e: Sparker seismic section and interpretation of profile D5, north of Lake Sibaya

against Reflector a. These high continuity medium amplitude reflectors dip at the same angle as the continental slope in this area. On poorer quality records thickness of Sequence B can be calculated on the continental slope by measuring the vertical distance between Reflector a (and reasonable extrapolations thereof) and the slope /sea-water interface. On some the position of Reflector a outcrop is marked by a decrease in the continental slope angle (Figs. 3.12b, c and d). The continental slope changes from an angle approximately similar to the angle of dip of Sequence B Facies 3 reflectors to an angle of approximately similar to the angle of dip of Sequence A reflectors. The continental slope angle in this area is therefore controlled by the primary depositional dip angle of the underlying sediments. Facies 2 sediments of Sequence B beneath the continental shelf are chaotic discontinuous medium amplitude reflectors (Fig. 3.13).

Sequence C sediments are not discernible on poorer quality seismic records. In Figures 3.12b and c, the presence of Sequence C sediments is highlighted by the presence of the underlying Sequence C boundary, Reflector b. On these profiles, Reflector b is a high amplitude reflector exhibiting medium to low continuity. Reflector b has a degree of vertical relief interpreted as subaerial erosional morphology. Sequence C reflectors exhibit similar characteristics to Reflector b. The upper limit of Sequence C, Reflector c is not visible on poorer quality seismic records. In Figures 3.12b and c, it is visible in places but for the most part is obscured by the reflection package of the sea-water/sediment interface caused by the bubble pulse effect. Outcrop of Sequence C in this area is shown in Figure 3.13.

Sequence D sediments are visible on the outer continental approximately 3Km from the coastline (Figs. 3.12b and c). They have a maximum vertical relief of approximately 6m and occur at a depth of approximately 62m off Hully Point and 67m off Sodwana Bay. Occurrence of Sequence D is shown in Figure 3.13.

Sequence E sediments are clearly visible on some seismic profiles in this area (Figs. 3.12a, c, d and e). Bounded by the underlying high amplitude, continuous smooth Reflector c and the sea-water/sediment interface, acoustically transparent to chaotic, low amplitude Sequence E reflectors attain a maximum thickness of approximately 8m. On other shelf sections Sequence E sediments are obscured by the multiple reflection



SEQUENCE B

SEQUENCE C

SEQUENCE D

Fig. 3.13: Occurrence and thickness of Sequences B, C and D between Lake Bhangazi and Lala Nek

package of the sediment/sea-water interface caused by the bubble pulse effect.

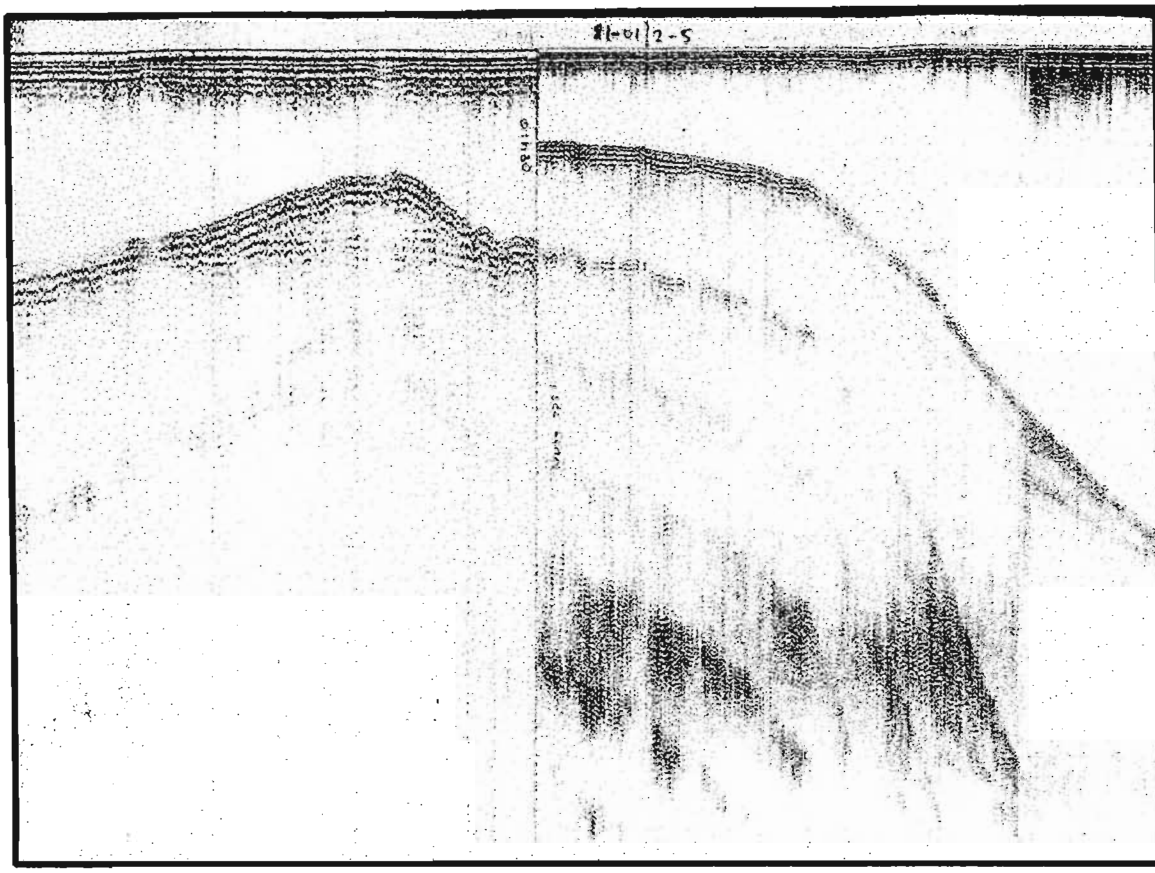
3.4.7.5 Lala Nek to Kosi Mouth

Some representative seismic sections and line drawing interpretations are shown in Figures 3.14a to d. The continental shelf width increases gradually in this area from approximately 3km at Lala Nek to approximately 6.5km at Kosi Mouth. The relatively smooth nature of the -100m isobath indicates a continental shelf uninfluenced by submarine canyon development. The continental shelf profile is generally smooth except where submerged Pleistocene aeolianites (Sequence D) interrupt this profile in the northern part of this area (Figs. 3.14c and d).

From the coast perpendicular seismic profiles, the upper continental slope was calculated to be 3° at Kosi Mouth and 7° just to the north of Dog Point. The upper continental slope varies between both concave and convex between profiles. The profile of the upper continental margin in this area is strongly influenced by seismic sequence outcrop patterns, with slope angle decreasing in an offshore direction where Sequence A crops out.

Beneath the continental shelf, Sequence A reflectors are obscured by the first multiple reflection package of the sea-floor. Beneath the upper continental slope, Sequence A reflectors are medium to high amplitude and continuous. On coast-perpendicular seismic section (Fig. 3.14d) it was calculated that Sequence A reflectors dip seawards at approximately 1° while in Figure 3.14b, Sequence A reflectors dip seawards at approximately 4.1°. Reflector a in this area has a continuous and high amplitude nature and dips seaward at an angle approximately similar to the underlying Sequence A reflectors. Reflector a therefore erosionally truncates Sequence A reflectors in Figures 3.14c and d.

Sequence B Facies 2 (Shelf Facies) reflectors are chaotic and discontinuous beneath the continental shelf. Beneath the continental slope, Sequence B Facies 3 (Slope facies) reflectors are slightly more continuous and dip seawards at approximately the same angle as the continental slope. In Figures 3.14b, c and d, Sequence B Facies 3 reflectors clearly downlap against Reflector a. Sequence B attains a maximum



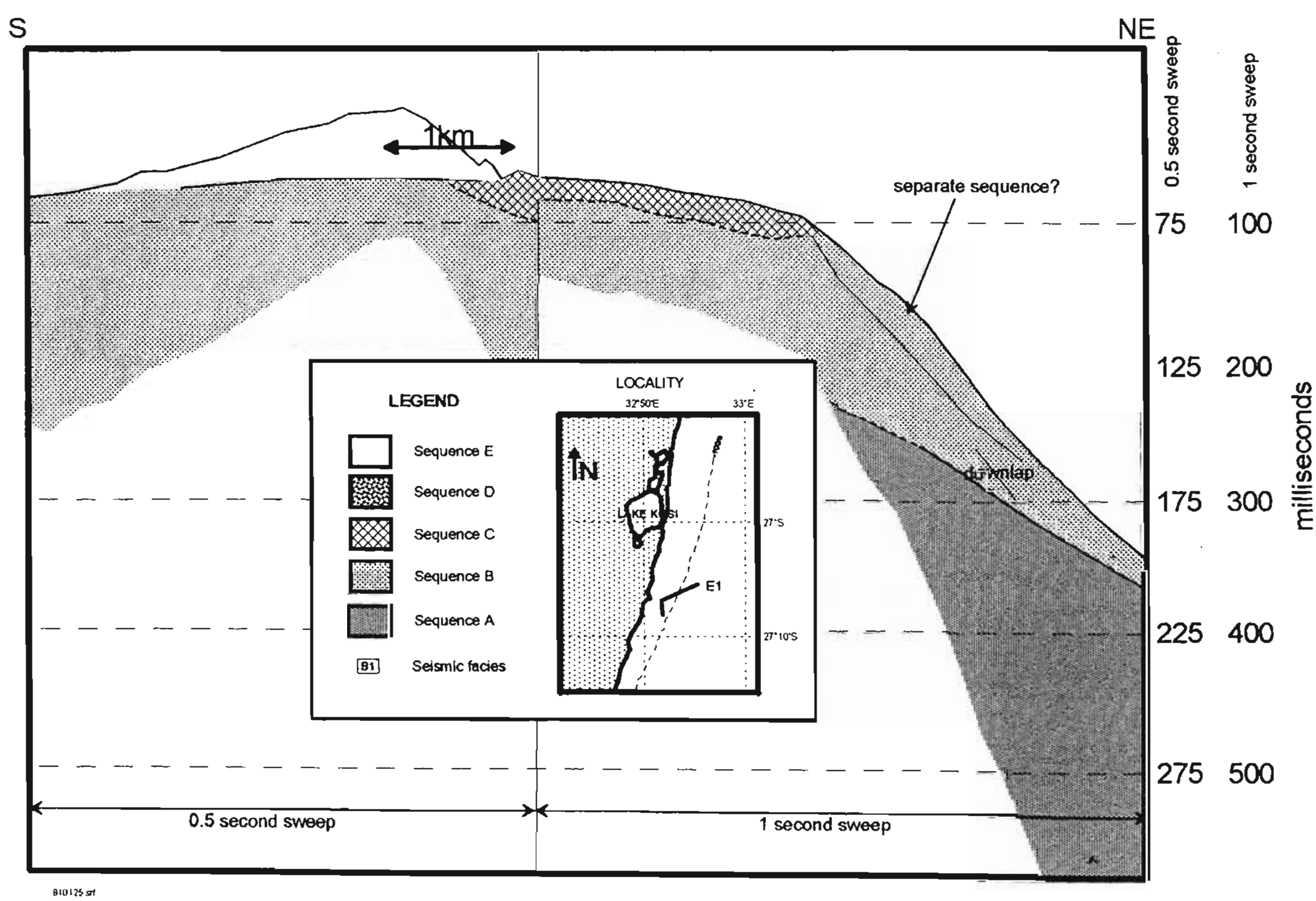


Fig. 3.14a: Sparker seismic section and interpretation of profile E1, south of Lake Kosi

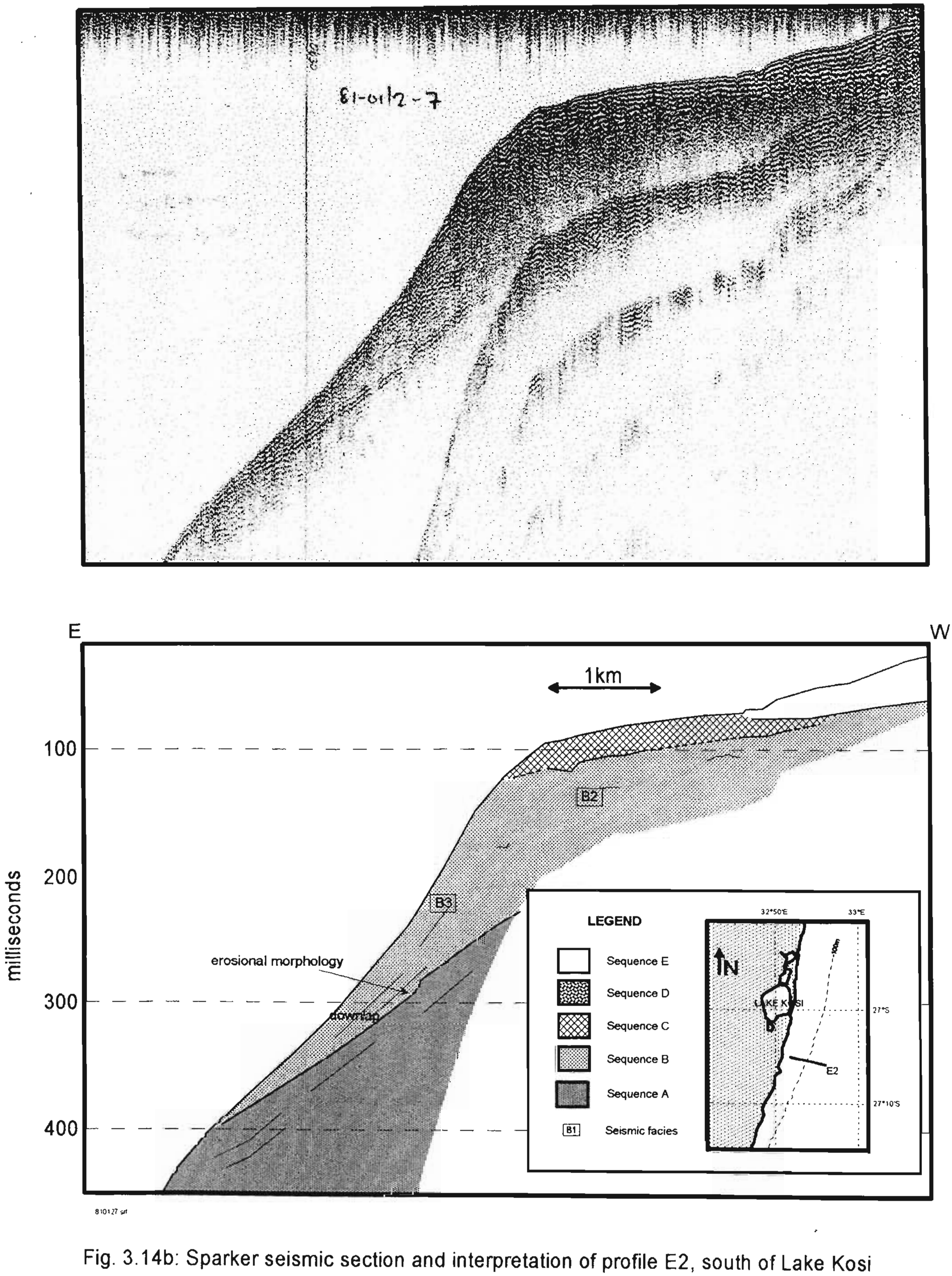


Fig. 3.14b: Sparker seismic section and interpretation of profile E2, south of Lake Kosi

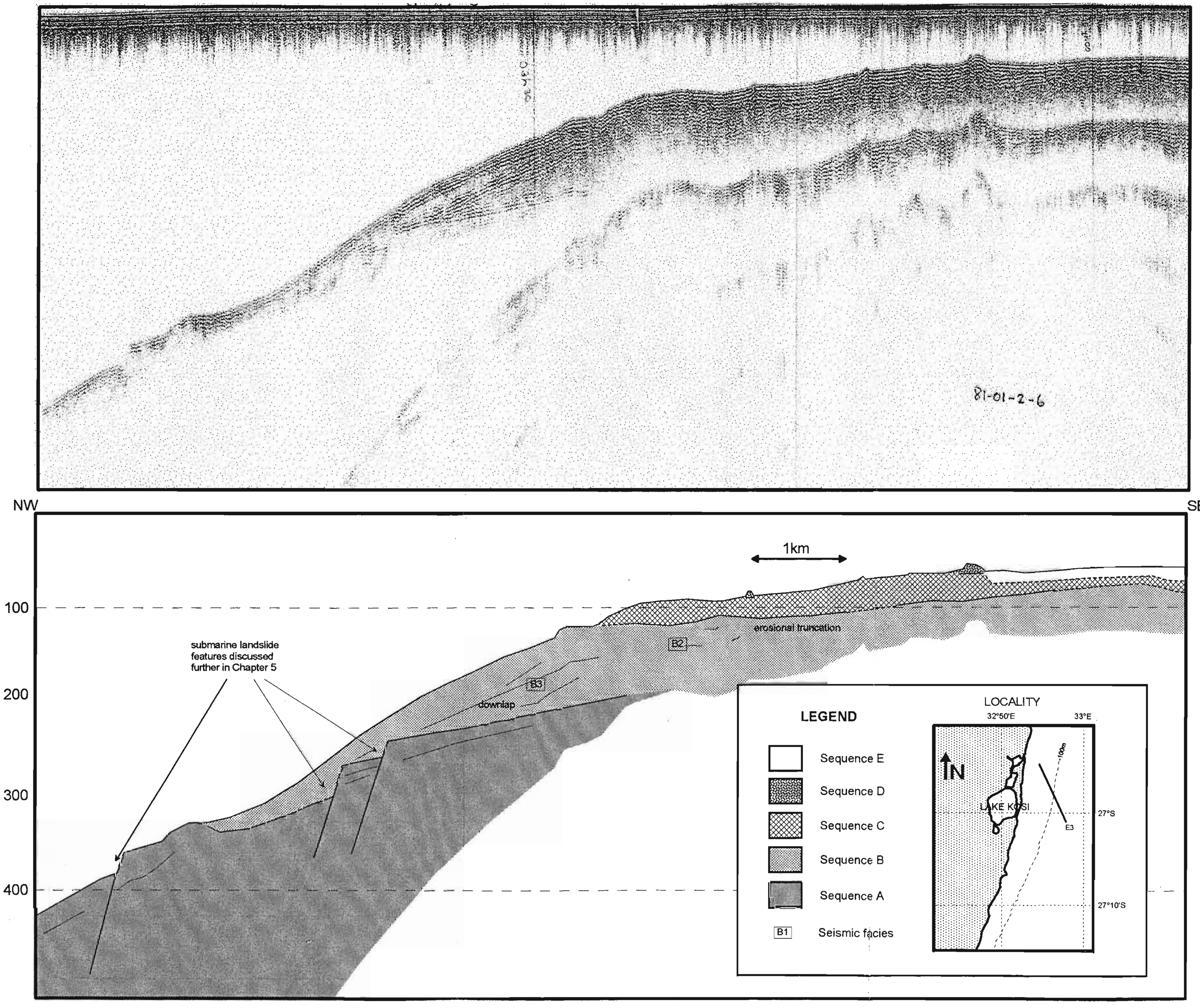


Fig. 3.14c: Sparker seismic section and interpretation of profile E3, offshore Lake Kosi

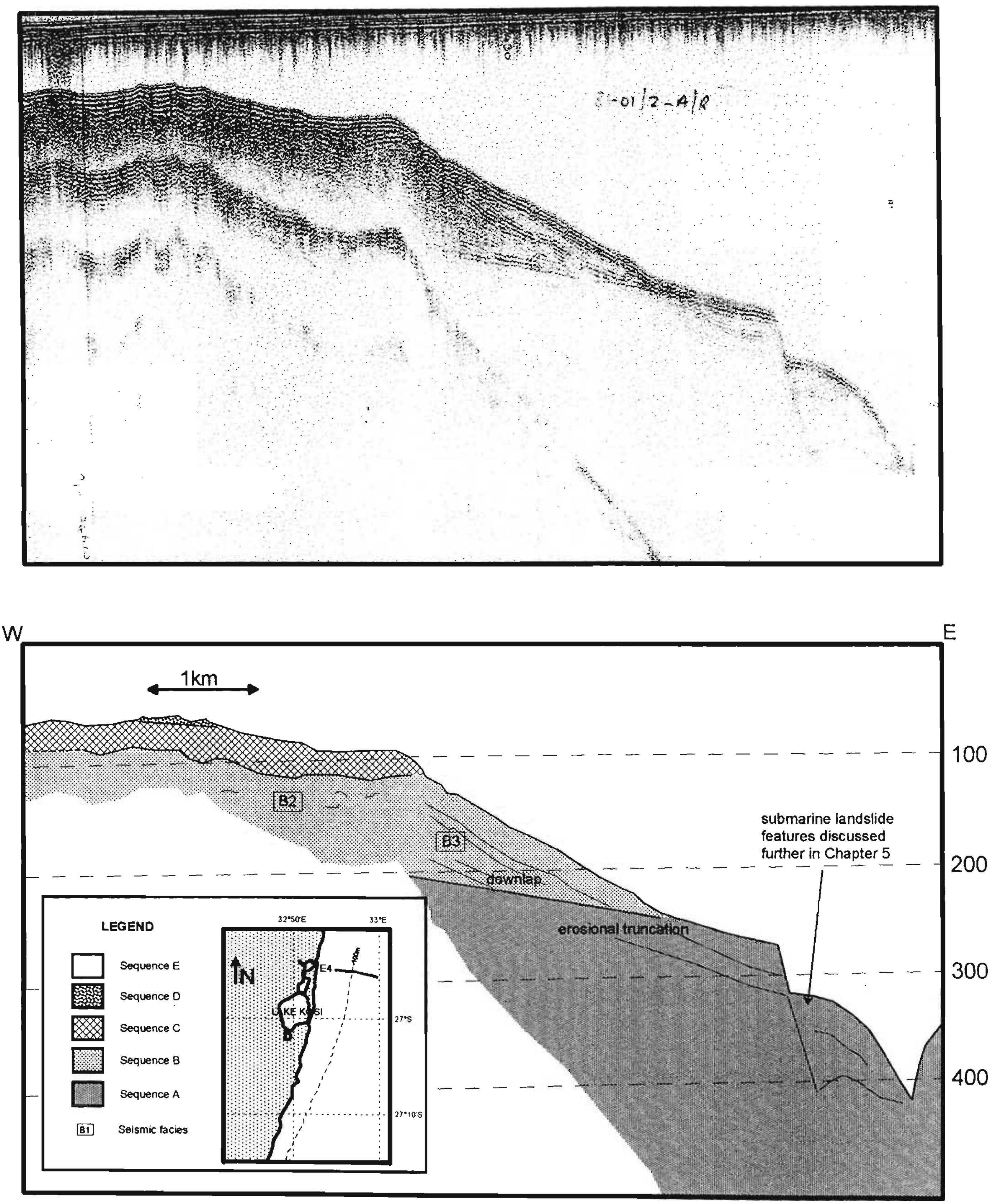


Fig. 3.14d: Sparker seismic section and interpretation of profile E4, offshore Kosi Bay

thickness of approximately 88msec beneath the continental shelf break (Fig. 3.15).

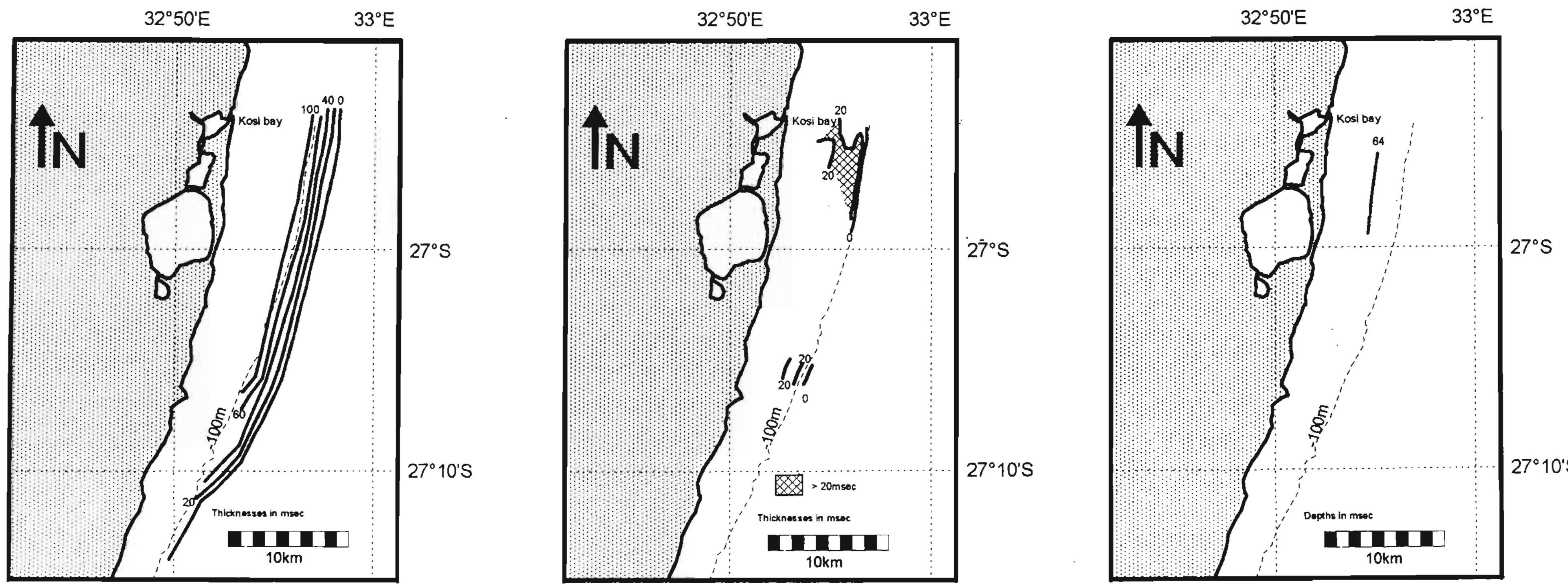
On a coast parallel seismic profile (Fig. 7.2, see Chapter 7), Reflector a clearly exhibits subaerial exposure morphology. This reflector has a vertical relief of up to 14m over a horizontal distance of approximately 15Km. This reflector appears to be erosionally truncated just south of Black Rock by a lower amplitude continuous reflector exhibiting a lesser degree of vertical relief. Where Reflector a exhibits this channel-like morphology, thickness of Sequence B sediments is controlled by the morphology of this undulating reflector. Due to the high degree of vertical relief, the thickness of the sequence varies considerably over a short distance. These features are discussed more fully in Chapter 7.

Sequence C reflectors in this area are high amplitude discontinuous and hummocky. On the outer continental shelf Sequence C sediments are obscured by the bubble pulse multiple reflection package of the sea-floor. The underlying sequence boundary Reflector b, is high amplitude discontinuous. Approximate thickness of Sequence C sediments where discernible is shown in Figure 3.15.

Sequence D sediments manifest themselves as minor interruptions of the usually smooth continental shelf profile. These features have a vertical relief of between 2m and 4m. These submerged aeolianites are not as common as is the case in areas described further south. Due to the thin nature of this sequence internal reflection configuration is obscured by the multiple reflection package caused by the bubble pulse effect. Occurrence of Sequence D is shown in Figure 3.15.

Sequence E sediments where visible are acoustically transparent to low amplitude chaotic. They are clearly bounded below by the high amplitude continuous Reflector c.

The continental margin profile is strongly influenced by the seismic structure of this area. In Figures 3.14c and d, upper continental slope angle changes abruptly at the point where Sequence B Facies 3 sediments pinch out. At this point slope angle decreases from 3° to 1°. In Figure 3.14d, the continental slope profile is strongly influenced by submarine landslide features. Where this occurs, the slope increases abruptly from approximately 1° to 15° (Submarine landslide features are described



SEQUENCE B

SEQUENCE C

SEQUENCE D

Fig. 3.15: Occurrence and thickness of Sequences B, C and D between Lala Nek and Kosi Mouth

more fully in Chapter 5). The upper continental slope angle in this area tends towards the angle of prominent reflectors within the seismic sequence it comprises. Sequence A reflectors dip seawards at shallower angles than Sequence B, so that the continental slope angle where Sequence A crops out is shallower than the slope angle where Sequence B crops out. In Figure 3.14b, continental shelf profile is influenced by the occurrence of Sequence E sediments. Where these sediments pinch out, shelf profile changes are evident.

Overall sequence distribution, possible correlations relationships with onshore successions and geological development of the study area, based on the seismic stratigraphy is discussed in Chapter 8.

CHAPTER 4

INTERPRETATION OF EDO-WESTERN SUB-BOTTOM PROFILING RECORDS ON THE SODWANA BAY CONTINENTAL SHELF.

Chapter 3 described the broad seismic stratigraphy of the northern KwaZulu-Natal upper continental margin, as discernible on sparker seismic records. Although this tool is commonly referred to as having a relatively high resolution, it is still unable to resolve discreet sedimentological features less than a few metres in thickness. Thin unconsolidated sediment veneers are therefore not discernible using this seismic tool.

In this study approximately 150km of high-resolution 3.5KHz Edo-Western seismic sections acquired by the Council for Geoscience aboard the RV *Benguela* between 18 May and 2 June 1990 between Jesser Point and Gobey's Point (Figs. 4.1 and 4.2) were interpreted. Technical aspects of data acquisition and interpretation are included in Appendix B.

4.1 Geological setting and physiography of the Sodwana Bay continental shelf

Ramsay's (1991) bathymetric study of the Sodwana Bay area showed that the shelf north of Jesser Point has well defined shelf break at -65m 3km offshore, while south of Jesser Point the shelf break is not clearly defined (Fig. 4.3).

Several sea-level oscillations across the Maputaland coastal plain that occurred during the Pleistocene have led to the deposition of the Port Durnford Formation comprising nearshore sediments, dune sands and swamp deposits (Hobday, 1979). Calcareous cementation in the phreatic zone transformed these Pleistocene sands into aeolianite and beach rock which during the Holocene transgression were submerged and are now present as prominent, rugged, semi-continuous, linear shoals on the continental shelf (Ramsay, 1991). Intermittently exposed during spring low tides are late-Holocene beachrock platforms formed during and above present sea-level (Ramsay, 1995).

A generalised east-west geological section at Sodwana Bay (Fig. 4.4) has been

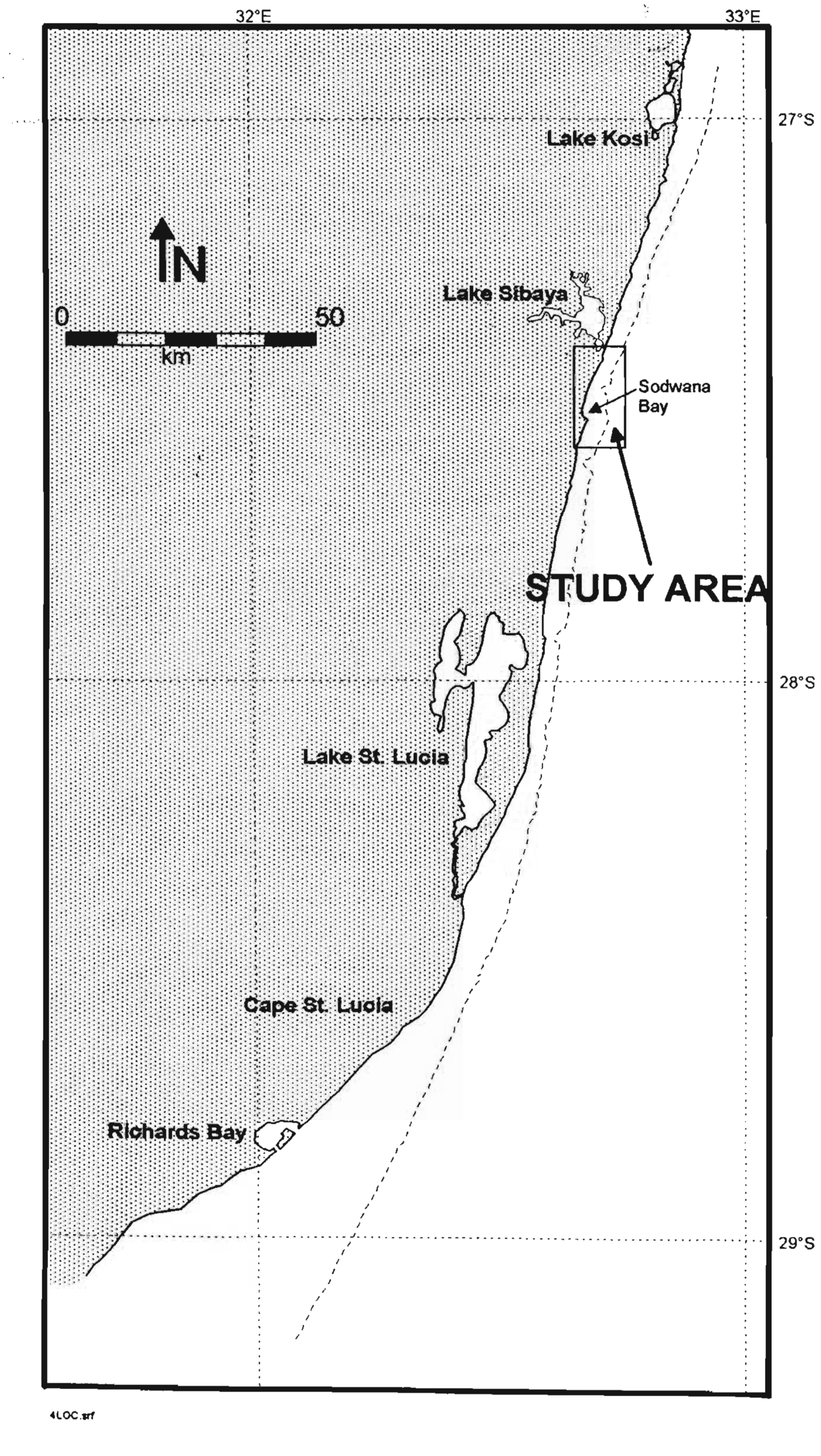


Fig. 4.1: Locality of the Sodwana Bay study area

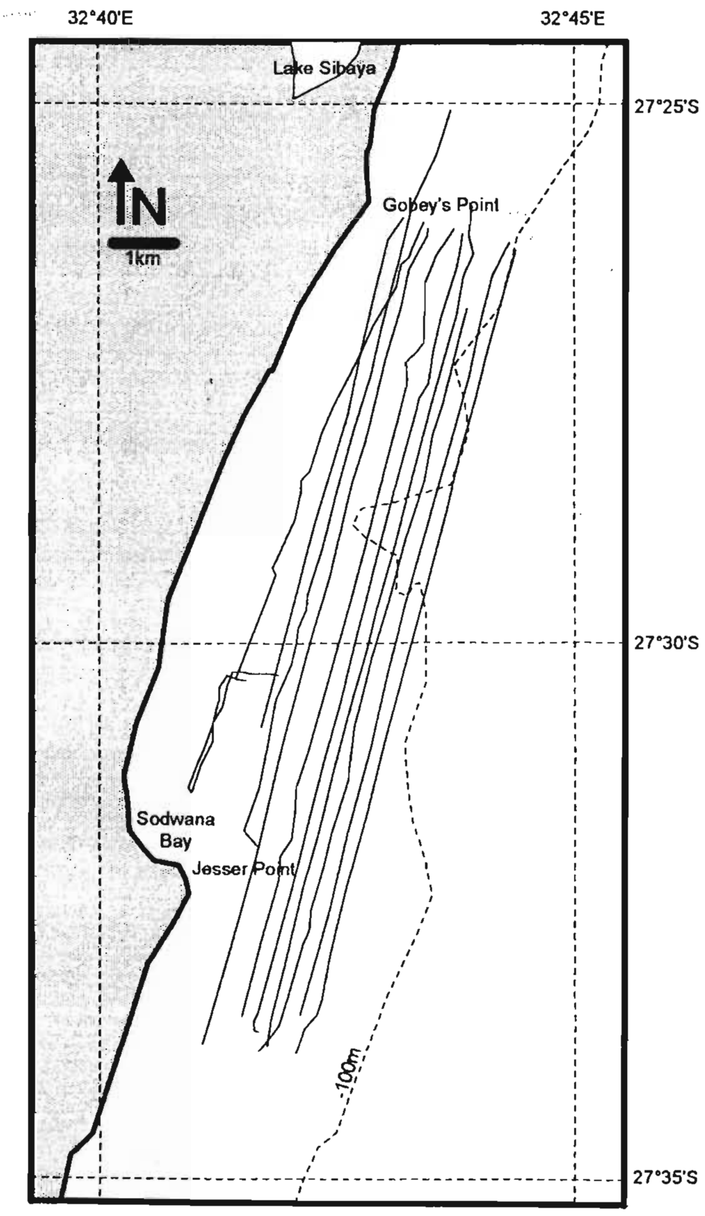


Fig. 4.2: Track lines of interpreted Edo-Western seismic lines in the Sodwana Bay area

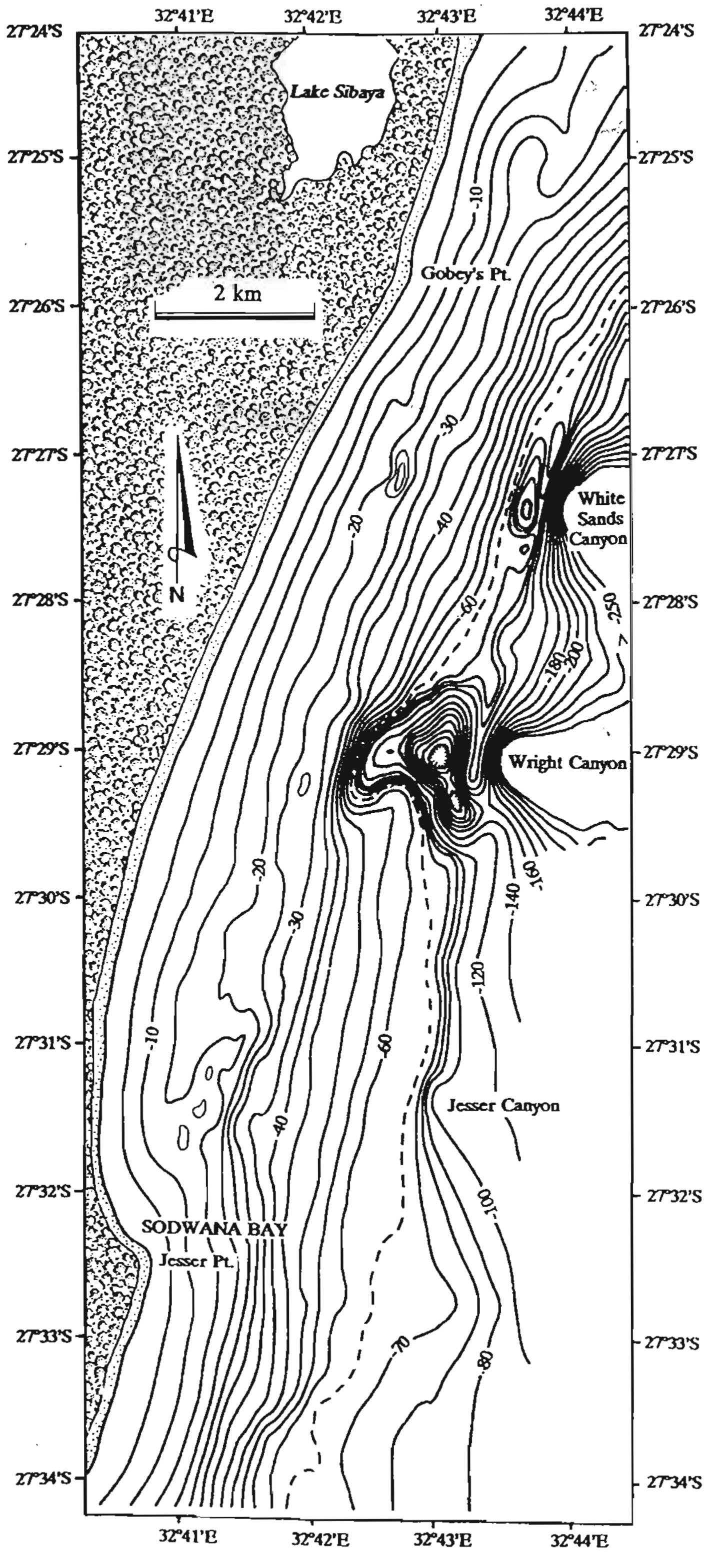


Fig. 4.3: Bathymetry of the Sodwana Bay continental shelf (from Ramsay, 1994)

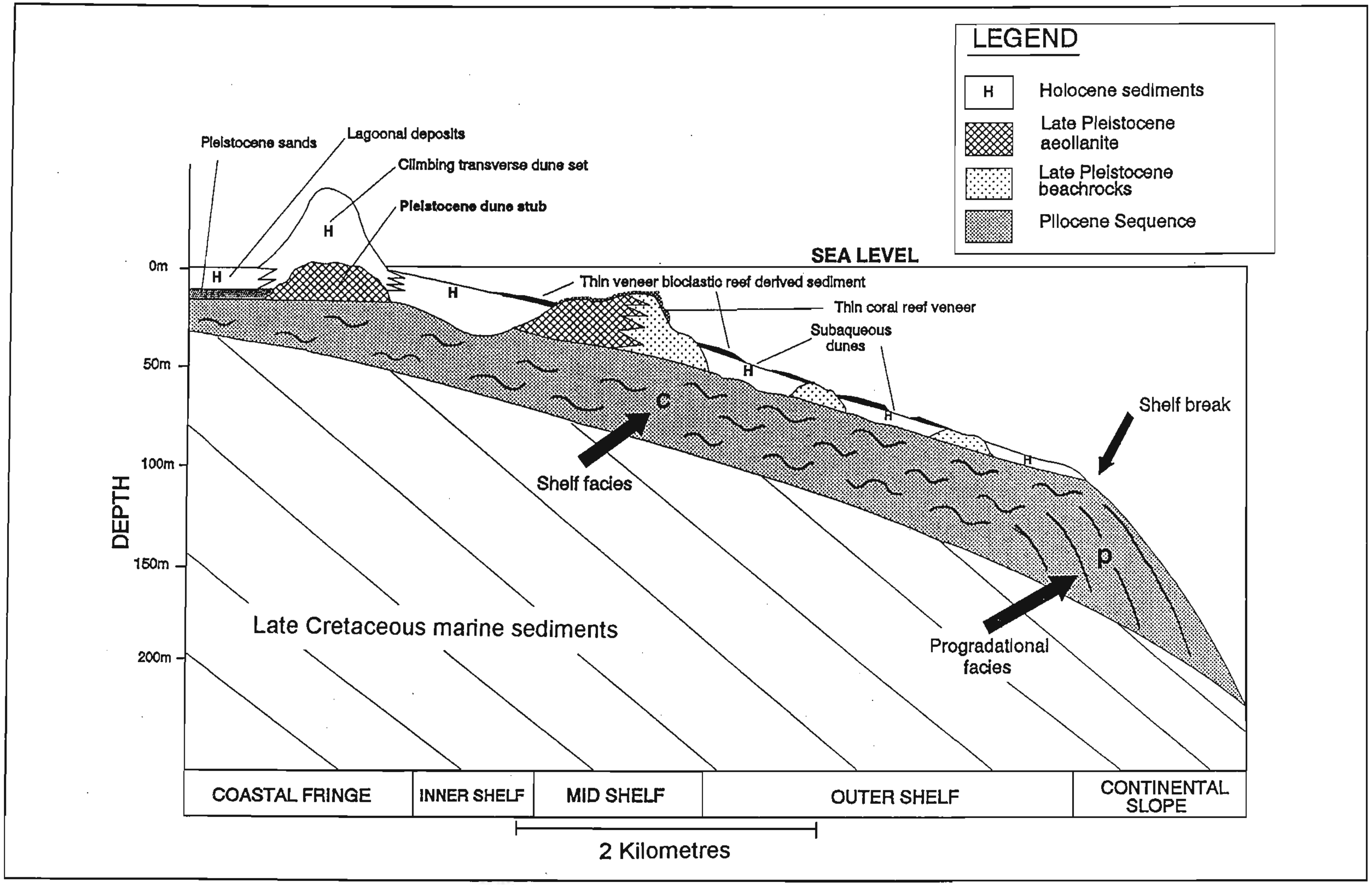


Fig. 4.4: Idealised geological cross section through the Sodwana Bay continental shelf (from Ramsay, 1994)

compiled from interpretation of Sparker and Edo Western seismic profiles and terrestrial oil exploration borehole data (Ramsay, 1994). In this section the gentle seaward-dipping, fossiliferous late Cretaceous sediments are unconformably overlain by a steeply dipping progradational marine facies ("p" on Fig. 4.4) and shelf facies of Pliocene age ("c" on Fig. 4.4). This Pliocene sequence is overlain on land by Pleistocene sands and aeolianites and Holocene lagoonal and aeolian deposits. Offshore they are unconformably overlain by late-Pleistocene regressive aeolianites and beachrocks and Holocene shelf sand (Ramsay, 1994). A major submerged late Pleistocene dune ridge is located close inshore, 1.5km from the coast, dated at 84000 ±3000BP (Ramsay, 1994). These outcrops are capped by a thin veneer of coral. Erosion of this veneer of coral reef present at water depths shallower than -25m resulted in the deposition of a thin (<1m) bioclastic sediment wedge on the Holocene shelf sand adjacent to the reefs (Ramsay, 1994). The only offshore Pleistocene sediments represented in this section are beachrock and aeolianites. Between linear beachrock and aeolianite outcrops, unconsolidated Holocene shelf sand rests directly upon the Pliocene shelf sequence.

4.2 Reflection characteristics of seismic facies

Interpretation of Edo-Western seismic sections was aided by Ramsay's (1994) sediment distribution map (Fig. 4.5) of the study area compiled from side-scan-sonar records, SCUBA dive observations and SHIPEK grab sediment samples.

Consolidated lithologies (Pleistocene beachrock and aeolianite) are characterised by higher amplitude (dark) reflections and relatively thick apparent seismic penetration, approximately 7m (Fig. 4.6).

Unconsolidated sediment (Holocene shelf sand and bioclastic reef derived sediment) is characterised by lower amplitude (lighter) reflections and shallower apparent penetration. Unconsolidated sediment usually appears as a "crust" of high amplitude reflections overlying 3 to 4m of lower amplitude reflections (Fig. 4.6)

Consolidated sediment is often visible below unconsolidated sediment (Figs. 4.6 and 4.7). Doubts about the nature of reflected lithologies were resolved by referring to echo-

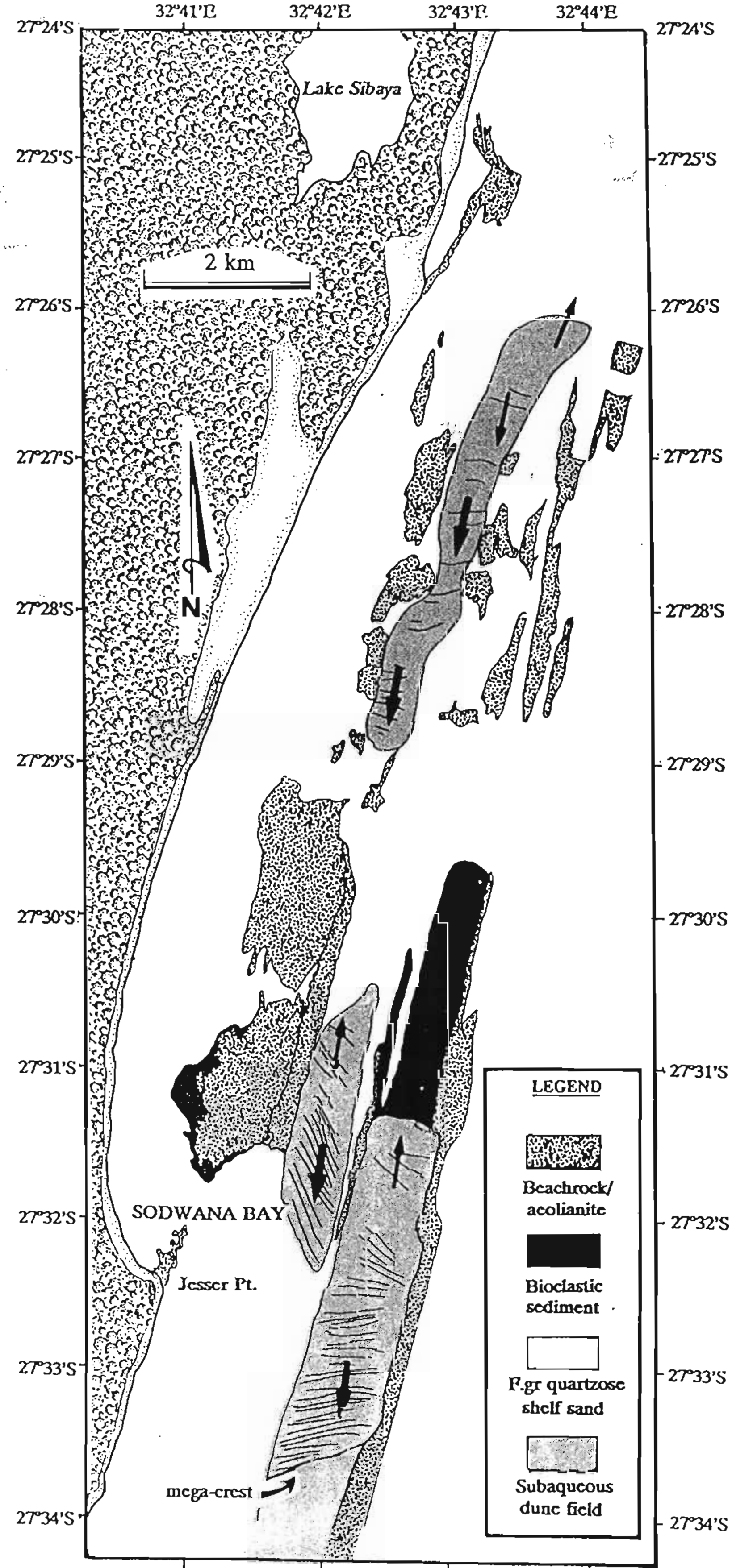


Fig. 4.5: Simplified sediment distribution map of the Sodwana Bay continental shelf (from Ramsay, 1994)

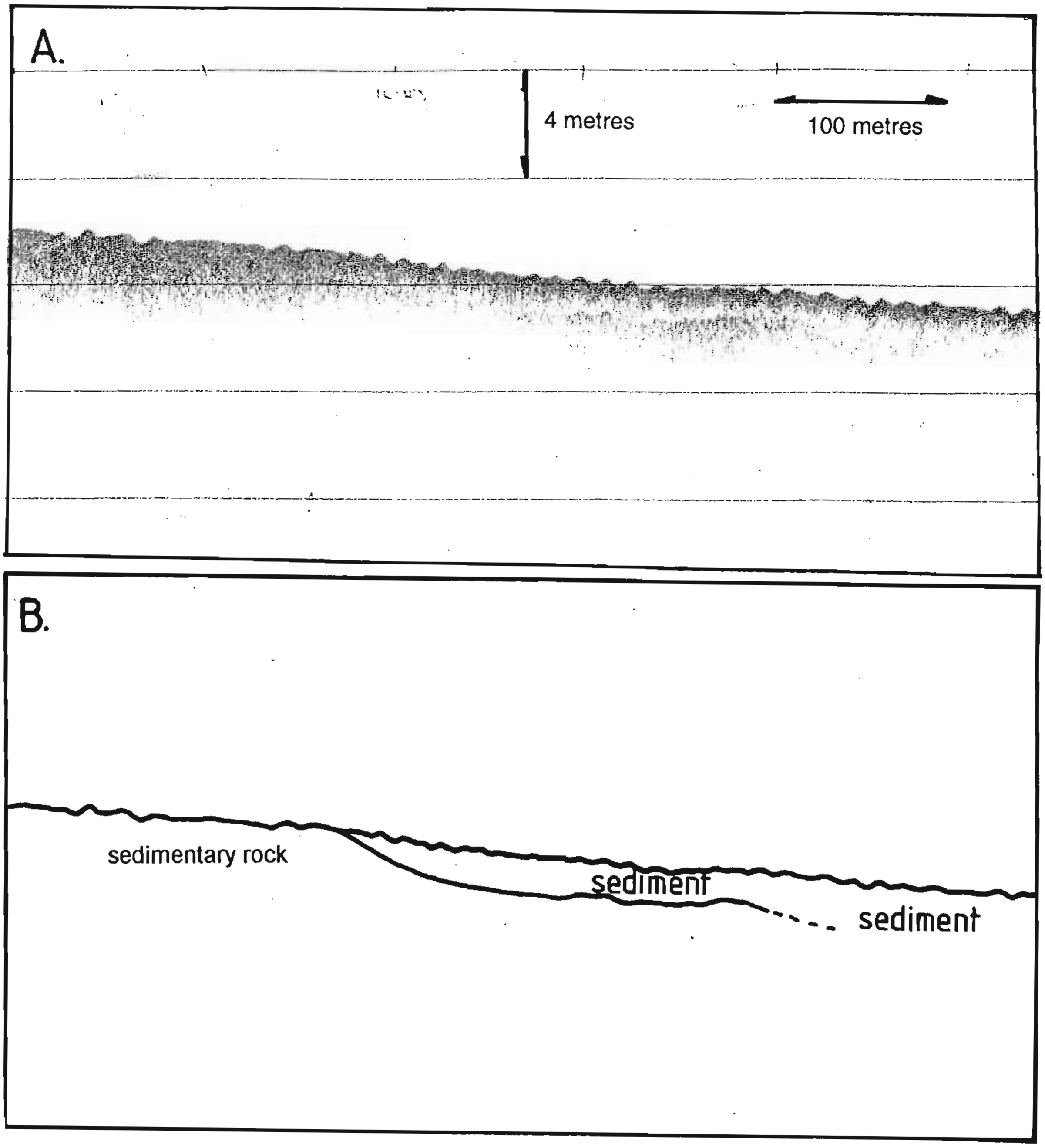


Fig. 4.6: Edo-Western seismic profile (A) and line drawing interpretation (B) showing seismic characterisation of unconsolidated sediment and sedimentary rock

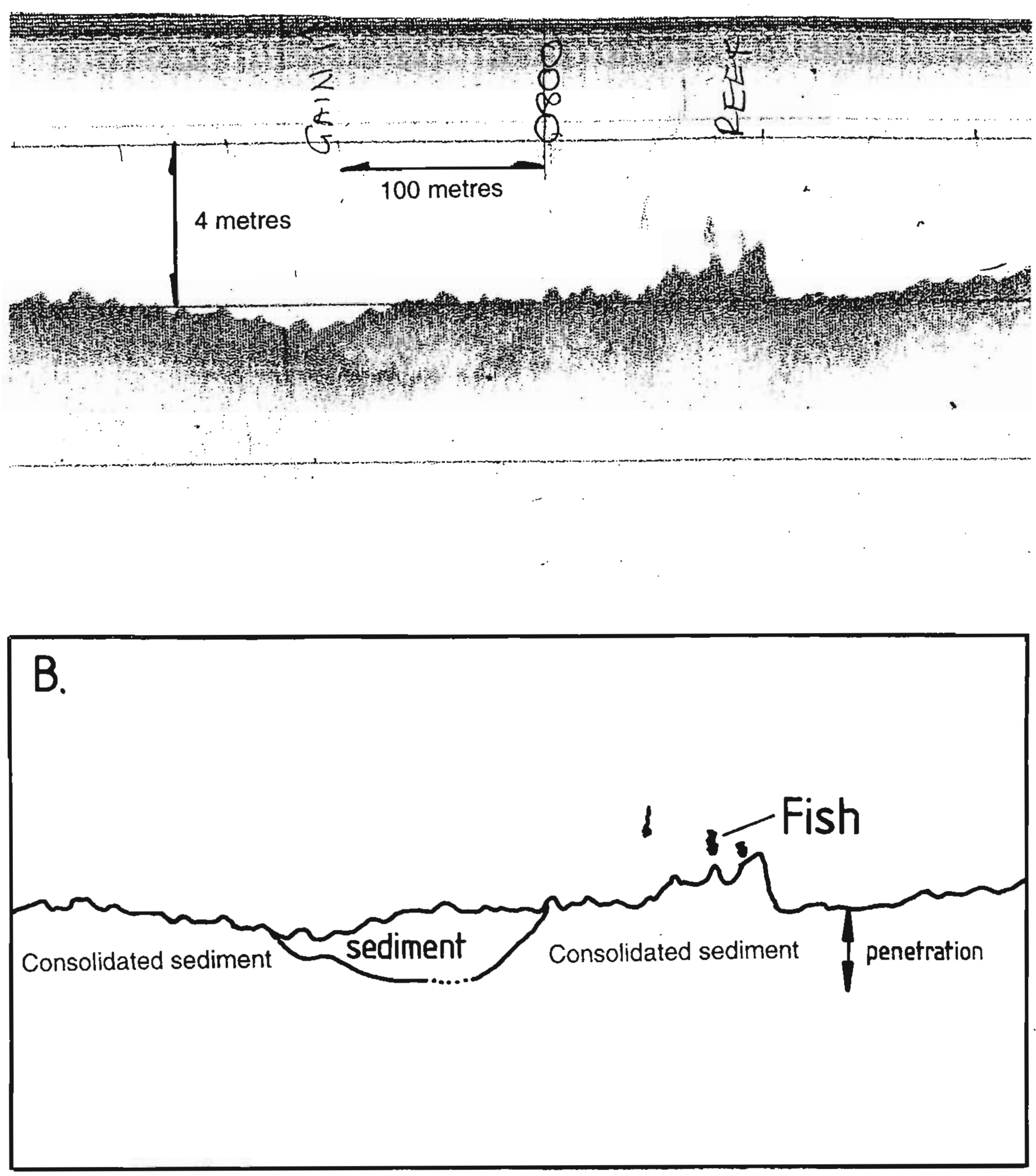


Fig. 4.7: Edo-Western seismic profile (A) and line drawing interpretation (B) showing presence of fish over consolidated sediment, and unconsolidated sediment overlying consolidated sediment

sounding records. Fish shoals which often indicate presence of a coral or rocky reef and hence consolidated substrate, are often visible on echo-sounding rolls (Fig. 4.8) and more rarely on Pinger sections (Fig. 4.7). Figure 4.9 summarises features visible on inshore Edo-Western seismic records.

4.3 Characteristics of subaqueous dunes on Edo-Western sections

Subaqueous dune sedimentology of the Sodwana Bay continental shelf has been described in detail in Ramsay (1991, 1994). The position of this dune field is indicated on Ramsay's simplified sediment distribution map (Fig. 4.5).

Ramsay (1991) recognised dunes forming on the continental shelf in two distinct fields at depths -35m and -70m. The major sediment transport direction is towards the south with the Agulhas Current flow acting as sediment conveyor. Detailed morphology on the basis of sidescan-sonar image and echosounding record interpretation is contained in Ramsay (1991). In addition he recognised bedload parting zones where sediment transport direction changes from south to north as a result of topographically induced vorticity changes in the geostrophic flow and/or the response to atmospheric forcing caused by coastal low-pressure systems moving up the coastline (Ramsay, 1991).

In this study some important sub-bottom features were noted in the subaqueous dune fields.

4.3.1 Buried bioclastic sediment

Subaqueous dunes morphology interpreted from sonograph images show that dune troughs contain a substantial amount of bioclastic debris. It was discovered (Ramsay, 1991) that sediment with a greater than 20% $CaCO_3$ content shows up on side-scan-sonar images as regularly spaced, highly reflective, even toned reflections. Finer grained non-bioclastic dune lee slopes show a weakly reflective even toned reflection signal. When the subaqueous dunes are active, finer grained lee slope sediment will override bioclastic sediment in the dune troughs thereby burying it (Fig. 4.10). Buried bioclastic sediment is visible on some Pinger sections through subaqueous dune fields as dark, irregular surfaces below the undulating, less reflective finer grained stoss-

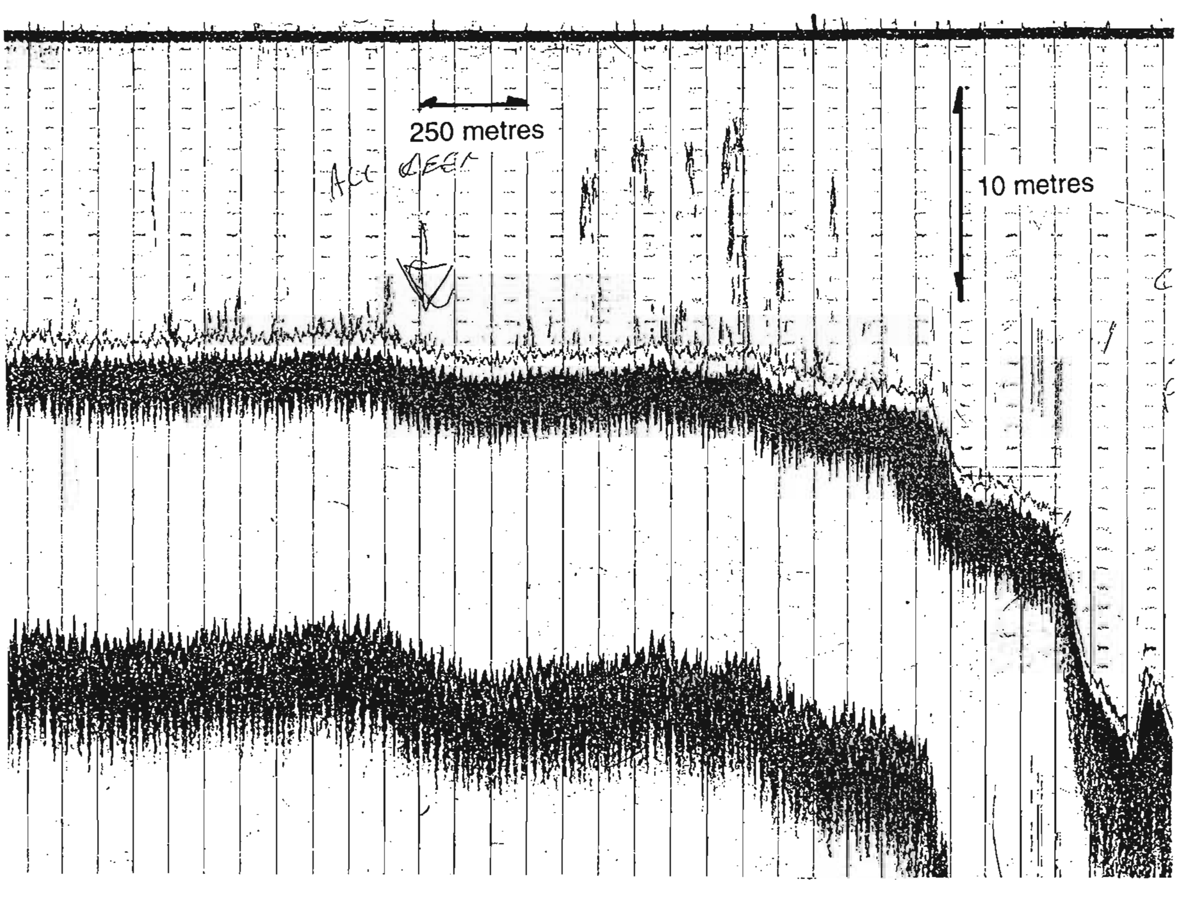


Fig. 4.8: Echo-sounding record showing presence of fish over consolidated substrate

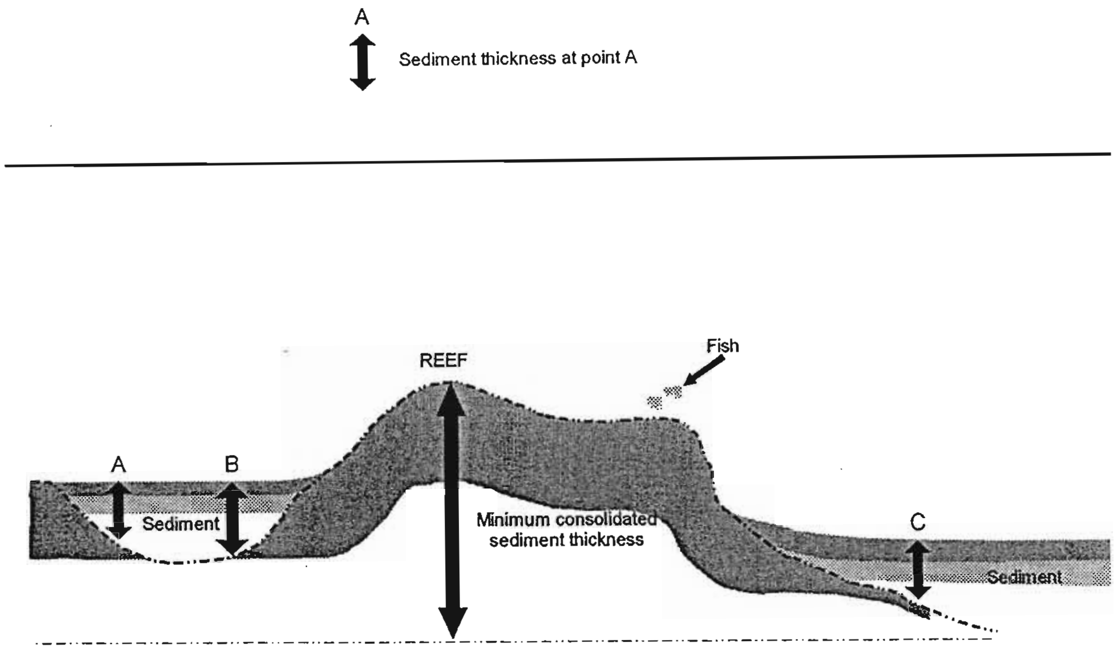


Fig. 4.9: Schematic summary of features visible on inshore Edo-Western seismic profiles

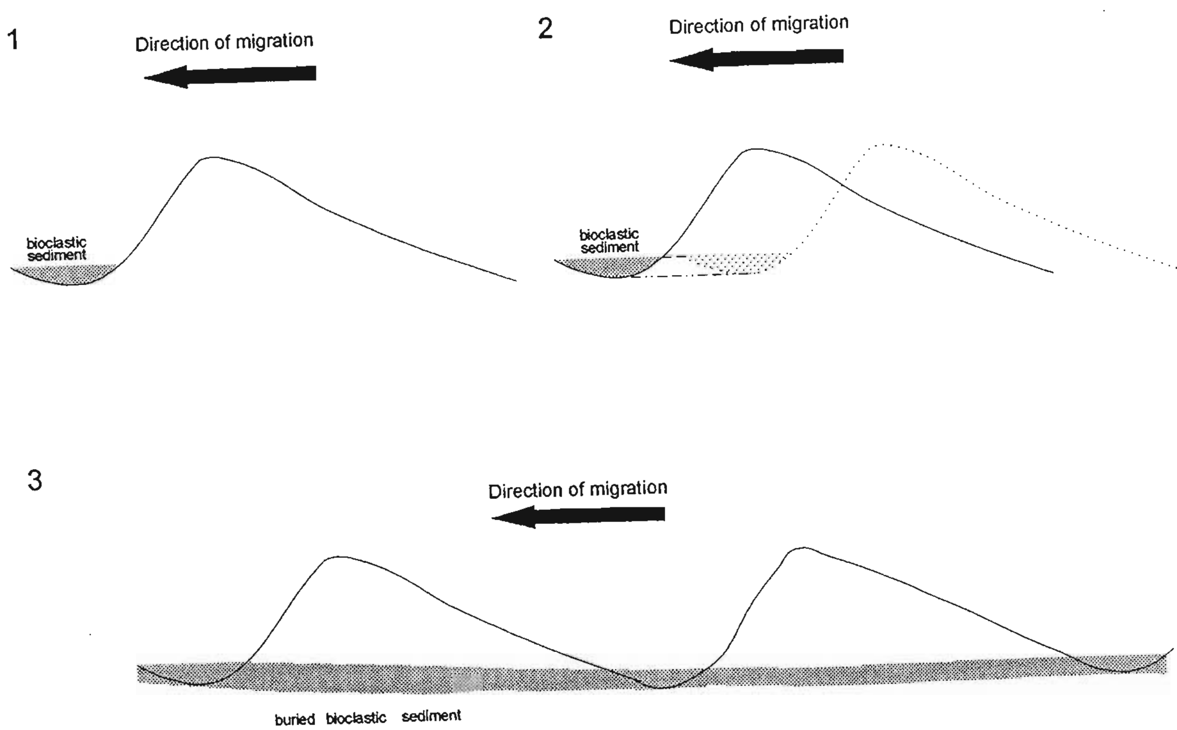


Fig. 4.10: Schematic representation showing migration of subaqueous dunes and consequent burial of bioclastic sediment in dune troughs

slope sediment (Fig. 4.11).

4.4 Interpretation of shelf-edge Edo-Western sections

Figure 4.12 shows an Edo Western section acquired in deep water close to the edge of the continental shelf, corresponding echo-sounding record and a schematic interpretation. On the Edo Western section, a depression showing reflection characteristics of unconsolidated sediment is bordered on both sides by high relief areas showing reflection characteristics of consolidated beachrock or aeolianite. On the corresponding echo-sounding record, fish are visible above the two prominent areas. Consolidated beachrock/aeolianite up to 6m thick, perches directly upon unconsolidated sediment. The depression in which unconsolidated sediment is present is interpreted as an area where either the consolidated beachrock has been eroded through, or where beachrock was not originally developed.

4.5 Sediment thickness interpretation

Unconsolidated sediment thicknesses of the Sodwana Bay continental shelf are shown in Figure 4.13. The main control on unconsolidated sediment thickness distribution in the study area are the locations of submerged Late Pleistocene aeolianite and beachrock outcrops. Where these outcrops were observed on sidescan sonar images and Edo Western profiles, unconsolidated sediment thickness is assumed to be 0m. On this sediment thickness map, 0m sediment thickness contours corresponding to various mapped reefs (Ramsay, 1994, see Fig. 4.5) are visible close to the coastline.

Thin beachrock outcrops furthest offshore are also represented as zero thickness contours. These elongate thin linear beachrock outcrops lie at the outer limit of the data acquisition area and interpretation of the Pinger seismic records show that they perch directly upon unconsolidated Quaternary sediments (Fig. 4.12). Where these beachrocks have been eroded, unconsolidated sediment underneath is exposed. Thickness of this unconsolidated sediment is unknown due to the limited penetration of the Edo Western system. On the isopach map, the thin beachrock is represented as 0m contours surrounded by an area of sediment thickness >5m. Thus although beachrock outcrops are represented as 0m contours, unconsolidated sediment is

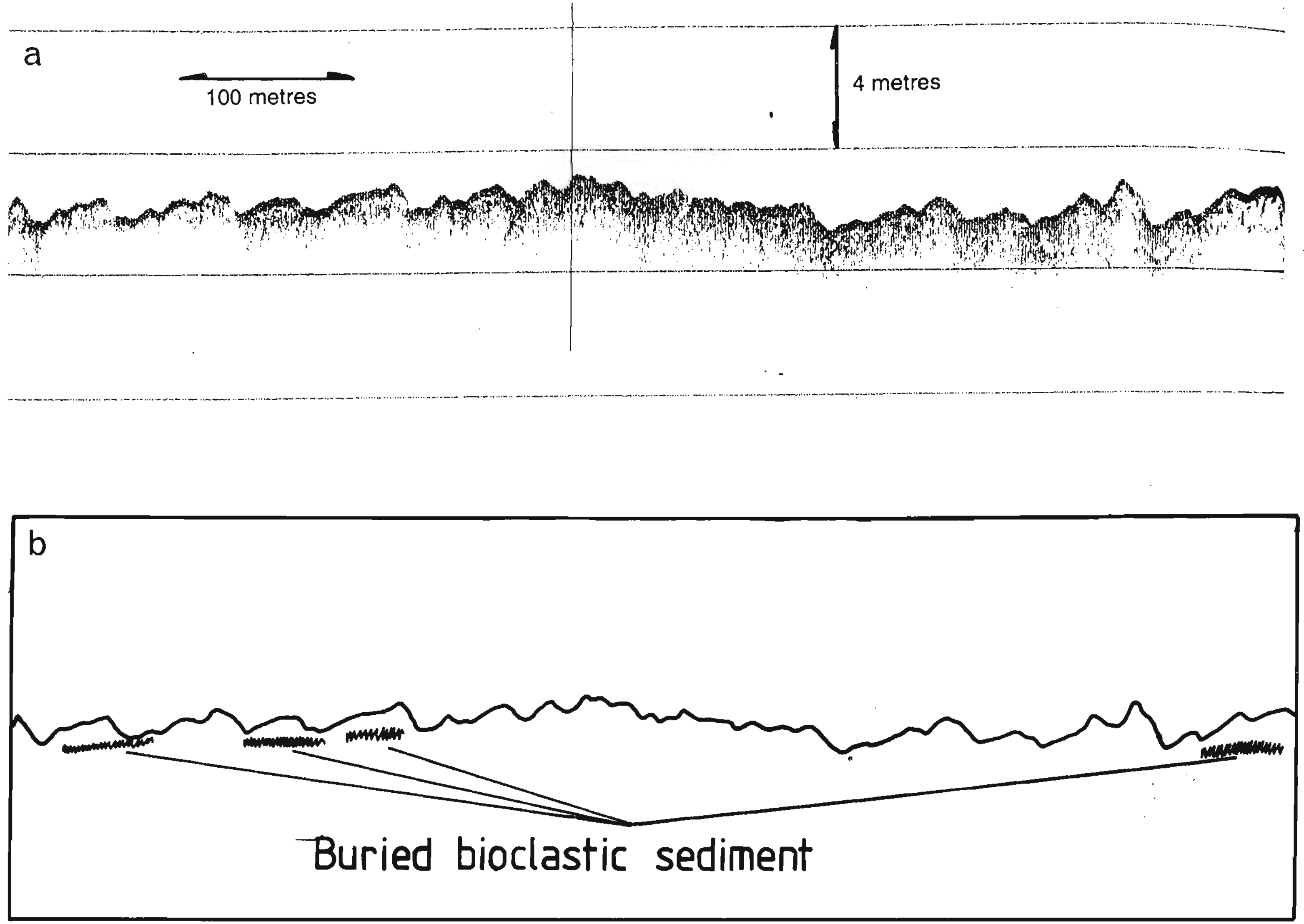


Fig. 4.11: Edo-Western seismic profile and line drawing interpretation showing buried bioclastic sediment in subaqueous dune fields

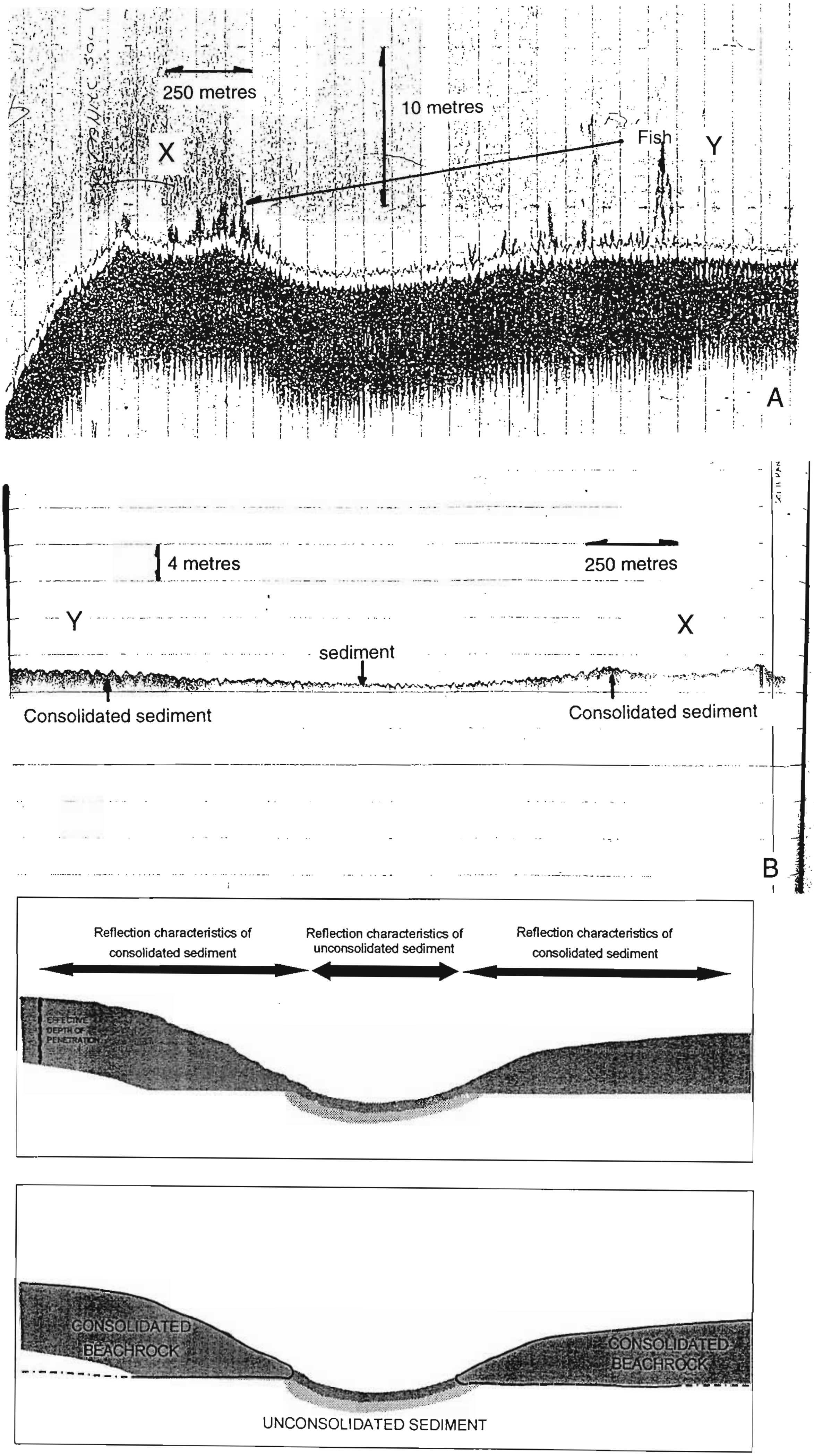
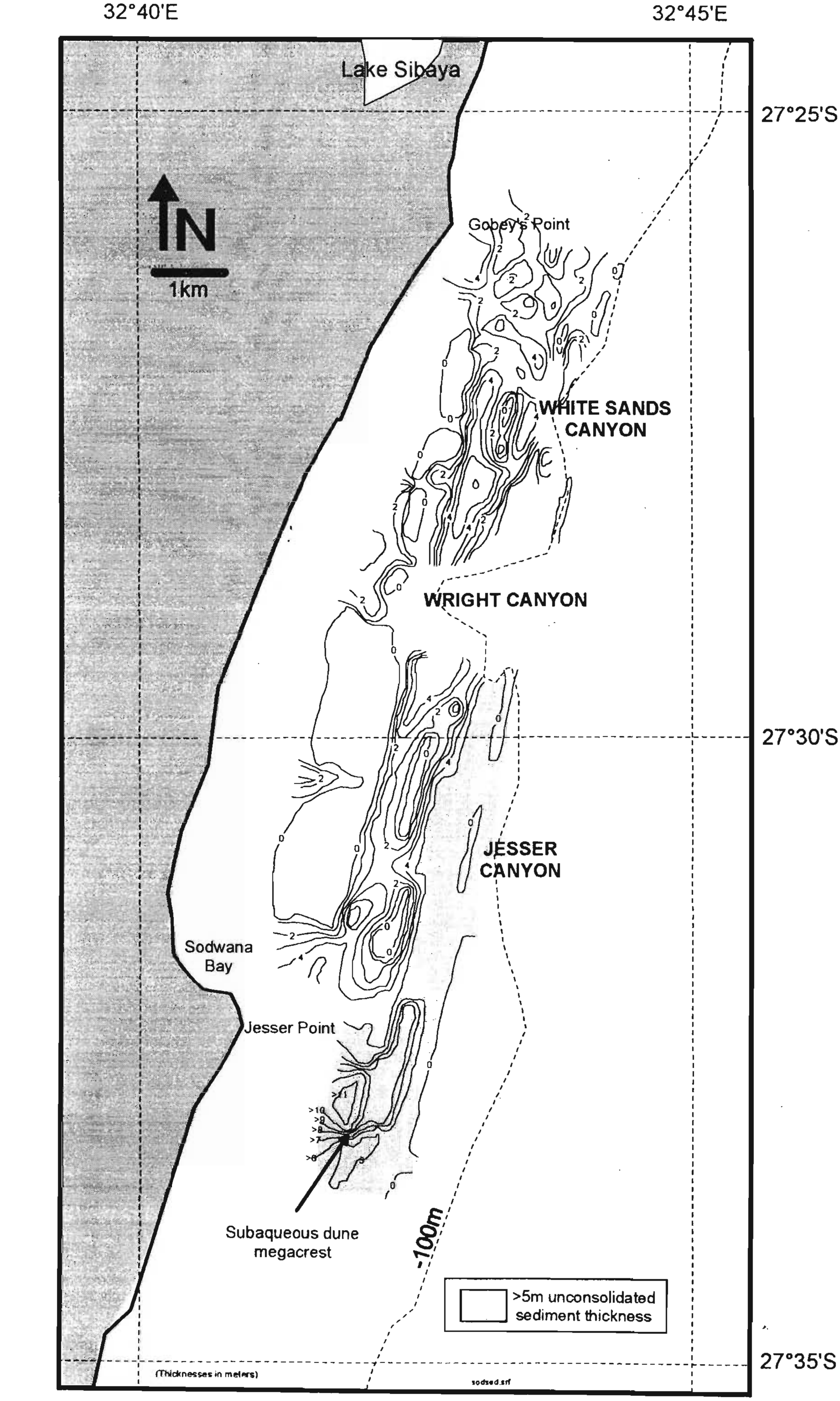


Fig. 4.12: Echo-sounding record (A), corresponding Edo-Western seismic


32°40'E
32°45'E
27°25'S
27°30'S
27°35'S
Lake Sibaya
N
1km
Gobey's Point
WHITE SANDS
CANYON
WRIGHT CANYON
JESSER
CANYON
Sodwana
Bay
Jesser Point
Subaqueous dune
megacrest
-100m
>5m unconsolidated
sediment thickness
(Thicknesses in meters)
sodsed.srf

present underneath.

The most significant unconsolidated sediment accumulations occur in subaqueous dune fields seaward of the major submerged dune ridge. In the south-eastern outer subaqueous dune field (see Fig. 4.5) unconsolidated sediment thickness is at least 11m. Discernible also in the south-eastern outer subaqueous dune field is a mega-crest observed during SCUBA diving surveys (Ramsay, 1991) and on sidescan sonar records. This manifests itself as a west-south-west to east-north-east sub-parallel set of contours decreasing sharply from >10m to >5m. The inner subaqueous dune field to the north of Wright Canyon (see Fig. 4.5) also has substantial sediment thicknesses of 5m and greater. In the extreme north of the study area, unconsolidated sediment thicknesses are low, varying mostly between 1 and 3m.

4.6 Discussion

Unconsolidated sediment thickness maps of the northern KwaZulu-Natal continental shelf have previously been compiled from seismic data by other workers. These are becoming of increasing importance due to the current interest in possible economic concentration of heavy minerals in offshore unconsolidated sediment wedges. Martin (1985) compiled an isopach map of unconsolidated sediment on the continental shelf between 28° and 29°S (from Cape Vidal to Mtunzini) from interpretation of Sparker and Boomer seismic profiles while Birch (1996) estimated unconsolidated Quaternary sediment volumes from Cape Vidal to Cape Padrone (near East London) from interpretation of airgun seismics (Fig. 4.14). In addition, Sydow (1988) also produced a map of unconsolidated sediment thickness in the Leven Canyon area. Thus, besides Sydow's isolated study, no unconsolidated sediment thickness maps are available for the Maputaland continental shelf north of Cape Vidal.

Martin (1985), recognised 3 major depocentres in his study area. Depocentre 1, 8km south-east of Richards Bay, extending over 30km in a north-easterly direction, is 4-5km wide, reaches a maximum thickness of 17.6m and contains 809.74 x $10^6 m^3$ of sediment. Depocentre 2 stretches 24km south-south-west from Cape St. Lucia, reaches a maximum thickness of 25.6m and contains 964.65 x $10^6 m^3$ of sediment. Depocentre 3 stretches from St. Lucia Estuary Mouth, northwards beyond 28°S,

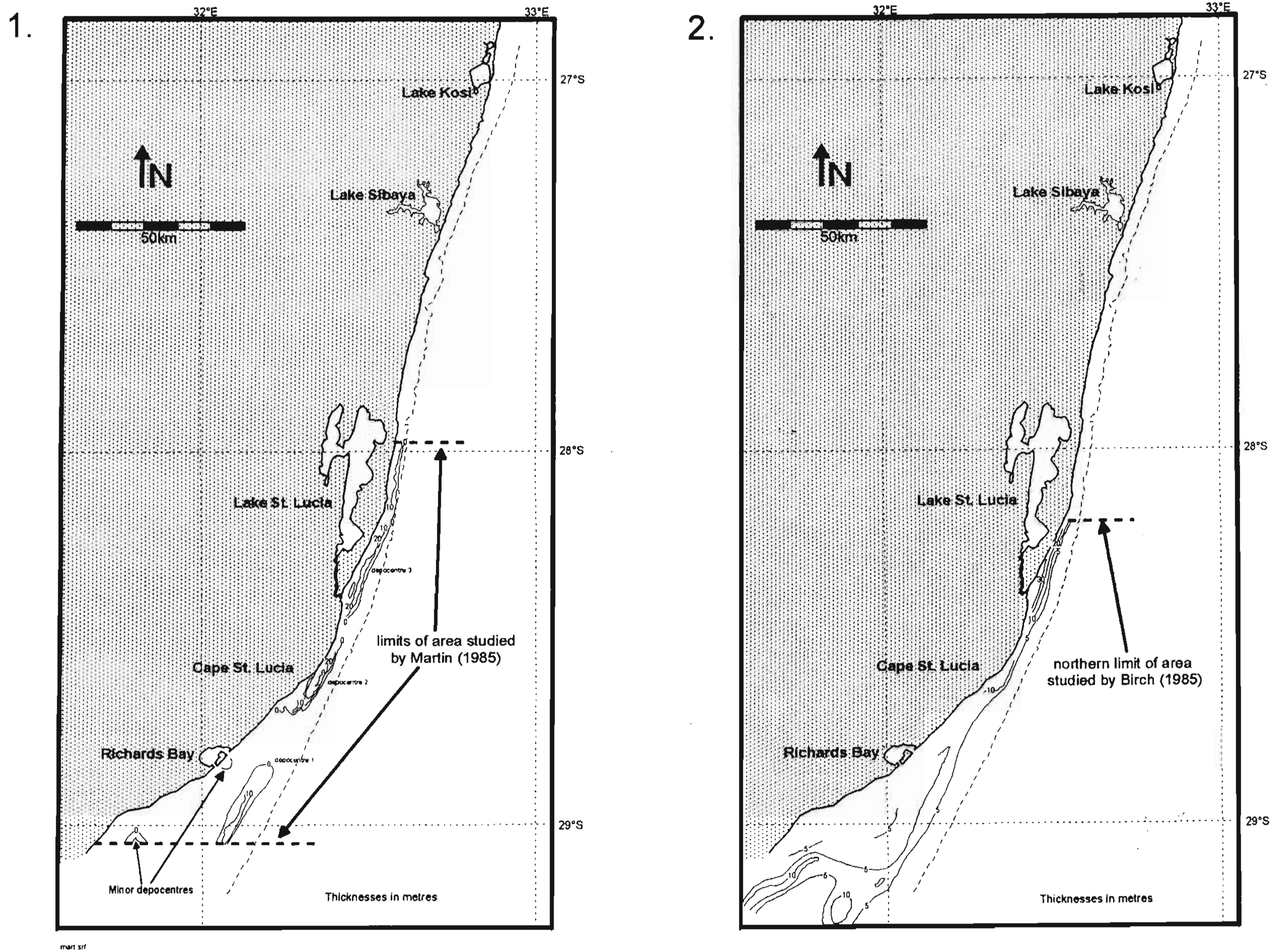


Fig. 4.14: Unconsolidated sediment thickness maps of 1. Martin (1985) and 2. Birch (1996)

extends over 6km offshore in the south narrowing to less than 3km in the north, reaches a maximum thickness of 27.2m off St. Lucia estuary and contains 2.5 x $10^9 m^3$ of sediment.

Birch also lists the greatest unconsolidated sediment thickness as being located offshore from the St. Lucia Estuary Mouth where up to 22m of sand is present. This compares favourably with Martin's figure of 25.6m. Birch also recognises another major depocentre up to 10m thick south of Durnford Point. The minor depocentre recognised by Martin (1985) is probably the northern limit of this sediment wedge.

Birch (1996) notes that there is a dearth of unconsolidated Quaternary sediments on the eastern continental margin compared to other continental shelves. Unconsolidated Quaternary sediment build-up is greatly influenced by the activity of the Agulhas Current. The most significant Quaternary sediment accumulations on the continental shelf are located where the effect of the Agulhas current is reduced, i.e. in major structural offsets, in zones of bedload parting, in embayments, behind protective headlands and landward of submerged dune ridges.

Martin's (1985) Depocentre 1 off Richards Bay is interpreted to be related to the structural offset of the coastline where the coastline orientation changes from NNE to NE. This coastline morphology is a product of the transform fault processes operative during the break-up of Gondwana (Martin, 1984). Where these changes in coastline orientation occur, the continental shelf widens and the Agulhas Current is pushed offshore, allowing conditions favourable to sediment build-up to prevail. Depocentres 2 and 3 are dammed on the landward side of submerged dune ridges.

On the Sodwana Bay continental shelf the submerged dune ridge close inshore (approx. 1.5km) has a great influence on unconsolidated sediment thickness, effectively damming up sediment on it's inshore side. Further south submerged dune ridges are located further offshore thereby creating more favourable conditions for a greater unconsolidated sediment build-up. Submerged dune ridges close inshore limit the damming effect to a 1.5km corridor between the surf zone and ridge outcrops. Seaward of the major submerged dune ridge, sediment build-up is limited by thin, less prominent beachrock outcrop. Minor beachrock outcrops furthest offshore perch directly upon unconsolidated Quaternary sediment. Limited penetration of the Pinger system limits thickness data in this area. Thus, while the offshore areas are depicted as a field with a >5m cover of unconsolidated sediment, it is probable that this thins to 0m further down the continental slope, where the strata of Sydow's (1988) Pliocene progradational sequence crop out (Fig. 4.3)

A comparison of sediment thickness data south of Cape Vidal and these data show that unconsolidated sediment thickness on the Sodwana Bay continental shelf is low. The narrowness of the continental shelf at Sodwana Bay allows the Agulhas Current to migrate close inshore. This current is responsible for much of the unconsolidated sediment being lost down submarine canyons. Ramsay (1991) noted evidence of sediment slumping in Wright, Jesser and White Sands Canyons. These slumps were seen on bathymetry echo-sounding records where the hummocky nature of canyon thalwegs were interpreted as being slumped sediment accumulations. While the Agulhas Current has been cited as limiting Quaternary sediment build-up on the northern KwaZulu-Natal continental shelf (Birch, 1996; Flemming, 1981), at Sodwana Bay this current is responsible for the greatest sediment thicknesses in the study area i.e. at the crests of very large subaqueous dunes. The Agulhas Current is thus an important control on sediment thickness control.

The low resolution of the Sparker (3 - 4.5m) and Boomer (1.5m) systems used to produce Martin's (1985) isopach map meant that thin sediment deposits less than 2m thick were not resolved. His isopach map therefore shows 5 localised depocentres separated by areas void of unconsolidated sediment. In this study, superior resolution of the Pinger system has enabled the identification and quantification of thin Quaternary sediment veneers which form a major portion of the sediment budgets for this continental shelf. The most accurate isopach map for the Sodwana Bay continental shelf would be compiled using both Pinger and another higher energy source. The low power, high resolution Pinger system would allow identification of thin sediment veneers while the higher power, lower resolution system would delineate large sediment accumulations such as that located off the St. Lucia Estuary Mouth.

The dearth of unconsolidated sediment on the Sodwana Bay continental shelf can be attributed to several factors. It has been estimated that sedimentation rates in the Natal

Valley are up to 22 times higher at present than during the last 5 million years (Martin, 1987; McCormick *et al.*, 1992). The well-developed submerged dune cordon along the coast ensures that while the abyssal areas below the continental slope are experiencing conditions of accelerated sedimentation, the continental shelf in the study area is currently experiencing fluvial sediment starvation. Besides the minor Mgobozeleni fluvial outlet just north of Jesser Point, the only other possible sources of terrigenous sediment input are Kosi Bay, 65km to the north, and the St. Lucia Estuary Mouth, 130km to the south (see Fig. 1.3, Chapter 1). Of these, the Mgobozeleni River has an extremely small catchment area of just 33km^2 with a sediment discharge rate of 3300 tons per annum (McCormick *et al.*, 1992). The Sodwana Bay continental shelf is therefore situated within a 200km stretch virtually devoid of terrigenous sediment input. These conditions of sediment starvation are thought to have prevailed for the last 5000 years. Prior to this, it is thought that terrigenous sediments were introduced to the continental shelf in the area via an inlet to Lake St. Lucia near Leven Point (Sydow, 1988; Van Heerden, 1987). Miller (1993) states that it is possible that Lake Sibaya was open to the sea in early Holocene times. If this was the case then this outlet is another possible source of terrigenous sediment for the Zululand continental shelf during Holocene times. The narrow shelf allows the Agulhas Current to migrate close inshore. It is able to transport sediment both north and south into submarine canyons where these sediments are lost to the abyssal plains below the shelf. There are no protective headlands in the lee of which sediments can accumulate unhindered by ocean currents. Submerged dune ridges are located too close inshore to cause a substantial damming effect. It is therefore possible that there is currently a net loss of sediment from the Sodwana Bay continental shelf.

CHAPTER 5

SUBMARINE LANDSLIDES

In this chapter, submarine landslide features in the study area are described with respect to their morphology and style of failure.. Their possible causes and importance with regard to the development and morphology of the Zululand upper continental margin is discussed. Later in the chapter, submarine landslide features observed on a sparker seismic profile of the continental slope near to the St. Lucia Estuary mouth are described and discussed in a case study which investigates slope stability parameters and possible causes. Submarine landslide terminology and classification is described in Appendix C.

Submarine canyons and submarine landslides are closely related. Mass-wasting processes contribute significantly towards the development of submarine canyons. In many cases they are the sole agent of development of submarine canyons (Shepard, 1963).

5.1 Previous Work

Several submarine landslides have been documented on the southern African continental margin. Dingle (1977) described the world's largest modern submarine landslide feature situated on the southern African continental margin between East London and Cape Agulhas. This landslide covered an area 750km long and 106km wide and affected approximately 20 000km^3 of sediment. A post-Pliocene age and seismic triggering mechanism for this slump is tentatively proposed (Dingle, 1977).

Goodlad (1986) recognised four much smaller submarine landslides in the mid-Natal Valley affecting between 21km^3 and 90km^3 of sediment over a 1125km^2 area. Goodlad tentatively assigns a Pleistocene age to these slumps and cites a combination of high sedimentation rate, downslope undercutting by deep ocean currents and perhaps seismic activity as the cause for these slope failures.

Sydow (1988) recognised submarine landslide features in his study area directly offshore Leven Point. He noted that most submarine landslide features in the Leven Point area are focussed within submarine canyons although some submarine landslide features were also recognised on the unconfined slope.

5.2 Submarine landslide features in the area.

In the study area, 9 sparker seismic profiles display submarine landslide features (Fig. 5.1). The southernmost occurrence is offshore Richards Bay and the northernmost occurrence is directly offshore Kosi Mouth. Although a single section through a submarine landslide may tend to indicate a relatively small feature, the possibility exists that the features observed are the peripheral extreme of a much larger feature.

5.2.1 Richards Bay

On the upper continental slope offshore Richards Bay (Fig. 5.2), a sudden and distinct increase in continental slope angle from 2° to 12° at a depth of approximately 220msec indicates the presence of an obvious glide plane scar with a vertical relief of approximately 20msec. A 2m deep tensional depression is visible at the base of this glide plane scar. Sequence B Facies 3 reflectors are truncated where the continental slope angle suddenly increases. It is also possible to discern two smaller glide plane scars above and below the most pronounced glide plane scar. Although the quality of the seismic record is quite poor, disruption of reflectors indicates the presence of a possible glide plane. These features indicate incipient allochthonous sediment transport with sediment not having been transported much more than 150m in any direction. Although internal reflectors are discernible within the failed sediment mass, their wavy and discontinuous nature suggests that internal coherency of the sediment mass has not been fully maintained. More substantial vertical disruption of reflectors is visible deeper and further offshore. Sequence A reflectors have been vertically displaced by approximately 50msec. In contrast to the failed sediment higher up and closer to the shore, the more continuous reflectors indicate a greater degree of internal coherency maintained during failure of the sediment mass. Together these features indicate that these small scar features may be the landward extreme of a deeper much larger submarine landslide feature. Internal disruption of sediments higher up relative to

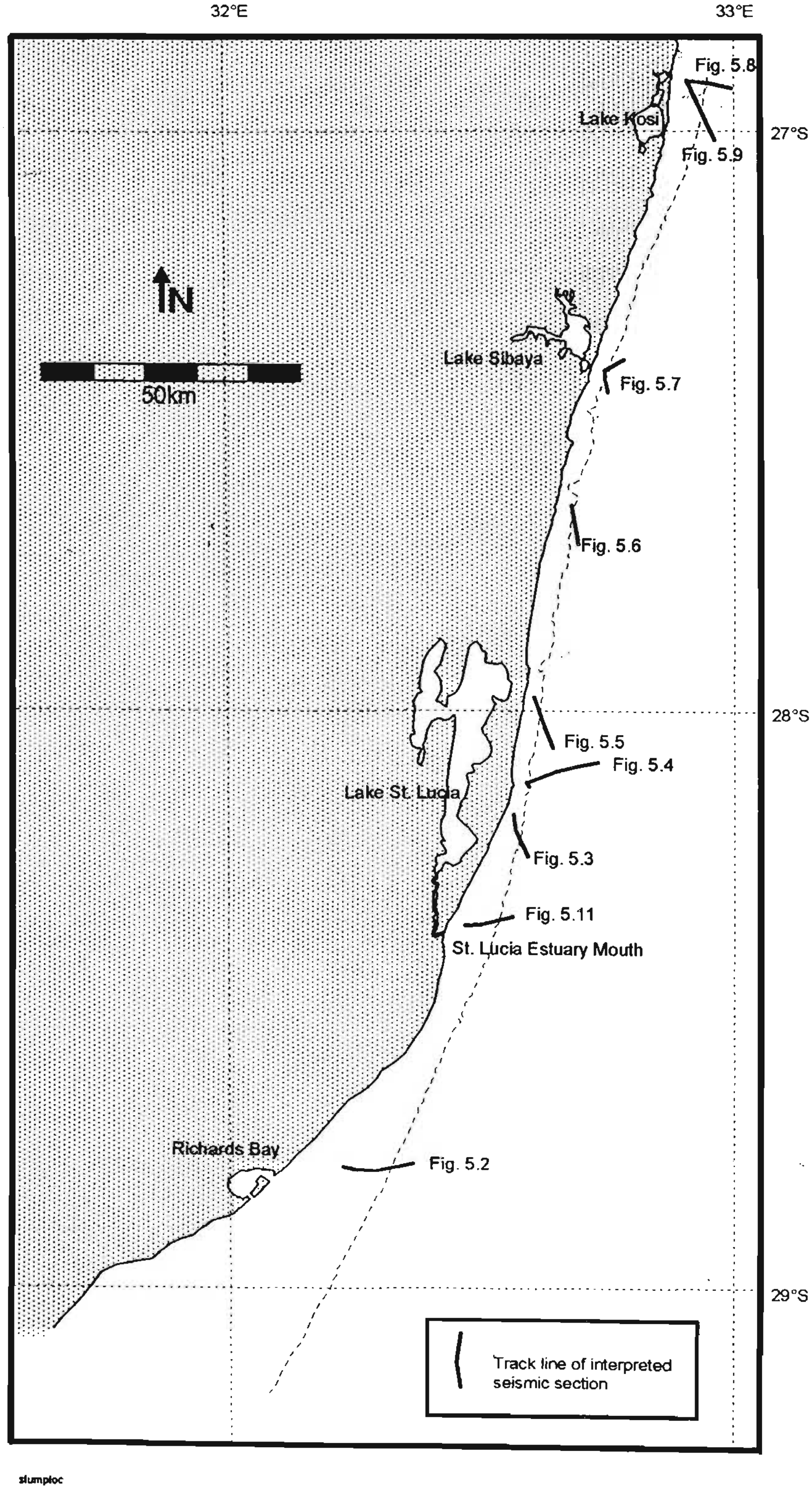


Fig. 5.1: Track lines of sparker seismic profiles in which submarine landslide features are present

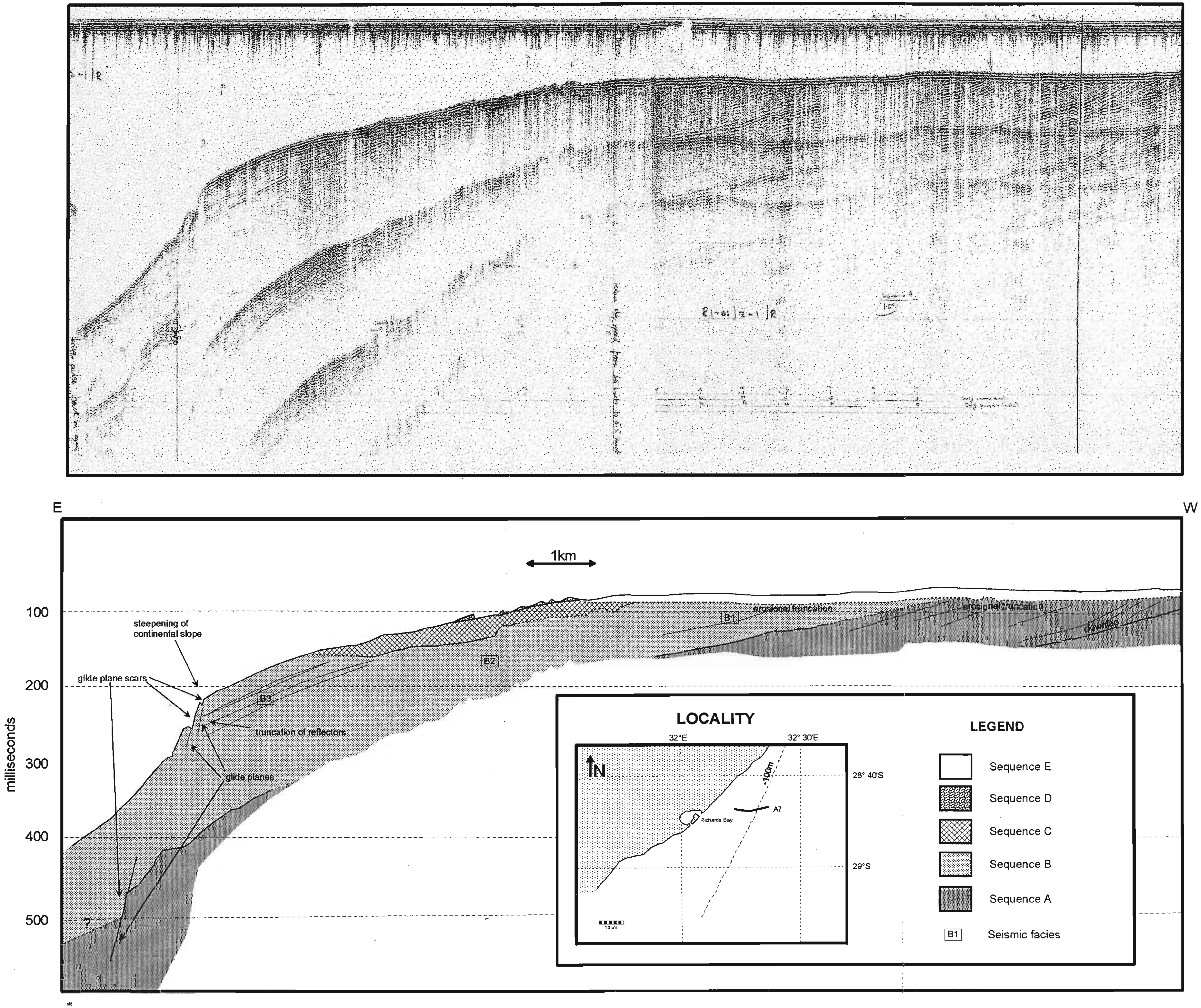


Fig. 5.2: Sparker seismic section and line drawing interpretation of profile A7, north of Richards Bay showing submarine landslide features on the upper slope

undisturbed continuous reflectors lower down in the sequence indicates a transition between a mass flow style of failure and an internally coherent slide type failure. This is probably related to the degree of lithification of the sediment body concerned.

5.2.2 Mission Rocks

On this oblique section (Fig 5.3), a prominent seaward dipping reflector possibly marking the base of Sequence B sediments is truncated by a faint seaward dipping glide plane. This reflector has a high amplitude continuous nature within the failed sediment mass, but the apparent angle of dip changes from seaward dipping to landward dipping. A tensional depression and glide plane scar are also clearly discernible. The 11m vertical relief of the glide plane scar compared to the 51m vertical offset of the prominent reflector across the glide plane means that a simple downward shift in sediment cannot explain the geometry. To explain this movement it is necessary to invoke a differential movement transverse to the plane of the section.

Further offshore, another glide plane scar, glide plane and accumulation of failed sediment are interpreted indicating that these features described may be the upper landward extreme of much more substantial deeper features similar top that observed north of Richards Bay.

5.2.3 Cape Vidal

The presence of a submarine landslide is indicated by a sudden steepening of the continental slope angle from 3° to 17° and also the erosional truncation of a continuous reflector at a depth of approximately 300msec (Fig. 5.4). This is interpreted as a glide plane scar with a vertical relief of approximately104m. Further offshore an irregular acoustically transparent accumulation much lower down on the slope is probably an accumulation of the failed sediment package.

5.2.4 King Oscar Hill

This seismic section (Fig. 5.5) is oriented at a very oblique angle to the coast. The

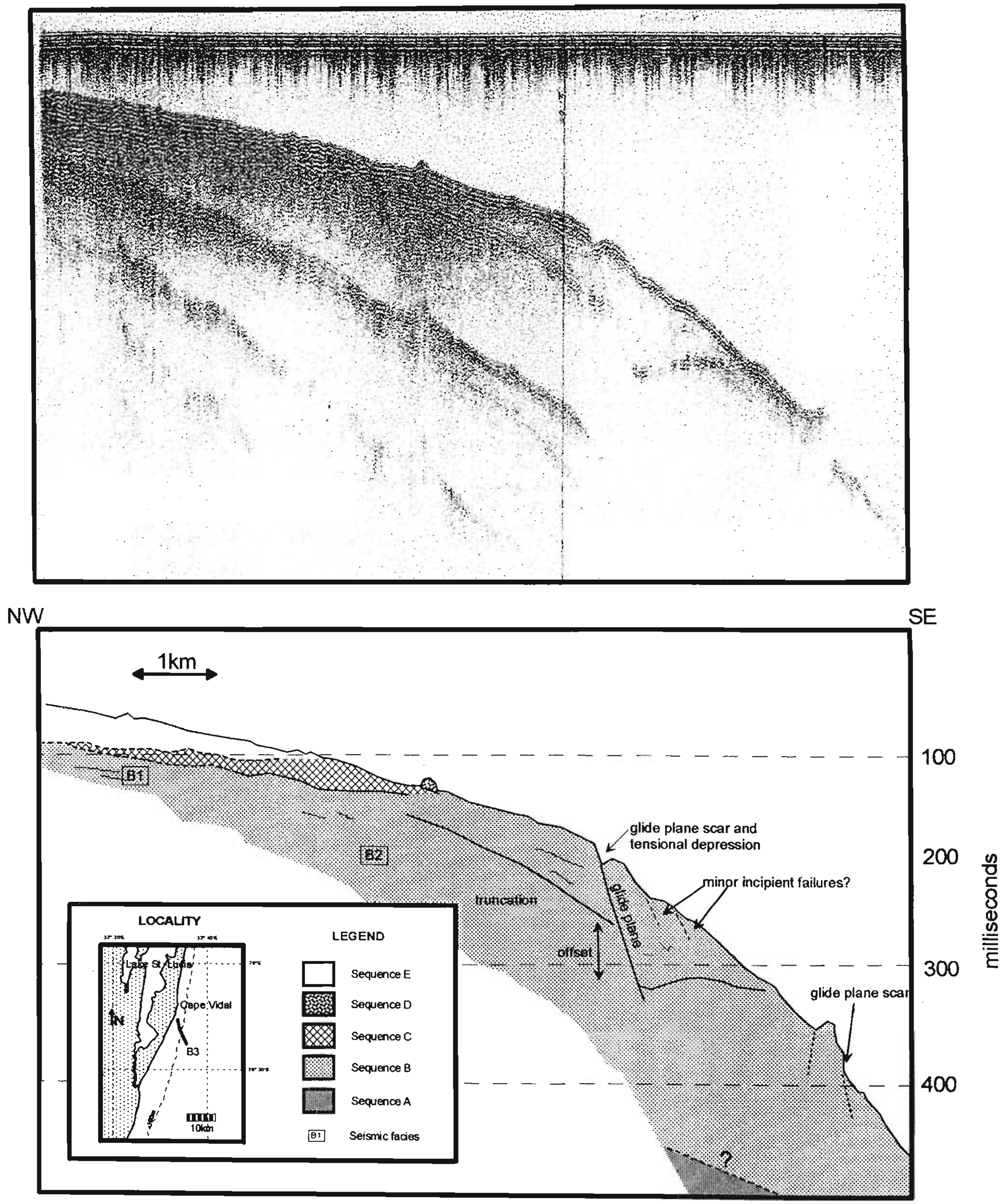


Fig. 5.3: Sparker seismic section and line drawing interpretation of profile B3, offshore Lake St. Lucia showing submarine landslide features on the upper slope

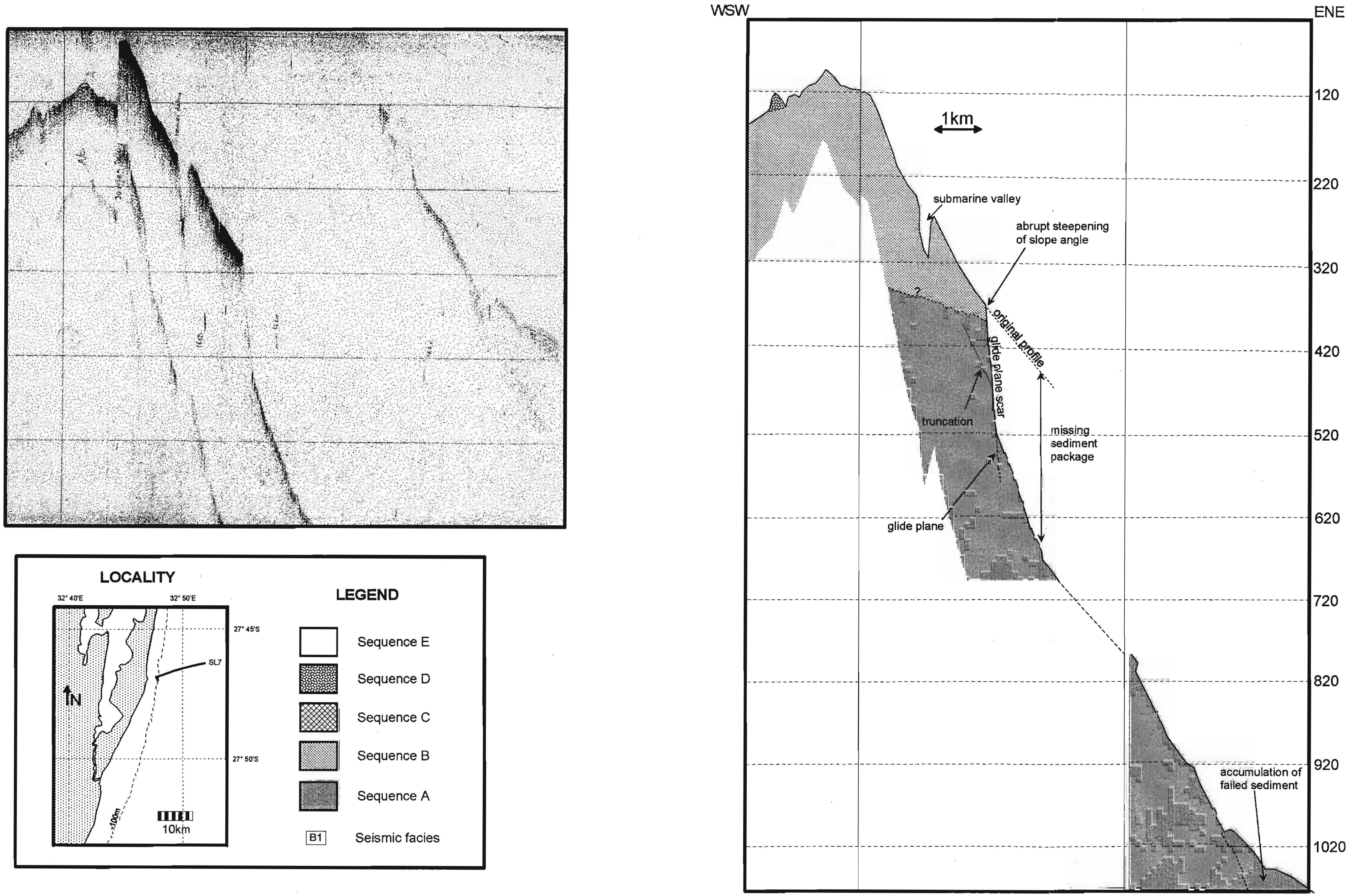


Fig. 5.4: Sparker seismic section and line drawing interpretation of profile SL7 showing submarine landslide features offshore of Cape Vidal. Interpretation corrected for delay changes.

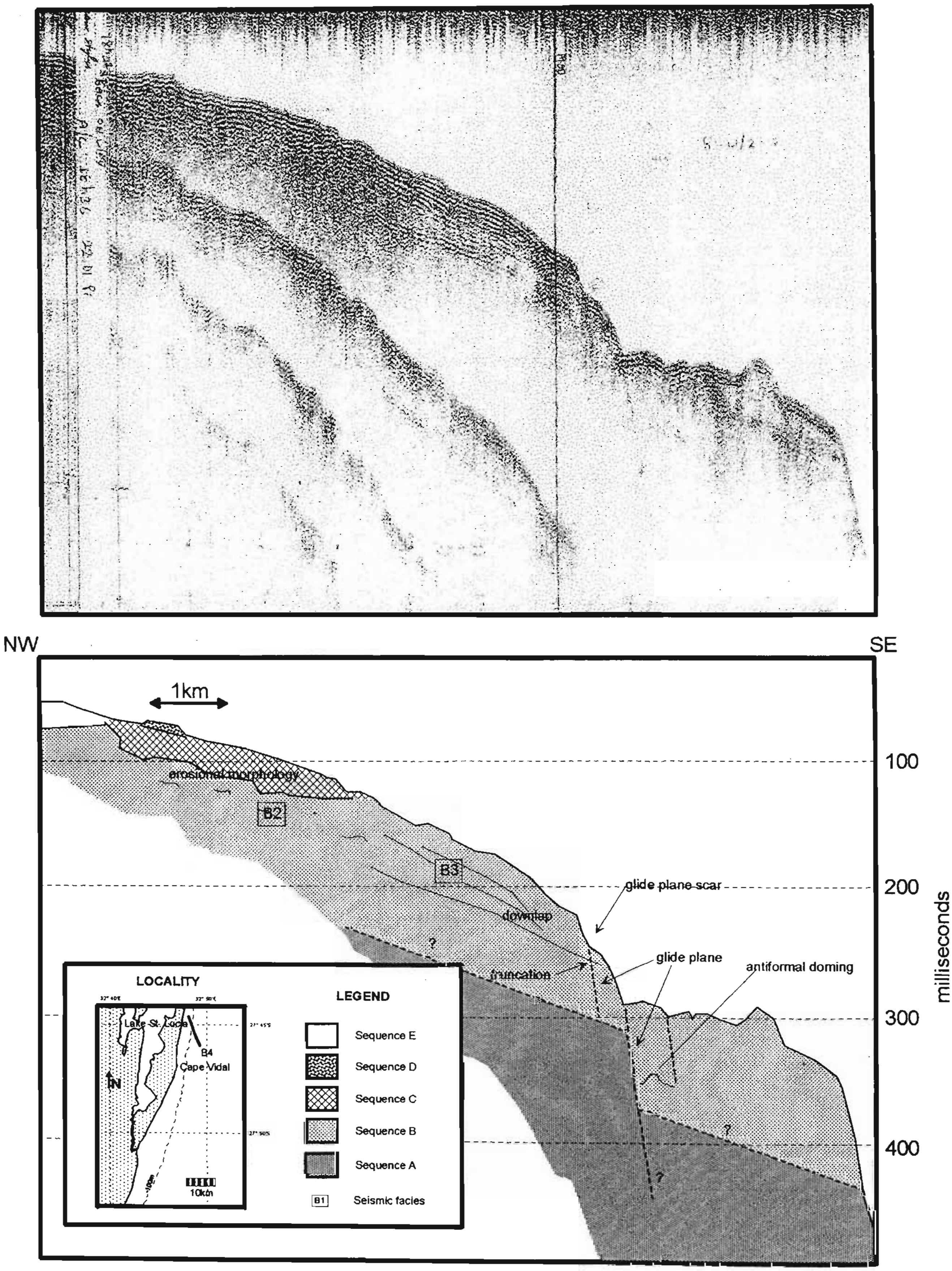


Fig. 5.5: Sparker seismic section and line drawing interpretation of profile B4, offshore northern Lake St. Lucia showing submarine landslide features on the upper slope

presence of a probable submarine landslide is indicated by a sudden slope profile change where apparent slope angle suddenly increases from 1.8° to 7.4° over a horizontal distance of approximately 160m. This slope change is interpreted as a glide plane scar. Further offshore it is possible to discern a further four subsidiary glide plane scars and a slight tensional depression. Although the seismic record is not very clear, it is just possible to discern internal reflectors and a glide plane. One of the discernible reflectors exhibits an antiformal doming against the glide plane. The sediment accumulation just below the main glide plane with the concave downwards profile, probably represents failed Sequence B material. Overall these features indicate a complex collapse structure. These features could demonstrate processes of headward erosion of a submarine canyon that has not yet breached the shelf break. A submarine canyon however has not been documented in this area, possibly due to lack of bathymetric data. This submarine landslide affects both Sequence A and B material.

The undisturbed reflector within Sequence A compared to the concave downward profile and chaotic internal reflection configuration of the Sequence B material suggests that the failure has both mass flow and slide components, mass flow occurring in the Sequence B sediments and translational sliding in the more lithified Sequence A sediments.

5.2.5 Lake Bhangazi

A hummocky sediment body at the base of the continental slope (Fig. 5.6) indicates the possible presence of a failed sediment accumulation constituted of unstable upper slope Sequence B material.

5.2.6 Lake Sibaya

These submarine landslides (Fig. 5.7) exhibit similar characteristics to that opposite Lake Bhangazi whereby continental slope irregularities indicate the possible accumulations of failed sediment masses at the base of the upper slope where Sequence A crops out. A marked slope change is evident on the southern coast perpendicular section, while on the northern section the change in slope angle is accompanied by a characteristic hummocky sea floor. Maximum vertical thickness of

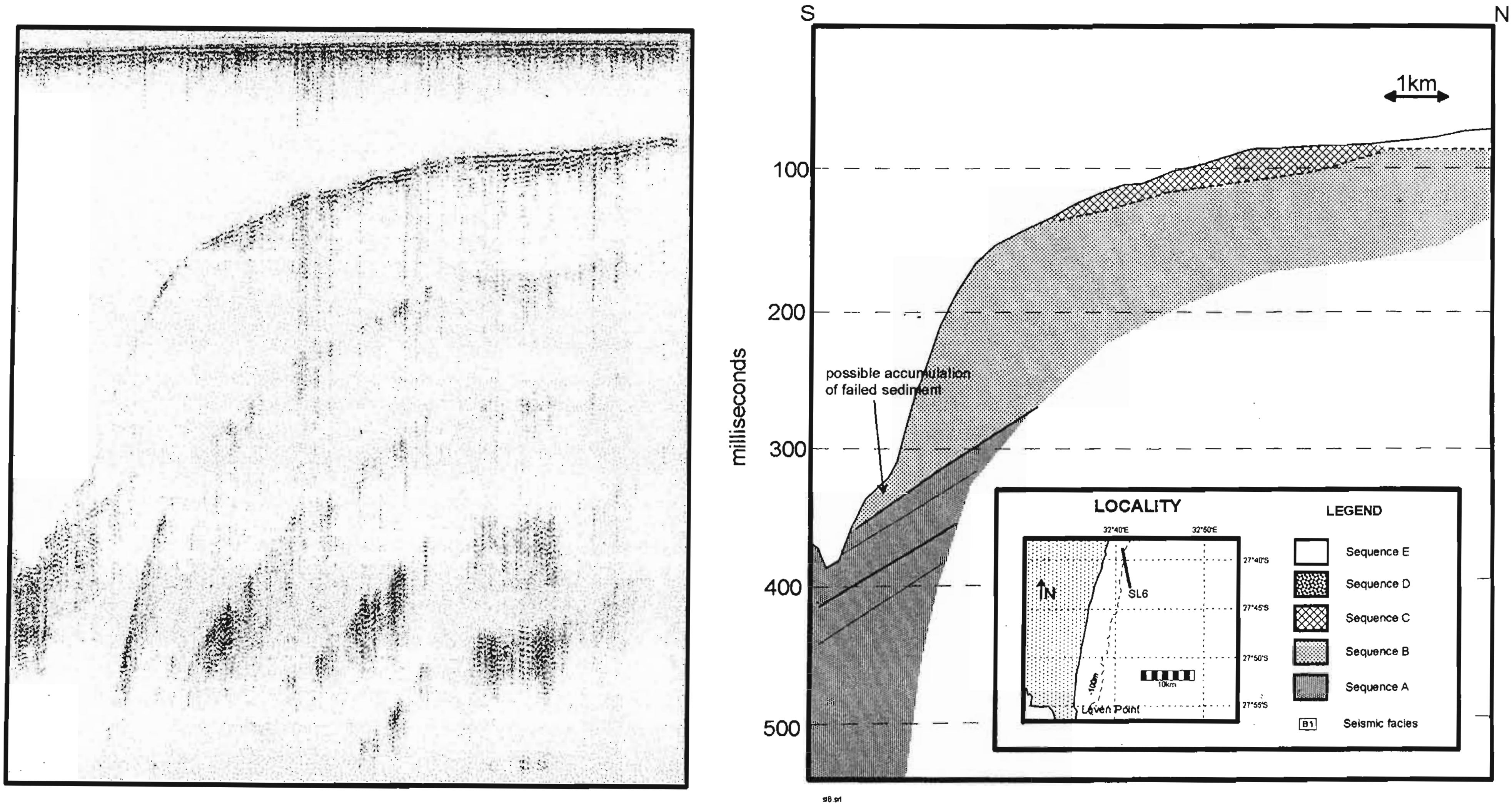


Fig. 5.6: Sparker seismic section and line drawing interpretation of profile SL6, north of Leven Point, showing possible submarine landslide feature on the upper slope

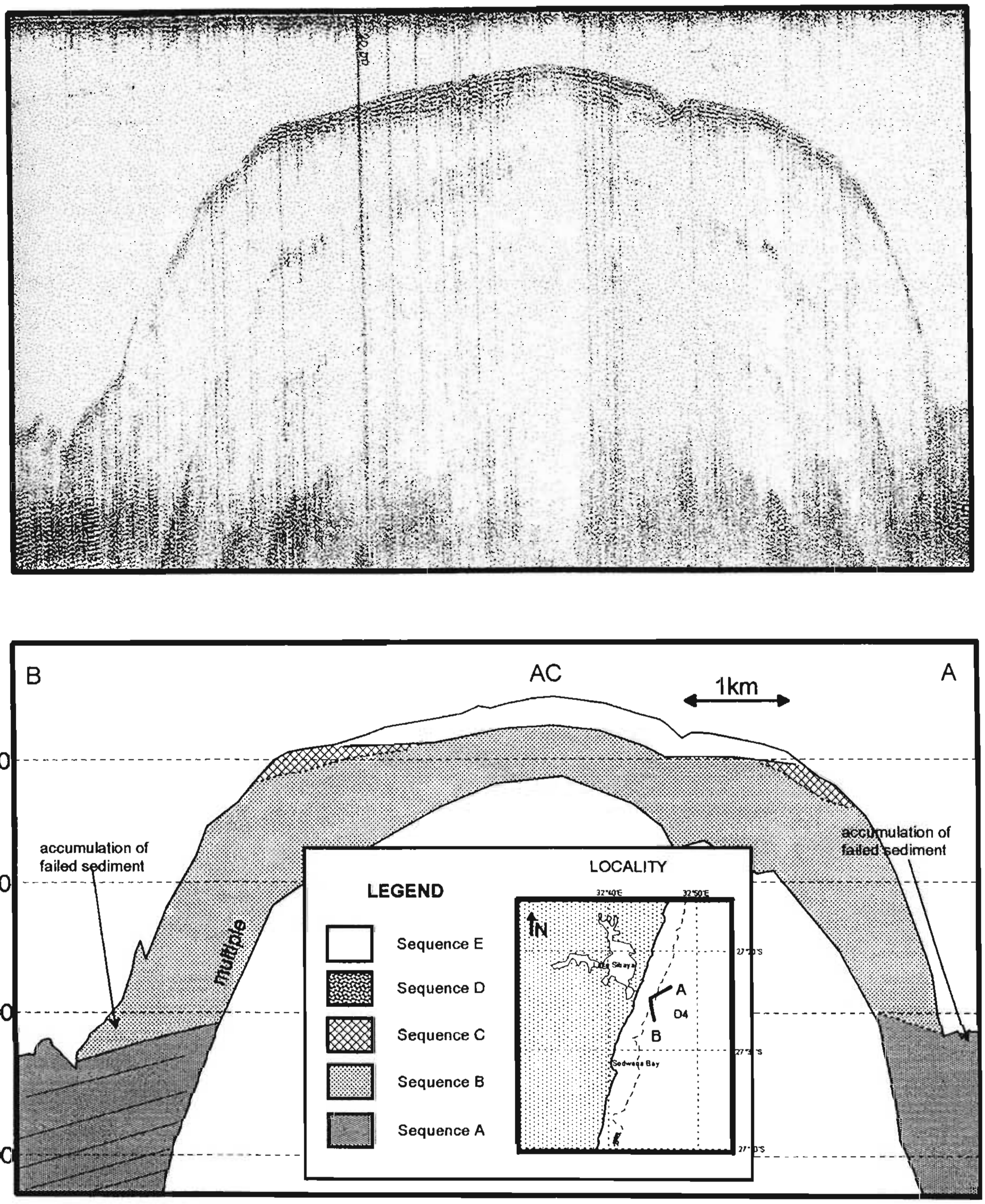


Fig. 5.7: Sparker seismic section and line drawing interpretation of profile D4, offshore of Lake Sibaya showing possible submarine landslide features on the upper slope

this failed sediment accumulation is approximately 13m. If part of a continuous feature, a minimum of approximately 0.07km^3 of sediment has been affected.

5.2.7 Kosi Lakes

Directly offshore Kosi Mouth an abrupt continental slope angle increase from 1° to 15°, 10km offshore at a depth of approximately 224m indicates the presence of a definite submarine landslide (Fig. 5.8). This slope steepening is interpreted as a glide plane scar. Sequence A reflectors are clearly truncated against this glide plane scar. A distinct glide plane is visible to a depth of approximately 88m beneath the sea-floor. This glide plane is approximately straight and has an apparent dip similar to the glide plane scar. The failed sediment mass has a concave, downwards steepening profile. A prominent reflector is visible within the failed sediment mass, near to the penetration limit of the sparker seismic tool. This reflector has a domed morphology, dipping towards the shore and onlapping against the inclined glide plane. Further seawards this reflector dips in an offshore direction. The internal reflection configuration of the failed sediment overlying this prominent reflector is nearly chaotic. Some low amplitude discontinuous reflectors however are discernible within this sediment mass.

Similar submarine landslide features were observed in the seismic profile acquired directly south but oriented more obliquely to the coastline (Fig. 5.9). Three parallel glide planes with similar geometry to that directly offshore Kosi Mouth (Fig. 5.8) are visible. The farthest of these glide planes occurs approximately 8Km offshore at a depth of approximately 300m. The other two glide planes are close to one another approximately 7.3km offshore. The two inshore glide planes are buried by Sequence B sediments. A glide plane scar with a vertical relief of approximately 8m is visible on the outer portion of the seismic section. Sequence A reflectors are truncated by the two buried inshore glide plane scars. The inner and outer buried glide plane scars have a vertical relief of approximately 6m and 4m respectively. Reflectors within the inner-most failed sediment mass abutting against the glide plane dip in an onshore direction. The internal reflection configuration of the two inshore failed sediment masses is semi-chaotic. The failed sediment mass farthest offshore consists of medium to low amplitude reflectors of high continuity. The profile of the continental slope directly above the buried glide plane scars is smooth concave downwards.

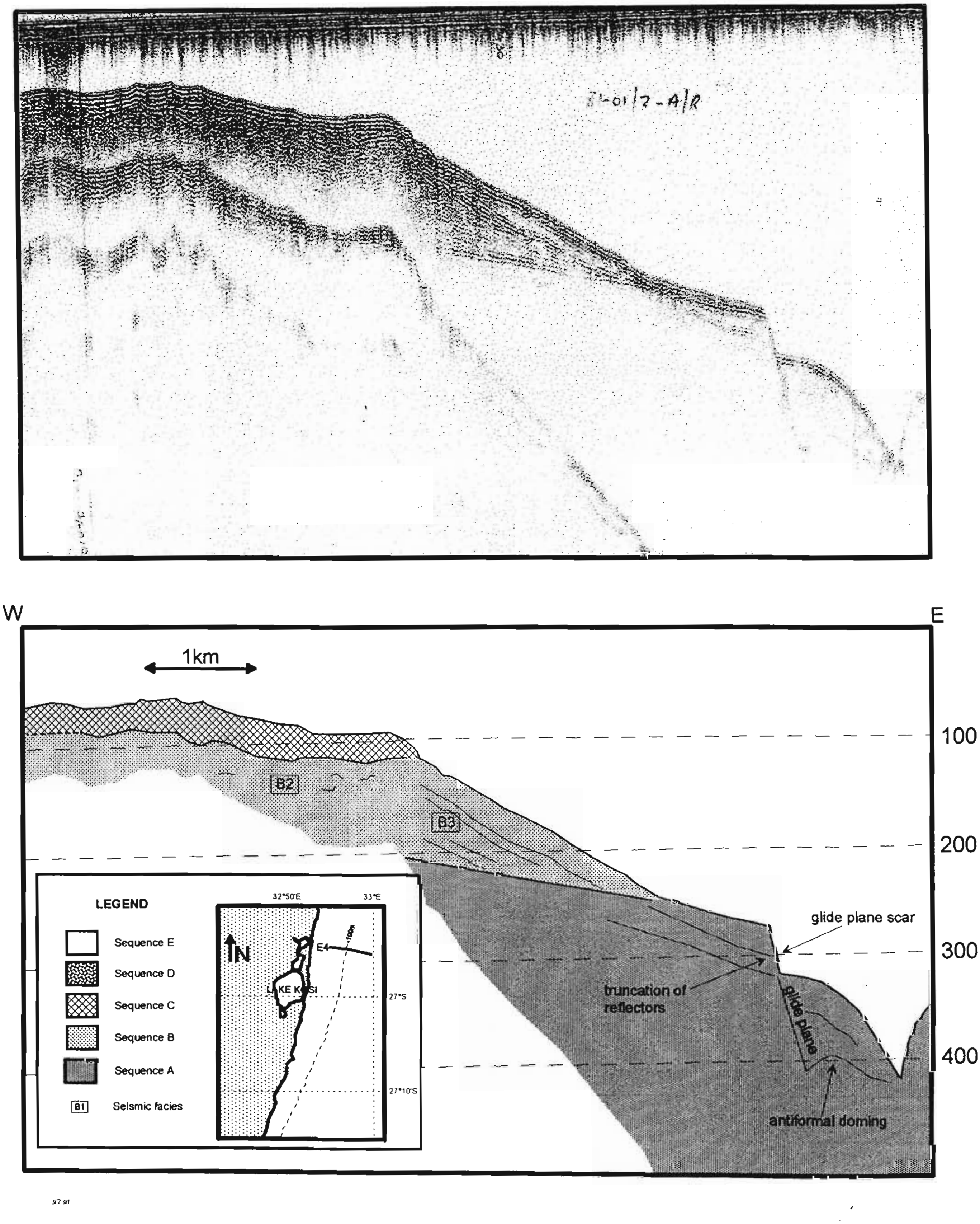
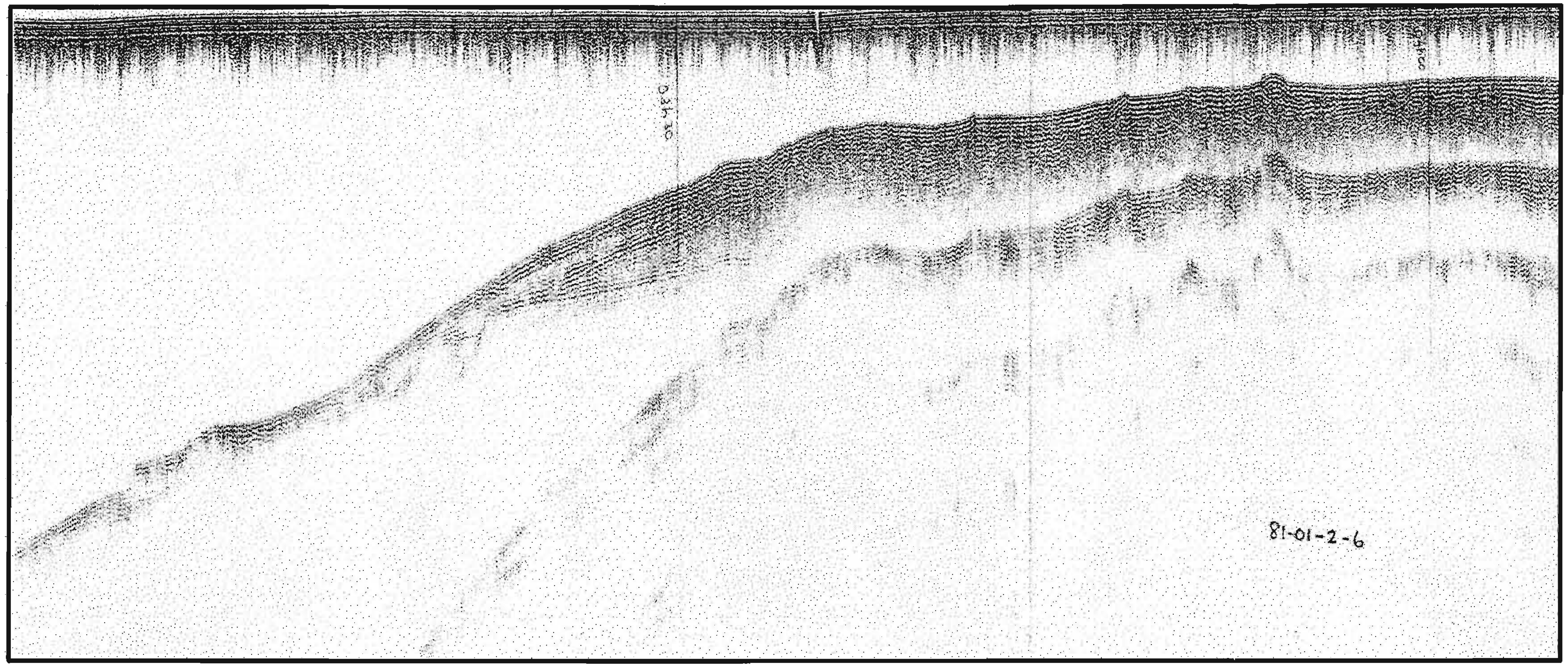


Fig. 5.8: Sparker seismic section and line drawing interpretation of profile E4, offshore of Kosi Bay, showing sumarine landslide features on the upper slope



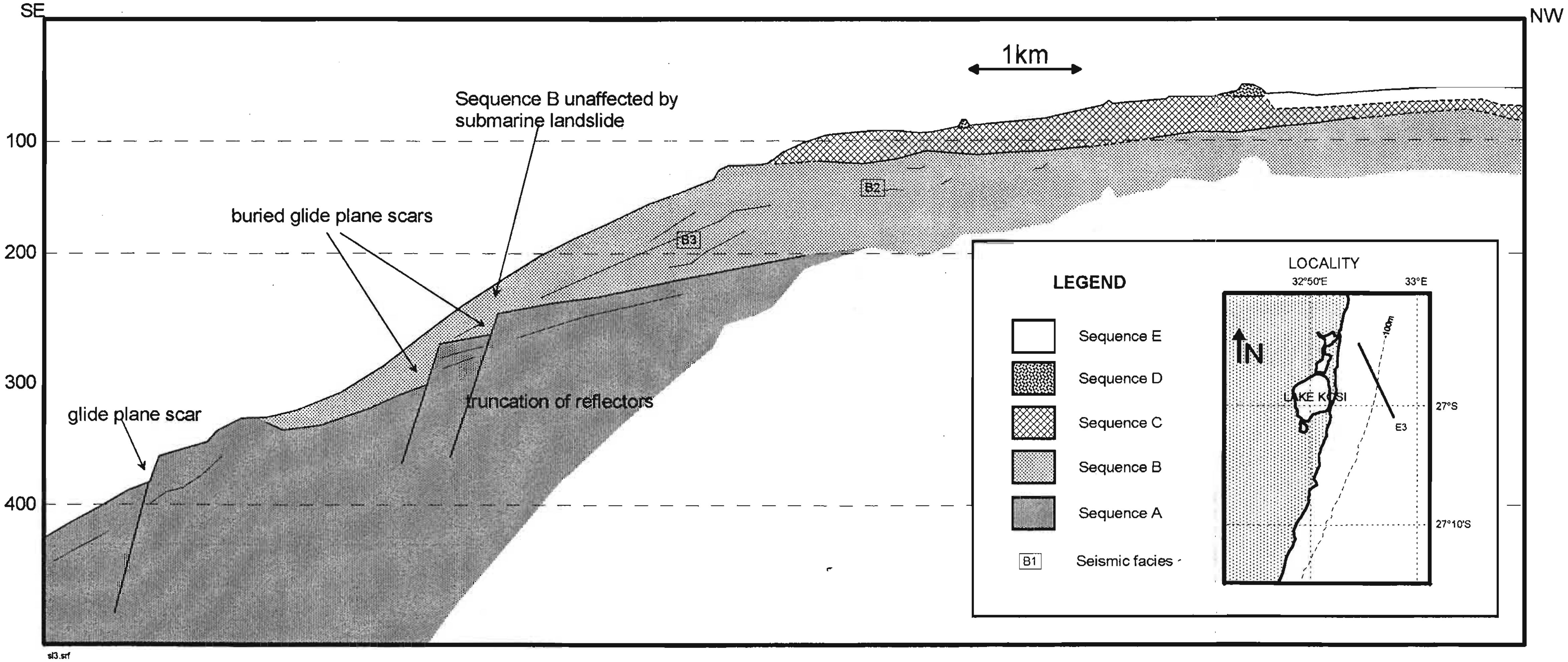


Fig. 5.9: Sparker seismic section and line drawing interpretation of profile E3, offshore of Kosi Bay, showing submarine landslide features buried beneath Sequence B

The similarity of the submarine landslide features observed on these two adjacent seismic profiles near Kosi Mouth indicates that the features are probably part of a single submarine landslide with a lateral continuity of at least 7.8km. Furthermore the seaward dipping characteristics suggest that these features may be the landward extreme of a larger, much more substantial structure.

The smooth continental slope profile above the buried glide plane scars in the southern profile indicates that sediment failure predates the deposition of the sediments that constitute the continental slope, i.e. Sequence B. Since Sequence A sediments are affected, the failure must post-date Sequence A deposition. According to the postulated sequence ages it can therefore be concluded that the sediment failure is at oldest Late Cretaceous and at youngest Late Tertiary. Onshore dip of reflectors within the failed sediment mass and continuity of strata suggests that internal coherency has been maintained and therefore that rotational sliding or slumping has occurred. Although there has been a certain degree of internal structural disruption, the failed material would not have achieved a viscous fluid form, thereby excluding the possibility of it being termed a mass flow style of movement.

5.3 Discussion

Most mass wasting features on the unconfined continental slope recognised in the study area indicate failure of the steeply dipping Sequence B slope facies sediments.

Submarine landslide features observed in the study area are summarised in Table 5.1.

Generally speaking, two major types and ages of submarine landslide were recognised on the sparker seismic records. Fairly small scale, mass flow style submarine landslides characterised by a high degree of internal deformation were recognised at Cape St. Lucia, Lake Bhangazi and Lake Sibaya. These affect only Sequence B slope facies sediments and must post date Sequence B deposition. Since these submarine landslides also seem unaffected by numerous subaerial exposure episodes that have occurred since the Late Tertiary, it is likely that these

Locality	Affected Sequence	Style of Movement	Age Constraints
Richards Bay	B and A	slide and mass flow	Post Sequence B
Mission Rocks	B and A	slide	Post Sequence B
Cape Vidal	A	mass flow	Post Sequence A
King Oscar Hill	B and A	slide and mass flow	Post Sequence B
Lake Bhangazi	B	mass flow	Post Sequence B
Lake Sibaya	B	mass flow	Post Sequence B
Kosi Lakes	A	slide	Post A-pre B

Table 5.1 Summary of submarine landslide features in the study area

features are relatively young features, perhaps as young as Holocene (possible evidence is presented later in this chapter).

In seismic sections north of Richards Bay, King Oscar Hill and Mission Rocks features were recognised that indicate failure of both sequence A and B sediments. In these cases Sequence B sediments were interpreted to have undergone a mass flow style of failure while deeper down, Sequence A sediments were interpreted to have undergone a slide type of failure. Indications are that these features may be related to larger deeper structures. Close proximity of the Richards Bay submarine landslide to Goodlad's (1986) Slide IV (Fig. 5.10) and the Cape Vidal and King Oscar Hill submarine landslides to Goodlad's (1986) slide I suggests a possible relationship between them.

Submarine landslides recognised offshore of Cape Vidal and Kosi Lakes are similar in that they are probably related to larger deeper structures. The slide offshore Kosi Lake is definitely older having occurred between the Late Cretaceous and Late Tertiary.

Without exception, the style of failure of Sequence A sediments tends towards slides whereas failures in Sequence B tend towards mass flows as indicated by the lack of internal coherency. This indicates greater degree of competency attained by the older Sequence A sediments, compared to the younger Sequence B sediments. This indicates that Late Cretaceous sediments of which Sequence A is thought to be composed is at least partly lithified, and that brittle failure has taken place with the preservation of coherent blocks.

It was considered whether the submarine landslide features offshore the Kosi Lakes could represent a brittle fault-type deformation. The relatively high angle of the plane of failure, compared to sediment failures in the Sequence B slope facies sediments and also the high angle of truncation of Sequence A reflectors is similar to a normal fault-like morphology. However, although a degree of internal coherency was maintained, the internal deformation of reflectors is more suggestive of a slide-type mass movement than pure brittle deformation. The uninterrupted slope profile above the inshore failures precludes ongoing brittle deformation.

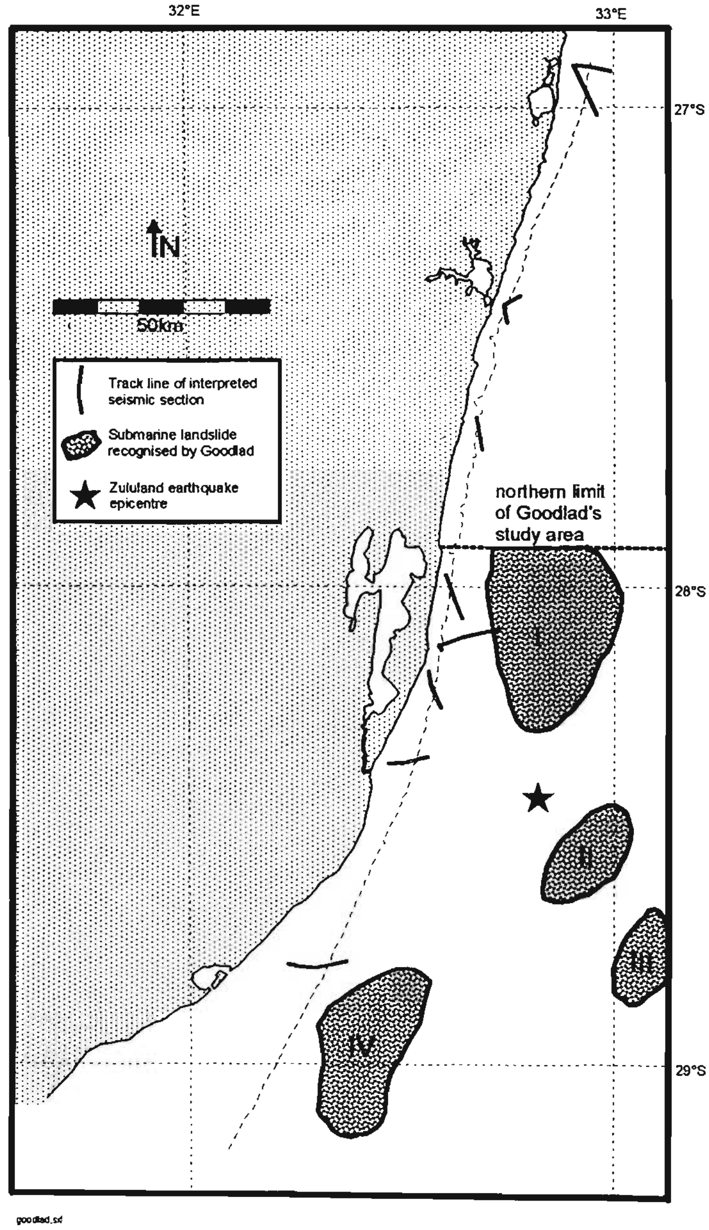


Fig. 5.10: Locality of submarine landslides recognised by Goodlad (1986) in the northern Natal Valley in relation to submarine landslide features in this study and the 1932 Zululand earthquake epicentre

Mention should also be made of minor submarine landslide features recognised in submarine canyons (see Chapter 6). These manifest themselves as profile irregularities on canyon walls and hummocky canyon thalwegs where failed sediment has accumulated. These features are still presently operative.

5.3.1 Slope stability analysis: a case study

Most accounts of submarine landslides are qualitative since quantitative slope stability analysis requires knowledge of various engineering properties of the failed sediment mass and this information is seldom available. Assessments of sediment strength and magnitude of stresses acting downslope are needed. Because so little is usually known of properties and geometries of submarine slopes, quantitative investigative methods are simplified. Some sophisticated quantitative methods have been developed, but the complex stress-strain relationship under dynamic conditions (storm waves or earthquakes) and poor sample quality severely limit the accuracy of these advanced methods (Schwab *et al.* 1993). These analysis methods should therefore be used only as a rough guideline.

In the following section, a quantitative slope stability analysis method published by Booth *et al.* (1985) is used to make some approximations with regard to stability of a particular failed sediment body with a view to establishing likely causes of this particular submarine landslide.

5.3.1.1 Detailed description of seismic section

Figure 5.11 shows the sparker seismic section and line drawing interpretation. 4 sequences are identifiable in the section. Parallel continuous seaward dipping Sequence A reflectors are beneath the inner shelf and upper slope cropping out in the lower part of the section.

Discontinuous Sequence C reflectors downlap against an unconformity marking the top of Sequence B.

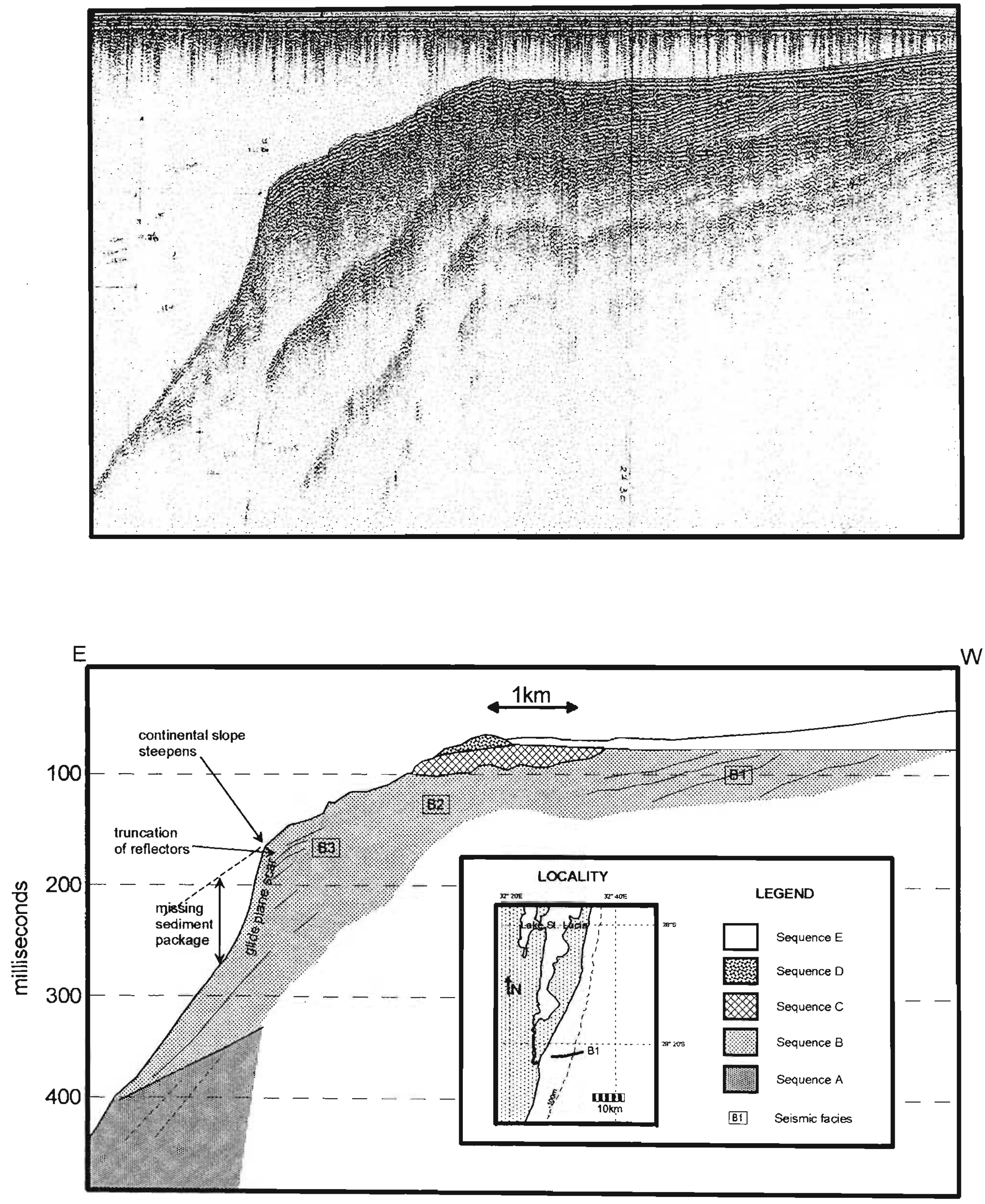


Fig. 5.11: Sparker seismic section and line drawing interpretation of profile B1 offshore of the St. Lucia Estuary Mouth, showing submarine landslide features on the upper slope

The top of Sequence C is marked by a poorly defined unconformity close to the shelf edge. Maximum thickness of Sequence C is approximately 150m. Above this, a topographic high at the shelf break is interpreted as a submerged Pleistocene aeolianite ridge (Sequence D) attaining a maximum thickness of approximately 20m.

Present on the inner shelf is a 24m thick unconsolidated Quaternary age sediment wedge. This sediment wedge is part of the so-called the St. Lucia Spit Bar (Martin, 1985) and is associated with fluvial discharge from the St. Lucia Estuary system.

The continental slope profile suddenly increases at a depth of 160msec. Whereas the upper slope is characterised by a convex deepening profile, 80msec below the shelf break the profile changes to concave and the slope gradient suddenly increases from 3.2° to 12°. Discontinuous Sequence B reflectors are truncated by this abrupt gradient increase. Collectively, these features indicate a missing sediment package, and consequently the sea floor below the point where the gradient steepens is interpreted as a glide plane scar. Maximum vertical thickness of the failed sediment body is approximately 91m. No seismic data exist which can confirm the presence/absence of failed sediment accumulations lower down the continental slope, although a subtle profile aberration lower down the slope is interpreted as a small slump deposit representing part of the larger sediment body which was deposited further down the continental slope.

These submarine landslide-type features are not duplicated on the nearest coast perpendicular seismic sections acquired 15km to the north and 10.5km to the south, the lateral extent of this feature is therefore less than 25km.

5.3.1.2 Slope stability analysis

Booth *et al.* (1985) constructed a nomogram (Fig. 5.12) for interpreting slope stability of fine grained deposits in modern and ancient marine environments. Although designed as a mere interpretive aid, it provides an adequate basis for making approximations in this regard. Used here, the nomogram assists in reconstructing the approximate slope stability of the failed sediment body.

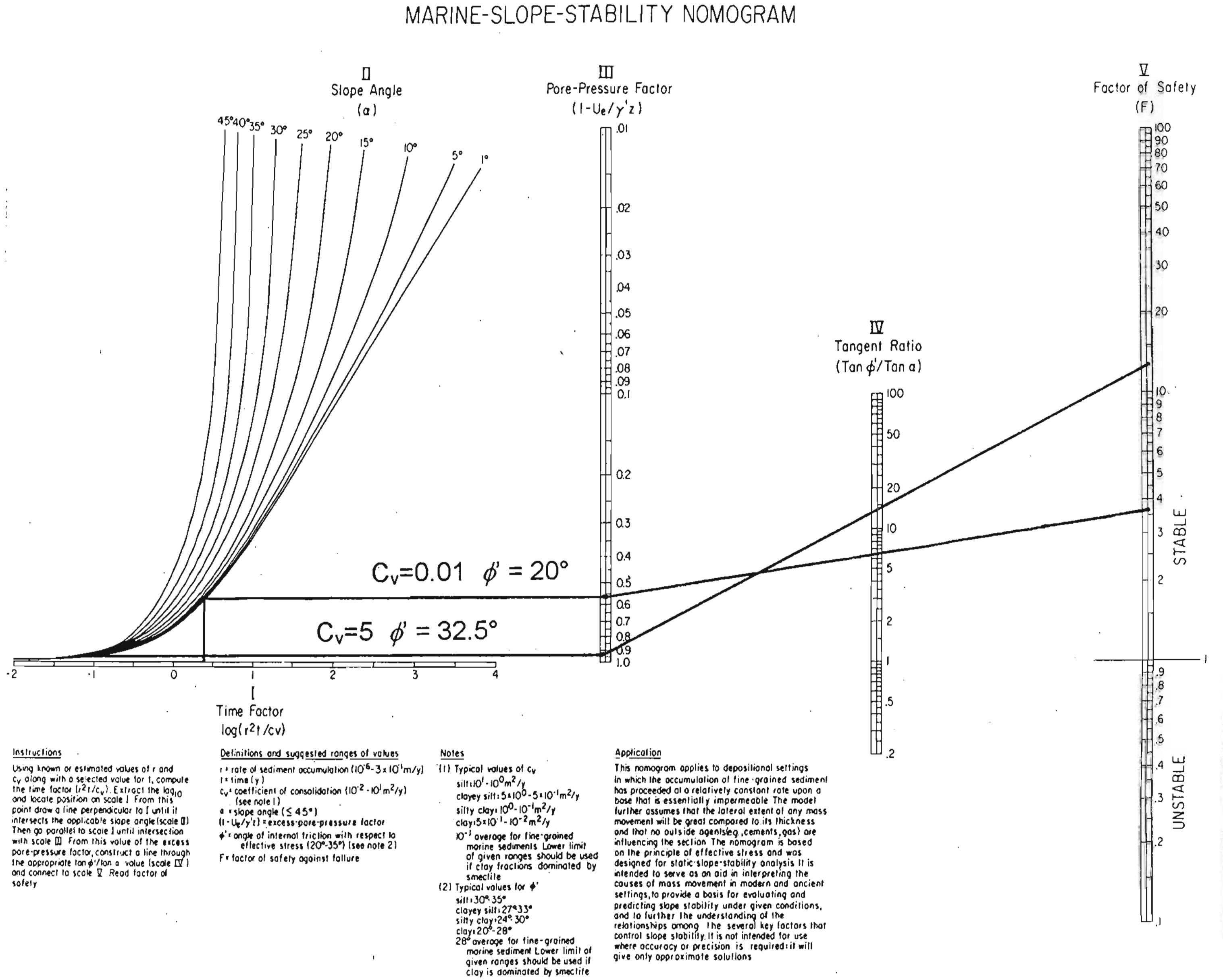


Fig. 5.12: Marine slope stability nomogram and predicted Factors of Safety for St. Lucia estuary mouth submarine landslide (from Booth *et al.*, 1985)

The nomogram combines two theories of soil mechanics, namely the effective stress infinite-slope model of slope-stability (see Morgenstern and Sangrey, 1978) and the consolidation theory of Gibson (1958). Assumptions made are that fine-grained sediments accumulated at a relatively constant rate upon a base that is essentially impermeable, that the lateral extent of the sediment affected by the mass movement is great compared to its thickness and that no outside agents such as cement and gas are influencing the section.

In the St. Lucia submarine landslide it has been deduced that Sequence B sediments are relatively fine grained (indicated by the "drape fill" internal reflection configuration of sediments offshore the Kosi Lakes (see Chapter 7, Fig. 7.2). In other localities described earlier failed sequence B sediment accumulations exhibiting near total internal disruption and acoustically transparent characteristics suggest that Sequence B is probably uncemented. The consolidated marine sediments of the St. Lucia Formation can be considered essentially impermeable. The lateral extent of the failure is not known.

Since not much is known of the sedimentary properties of the failed sediment it will be assumed initially that failure took place prior to any cementation. The effect of cementation would be to increase the strength and thus decrease the likelihood of failure for given dynamic conditions.

The end product of the nomogram is a numerical figure (*F*) representing factor of safety. *F* represents the ratio between resisting forces and shearing. Values of $F>1$ indicates slope stability while values of $F<1$ indicate slope instability. Variables required for operating the nomogram are rate of sediment accumulation, time in which sediment accumulated, coefficient of consolidation, slope angle and angle of internal friction with respect to effective stress. Rate and time of sediment accumulation can be reasonably estimated from geological studies of the area, slope angle has been calculated from the seismic section. Booth *et al.* (1985) provide typical values of coefficient of consolidation and internal friction angle for certain sediment types.

The nomogram (Fig. 5.12) is composed of five scales namely time factor (scale I), slope angle (scale II), pore pressure factor (scale III), tangent ratio (scale IV) and factor of safety. To calculate the factor of safety the following is carried out.

i) Compute the time factor given by the equation

$$\log(r^2 t / c_v) \qquad \textbf{1}$$

where r is rate of sediment accumulation in metres per year, t is time of sediment accumulation and c_v is coefficient of consolidation in m^2 per year.

ii) Locate position on scale I and from this point draw a line perpendicular to I until intersection with applicable slope angle (α).

iii) Construct a line parallel to scale I until intersection with scale III, i.e. the value of the excess pore pressure given by the equation

$$(1 - U_e / \gamma' z) \qquad \textbf{2}$$

where U_e is excess pore pressure, γ' is submerged unit weight of the sediment and z is the thickness of sediment under consideration.

iv) From this point on scale III, construct a line through the appropriate value on scale IV given by the equation

$$(\tan \phi' / \tan \alpha) \qquad \textbf{3}$$

where ϕ' is internal friction angle with respect to effective stress, until it intersects scale V (F) to give a factor of safety.

In this study very little is known of the mechanical properties of the failed sediment mass, thus two scenarios are considered representing upper and lower extremes of likely conditions. These two scenarios yield probable maximum and minimum stability factors.

The maximum thickness of the failed sediment body is approximately 91m. It has been estimated (Martin, 1984) that sedimentation rates in the adjacent Natal Valley during deposition of the slumped sediment was as high as 234m per million years, the slumped mass therefore represents a time period of approximately 388 889 years. Coefficient of consolidation (c_v) and angle of internal friction (ϕ') varies according to sediment grain size, for silt typical values of c_v and ϕ' are 5m^2/year and 32.5° respectively, while for clay values can be as low as 0.01m^2/year and 20°. From the seismic record it was calculated that slope of the failed sediment body was approximately 3.2°. Taking two extreme scenarios, one for a silty sediment body (c_v=5; ϕ' =32.5°) and one for a clayey sediment body (c_v=0.01; ϕ' =20°), factors of safety were calculated, results of the nomogram calculation (Fig. 4) are shown in the following table.

	$\log(r^2t/c_v)$	$\tan \phi'/\tan \alpha$	F
c_v=5; ϕ' =32.5°	-2.3	11.39	12
c_v=0.01; ϕ'=20°	0.3	6.51	4

Since F (Factor of Safety) is greater than 1 in both scenarios it is suggested that that the failed sediment mass was stable under static conditions. A triggering mechanism was therefore necessary to induce slope failure.

5.3.1.3 Possible causes of failure

In order to induce failure of a statically stable sediment body, dynamic loading must take place. This affects the inherent stability of a slope deposit by increasing the shear stress and increasing the pore pressure (Booth *et al.*, 1985). Dynamic loading can either occur as a result of storm waves or earthquakes.

5.3.1.3.1 Stormwaves

Since slope deposits are by definition deposited below the shelf break and therefore below wavebase it follows that syn-depositional failure could not have taken place unless substantial sea-level fluctuations took place during the period of deposition. Siesser and Dingle's (1981) sea-level curve (see Chapter 7, Fig. 7.5) shows that sea level could have dropped as low as 200m below present sea-level during the late

Pliocene. The Quaternary is also widely known to have been characterised by several regressions and transgressions and it is widely known that sea-level dropped to approximately 130m below present levels during the Late Pleistocene during the Last Glacial Maximum. The age of the slumped sediment mass is unknown although Sydow's (1988) work tentatively dates this shelf sequence as being of Miocene or Pliocene age. Since the glide plane scar is present at a depth of approximately 130m below present sea-level it follows that if the trigger mechanism of the sediment failure was influenced by lowered sea-levels, the only time at which this could have occurred is during the late Pliocene or a Pleistocene sea-level lowstand.

5.3.1.3.2 Earthquakes

Earthquakes have long been known to cause submarine landslides (Moore, 1977) the most oft quoted and famous examples being the Grand Banks earthquake of 1929 and associated sediment failure (Heezen and Drake, 1964) and also the Valdez earthquake of 1964 (Hampton *et al.* 1993).

Booth *et al.* (1985) present a graph (Fig. 5.13) from which horizontal ground acceleration necessary to reduce Factor of Safety (F) to a value of 1, for a given slope angle. Applied to this study, the graph predicts that horizontal accelerations of between 0.07g (value for clay) and 0.2g (value for silt) were necessary to reduce factor of safety (*F*) to 1. Using Murphy and O'Brien's (1977) equation relating horizontal acceleration to earthquake intensity,

$$\log_{10} a_H = 0.25I + 0.25 \qquad \textbf{4}$$

where a_H is horizontal acceleration in cms^{-2} and I is earthquake intensity, these horizontal accelerations approximately correspond to Modified Mercalli Intensities (MMI) of VI and VIII respectively (Murphy and O'Brien, 1977). In other words, if the failed sediment is clay-sized then an earthquake intensity of at least VI is necessary to induce failure while for silty sediment, the intensity necessary is much higher at VIII. Therefore, if an earthquake served as the failure trigger mechanism, an earthquake of minimum intensity VIII must have occurred sometime in the geological past. It must be

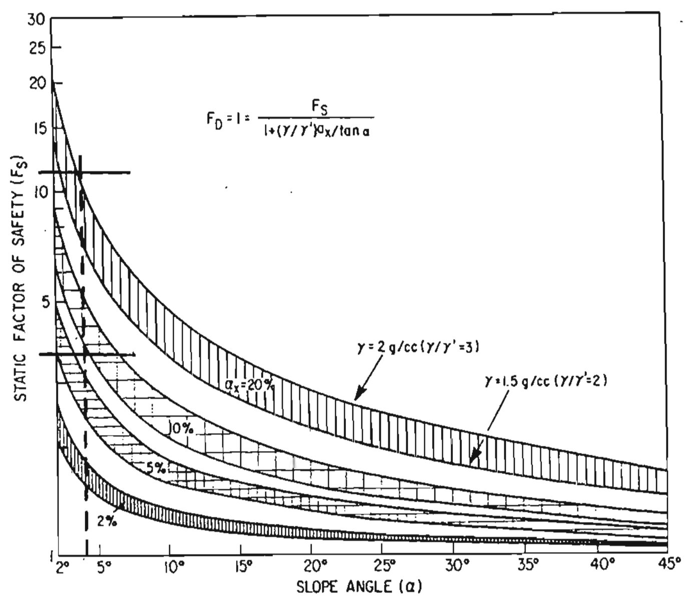


FIG. 4.—Accelerations required to reduce the static factor of safety to a value of 1 for given slope angles. F_D is the dynamic factor of safety (which is made equal to 1), F_S is the static factor of safety, γ and γ' are the unit weight and submerged unit weight, respectively (with the swath boundaries in unit weight corresponding to bulk densities of approximately 1.5 g/cm³ and 2.0 g/cm³), α is the slope angle, and a_x is the horizontal ground acceleration coefficient expressed in terms of gravity (e.g., a_x = 5% g). To use, take specified slope angle along with the factor of safety value determined from nomogram (scale V) and find the intersection. Corresponding a_x value indicates earthquake acceleration required to reduce slope in question to limit equilibrium.

Fig. 5.13: Graph relating horizontal ground acceleration necessary to reduce given factor of safety to 1, for varying slope angle (from Booth *et al.*, 1985)

remembered that this intensity represents a minimum value, since the assumption is made that the failed sediment mass had not undergone any cementation. It follows that any degree of cementation would increase sediment strength and therefore the earthquake intensity necessary to induce failure.

At present South Africa is considered to be relatively seismically inactive (Fernandez and Guzman, 1979). Despite this, numerous naturally occurring earthquakes are recorded each year, seldom though are they of sufficiently high magnitude to be noticed by the general public or warrant media coverage. The Ceres earthquakes of September 1969 which caused widespread damage to property are notable exceptions (Fernandez and Guzman, 1979). However, not much is known of seismicity during past geological periods. Hobday and Jackson (1979) speculate that earthquake could have been responsible for syndepositional deformation of Pleistocene age Port Durnford Formation transgressive shore zone deposits at nearby St. Lucia, perhaps indicating a more seismically-active past.

More recently, a major earthquake took place in Zululand and although less well-known and documented than the Ceres earthquakes, was the second most powerful earthquake recorded or documented in South Africa (Fernandez and Guzman, 1979).

The earthquake occurred on the morning of 31 December 1932, with a calculated epicentre situated at 28° 30'S, 32° 50'E i.e. offshore Cape St. Lucia (see Fig. 5.10). The shock was felt as far away as 400km and microseismic tremors were recorded as far afield as Finland and California, USA, distances of 10 000km and 17 000km respectively (Krige and Venter, 1933).

Since the quake's epicentre was located offshore, the intensity at the epicentre is unknown. Along the coast, north of Cape St. Lucia it was estimated that the earthquake effects reached the 9th Degree of intensity on the Modified Mercalli Intensity Scale of 1932. It is therefore possible that shocks on the sea-floor at the earthquake epicentre attained intensity 10. The Ceres earthquakes were measured as achieving intensity 9, it is therefore possible that the Zululand earthquake was in fact more powerful.

Krige and Venter (1933) speculate that the earthquake was caused by movement along an approximately coast-parallel, steeply inclined fault plane located off the shore of Cape St. Lucia. There have been no further speculations regarding the cause of the 1932 Zululand earthquake.

The close proximity of the earthquake epicentre to the sediment failure and the fact that the intensity of the Zululand earthquake exceeds the calculated minimum required intensity to cause failure presents the possibility that the Zululand earthquake itself could have been the trigger mechanism responsible for causing the described slump feature (assuming no cementation of failed sediment). There is certainly more evidence in favour of this, than there is against.

It is also interesting to note that four submarine landslides recognised in the Natal Valley by Goodlad (1986) (Fig. 5.10) are grouped around the Zululand earthquake epicentre. If the Zululand earthquake itself was not responsible for these failures, they are probably related to a specific localised seismically active area, which is probably still active (as manifested by the Zululand earthquake).

Although more attention is paid here to seismic triggers, it is not intended to imply that seismicity is the more likely cause of sediment failures in the study area. Seismic triggers are afforded more detail here since more is known of effects of ground accelerations on slope deposits than the effects of storm waves.

CHAPTER 6

SUBMARINE CANYONS

In this chapter, submarine canyon terminology is briefly described, and submarine canyons known to be present in the study area are briefly described. Thereafter features observed on submarine canyon seismic sections acquired in the study area are described and their significance with regard to possible origins of KwaZulu-Natal submarine canyons is discussed.

6.1 Submarine canyon classification

Submarine canyons are classified simply as youthful- or mature-phase canyons according to the degree to which they incise the continental shelf (Farre *et al.*, 1983). Mature-phase canyons are deeply incised canyons that traverse the shelf. Youthful-phase canyons are less deeply incised features which have not yet breached the shelfbreak.

6.2 Submarine canyons in the study area

Eight submarine canyons are present in the study area. The approximate locality of these submarine canyons is shown in Figure 6.1. From north to south these canyons are Wright, Beacon, White Sands, Jesser, Ntabende, Leadsman Valley, Leven and Shakas Valley. According to the classification of Farre *et al.* (1983), Beacon, Shakas Valley, Leadsman Valley and Jesser Canyons have been classified as youthful-phase canyons while White Sands, Wright, Ntabende and Leven Canyon have been classified as mature-phase submarine canyons (Bang, 1968; Botes, 1988; Sydow, 1988 and Ramsay, 1991). Some characteristics of these submarine canyons are summarised in Table 6.1.

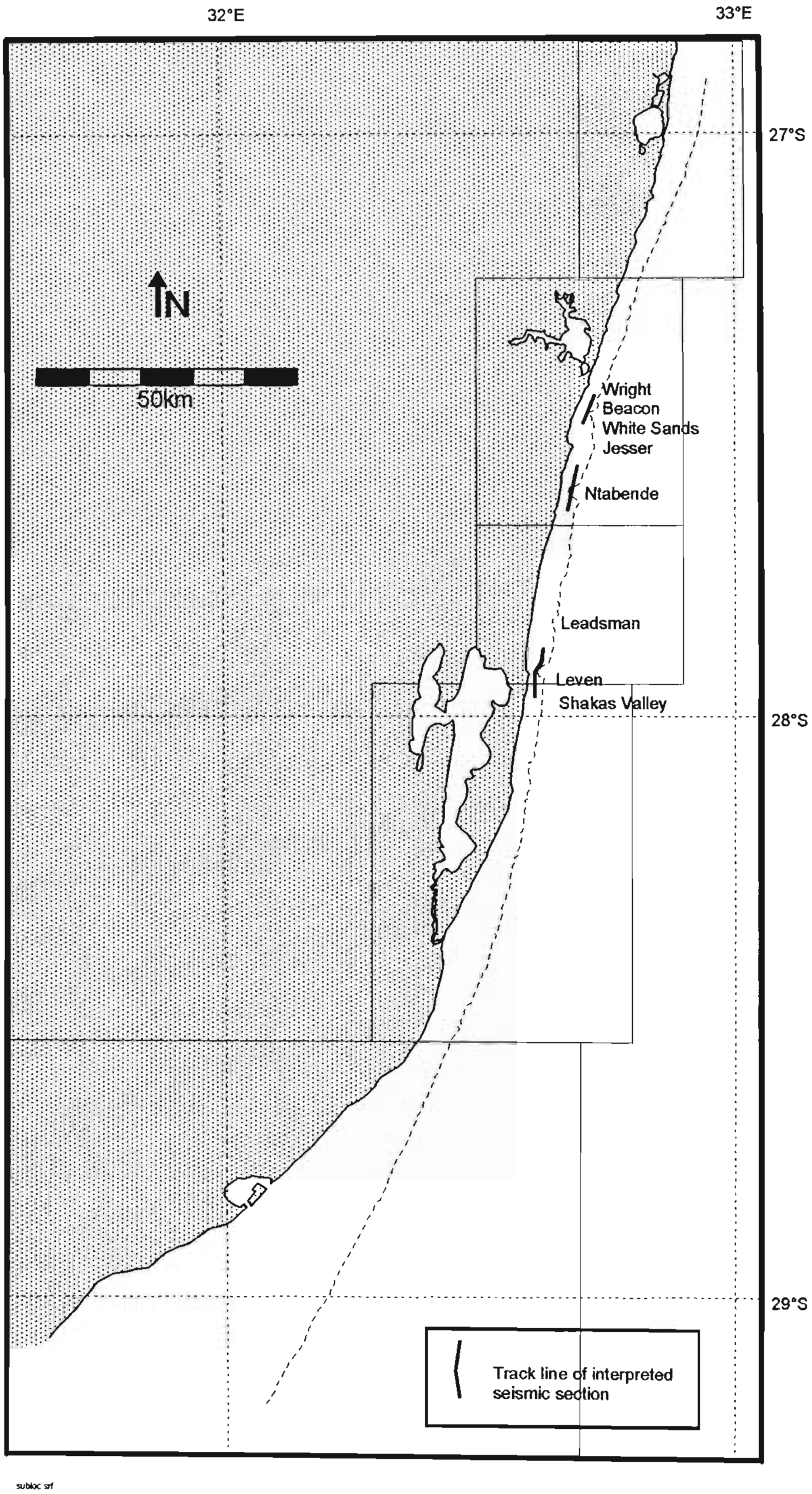


Fig. 6.1: Approximate locality of submarine canyons in the study area and track lines of interpreted sparker seismic sections

Submarine canyon	Dist. from shore	Depth of head	Classification*
White Sands	3km	-70m	Mature-phase
Beacon			Youthful-phase
Wright	2km	-35m	Mature-phase
Jesser	4km	-70m	Youthful-phase
Ntabende	1km	-30m	Mature-phase
Leadsman Valley	4km	-90m	Youthful-phase
Leven	600m	-40m	Mature-phase
Shaka's Valley	3km	-100m	Youthful-phase

*According to Farre *et al.*, (1983).

Table 6.1: Characteristics of submarine canyons in the study area.

6.3 Submarine canyon seismic data

Track lines of interpreted seismic data acquired across submarine canyons is shown in Figure 6.1. Substantial seismic data have been acquired in the submarine canyons of northern KwaZulu-Natal. In this study, only good quality seismic sections acquired on the continental shelf or upper slope exhibiting sub-seafloor structures were interpreted. Many good quality seismic sections acquired in submarine canyons in water depths greater than 400m also exist but these data are outside the study area. A number of seismic sections were also acquired which are of poorer quality and do not reveal sub-surface structure. Unless these sections displayed some other interesting features such as submarine landslide morphology, they have not been discussed here.

6.3.1 Wright Canyon

Figure 6.2 shows a seismic section and interpretation of the upper reaches of Wright Canyon. In this seismic section, the vertical elevation difference between the continental shelf and the centre of the canyon is approximately 13m. The northern canyon wall is visibly steeper than the southern canyon wall and the canyon thalweg is

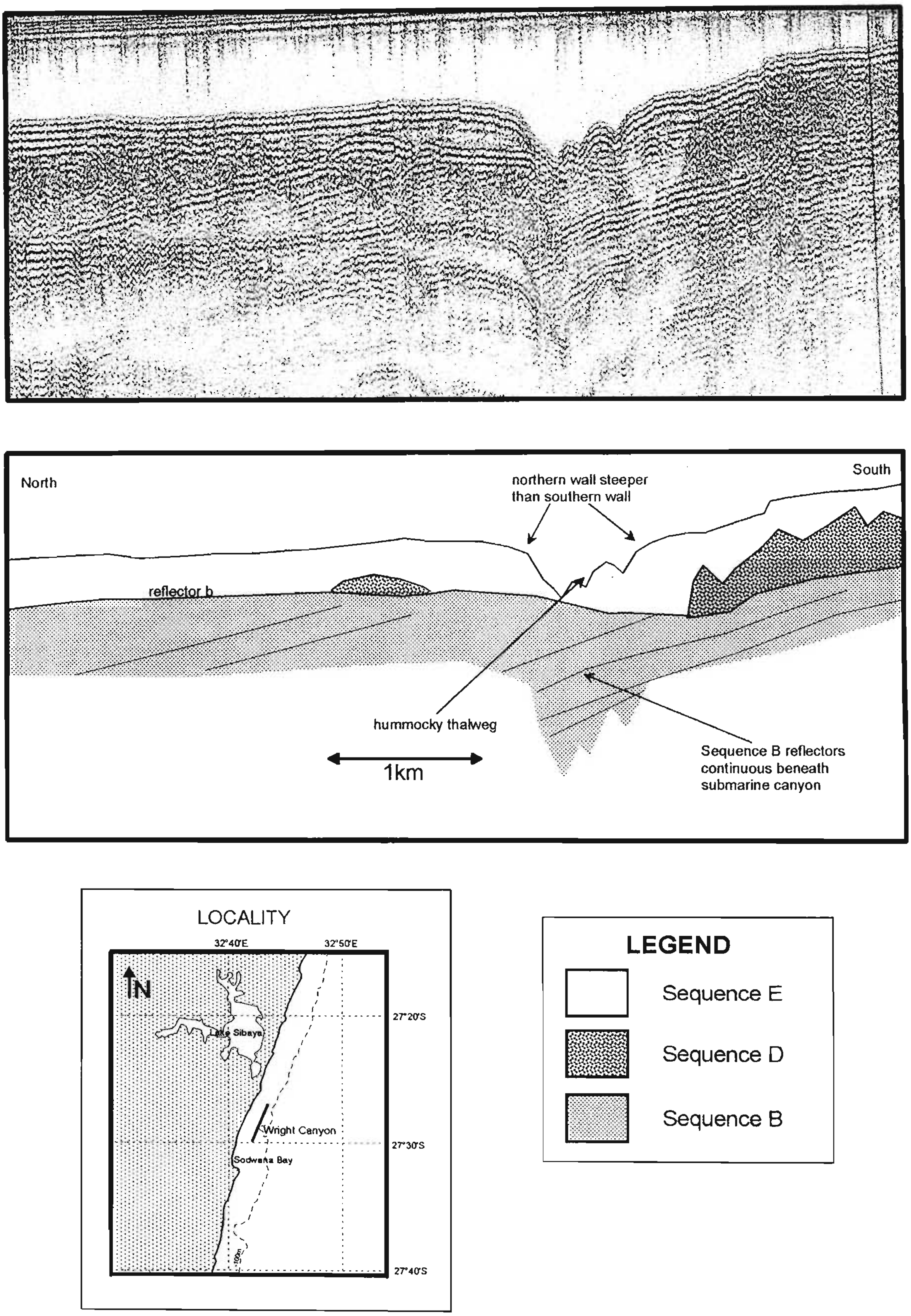


Fig.6.2: Sparker seismic section and line drawing interpretation across the upper reaches of Wright Canyon

hummocky. From the seismic data and interpretation it can be seen that the northern canyon wall consists entirely of acoustically transparent unconsolidated Quaternary sediment (Sequence E) due to the fact that the seismic section has been acquired in the very upper reaches of the canyon.

The reflector marking the base of the Quaternary Sequence E sediments (Reflector b) is clearly visible on the northern flank of the submarine canyon. Due to the thin Sequence E cover from the canyon centre northwards, Reflector d is obscured by the strong sea-floor reflection package. High amplitude, northward dipping reflectors within Sequence B are continuous beneath the submarine canyon and are undisturbed or displaced of any kind for as long as they are visible (they are obscured to the north and south by the multiple reflection package of the sea-floor).

6.3.2 Leven Canyon

Figure 6.3 shows a seismic section and interpretation of the upper reaches of Leven Canyon. This seismic section shows features similar to those observed at the head of Wright Canyon. Both the northern and southern canyon walls consist entirely of unconsolidated Quaternary sediments (Sequence E). The northern canyon wall is also visibly steeper than the southern canyon wall. The vertical relief of the canyon wall in this section is just 8m.

Reflector b is distinctly visible beneath the submarine canyon axis and displays no obvious displacements but shows a slight depression of approximately 4m beneath the submarine canyon features.

6.3.3 Ntabende Canyon

A striking coast-parallel seismic section was acquired across Ntabende Canyon showing the classic V-shape morphology of the canyon and the presence of failed sediment accumulations on the canyon walls (Fig. 6.4). Although the canyon thalweg is not clear, it appears to have a hummocky nature due to the accumulation of failed sediment. The upper-most canyon walls consist of unconsolidated Quaternary sediment and while the two upper walls have a similar gradient, the southern wall has a

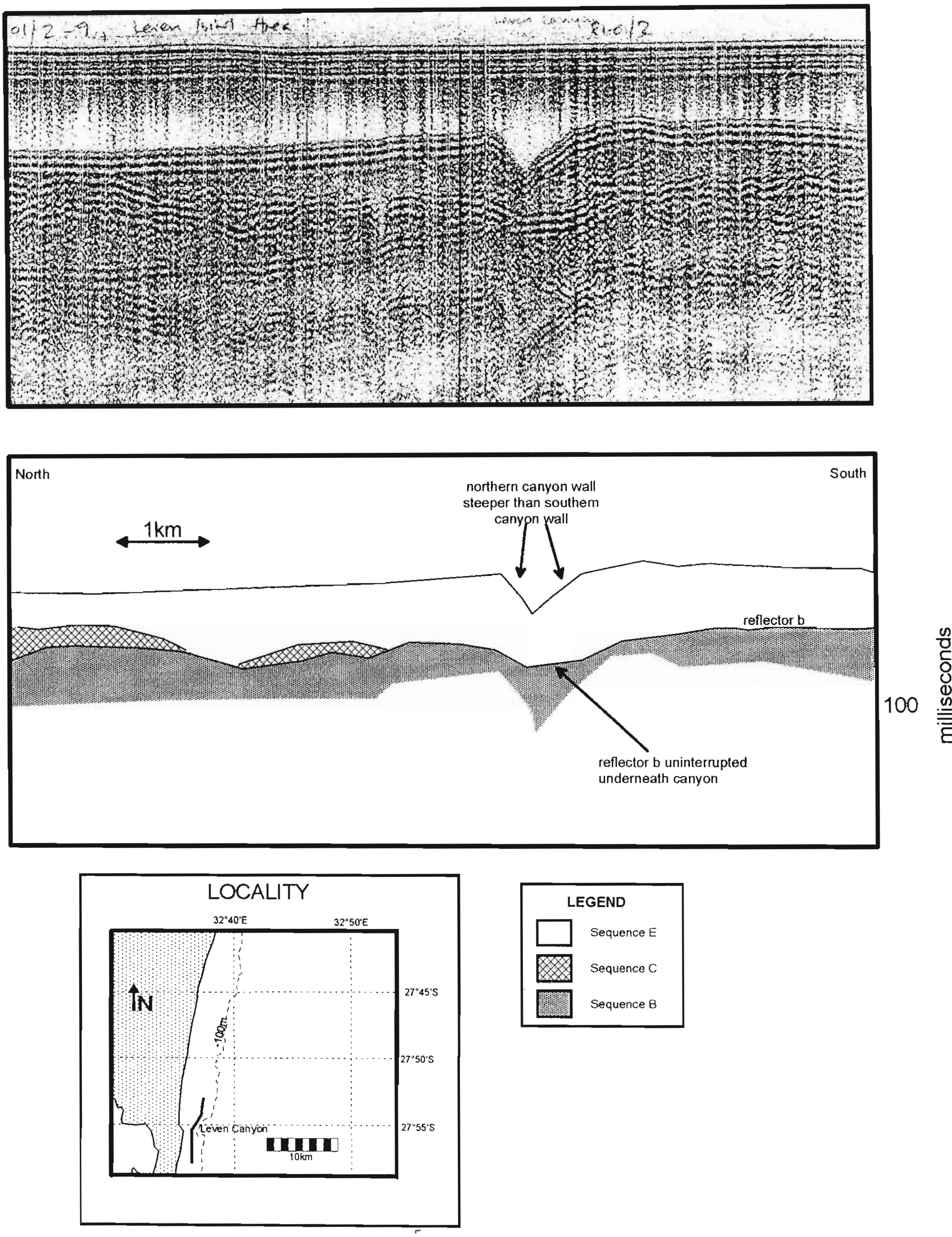
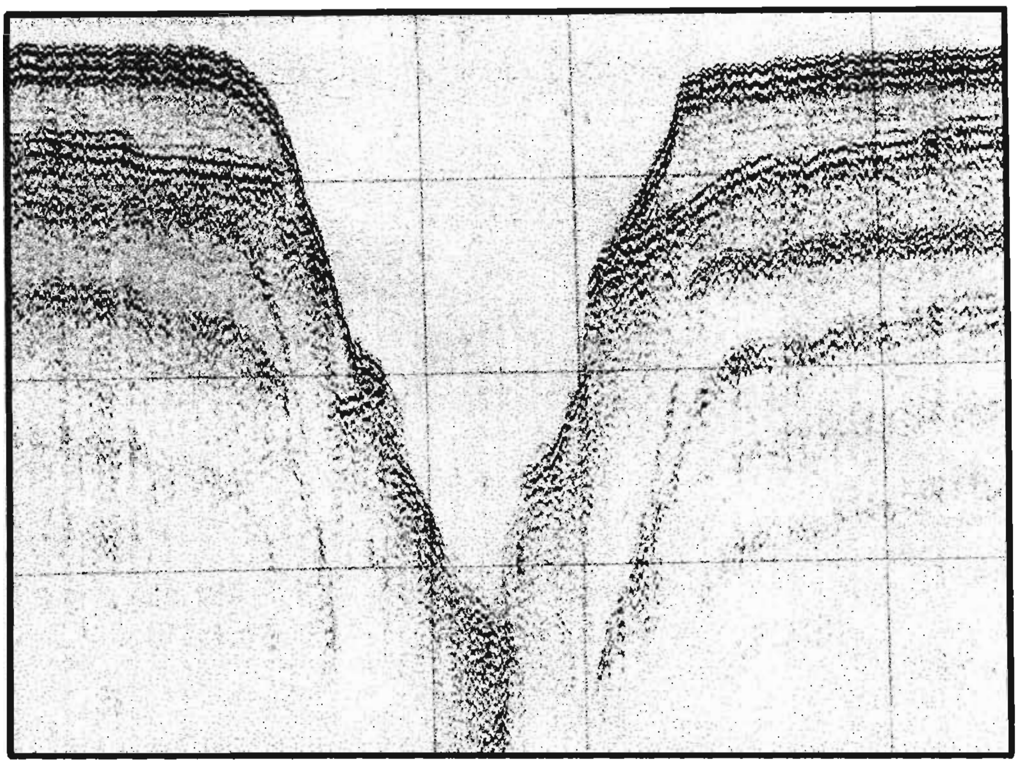


Fig.6.3: Sparker seismic section and line drawing interpretation across the upper reaches of Leven Canyon



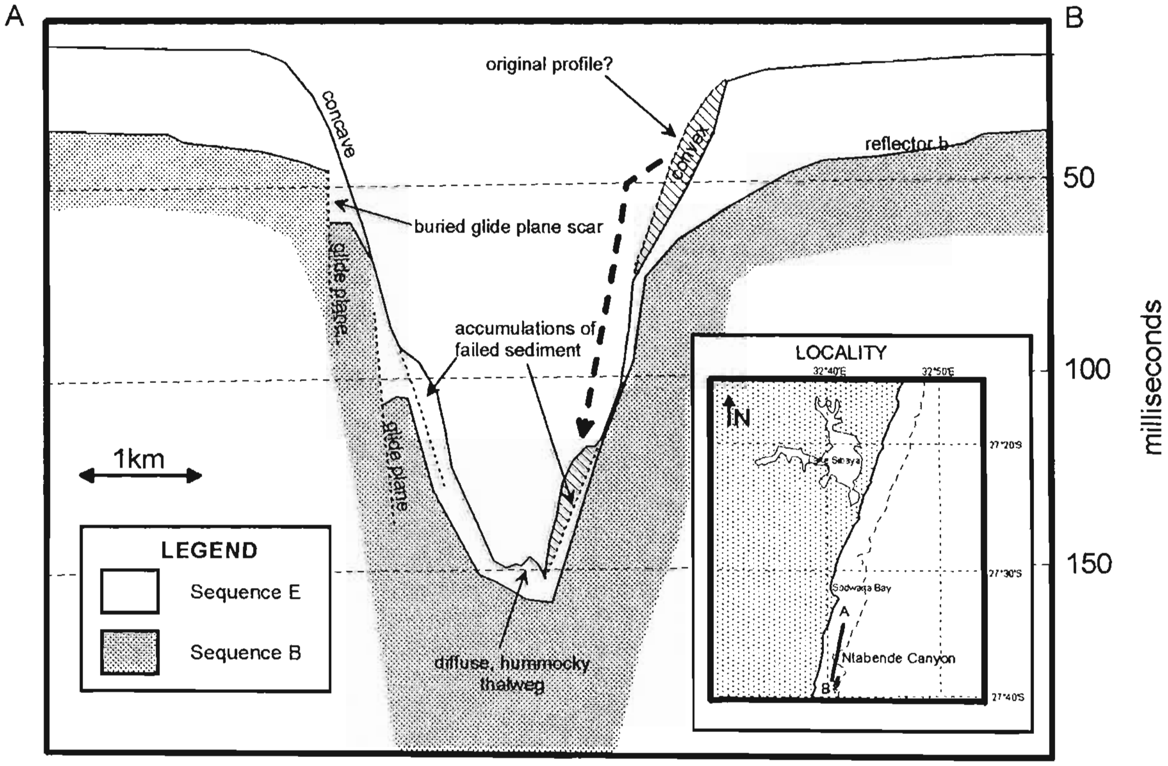


Fig.6.4: Sparker seismic section through Ntabende Canyon and line drawing interpretation

convex downwards profile while the northern wall has a concave downwards profile. The convex downwards profile of the southern wall probably indicates that this portion of the canyon wall is a glide plane of a fairly recent sediment failure. The canyon wall profile irregularity near to the canyon thalweg could in fact be an accumulation of this failed sediment. The smooth concave upper northern canyon wall probably indicates natural maximum angle of repose of sediments of which it is constituted.

The base of the acoustically semi-transparent unconsolidated Sequence E is clearly visible on the seismic section as a continuous high amplitude reflector. To the immediate north and south of the canyon this reflector exhibits little vertical relief. To the immediate south however, this reflector dips suddenly downwards towards the canyon axis, to subcrop at the canyon wall at a water depth of approximately 100msec. To the south of the canyon wall, this reflector is continuous and is not affected by any vertical displacements. To the north of the canyon, this reflector is also smooth and continuous. Directly beneath the northern canyon wall however, this reflector has a stepped appearance, dropping in two places by a vertical distance of 5m and 16m. Buried, sub-vertical scarps are unlikely to be palaeo-subaerial topographical features. They are therefore interpreted as glide planes of submarine landslides. The northward dipping nature of the lowermost step feature indicates a possible rotational component to the style of failure.

6.4 Discussion

Various workers have considered possible origins of the KwaZulu-Natal submarine canyons. Bang (1968), was the first to note their existence and to speculate on their possible origins and causes. Botes (1988), briefly considered possible origins of Ntabende Canyon. Sydow (1988) considered in some detail possible origins of Leven Canyon and Shaka's Valley and Ramsay (1991) discussed the possible origins of Jesser, Wright and White Sands Canyons.

A wide variety of mechanisms have been invoked to explain the development of submarine canyons throughout the world. Bang (1968) considered possible causes for conditions relevant to the KwaZulu-Natal continental margin. One mechanism invoked in the past is erosion of submarine sediment by the emergence of freshwater springs on or along the edge of the continental shelf. Although he generally refutes this mechanism, he mentions that in the case of the continental shelf adjacent to Lake Sibaya, there is no visible hydrological outlet. Wright and White Sands canyons could therefore represent centres of seepage emergence. He states that sediment accumulations in these areas would be susceptible to erosion due to the effects of freshwater lubrication. He rejects the possibility that submarine canyons are formed by processes of faulting since a faulting mechanism capable of causing a V- shaped morphology is unlikely. He nevertheless concedes that faulting could have played a part by providing lines of weakness along which erosion could be initiated. He refutes, also the possibility that submarine canyons are caused by processes of fluvial incision during subaerial exposure on the basis that sea-level lowerings were not of sufficient magnitude and that there are no onshore relics of the responsible river systems onshore. He concedes however that possible clues as to the existence of palaeo-rivers could be obscured by the extensive Quaternary cover on the Zululand continental shelf. Bang (1968), prefers an origin of KwaZulu Natal submarine canyons due to erosion by submarine sediment movements.

Ramsay (1991) states that the mature-phase Wright and White Sands Canyons were probably initiated by processes of mass-wasting which rapidly progressed to become mature-phase submarine canyons, possibly due to a link with the palaeo-outlet of the Pongola River. The youthful-phase Jesser Canyon on the other hand is thought to have been initiated due to mass-wasting of the unstable, rapidly deposited, steeply dipping Pliocene shelf sediments (Sequence B in this study) and is interpreted not to have been affected by fluvial processes. (Ramsay, 1994)

Sydow (1988) proposes that the inception of Leven Canyon was influenced by a combination of mass wasting processes and fluvial degradation. He postulates that a palaeo-valley underneath northern Lake St. Lucia (Fig. 6.5) interpreted from seismic records acquired by van Heerden (1987), was linked to the head of the canyon and caused extensive degradation. He also postulates that during times of higher sea-level, a palaeofluvial outlet at Leven Point provided input of abrasive detritus thereby accelerating mass-wasting processes. He concluded that although there is probably a link between fluvial processes and submarine canyons, their inception and growth are closely associated with upper-slope instability induced by deposition of steeply dipping

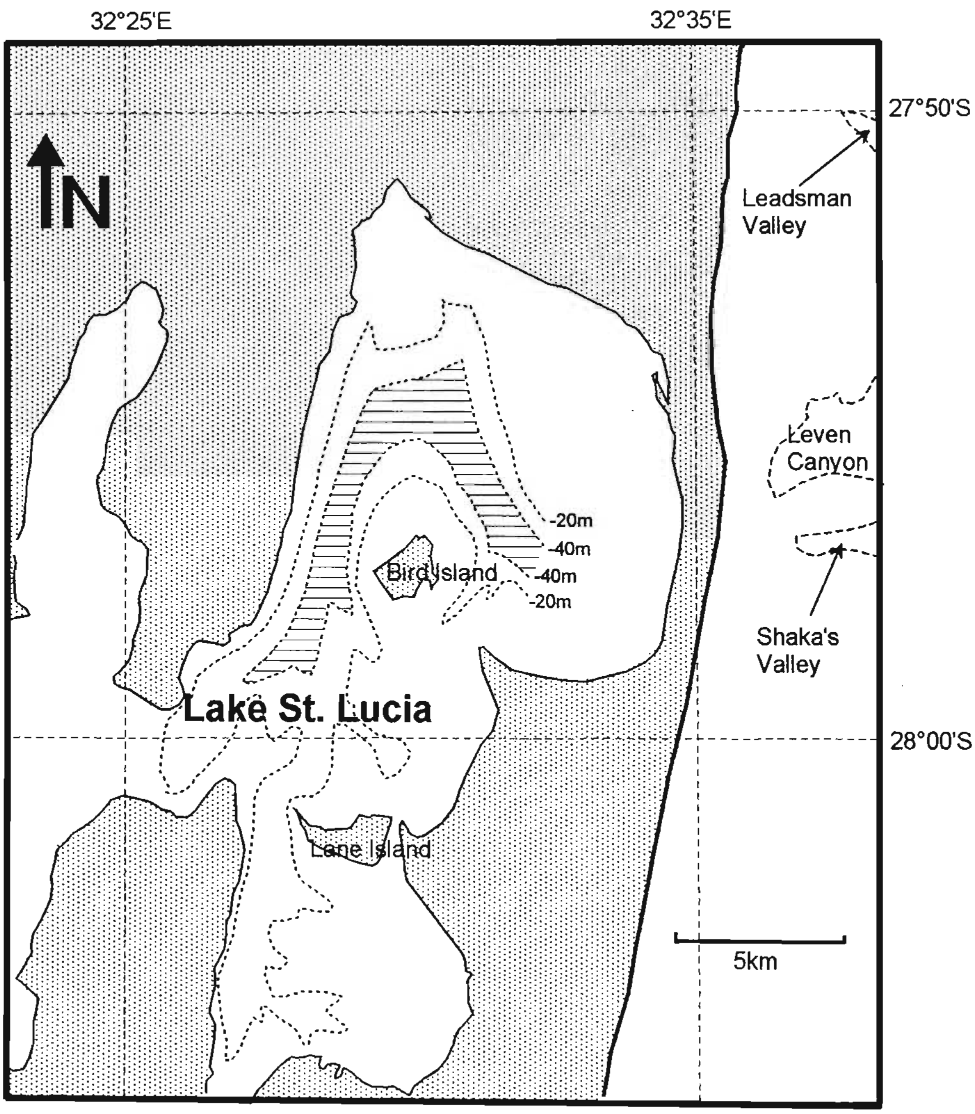


Fig. 6.5: Palaeo-drainage beneath Lake St. Lucia and relationship to offshore submarine canyons (simplified

Tertiary shelf sediments onto the Zululand continental margin.

Except for the study of Sydow (1988), speculations regarding the causes and origins of submarine canyons were based on morphological/bathymetric features only. Features observed on seismic sections during this study shed some further light on the possible causes and origins of submarine canyons.

Seismic sections through the upper reaches of Leven, Wright and Ntabende Canyons show that the upper canyon walls consist of unconsolidated Holocene sediment. These unconsolidated sediments have therefore been affected by the presence of the submarine canyons. It has been proved during side-scan-sonar studies and underwater observations (Flemming, 1978; Ramsay, 1991) that unconsolidated sediment on the continental shelf is transported by the Agulhas Current so that it is flushed down submarine canyons. The convex upper canyon wall profile of Ntabende Canyon probably indicates active headward erosion in unconsolidated Sequence E Quaternary sediments. These observations confirm that processes of canyon enlargement are presently active and independent of fluvial influence.

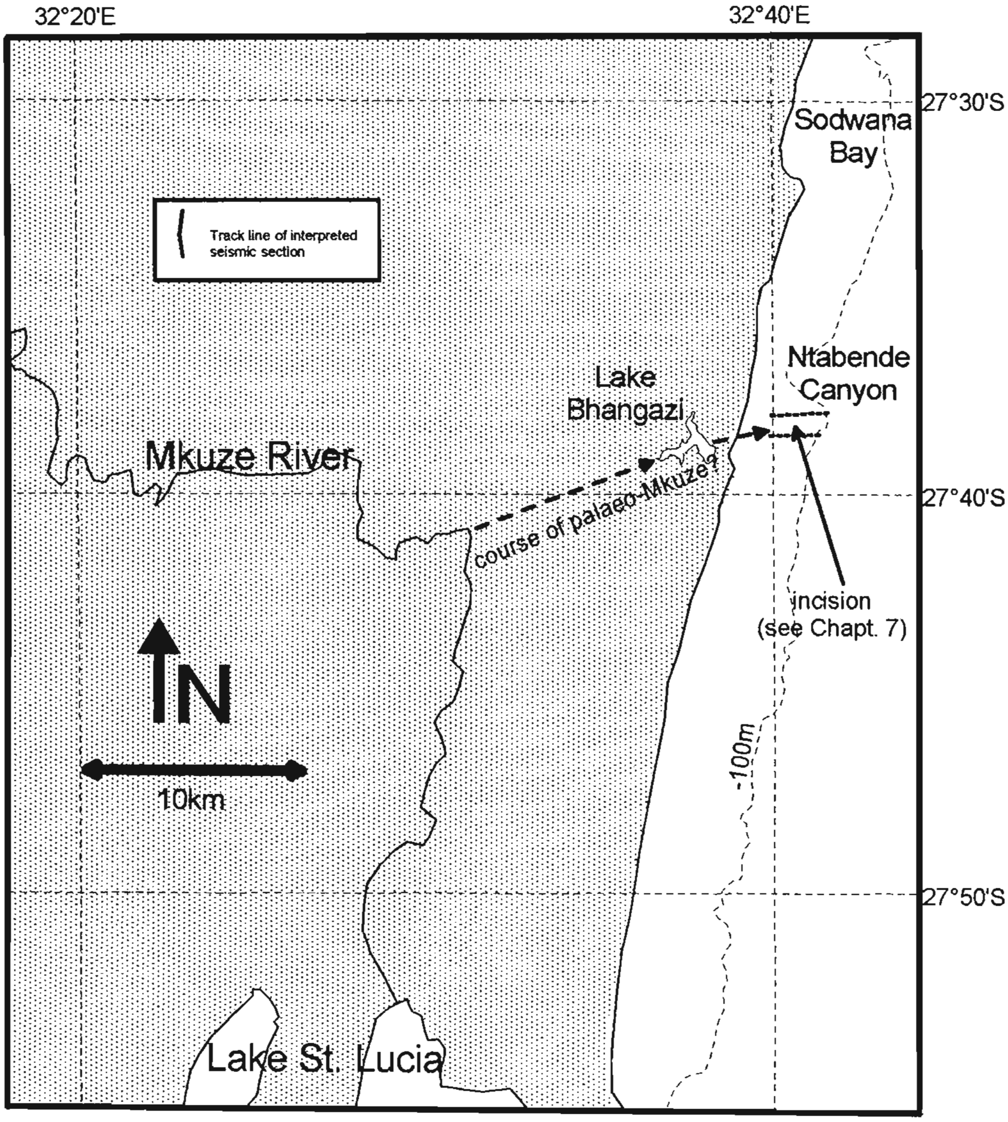
The continuity of Reflector b marking the base of the unconsolidated Quaternary sediments in upper canyon, coast-parallel seismic sections and the continuity of northerly dipping Sequence B reflectors in Wright Canyon discounts recent and pre-Late Tertiary faulting as a submarine canyon developmental influence.

In Ntabende Canyon, submarine landslides, affecting pre-Holocene sediments were observed. Reflector d has maintained its distinct, high amplitude nature, despite it having failed over a vertical distance of approximately 16m during a submarine landslide. The fact that this sediment body has maintained some degree of external coherency must indicate some degree of internal competence. This confirms that canyon growth processes occurred, even though the sediment in which failures occurred were slightly lithified.

When workers have considered possible causes and origins of submarine canyons, a common denominator is that mature-phase submarine canyons (Wright, White Sands and Leven) are thought to have progressed rapidly to mature-phases due to the influences of palaeofluvial outlets. In the case of Wright and White Sands, the palaeo-Pongola outlet and in the case of Leven, a palaeo-outlet at Leven Point are thought to have been the influential factors. The youthful-phase status of Jesser and Shaka's Valley is ascribed to the lack of a palaeofluvial link. If a palaeofluvial link is necessary in order for a Maputaland submarine canyon to have progressed to a mature-phase submarine canyon, then Ntabende Canyon should also be investigated with a view to establishing a possible palaeofluvial link. It is possible that the Mkuze River could provide this link. The Mkuze River flows in an easterly direction before diverting southwards towards Lake St. Lucia (Fig. 6.6). It is possible that this river flowed straight towards the present coastline prior to the establishment of the coastal dune cordon and St. Lucia drainage system. If the easterly trend of the Mkuze River were extrapolated, the intersection with the present coastline would be in the area of Lake Bhangazi. Probable buried fluvial incision was noted in a coast-parallel seismic section acquired directly offshore from Lake Bhangazi (see Chapter 7). This fluvial incision could be a remnant of the palaeo-outlet of the Mkuze River. Given the short distance of this proposed palaeo-outlet to Ntabende Canyon, it is possible that the palaeo-Mkuze outlet could have influenced the development of the canyon to mature-phase by supplying large quantities of fluvial detritus thereby accelerating mass-wasting processes.

Slight depressions in Reflector b in the case of Leven Point and Ntabende Canyon indicates possible fluvial incision in the area of submarine canyons in a manner similar to the postulated palaeo-outlet at Leven Point (Sydow, 1988).

In conclusion the seismic evidence from this study seems to confirm previous speculations regarding the origins of submarine canyons. The submarine canyons are not related to any post-Late Tertiary faulting, but there is a definite relationship between mature phase submarine canyons and palaeo-river courses. Interesting to note is that in the cases of the mature-phase Leven, Wright and White Sands submarine canyons there is no direct proof of any palaeofluvial links. In the case of the palaeofluvial outlet of the Mkuze River, its position is confidently inferred, yet no submarine canyon is present at this locality. Rather the fluvial incision has been infilled by unconsolidated Quaternary sediment (see Chapter 7). This indicates that palaeofluvial links do not have to be direct, i.e. palaeofluvial courses and submarine canyons would seem to not have to coincide exactly in order for submarine canyons to rapidly reach a mature-


32°20'E
32°40'E
27°30'S
27°40'S
27°50'S
Sodwana Bay
Track line of interpreted seismic section
Ntabende Canyon
Lake Bhangazi
Mkuze River
course of palaeo-Mkuze?
incision (see Chapt. 7)
N
10km
-100m
Lake St. Lucia

mkuze.srf

phase. In the case of Ntabende Canyon it would appear the supply of detritus from the nearby palaeo-Mkuze River has accelerated mass-wasting processes in Ntabende Canyon and enabled it to reach a mature-phase of development. Although this detritus has not been discharged directly to the environs of the canyon head, continental shelf sediment transport dynamics ensured a higher than normal supply of material.

It must also be borne in mind that the very shallow nature of the KwaZulu-Natal continental shelf ensured that during the Last Glacial Maximum, palaeorivers in the study area discharged from a mouth on the upper continental slope, thereby causing the development of palaeovalleys across the present submerged shelf, in turn, aiding the development of submarine canyons.

CHAPTER 7

FLUVIAL INCISION

Many workers have discussed possible palaeofluvial drainage patterns on the Zululand coastal plain since they are important with regard to their effect on continental margin morphology and sedimentological development of the Zululand coastal plain. Sydow (1988) postulated a palaeooutlet at Leven Point, open until 5000 years BP, as a developmental influence on Leven Canyon. Ramsay (1991), similarly implicated the palaeo fluvial factors as a developmental influence on Wright and White Sands Canyons near Sodwana Bay. Palaeofluvial processes have also been invoked as possible explanations of the existence of Lake Sibaya whereby the lake is thought to represent a palaeoestuary of a local drainage, at one time thought to be the palaeo-Pongola River (Miller, 1993; Wright and Mason, 1988; Maud, 1968; Meyer and Kruger, 1988).

As yet, no solid geophysical evidence acquired on the northern KwaZulu-Natal continental margin proving or disproving speculations regarding palaeo-fluvial patterns of the Maputaland coastal plain, has been presented. The continental shelf has been exposed on numerous occasions during glacial maxima in the geologic past. It would therefore be expected that if palaeorivers flowed across the exposed continental shelf, evidence of fluvial incision should be observed on some seismic records. As Bang (1968) stated when considering origins of KwaZulu-Natal submarine canyons, "Relics of [palaeoriver] channels may thus lie beneath surficial sediments of the plain". In this study, evidence of fluvial incision on the submerged continental margin was observed on two coast-parallel seismic sections, one on the upper continental slope north of Lake Sibaya, the other directly offshore of Lake Bhangazi (Fig.7.1).

7.1 Fluvial incision north of Lake Sibaya

North of Lake Sibaya, Reflector a, marking the top of the Upper Cretaceous St. Lucia Formation (Sequence A) displays a distinct irregular, channel-like, subaerially exposed morphology to a depth of 210msec (Fig. 7.2). These features have a width of between

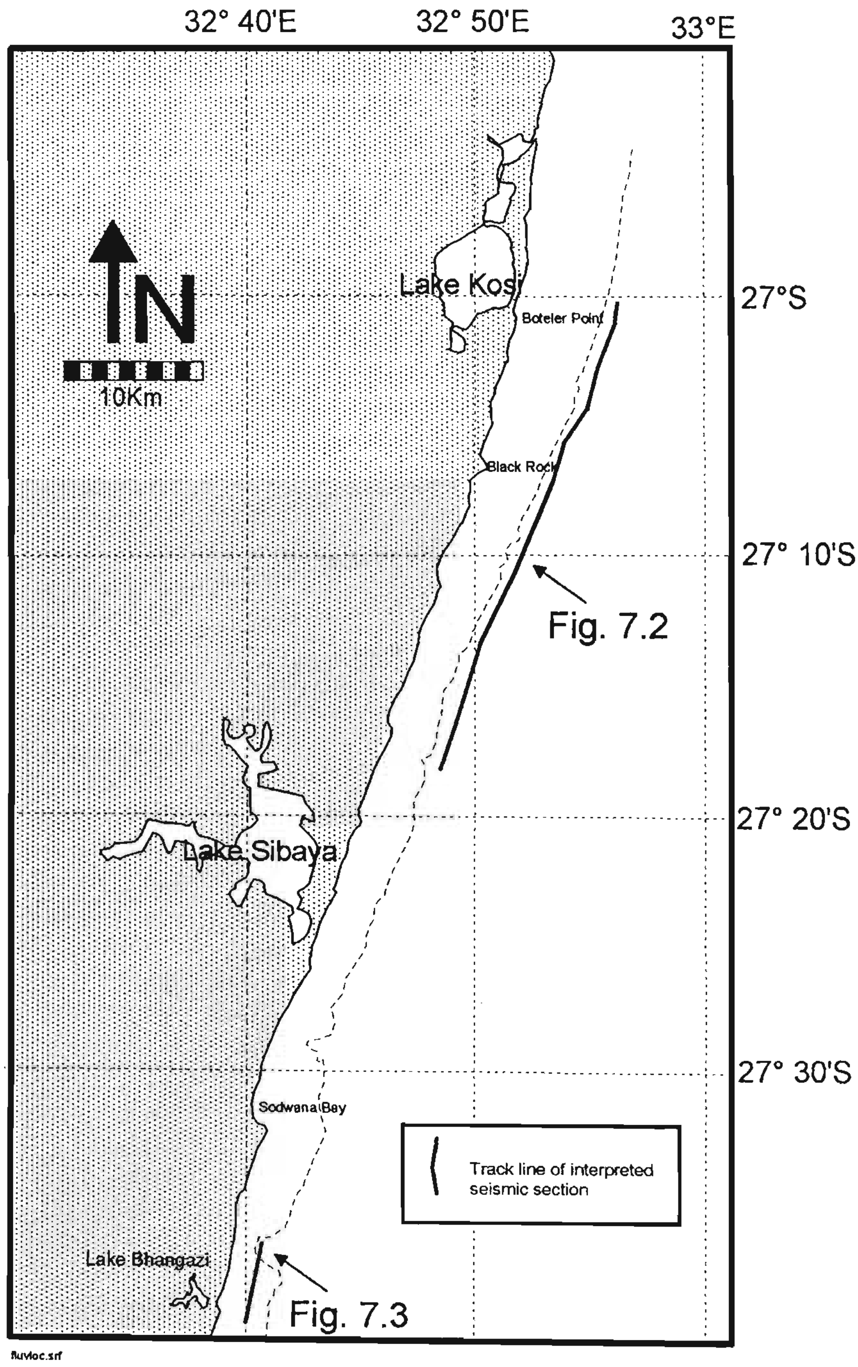


Fig. 7.1: Locality of sparker seismic sections showing evidence of palaeo-fluvial incision

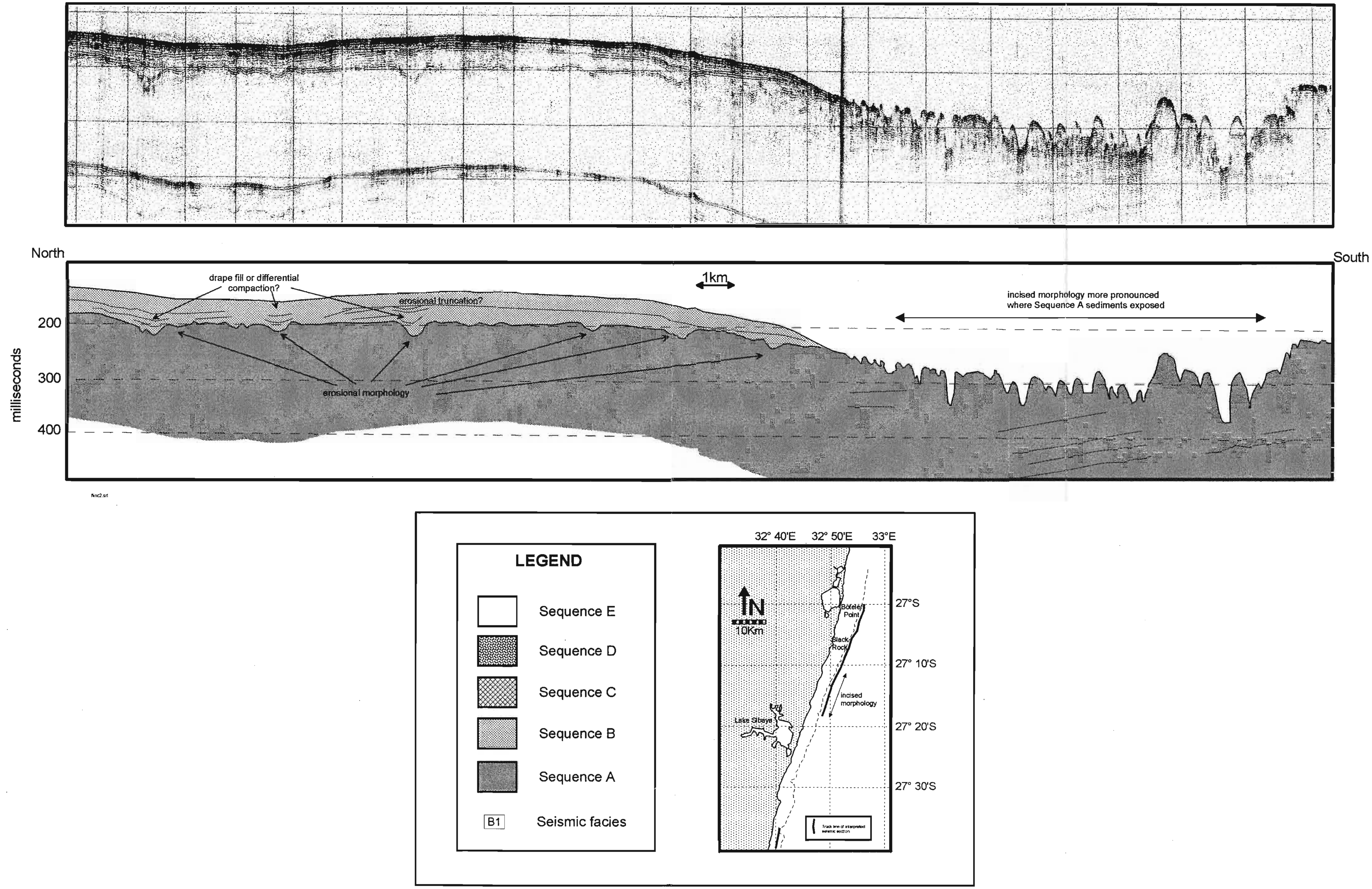


Fig. 7.2: Sparker seismic section and line drawing interpretation showing evidence of fluvial incision on the continental shelf north of Lake Sibaya

0.5Km and 1.2Km and a maximum vertical relief of approximately 14m. This channel-like morphology is buried by up to 28m of Sequence B sediments. Continuous, high amplitude reflectors within Sequence B exhibit slight depressions over three of the larger channel-like incisions. These are probably sediment collapses and further testify towards the instability of Sequence B, discussed in Chapter 5 (although an alternative explanation could be a fine-grained, drape-fill style of deposition).

Further south where Reflector a is not buried by Sequence B sediments the sea floor displays a more eroded appearance, with numerous submarine valleys. The exposed submarine valleys have greater vertical relief and steeper sides than the incised features buried by Sequence B. This probably indicates that the subaerially exposed topography displayed by Reflector a has been further eroded where it is not buried by Sequence B slope facies sediments. Two contrasting seafloor morphologies are therefore juxtaposed and these styles are determined by the sequence stratigraphy of the continental margin in the area.

7.2 Fluvial incision offshore of Lake Bhangazi (Fig. 7.3)

Directly offshore Lake Bhangazi, Reflector b has been incised to a depth of 55msec over a horizontal distance of approximately 1.2Km. The vertical relief of this fluvial incision is approximately 10m. This incision is buried by acoustically transparent unconsolidated Sequence E sediments.

7.3 Discussion

Two ages of fluvial incision have been identified. North of Lake Sibaya, Reflector a marking the top of Sequence A has been incised and the resultant channel-like features have been buried by Sequence B sediments. This indicates a Late Cretaceous to Late Tertiary date of incision. Directly offshore Lake Bhangazi, Reflector b has been incised. It is not clear on the seismic section whether Sequence C or Sequence B sediments have been incised or whether Sequence C sediments are present. The age of this incision can therefore not be confidently inferred. It must however either be Late Tertiary to Holocene or Late Pleistocene to Holocene and probably represents fluvial incision during the Last Glacial Maximum. The writer believes that the incision is into a

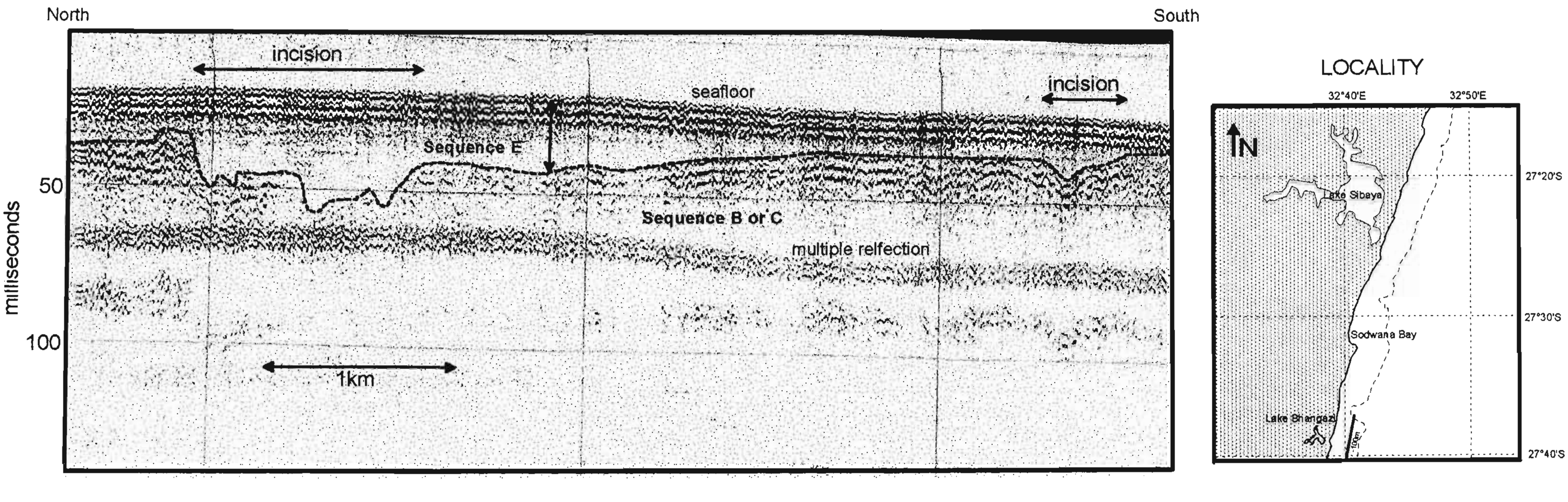


Fig. 7.3: Sparker seismic section and line drawing interpretation showing evidence of fluvial incision on the continental shelf offshore Lake Bhangazi

thin Sequence C layer not discernible on the seismic record, thereby indicating a Late Pleistocene to Holocene age of incision.

Of particular interest is the close proximity of the incision to the onshore Lake Bhangazi. It has been postulated (pers. comm., MK Watkeys), that lake Bhangazi represents a palaeo-estuary of the Mkuze River, which prior to the formation of the obstructive coastal dune cordon, probably flowed directly onto the continental shelf at around this locality as recently as 8000 years ago. Certainly, the position of this incision on the continental shelf , lends weight to this argument, discussed also in Chapter 6 (see Fig. 7.4).

Evidence of fluvial incision on the continental shelf or slope indicates a lowering of sea-level. These seismic data can therefore contribute further towards sea-level curve data that have been compiled for the southeast African continental margin. Siesser and Dingle (1981) proposed a sea-level curve for the Late Cretaceous and Tertiary, based on onshore outcrop dates and offshore seismic and borehole evidence published by numerous authors (Fig. 7.5). According to their sea-level curve, the Late Cretaceous is characterised by a gradual transgression followed by a more sudden regression. A transgression continuing throughout the Palaeocene peaked in the Early Eocene. Thereafter, a regression lasted throughout the rest of the Eocene (with a short-lived transgression in the late Eocene) until the early Miocene. The Late Miocene and Pliocene period is characterised by two transgressions and regressions. Fluvial incision on the present day continental shelf or slope must represent sea-level regression. Subaerial erosion into the Upper Cretaceous Sequence A reflectors north of Lake Sibaya is thought to have occurred during the major Oligocene-Miocene regression. Other seismic evidence supporting this major regression spanning most of the Tertiary is reported by Dingle (1971) and Siesser and Dingle (1981) who report a widespread Oligocene unconformity on the Southern African continental shelf and slope. They report erosion levels to depths of approximately 530m and 425m in the sediment basins of the continental margin and at 375m on the flanks of the Agulhas Arch.

Late Pleistocene to Holocene subaerial exposure morphology directly offshore Lake Bhangazi probably represents erosion during the Last Glacial Maximum, 18000 years before present, when sea-level was as much as 130m below its present level, well

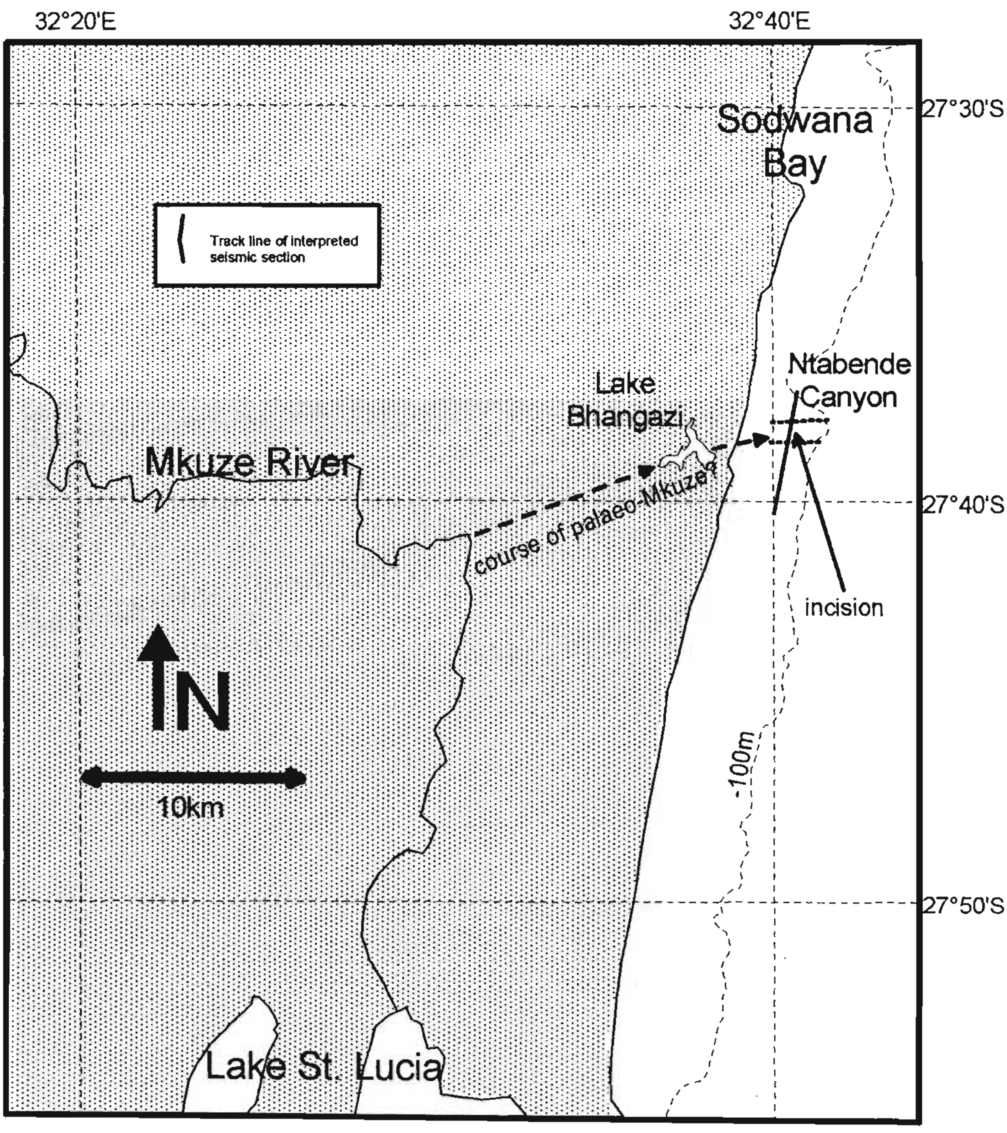


Fig. 7.4: Drainage course of the lower reaches of the Mkuze River in relation to Lake Bhangazi and continental shelf incision

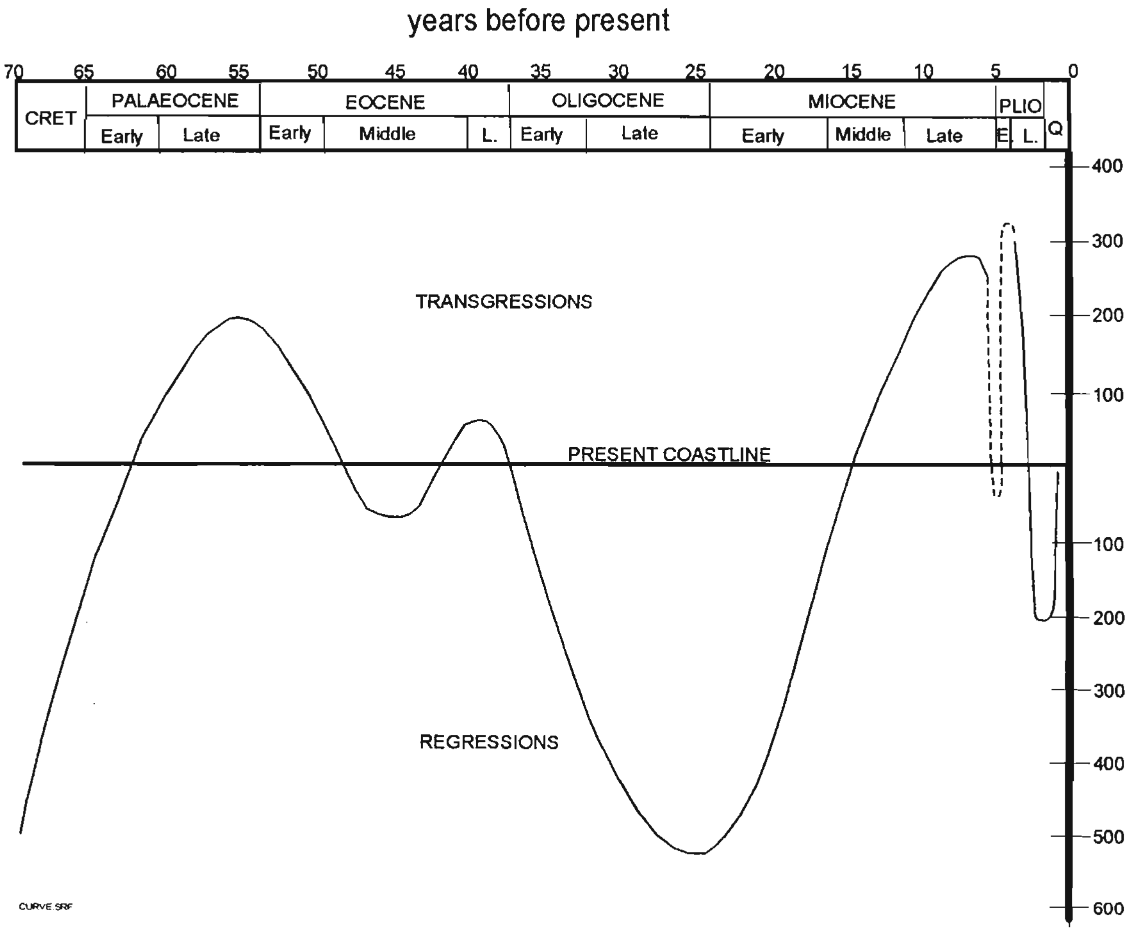


Fig. 7.5: Sea level curve of Siesser and Dingle (1981)

below the shelf break at a depth of approximately 70m.

CHAPTER 8

CONCLUSIONS AND DISCUSSION

A problem of attempting to broadly explain the geometry and development of the northern KwaZulu-Natal upper continental margin is the lack of both offshore and onshore age control. Nevertheless, this study has revealed a broad stratigraphic structure which contributes to understanding the broad geological evolution of the study area.

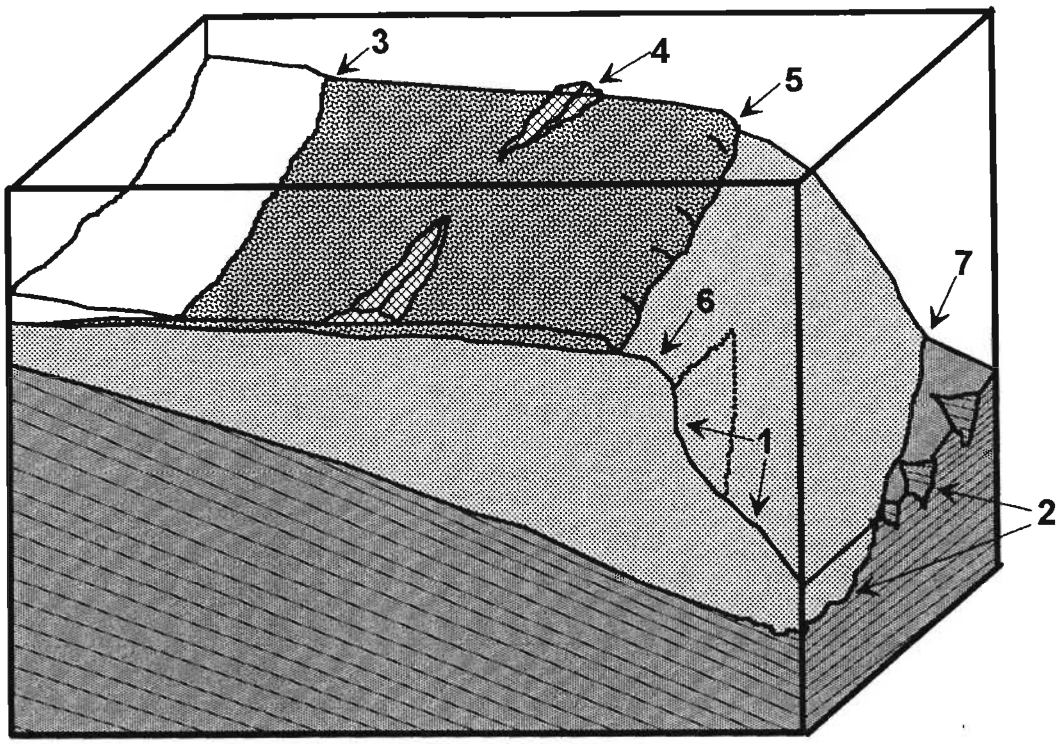
8.1 Upper continental margin morphology overview

Although macro-dynamic controls during the Gondwana breakup must undoubtedly have influenced the external morphology of the study area, this study has revealed an upper continental margin morphology strongly influenced by sequence stratigraphy (Fig. 8.1).

The position of the present day shelf-break is determined by the outer limit of Sequence B Facies 2 (shelf facies) sediments. Immediately below the shelf - break, the upper slope angle is determined by the depositional dip angle of Sequence B Facies 3 sediments as indicated by the sea-floor parallel reflectors within this unit, except where slope steepening due to mass-wasting processes has taken place.

Slope angle changes are frequently evident at the point where Sequence B (Facies C) pinches out. At this point the slope angle changes from the relatively high dip angle of the slope facies reflectors to the lower dip angle of the Sequence A reflectors. This is especially evident in the northern portion of the study area.

On the outer continental shelf, the eastern limit of Sequence C is visible as a localised steepening of the shelf angle at the point where this sequence pinches out. Sequence D manifests itself on the continental shelf as localised prominent features sometimes with a vertical relief of up to 20m. The Sequence E shelf sediment prism also has a distinctive external geometry in



LEGEND

SEQUENCE E

SEQUENCE D

SEQUENCE C

SEQUENCE B

SEQUENCE A

1	upper slope angle determined by depositional dip angle of Sequence B, Facies 3 sediments except where modified by mass-wasting processes
2	accentuation of of erosional morphology where Sequence A exposed
3	shelf angle decrease at outer limit of Sequence E
4	aeolianite dune ridges
5	shelf angle decrease at outer limit of Sequence C
6	shelf-break at outer limit of Sequence B, Facies 2
7	slope angle decrease at outer limit of Sequence B

Fig. 8.1: Conceptual illustration showing the influence of sequence stratigraphy on the external morphology of the northern KwaZulu-Natal upper continental margin

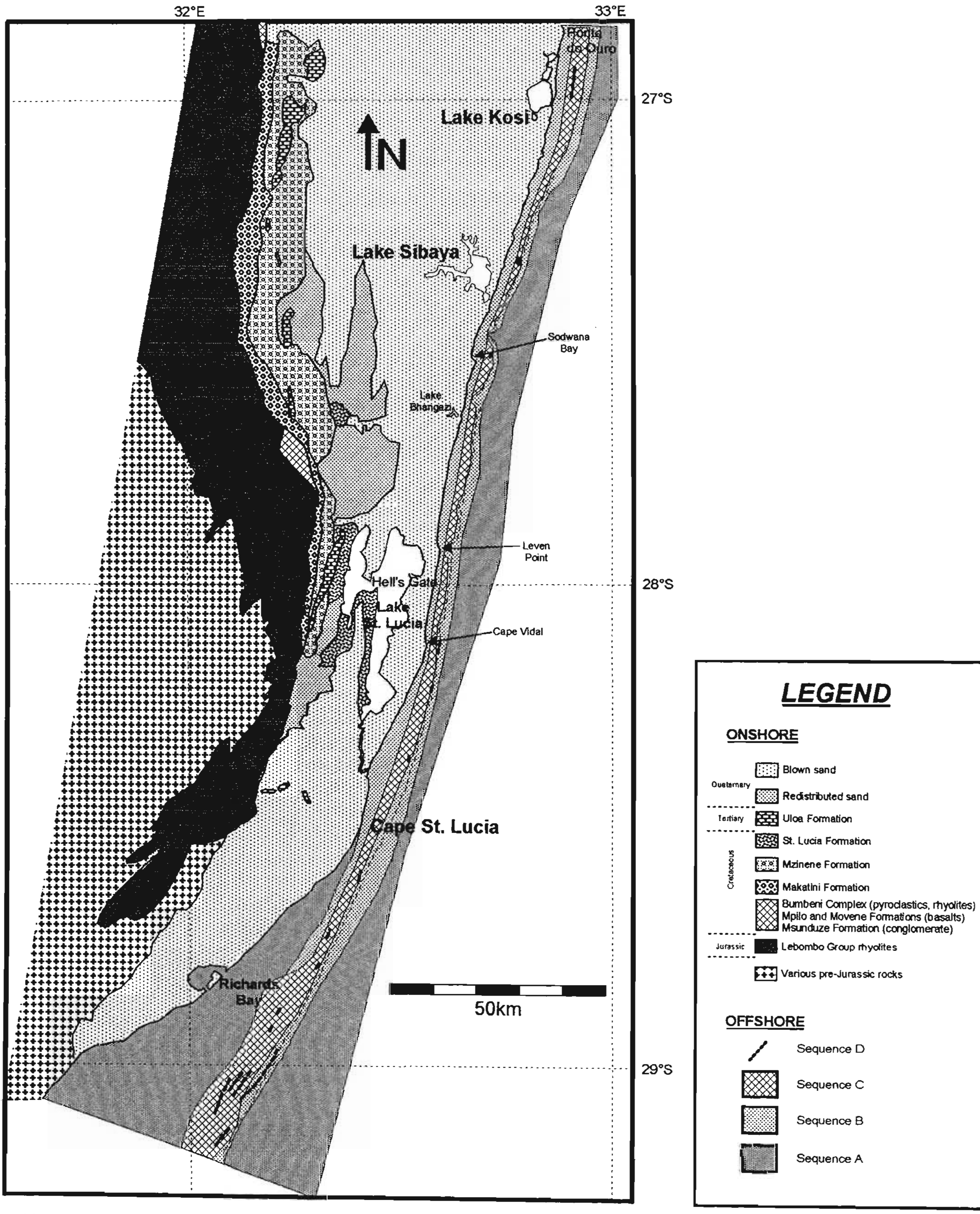
places, where the outer limit of the sediment wedge is characterised by a lessening of the continental shelf angle.

The external geometry of the continental margin has been modified in places by processes of mass wasting, leading to gradient steepening on the unconfined (by submarine canyons) upper continental slope. As discussed in Chapter 6 processes of mass wasting also appear to have been a key factor in the development of submarine canyons.

An interesting phenomenon was observed on the upper slope, north of Lake Sibaya in the northern portion of the study area (Fig. 7.2). The surface marking the top of Sequence A is clearly erosive in this area. Where this erosive topography is buried by Sequence B sediments, this buried topography is more subdued than is the case further south where clearly further erosion and steepening of this topography has taken place. This is perhaps an indication of an instance where exposed steep gradients have been further steepend by processes of mass-wasting due to exposure to the Agulhas Current. Where this erosive topography was afforded the protection of Sequence B sediments, mass wasting has not occurred. This phenomenon could be important with regard to submarine canyon formation processes. Although there are no known submarine canyon features that have breached the continental shelf in this area, landward propagation through further headward mass-wasting could plausibly lead to the development of such a feature. This could therefore be an argument for incipient submarine canyon development taking place in Sequence A which could promulgate to mature phase through headward erosion into Sequence B slope facies sediments and eventual breach of the shelfbreak.

8.2 Overall seismic sequence distribution

Overall (pre-Holocene) sequence distribution is shown in Figure 8.2. Although Sequence A is depicted as cropping out on the continental shelf close inshore in the southern part of the study area, a downlap surface observed on seismic sections north of Richards Bay (Figs. 3.5f, g and h) indicates the possible



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ig. 8.2: Pre-Holocene sequence outcrop on the northern KwaZulu-Natal upper continental margin, combined with onshore geology (simplified after Geological Survey of South Africa, 1985a and b and Watkeys et al., 1993) presence of a younger sequence. In the south of the study area, the inshore contact between Sequences A and B moves steadily inshore and crosses the coast somewhere in the region of Cape St. Lucia. This indicates that Sequence B subcrops in the coastal fringe north of this point. The offshore contact between Sequence A and B moves steadily inshore between Mtunzini and Cape St. Lucia (in a similar fashion to the -100m isobath). North of Cape St. Lucia it trends coast-parallel, at a distance of less that 10km from the coastline before moving further offshore in the Lake Kosi area, where the continental shelf-width also increases. Outcrop of Sequence C is widest on the continental shelves opposite Richards Bay and Kosi Bay.

8.3 Comparison between onshore geology and offshore seismic interpretation

As mentioned earlier, one of the difficulties of this study has been the lack of reliable groundtruthing and age data. One of the main problems is the correlation of the Sequence A sediments with the Late Cretaceous St. Lucia Formation. A simple correlation may not be possible over such a large distance, both in the east-west (dip) and north-south (strike) axes. There exists a strong possibility that much of Sequence A may in fact be younger sediments, perhaps of Palaeogene age and that in the considerable distance between the seismic Sequence A mapped in this study and the onshore outcrops of the Maastrichtian St. Lucia Formation there may be a major unobserved unconformity and younger sequence. It is interesting to note that a major downlapping unconformity is visible on the inshore portions of the seismic profiles in Figures 3.5f, g and h. Various workers have also documented Palaeocene sediments at localities both onshore and within this study area. Maud and Orr (1975) recognize a 46m Palaeocene succession overlying Upper Cretaceous sediments beneath the coastal dune cordon in the Richards Bay area. Dingle *et al.* (1983) and Dingle (1976) mention the existence of middle Palaeocene sediments on the continental shelf offshore of Cape St. Lucia. It is also interesting to note the Palaeocene age for marine clays dated by Siesser (1977) in the Leven Point area which led Sydow (1988) to interpret the existence of an erosional remnant of a Palaeocene marine sequence (his Sequence B) on the upper continental slope (see Chapter 2, Figs. 2.2 and 2.3), very close to his Sequence A outcrop. His correlation of Sequence A with the Late Cretaceous St. Lucia Formation was based on extrapolation. This in addition to the fact that the present study did not identify any discreet seismic sequence in a similar seismic stratigraphic position anywhere in the study area could indicate that the date mentioned by Siesser could actually be applicable to the much more widespread Sequence A material.

In the absence of offshore age control, one method of assigning dates to the relevant seismic sequences is to consider dating of onshore borehole sequences and to extrapolate offshore. Various workers have compiled cross sections for various areas onshore of this study area. In the Richards Bay area a well-constrained cross section exists based on a drilling study (Maud and Orr, 1975). This area is adjacent to the more complete (seismic stratigraphically speaking) Richards Bay upper continental margin. An attempted correlation between the cross section of Maud and Orr (1975) and the seismic stratigraphy presented in the present study is shown in Fig 8.3.

The unconformity at the top of the Upper Cretaceous sediments onshore is correlated with an unconformity observed in places on the continental shelf where downlap is visible. The unconformity observed at the top of the Palaeocene sequence onshore is correlated with the onlap surface observed offshore (Reflector a). These correlations would mean that a portion of the sediments observed on seismic sections on the continental shelf would be Palaeocene in age. The shelf sequence observed offshore (Sequence B) could therefore be the distal age equivalent of the remnant Upper Miocene sediments observed onshore.

In the north of the study area, seismic interpretation offshore of Kosi Mouth indicates the probable oversimplification of the shallow (<300m) coastal portion of the cross section accompanying the Geological Survey 1:250000 Kosi Bay geological map, (Geological Survey of South Africa, 1985a), especially that portion depicted close to the coastline (Fig 8.4). This cross

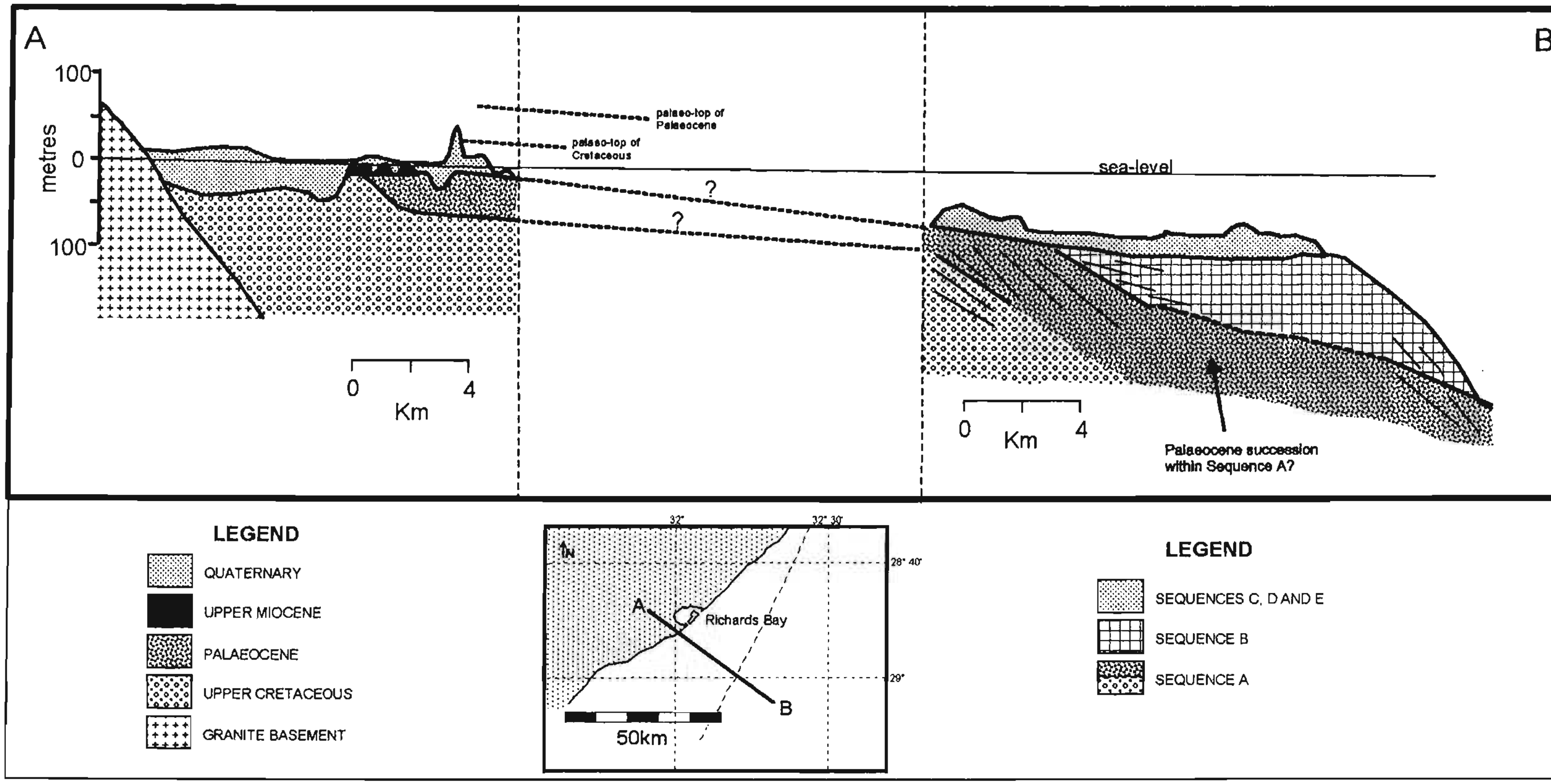

Fig. 8.3: Possible correlation between stratigraphy of Maud and Orr (1975) and seismic stratigraphy of the Richards Bay continental shelf

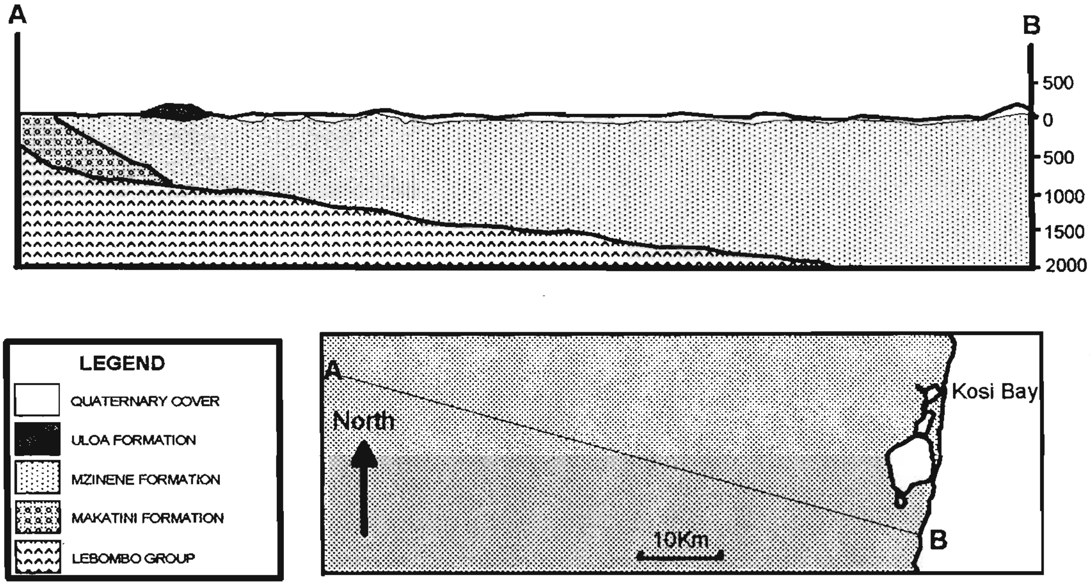

Fig. 8.4: Geological cross-section near Kosi Bay (simplified after Geological Survey of South Africa, 1985a)

section depicts sediments of the Lower Cretaceous Mzinene Formation subcropping beneath Quaternary cover at the coast. In contrast, this study, onshore extrapolation of seismic interpretation shows that the Late Tertiary Sequence B subcrops somewhere west of the coastal dune cordon.

The seismic interpretation for this area fits reasonably well though with aspects of an onshore cross- section compiled by Kruger and Meyer (1988) who recognise a seaward dipping wedge of Tertiary Age sediments in the Kosi Lake area based on borehole and geophysical evidence. A comparison of this cross-section and the seismic section directly offshore Kosi Mouth is shown in Figure 8.5. Onshore extrapolation of the seaward dipping Reflector a recognised in the seismic sections ties up with offshore extrapolation of the contact between the Tertiary sediments and those marked as Zululand Formation (Final Phase). Although the dates assigned to the sequences identified onshore could be debated (see footnote)[1], the physical geometry of the onshore and offshore interpretations fits well.

A problem regarding correlation of onshore and offshore geology in this study is the age of the Uloa Formation. In Kruger and Meyer's (1988) cross-section in the Kosi Bay area, the Uloa Formation is depicted as thinning in a seaward direction, pinching out somewhere near the coastline. The geometry of the Kosi Bay correlation shows that the Uloa Formation is a younger sequence than Sequence B. Geometrically speaking it would correlate better with Sequence C, thought to be a reworked Pleistocene shelf sequence.

The age of the Uloa Formation has been debated by various workers, with most of the postulated ages of deposition falling between Late Miocene and Early Pliocene (King, 1953; Frankel, 1968; Stapleton, 1977; Siesser and Miles, 1979). Evidence has been published however for a Latest Pleistocene age of deposition (McMillan, 1993). Clearly this is quite different from the generally debated age range, militating against much published evidence. It is

[1] The Palaeocene age of the lower-most unit is almost definitely erroneous, and resulted from misinterpretation by the authors of information supplied to them by Dr. IK McMillan, upon which the ages listed in the cross section are heavily dependant.

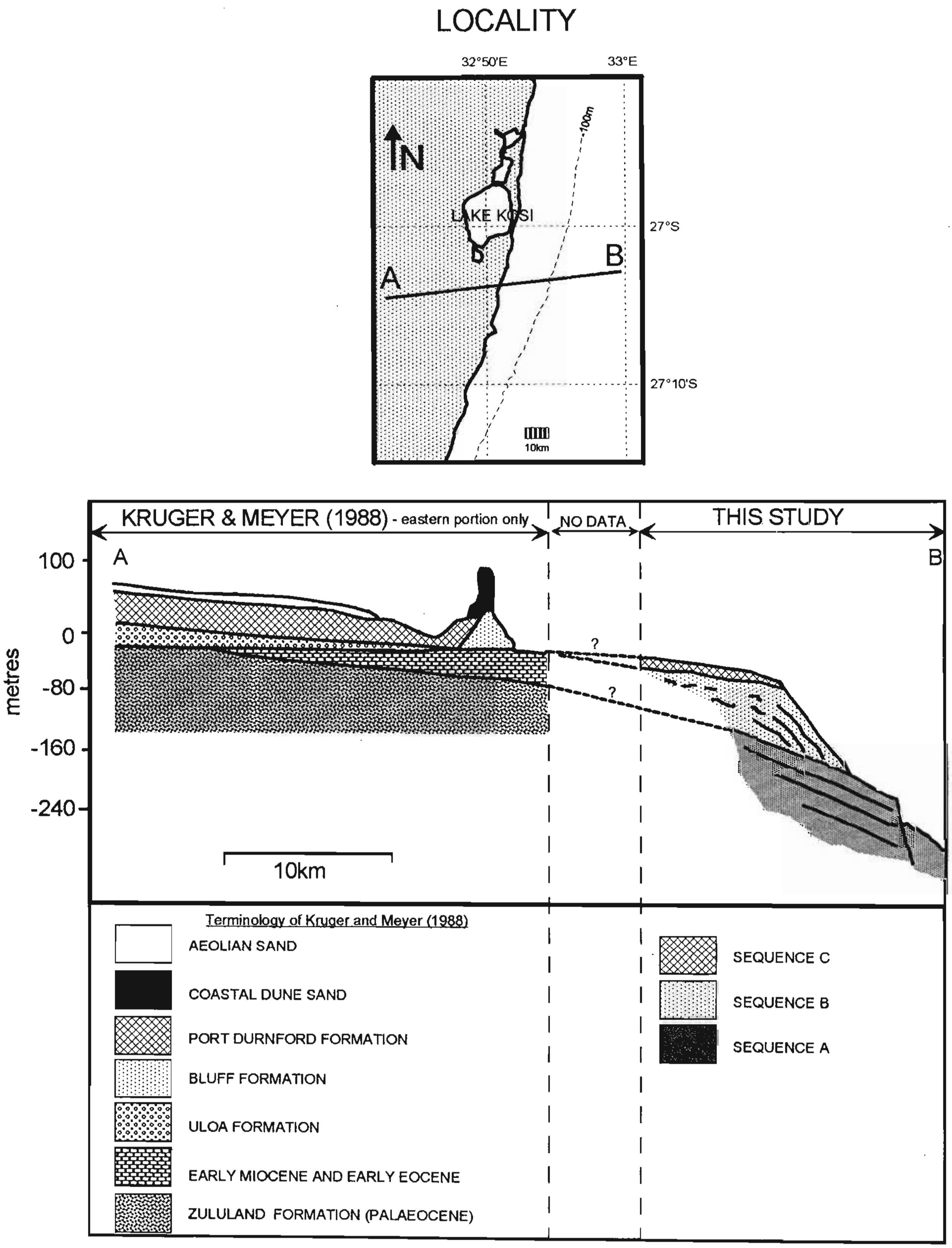

Fig. 8.5: Possible correlation between stratigraphy of Kruger and Meyer (1988) and seismic stratigraphy of the continental shelf near Kosi Bay

not the intention of this work to review these issues, but the Kosi Bay cross-section (Fig. 8.5) in which the onshore Uloa Formation correlates much better with the offshore Pleistocene shelf sequence than with the Tertiary shelf sequence clearly raises questions which need to be answered before a broad sequential geological history can be confidently forwarded for the northern kwaZulu-Natal upper continental margin.

8.4 Correlation between shelf seismics and adjacent deep ocean seismic studies

Correlation between the seismic interpretations of this study and the Natal Valley seismic interpretations by Dingle, Goodlad and Martin in their late 1970's and 1980's studies is perhaps not very straightforward due to the fact that most of their regionally developed seismic reflectors are interpreted as being strongly influenced by the Agulhas/Mozambique Current. These reflectors therefore developed due a rather more complex set of circumstances than just erosive hiatuses as is the interpretation on the continental shelf and uppermost slope. Horizon McDuff, which is interpreted as a Mid-Cretaceous (Cenomanian/Turonian) non-depositional hiatus (Goodlad, 1986) is stratigraphically below units addressed in this study. Although Horizon Angus is interpreted as an erosive hiatus formed during invigorated deep current action during the Oligocene, it could also be related to the major depositional hiatus and corresponding major sea-level regression thought to have spanned throughout most of the Oligocene. If this is the case then Horizon Angus could well be correlateable with Reflector a of this study since as discussed in Chapter 7, incision into this reflector is interpreted as erosion during subaerial exposure during the Oligocene low relative sea-levels. Similarly Horizon Jimmy could well be relateable to the sometimes erosive Reflector b marking the base of Sequence C. Material deposited in the Natal Valley above Horizon Jimmy could be derived from both failed upper slope material and sediments eroded from the Upper Tertiary shelf sequence of which Sequence B is the lower remnant.

8.5 Sea-level change indicators

The broad seismic sequence stratigraphic relationships observed in the study area provide some insight into relative sea-level movements since the Late Cretaceous (Fig. 8.6).

The fact that Sequence A sediments, the top contact of which has been erosionally truncated, can be extrapolated onto the Zululand coastal plain indicates deposition during conditions of relatively high sea-level ("1" in Fig. 8.6). The erosional truncation of Sequence A reflectors on the continental shelf and the erosive morphology of the reflector marking the top of this sequence to a depth of at least -320m indicates a subsequent lowering of relative sea-level to at least this depth sometime during the Late Cretaceous to the Miocene ("2" in Fig. 8.6) probably during the major Oligocene regression. Onlap of Sequence B Facies reflectors onto the unconformity marking the top of Sequence A probably indicates a gradual sea-level rise during the deposition of these sediments ("3" in Fig. 8.6). The inshore erosional truncation of Sequence B Facies A sediments indicates removal of an unknown thickness Sequence B sediments during lowered sea-levels ("4" in Fig. 8.6). Clear incision into the top of Sequence B as observed offshore Lake Bhangazi (see Chapter 7) indicates probable fluvial incision during a lowered sea-level, probably during the Last Glacial Maximum 18000 years before present ("5" in Fig. 8.6). Sequence C represents the probable remnant of a shelf sequence deposited during a sea level highstand probably during the Pleistocene ("6" in Fig. 8.6). Other relative sea-level indicators are the occurrences of Sequence D aeolianite dune ridges documented at approximately 56, 60, 67 77 and 109m below present day sea-level which possibly indicate relict coastal dune ridges formed during short-lived sea-level stand stills during the Flandrian Transgression ("7" in Fig. 8.6).

These relative sea-level indicators fit in fairly well with established and current thinking regarding sea level movements since the Late Cretaceous. Perhaps the most interesting sea-level indicators being the incision into the upper limit of Sequence B sediments which offers further evidence for the existence of a

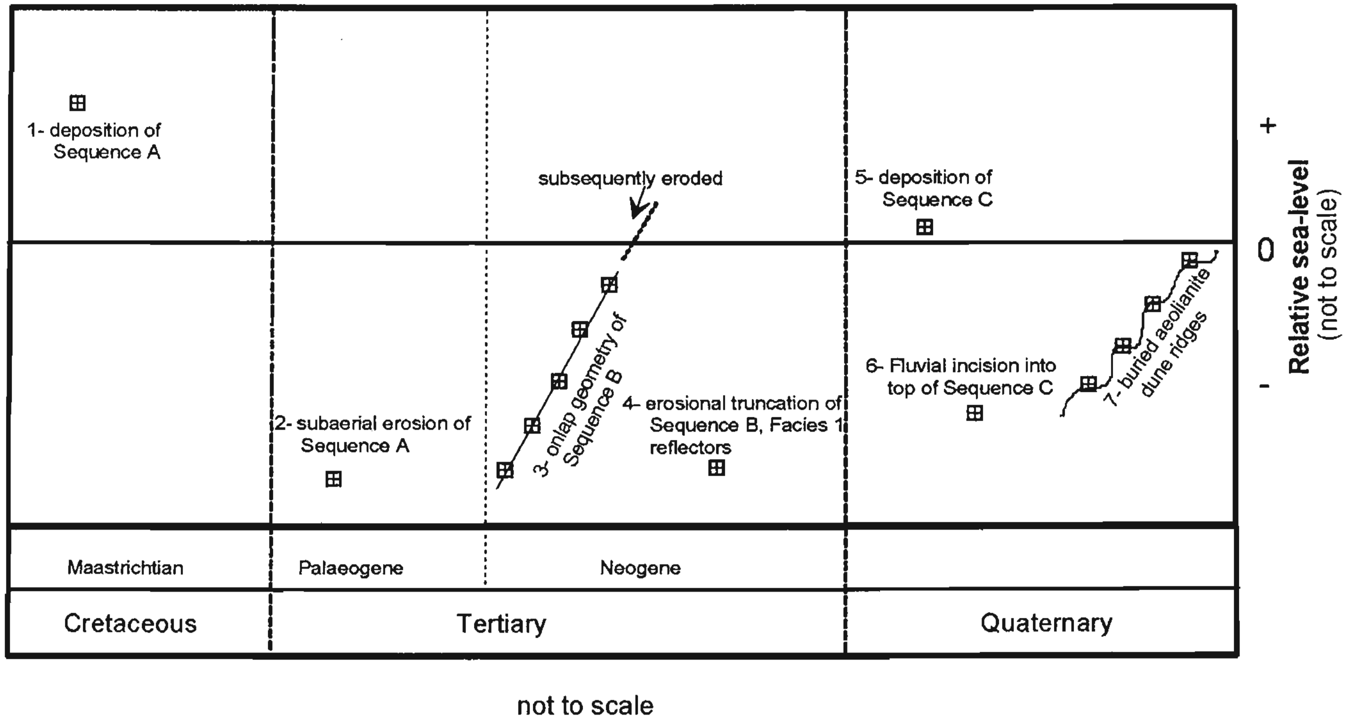

Fig. 8.6: Summary of seismic stratigraphic relative sea-level movement indicators in the study area

major widespread unconformity on the southern African continental margin occurring probably due to a prolonged sea-level low period lasting throughout the Oligocene and Early Miocene (Siesser and Dingle, 1981).

8.6 Geological development of the northern KwaZulu-Natal upper continental margin

Based on the correlations described above and established relative sea-level movements since the Late Cretaceous a schematic 6-stage development of Maputaland and the adjacent upper continental margin is proposed (Fig. 8.7).

Sequential development is shown in Figure 8.7. Although relative sea-level movements are fairly well known for southern Africa, absolute details of heights above and below present day sea-level are at best approximations. Sea-levels as depicted in the sequential diagrams are therefore not drawn to an absolute scale and should also be regarded as approximations showing overall relationship to present day sea-level.

8.6.1 Late Cretaceous

The earliest marine sediments recorded in Zululand are Upper Barremian, probably indicating establishment of marine conditions during those times (Dingle *et al.*, 1983). Widespread marine conditions were thought to have been established during the Aptian as indicated by the deposition of the exclusively marine sediments of the Mzinene Formation. The absence of marine and fluvial Makatini and marine Mzinene Formations on the Richards Bay portion of the Zululand coastal plain may indicate the later establishment of marine conditions in this more southerly area. The widespread occurrence of the Coniäcian to Maastrichtian marine St. Lucia Formation however indicates that marine conditions must have been established at the latest by this time. The widespread occurrence of St. Lucia Formation rocks both onshore and offshore (Sequence A) and the parallel reflection configuration as observed on seismic records indicate the deposition of these marine strata, probably on a uniformly subsiding shelf (Bally, 1987). Sedimentation rates

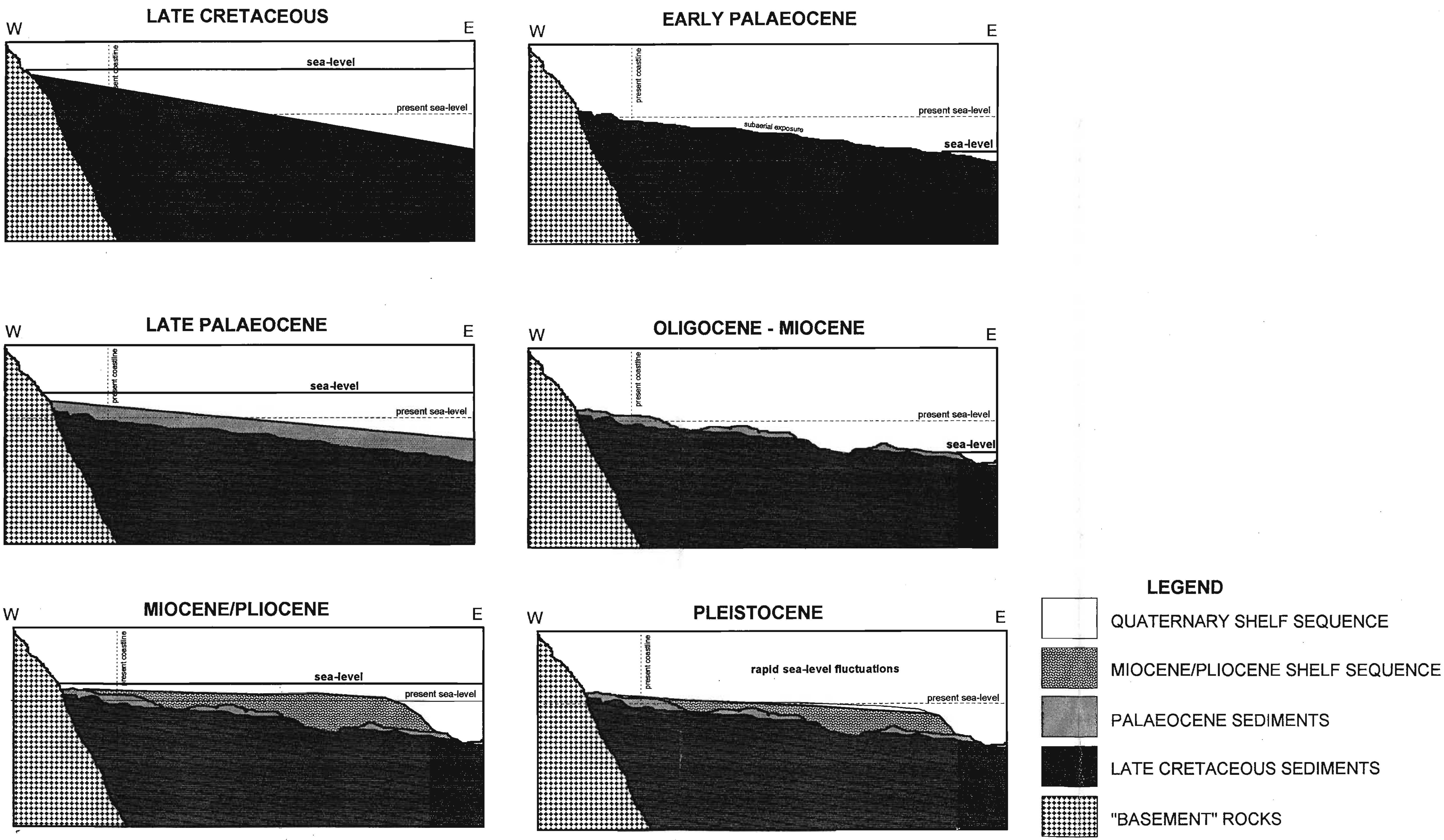

Fig. 8.7: Simplified sequential geological development of Maputaland and the adjacent upper continental margin based on interpretation of offshore sparker seismic records

were thought to be relatively high during this Cretaceous period, relative to later Tertiary deposition (Dingle *et al.*, 1983). Their widespread occurrence indicates deposition under conditions of elevated sea- level. Geotechnical studies of Latest Cretaceous Maastrichtian sediments of the St. Lucia Formation recovered from borehole cores in the Richards Bay area (Maud and Orr, 1975) indicate that approximately 120m of sediment have been removed from the top of the sequence studied in that area prior to the deposition of later sediments, it can therefore be concluded that the top of the Late Cretaceous St. Lucia Formation extended to approximately 60m above present sea-level at a position close the present coastline.

8.6.2 Early Palaeocene

During a sea-level regression (Siesser and Dingle, 1981), St. Lucia Formation sediments would have been subaerially exposed and partial denudation of these sediments would have taken place. It is probable that the denuded sediments were deposited on the wide continental shelf, but limited accommodation space (due to probable reduced subsidence) would mean that these sediments were extensively reworked.

8.6.3 Late Palaeocene

It is suggested that a shelf break had developed by the Late Palaeocene. Deposition of Palaeocene sediments during a transgression was probably not as extensive as deposition of Cretaceous sediments due to reduced sedimentation rates. The top of the Palaeocene sequence being depicted as being above present day sea-level is tentatively proposed on the basis of the borehole studies of Maud and Orr (1975) who show that the load equivalent of the Danian sediments was approximately 140m at a depth of 45m indicating that approximately 95m of sediment were removed from the top of this sequence. It is not known however what portion of this sequence consisted of post-Palaeocene sediments.

8.6.4 Oligocene to Miocene

Sea-levels are thought to have been drastically lowered during this period, possibly to depths as great as 500m (Siesser and Dingle, 1981). Indications of well developed subaerial erosion are seen in the seismic sections in the north of the study area (see Chapter 7, Fig. 7.2) possibly indicating extensive erosion during a relatively wet climate. Various other examples of suspected subaerial erosion of Sequence A sediments to a depth of approximately 320m are seen throughout the study area (Figs. 3.5b, 3.5d, 3.5g, 3.5l, 3.9b, 3.11b, 3.11c and 3.13b). During the consequent prolonged subaerial exposure, extensive denudation of the Palaeocene sediments would have taken place, possibly being completely removed in places, thereby opening up windows into the Late Cretaceous sediments. Dingle *et al.* (1983) indicate that warm and wet conditions probably existed during early Tertiary times.

8.6.5 Miocene/Pliocene

Maud and Orr (1975) indicate the presence of a pre-Upper Miocene planation surface which must have developed during a Miocene transgression. According to Sydow (1988) deposition of the Tertiary shelf sequence as a set of prograding clinoforms took place, during which time the shelf break would have migrated seaward. Onlap of Sequence B Facies 1 reflectors recognised on this study suggests that at least the lower portion of this sequence was deposited during sea-level rise and development of this sequence would have been marked by vertical aggradation rather than progradation. The present study also shows as well as being characterised by distal downlap, the Tertiary shelf sequence is characterised in places by an internal downlap surface. This possibly indicates an abrupt lowering of sediment input and progradation. Although not very clear, possible divergent reflection configuration of Sequence B Facies 1 reflectors could indicate deposition on a progressively tilting surface. This tilting depositional surface could be attributed to deposition in the Tugela cone to the south, perhaps having an influence into the study area. Chaotic internal reflection configuration of the Sequence B Facies 2 sediments indicates a complex internal structure of these sediments and could perhaps indicate that the Agulhas current was active during Late Tertiary times on the continental shelf. It should be borne in mind however that the chaotic internal reflection configuration of this acoustic facies could also be an artificial effect caused by chaotic reflections produced by a cemented unit higher up.

8.6.6 Pleistocene

The Pleistocene period was characterised by several sea-level transgressions and regressions. Toplap of Sequence B reflectors indicates that an unknown thickness of sediments has been removed. Denudation of this sequence was incomplete as indicated by the remnant probable Late Tertiary Uloa Formation cropping out in places onshore. Indications are that the sea-level regressions since the Pleistocene could have been relatively short-lived due to the fact that the external morphology of Sequence B on the present day continental shelf does not exhibit subaerial exposure morphology. The widespread evidence of mass wasting on the continental shelf however indicates though that failure could have taken place during conditions of lowered sea-level and storm wave base. Deposition of the Pleistocene Shelf sequence took place during a period of relatively high sea-level, under conditions of much lower terrigenous input compared to Late Tertiary times. It is probable also that this sequence has been extensively modified by current processes operative on the continental shelf during those times.

According to the above sequential geological development, the general external morphology of Maputaland and adjacent upper continental margin has not changed substantially since Late Tertiary times following deposition of the Tertiary shelf sequence. Subsequent Quaternary deposition has been limited to a thin veneer on top of this broad external geometry.

Clearly the situation in the north of the study area is markedly different to the situation in the south, the wide continental shelf south of Cape St. Lucia exposing much more of the sequence geometry.

8.7 Possible future work

Understanding the geological evolution of northern KwaZulu-Natal upper continental margin would be greatly improved with an integrated seismic/sediment sample study. Various sediment samples have been collected by various workers in the study area, many of these remain unstudied and/or undated. Currently, the southeastern African coast is the subject of renewed interest with respect to hydrocarbon exploration and it is possible that drilling programs will be initiated in the area in the near future. It wold be a very valuable exercise to examine the acquired data in the light of mapping carried out in terms of this study.

Further study of the complex reflection termination patterns in the outer portion of Sequence B, perhaps with a higher resolution seismic tool could also assist with understanding post Late Cretaceous geological development of the study area.

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APPENDIX A

SPARKER SEISMIC DATA ACQUISITION AND INTERPRETATION

The sparker system generates a pressure pulse by shorting electrical power in the water using a multi-tipped electrode powered by EG & G power supplies and capacitor banks. Energy of the pressure pulse varied up to 1000 joules. Reflected sound signals were detected by towed hydrophone arrays, amplified, band-pass filtered and displayed using either a EPC or EG & G graphic recorder. Band-pass filtering was generally in the range of approximately 150-700Hz but varied from time to time. Penetration achieved by the sparker system was greater than 200msec in places while the resolution of the system is approximately 6-8msec. Navigation during the cruise was by means of a DECCA navigator, radar or dead reckoning (all technical information from Martin, 1985).

All seismic interpretation was carried out directly on the seismic analogue records using film overlays. Where depicted, the seismic sections and line drawing interpretations are kept separate. Where mentioned or depicted, thicknesses were calculated using a sonic velocity through sediment of 1600ms^{-1} (D'Olier, 1979; Wellner *et al.*, 1993; Martin, 1985). Milliseconds can therefore be approximated to metres by multiplying by 0.8. Mostly however, thicknesses and depths are quoted in two-way travel time.

Strong individual acoustic horizons usually manifest themselves as a package of reflectors on sparker seismic records. This is due to the "bubble pulse" effect (Fig. A1). This effect is caused by the tendency of the gas bubble created by the sparker electrical discharge into water, to collapse and reform several times, producing a series of sound pulses rather than a single pulse (this is also referred to as "source-ringing". The "bubble pulse" phenomenon effectively lowers the resolution of the sparker seismic tool since the multiple reflection package can obscure individual features up to approximately 10-15msec below

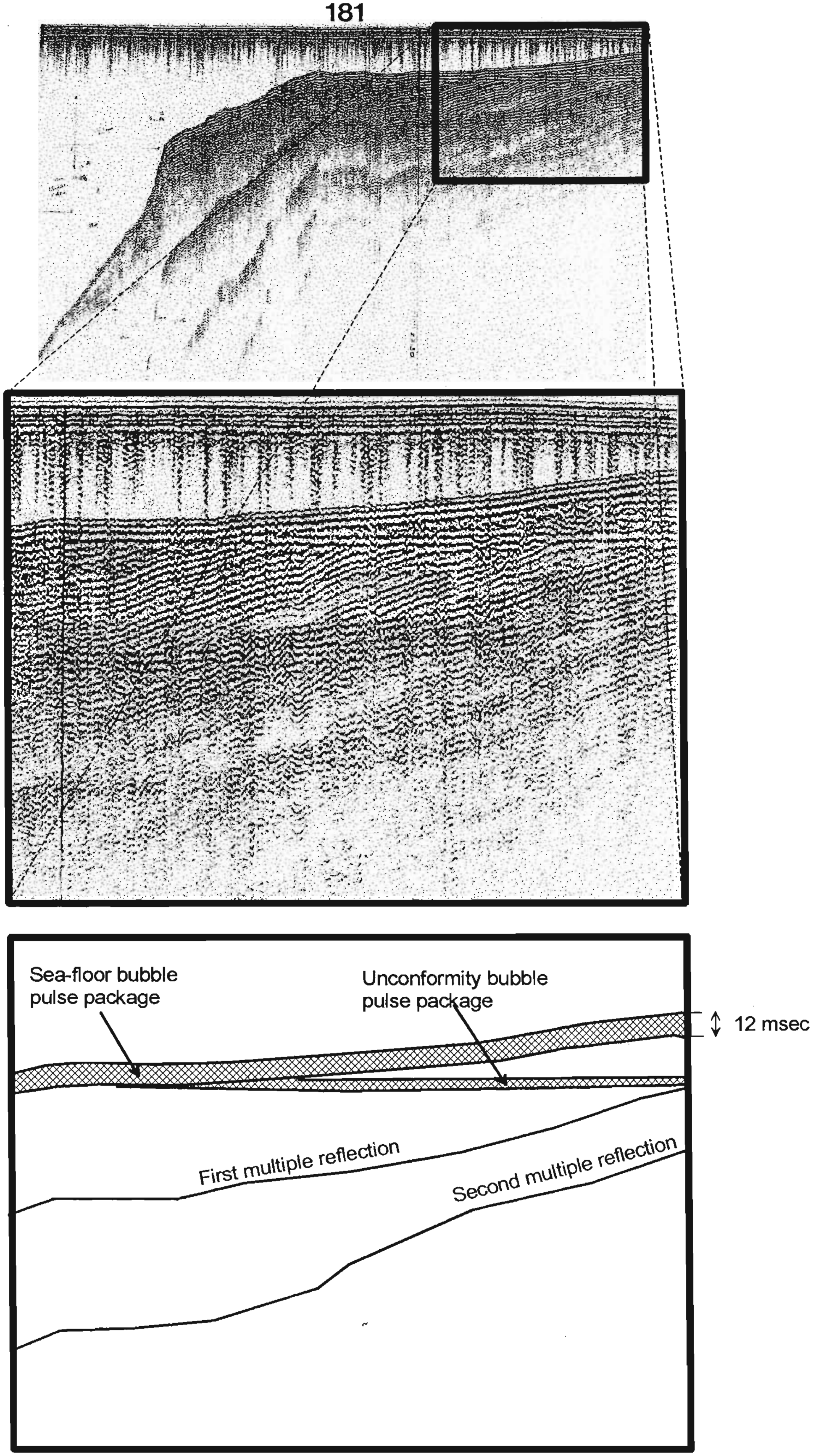

Fig. A1: Enlarged seismic profile and line drawing interpretation showing bubble pulse relfection package and multiple reflection package strong acoustic horizons. This effect is strongest at the sea-water/sediment interface thus obscuring shallow sedimentological features to a depth of 8-12m.

While the reported maximum penetration of the sparker system used was reported as being greater than 200msec, in shallow water, effective penetration is reduced by **multiple reflections** (Fig. A1). Although reflections from acoustic horizons are recorded by the seismic system, some of their energy is reflected back downwards by the sea surface and re-bounced off the sea floor and re-recorded by seismic system. The effect of this on seismic records is to duplicate seismic information at regular intervals equal to twice the water depth. This duplication mostly obscures any features present from this depth downwards. It follows therefore that maximum effective penetration can only be achieved in deeper water.

Sparker seismic profiles usually show apparent dips that are greatly exaggerated by the recording technique used. The low angle of dip prevents the use of a stereonet to calculate true angle of dip. True dip angle and direction was calculated by assuming that strike direction of sediment layers is approximately the same as the current trend of the continental shelf, i.e. approximately parallel to the -100m isobath.

APPENDIX B

EDO-WESTERN DATA ACQUISITION AND INTERPRETATION

Data acquisition formed part of a Council for Geoscience project in which the sedimentology and geological history of the Sodwana Bay continental shelf was studied. Interpretation of bathymetry and side-scan sonar data acquired during this cruise is presented in Ramsay (1991).

Seismics data acquisition

Data were acquired using a submerged 3.5KHz continuous reflection Edo Western system. Theoretical resolution of any seismic system is given as being between 0.25λ and 0.125λ, where λ = wavelength (Sheriff, 1977). In the case of an Edo Western seismic system this would equate to a resolution of between 8 and 15cm. Resolution is effectively lowered to approximately 30-50cm due to ringing of the sound source (i.e. the tendency of the transducer to reverberate upon initiation of the sound signal).

Navigation data acquisition

Navigational track charts used in this study were previously compiled for the purposes of bathymetry and side-scan-sonar interpretation (Ramsay, 1991). Vessel coordinates during traverses were recorded at approximately 30 second intervals either by means of a Global Positioning System (GPS) receiver (JRL 4200 GPS system) or alternatively (when the GPS receiver was off-line) ship-shore radar fixes at approximately 10 minute intervals. Position fixes were downloaded via a serial interface port to an XT computer and stored in ASCII format using the program NAVPCX. Following this, corrections were applied so that the data conformed to the locally used Cape Datum.

Data processing

Track lines were oriented coast-parallel because the primary objective of the geophysical cruise was to complete side-scan-sonar and bathymetry mapping of the continental shelf.

Interpretation of the Pinger sections was carried out directly on the analogue seismic records. For the unconsolidated sediment thickness map, where reflectors were visible, sediment thicknesses were measured at approximately 120m intervals and depths calculated assuming a velocity of sound through sea water and unconsolidated sediments of 1500ms^{-1} (D'Olier 1979). Other workers (eg. Wellner *et al.* 1993) give a higher value (1650ms^{-1}) for speed of sound through unconsolidated sediment, but since the Pinger system used in this study has a low effective penetration of approximately 7 metres, use of these higher values will have a negligible effect on thickness calculation. The steep gradient of submarine canyon walls causes echo reverberations on the Edo Western records (Fig. B1). Consequently Edo Western sections through submarine canyons are chaotic and unclear. Unconsolidated sediment thicknesses are therefore not available for submarine canyons and these areas were not considered during compilation of the sediment thickness map. The sediment thickness map (Fig 4.13) therefore does not include submarine canyon areas.

Unconsolidated sediment thickness data were contoured using the commercial contouring software package SURFER. The Kriging method of gridding using an octant search pattern and the nearest 10 data points was used. Grid density is 200 by 100 and a contour interval value of 1m was chosen. By choosing this interval, the sediment thickness map should remain representative of sediment thickness on the continental shelf possibly even after major storm events which are known to extensively alter sediment thicknesses on the continental shelf (Ramsay, 1991). The computer generated contour plot was modified taking into account morphology of subaqueous dunes and information from Edo Western sections acquired close to the edge of the continental shelf.

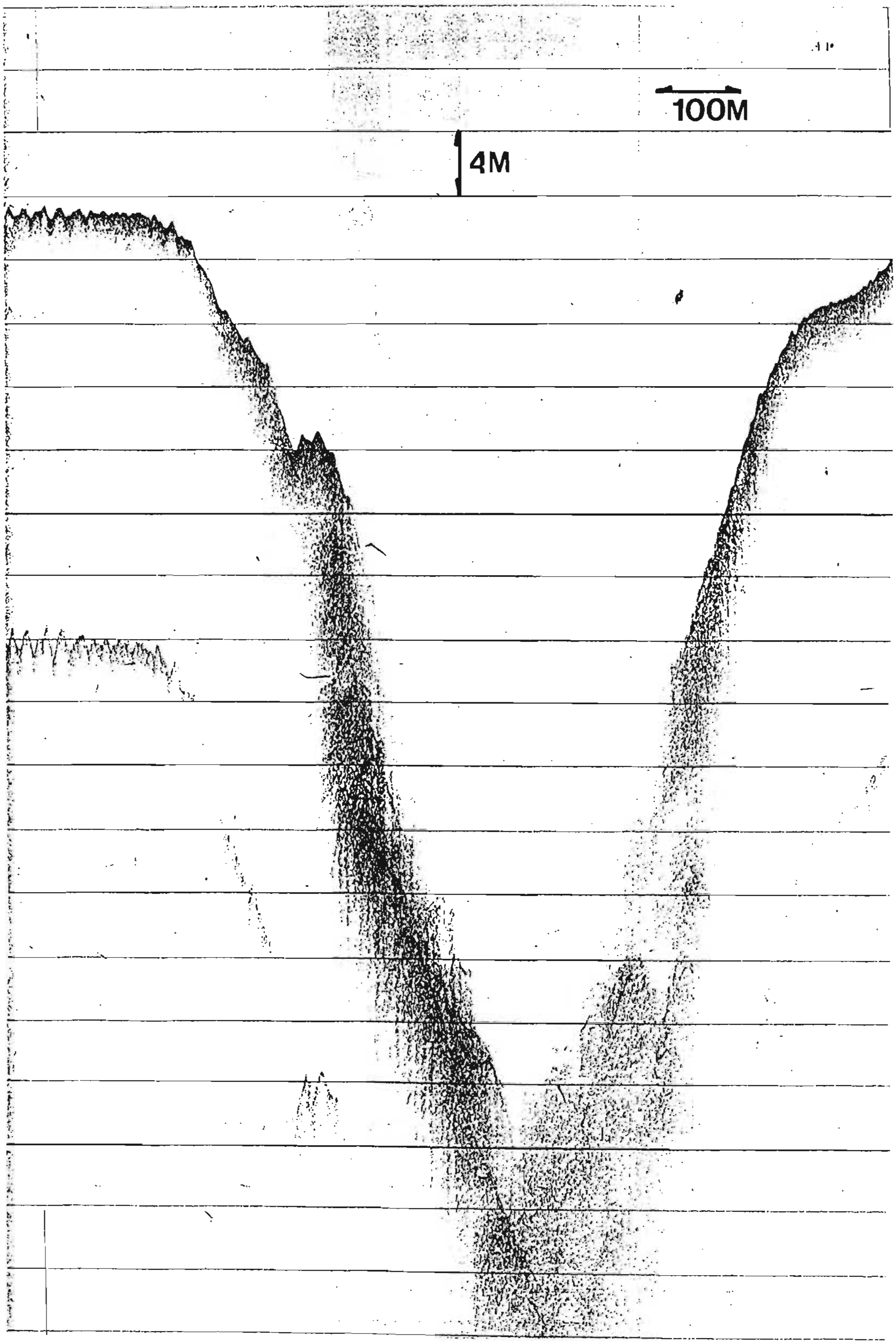

Fig. B1: Diffuse chaotic reflections in Wright Canyon, due to steep gradient of canyon walls

Limited penetration of the Pinger system necessitated "greater-than" values being used where reflectors are not visible on the seismic section. In places, reflector trends can be inferred over short distances thereby allowing sediment thickness to be measured when reflectors are below the effective penetration of the Pinger System.

In subaqueous dune fields sediment thickness values could be interpolated even though no reflectors were visible. Sediment thickness where subaqueous dunes are present is greater than the height of the dune (Fig. B2).

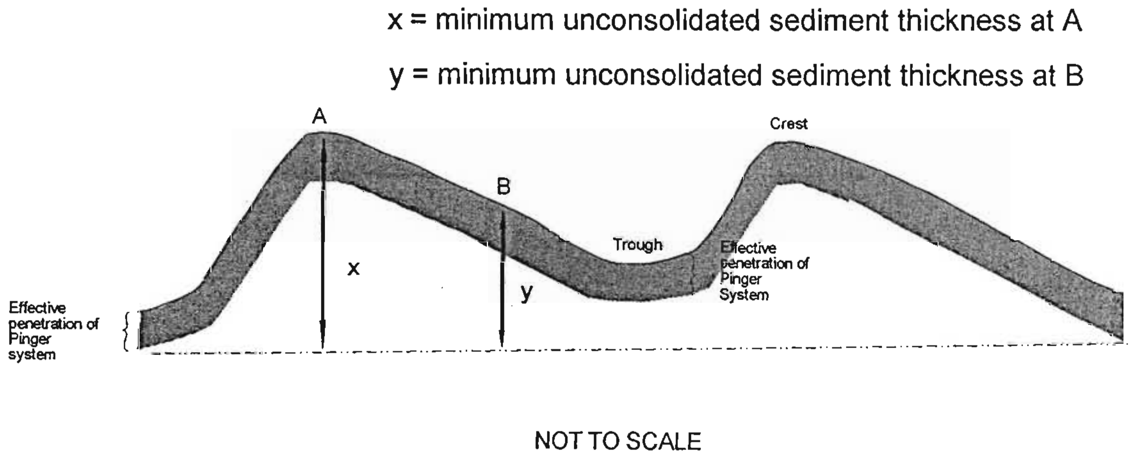

Fig. B2: Sediment thickness determination in subaqueous dune fields

APPENDIX C

SUBMARINE LANDSLIDE TERMINOLOGY AND MORPHOLOGY

Each work dealing with any form of submarine landslide has its preferred terminology. Terminology used in this study follows (Schwab *et al.*, 1993). and is outlined below.

Schwab *et al.* (1993) use the umbrella term "submarine landslide" to describe any *en masse* downslope movement of sea floor material or continental margin sediments. This term is interchangeable with the term "mass movement". A submarine landslide or mass movement will occur when "slope failure" has taken place. Slope failure occurs when downslope driving forces acting on the material composing the sea floor are greater than the forces acting to resist major deformations. Submarine landslides can be classified according to the style of the mobility involved. Classification terminology and feature nomenclature is illustrated in Fig. C1. If the failed sediment assumes a form that resembles a viscous fluid the failure process is termed *mass flow*. Considerable deformation of internal structures takes place during such failures. *Slides* are translational or rotational movements of essentially rigid, internally undeformed masses along discrete slip planes. The widely used term *slump* is restricted to indicate a special kind of submarine landslide in which blocks of failed material rotate along curved slip surfaces. *Debris flows* are flows of sediment in which the sediment is heterogeneous and may include larger clasts supported by a matrix of finer sediment. *Mudflows* involve predominantly muddy sediment. *Turbidity currents* involve the downslope transport of a relatively dilute suspension of sediment grains that are supported by an upward component of fluid turbulence. *Liquefaction* occurs when a loosely packed sediment collapses under an environmental load. Here the grains temporarily lose most contact with one another and the particle weight is transferred to the pore fluid. Excess pore water pressures are induced by this process. In this case material may flow downslope under the influence of gravity or spread laterally under the influence of stresses induced by earthquakes or storm waves. It is possible that

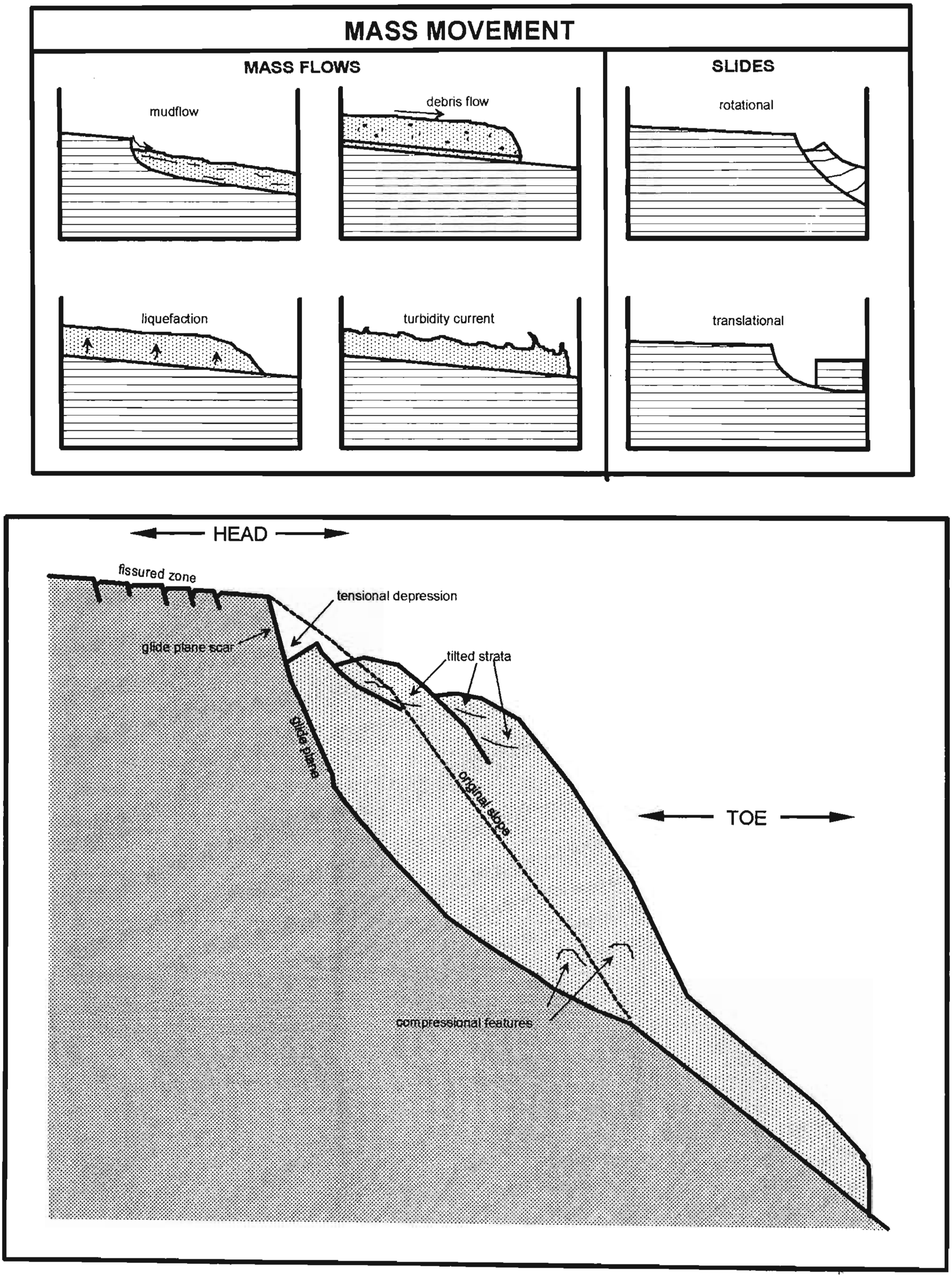

Fig. C1: Submarine landslide classification and feature terminology (from Lee et al., 1993 and Dingle 1977) different mobility styles occur within a single slope failure episode. The initial style of slope failure may be slide-type, but with continued downslope movement, a mass flow failure style may be achieved.

The type of submarine landslide features visible using seismic or bathymetric tools will obviously vary according to the style of movement that has occurred. Fig. C1 shows features that may be visible

A characteristically stepped or pitted sea floor upslope of the main glide plane is termed the *fissured zone*. This zone of disturbed bedding is caused by numerous small tensional faults. The *glide plane* scar is a steep scarp which marks the outcrop of the major glide plane where the slumped mass has moved vertically and horizontally away from the underlying strata. A *tensional depression* is a prominent bathymetric notch which occurs at the upper end of the slumped mass immediately adjacent to the glide plane scar.