SUBMERGED SHORELINE SEQUENCES ON THE KWAZULU-NATAL SHELF: A COMPARISON BETWEEN TWO MORPHOLOGICAL SETTINGS

by

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As the candidate’s supervisor I have approved this thesis/dissertation for submission.

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ABSTRACT

Holocene shoreline sequences and associated shelf stratigraphy are described from a high gradient, high wave energy shelf offshore the central KwaZulu-Natal and northern KwaZulu-Natal coastlines. These are examined using high resolution single-channel seismic and multibeam bathymetric means in order to describe the shallow stratigraphy and seafloor geomorphology of each area.

The development and preservation of two distinct planform shorelines at -100 m (northern KwaZulu-Natal) and -60 m (northern KwaZulu-Natal and central KwaZulu-Natal) is described. The shallow seismic stratigraphy of northern KwaZulu-Natal comprises three seismic units (Units 1-3) corresponding to calcarenite barriers (Unit 1), back barrier lagoonal sediments (Unit 2) and the contemporary highstand sediment wedge (Unit 3). At intervening depths between each shoreline the shelf is characterised by erosional surfaces that reflect ravinement processes during periods of slowly rising sea level. Where shorelines are not preserved, areas of scarping in the ravinement surface at depths coincident to adjoining shorelines are apparent. These areas represent rocky headlands that separated the sandy coastal compartments where the shorelines formed and are a function of the high gradient.

In central KwaZulu-Natal where the shelf is notably wider and gentler, shoreline building was more intense. Five major seismic units are identified (Units 1-5) with several subsidiary facies. The formation of the -60 m barrier complex (Unit 2) in central KwaZulu-Natal was accompanied by the simultaneous formation of a back-barrier system comprising lake-lagoon depressions (Unit 3) and parabolic dune fields aligned to the local aeolian transport direction, formed on a widened coastal plain. On the seaward margins of the barrier, gully and shore platform features developed coevally with the barrier system. Several relict weathering features (Unit 4) are associated with the barrier and reflect similar processes observed in contemporary aeolianite/beachrock outcrops on the adjacent coastline.

The two submerged shoreline sequences observed are attributed to century to millennial scale periods of stasis during which shoreline equilibrium forms developed and early diagenesis of beachrock and aeolianite occurred. These extensive phases of shoreline development are thought to have occurred during periods of stillstand or slowstand associated with the Bølling-Allerod Interstadial (~14.5 ka BP) and the Younger Dryas Cold Period (~12.7-11.6 Ka BP). Shoreline preservation in such an environment is considered unlikely as a result of intense ravinement during shoreline translation, coupled with the high energy setting of the KwaZulu-Natal shelf. Preservation of both the 100 m and 60 m shorelines occurred via overstepping where preservation was promoted by particularly rapid bouts of relative sea-level rise associated with meltwater pulses 1A and 1B (MWP-1A and -1B). This was aided by early cementation of the shoreline forms during stillstand.

Differences in shelf setting have led to variations in the style of barrier preservation and associated transgressive stratigraphies between the central KwaZulu-Natal and northern KwaZulu-Natal shelves. The main differences include a much thicker post-transgressive sediment drape, higher degrees of transgressive ravinement and an overall simplified transgressive system's tract (TST) architecture on the steeper and narrower continental shelf of northern KwaZulu-Natal. In comparison, the central KwaZulu-Natal shelf's 60 m shoreline complex reflects more complicated equilibrium shoreline facets, large compound dune fields formed in the hinterland of the shoreline complex, higher degrees of preservation and a more complicated transgressive stratigraphy.

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DECLARATION 2 – PUBLICATIONS

DETAILS OF CONTRIBUTION TO PUBLICATIONS

Publication 1

Salzmann, L., Green, A.N., Cooper, J.A.G., 2013. Submerged barrier shoreline sequences on a high energy, steep and narrow shelf. Marine Geology 346, 366-374.

As first author, I drafted the figures and wrote the manuscript. Dr. Green as supervisor collected the data, provided editorial input and introduced the conceptual framework, together with the third author Prof. Cooper.

Publication 2

Green, A.N., Cooper, J.A.G., Salzmann, L., (in press). Holocene shelf stratigraphy in the context of a stepped sea level rise: stratigraphic and geomorphic signature of meltwater pulses. Geology.

Dr. Green wrote the manuscript together with Prof. Cooper. I supplied preliminary interpretations from the northern KwaZulu-Natal data set, some of which were included in greater detail in publication 1.

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CHAPTER 1

1.1. Introduction

Over the last 18 000 years (18 ka) global changes in relative sea level (RSL) were initiated when large volumes of freshwater were released into the oceanic circulation system through the melting of major ice-sheets such as the Laurentide, North American, Antarctic and Arctic Ice Sheets (Severinghaus and Brook, 1999; Ganopolski and Rahmstorf, 2001). These changes in relative sea level have been documented by cores obtained from deep sea sediment, ice, coral and salt marshes. The RSL record reveals a strongly episodic pattern of RSL change with the overall long-term rise punctuated by several intervals of rapid rise associated with meltwater pulses (Liu and Milliman, 2004). Recently, attention has been focused on the stranded remnants of former shoreline complexes (such as barriers) that have been preserved as the continental shelves were drowned during transgression (e.g. Locker et al., 1996; Gardner et al., 2005, 2007). Based on the degree of preservation and the geomorphic maturity of the preserved sequence, these can provide compelling geomorphological evidence for shoreline position, the length of time of shoreline occupation and the rate of change in RSL rise over the last 18 ka. The formation of these sequences relies on stabilisation of the shoreline during slow rates of RSL rise or stillstand (e.g. Cooper, 1958; Thom, 1978; Pye, 1983; Cooper, 1991b) and their preservation is a function of the barrier shoreline being overstepped during transgression (cf. Carter, 1988; Green et al., 2013a). The conditions necessary for overstepping and for preservation of overstepped barriers, however, have been debated since first proposed by Curray (1964). Much of the argument (see Rampino and Sanders 1980; 1982; Swift, 1975; Swift and Moslow, 1982; Niedoroda et al., 1985) centres on the degree to which overstepped barriers are degraded or destroyed in the nearshore zone following overstepping (Rampino and Sanders, 1982). Preservation is believed to be enhanced by factors such as coarser grain sizes (Mellet et al., 2012); early cementation of the barrier form (Green et al., 2013a); gentle antecedent shelf gradient and reduced wave energy (Storms et al., 2008).

1.2. Research Aims

This thesis seeks to investigate the stratigraphic controls that influenced the development of the KwaZulu-Natal continental shelf (Fig. 1.1) during the late Pleistocene-Holocene transgression (Oxygen Isotope Stage 1). It builds upon previous work concerning the recent transgressive and highstand stratigraphies and resulting morphological features of the KwaZulu-Natal continental shelf by Richardson (2005), Bosman et al. (2007), Bosman (2012), Cawthra et al. (2012) and Green et al. (2012a; 2012b; 2013a, 2013b, in press). The objectives of this thesis are to:

1) examine the shallow seismic stratigraphy and seafloor geomorphology of the shelves offshore Durban and northern KwaZulu-Natal from a high resolution perspective

2) reconcile the seafloor morphologies with modern day coastal analogues

3) place the seismic stratigraphy into a sequence stratigraphic framework

4) to provide a better constrained model for shoreline/coastline behaviour during rising sea level, especially during stepped sea-level rise (e.g. Locker et al., 1996; Kelley et al., 2010; Green et al., in press)

5) to compare the transgressive stratigraphy and submerged shoreline morphology of the two study sites in order to elucidate the dominant controls on stratigraphic preservation

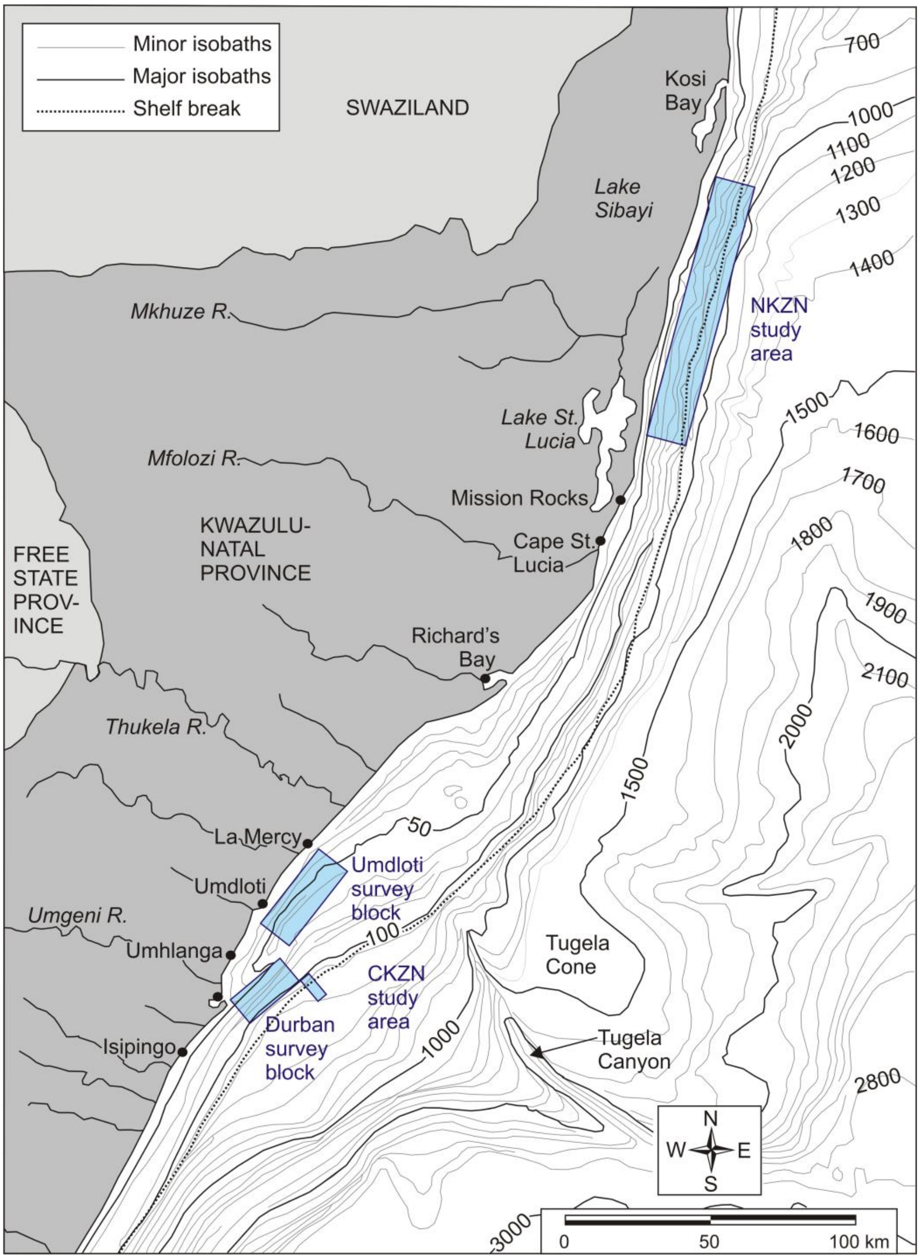

Figure 1.1. Map of the KwaZulu-Natal continental shelf showing isobaths and shelf break (dotted line) as well as landmarks of interest to the present study (modified after Flemming (1981), Martin and Flemming (1988) and Cawthra (2010)). Study areas are given in blue.

1.3. Importance of transgressive deposits, submerged shorelines and their use as sea level indicators

As Mellet et al. (2012) so aptly stated: "*drowned landscapes and their associated deposits are important sedimentological and geomorphological indicators that help improve our grasp on environmental response to rapid climatic and relative sea-level (RSL) change*".

Research that focuses on the transgressive deposits of the most recent sea-level cycle is particularly useful in that it improves our understanding of eustatic sea-level behaviour, resulting depositional processes and the framework that underpins sequence stratigraphy (Curray, 1964; Cattaneo and Steel, 2003). Transgressive deposits are also of economic importance in that they tend to provide mature sediments suited for use as aggregate in beach nourishment programs and industrial industries (Nordfjord et al., 2009) as well as forming first-rate hydrocarbon reserves (e.g., Snedden and Dalrymple, 1999; Posamentier, 2002).

Of particular interest are shoreline deposits that mark periods of stillstand superimposed on the overall transgressive cycle. Having escaped the erosion typically associated with wave ravinement across the formerly exposed palaeo-coastal plain, preserved shoreline features are amongst the few systems, apart from incised valley fills, that document the complex interplay between landform formation, preservation and sea-level fluctuation (Green et al., 2013a).

It is extremely rare for shorelines to be preserved on the continental shelf after being transgressed and even less common still for these features to remain well exposed from beneath a post-transgressive lag (Storms and Swift, 2003; Mellet et al., 2012; Green et al., 2013a). Such deposits are often thin and discontinuous due to erosion caused by the landward migration of the shoreline; consequently they are difficult to identify (Buck et al., 1999). Few high-resolution surveys have been conducted on modern transgressive deposits so as to resolve their complex depositional geometries (Nordfjord et al., 2009). This is most certainly the case in South Africa, making it all the more important to conduct research on this topic.

This study documents the collection of multibeam bathymetric and seismic data from the mid- to outer shelf offshore KwaZulu-Natal and provides new high-resolution details of submerged shorelines and their underlying and overlying transgressive stratigraphies. This thesis thus adds to the global archive of relict shoreline features found on continental shelves, together with the indicators or records of sea-level stillstands formed within the most recent transgression.

1.4. A review of shoreline response to RSL

Various models have been proposed concerning shoreline or barrier response to rising RSL and the resultant stratigraphic and geomorphological signatures produced on the newly formed continental shelf. The more established models tend to refer to barrier behaviour and modification on low-gradient shelves with a gradient of ~ 0.01° (e.g. Swift, 1968, 1975; Trincardi et al., 1994; Storms et al., 2008; Nordfjord et al., 2009). Until recently, the mainstream theory behind the behaviour of barrier-lagoon systems was that their retreat with rising sea levels occurs predominantly in a continuous fashion through a process called *rollover* (Fig. 1.2) (Swift, 1968; Swift et al., 1991; Belknap and Kraft, 1981). This involves the continuous landward retreat of the shoreface as it keeps pace with the rate of transgression through a combination of aggradation and landward migration. The barrier-lagoon deposits are entirely reworked by wave and tidal ravinement processes resulting in little preservation of these in the offshore sector (Swift and Moslow, 1982; Leatherman et al., 1983).

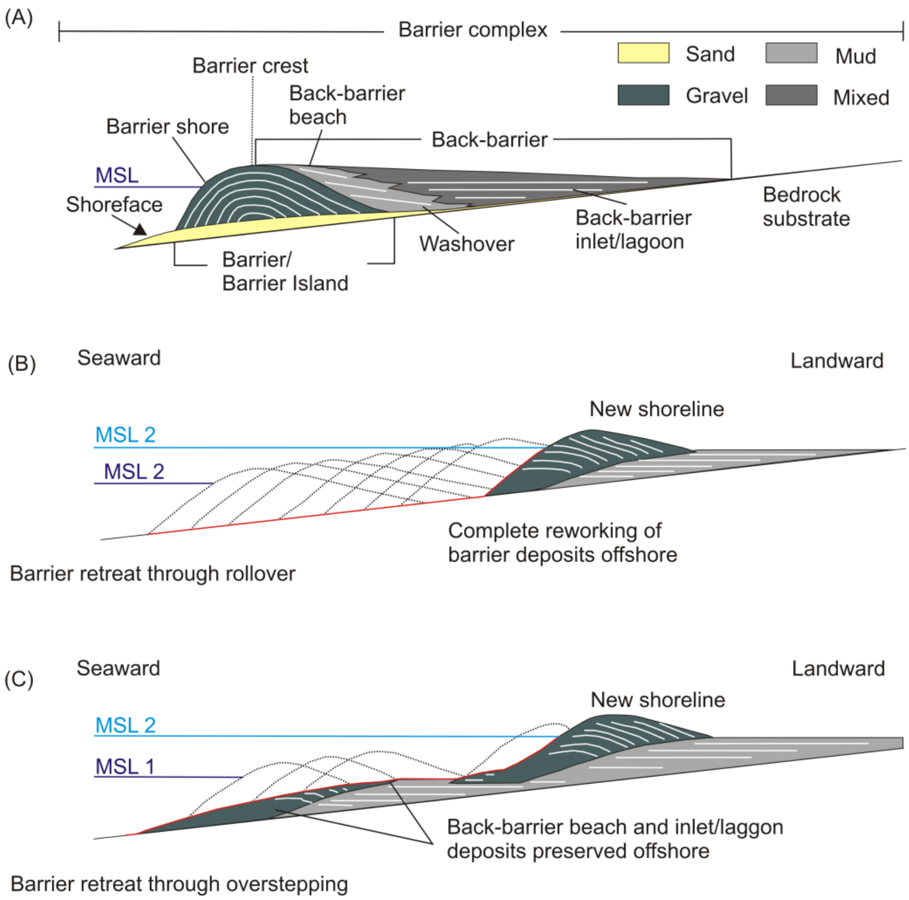

Figure 1.2. Barrier migration mechanisms depicting A) the main components making up a typical barrier or barrier island system, followed by two primary mechanisms of barrier movement, namely B) *rollover* and C) *overstepping* after Mellet et al. (2012).

Barrier *overstepping*, on the other hand, has been shown to occur where barriers fail to keep pace with rising sea-levels and are ultimately stranded on the continental shelf as sea levels continue to rise past them (Fig. 1.2) (Curray, 1964; Swift, 1968; Rampino and Sanders, 1980). This mechanism also involves the upward growth of the barrier-complex as sea-levels rise (through aggradation) and the simultaneous enlargement and trapping of sediment in the lagoons that bound these barriers and ultimately aided in their overstepping (Storms et al., 2008). When the shoreline is displaced landwards, the previously formed barrier-complexes tend to be either partially or fully preserved in place (Rampino and Sanders, 1980, 1982; Leatherman et al., 1983; Forbes et al., 1991; Storms et al., 2008; Hijma et al., 2010). This model has been further subdivided by Mellet et al. (2012) into: (1) "*Sediment surplus overstepping"*, which describes barrier retreat under conditions of rapid RSL rise with minimal wave reworking. This results in the almost complete preservation of the barrier complexes; and (2) "*Sediment deficit overstepping*", in which the shoreline moves landward in a sporadic, discontinuous fashion and lower degrees of preservation are attained.

High gradient shelves, such as that of northern KwaZulu-Natal, have received much less investigation in terms of their transgressive stratigraphies and geomorphologies. Recently a new model incorporating the equivalent of "*barrier overstep*" on high gradient coastlines has been proposed by Zecchin et al. (2011): the "*cliff overstep*" model. The authors suggest that on high-gradient shelves, coastal cliffs form during periods of low RSL rise otherwise known as *stillstands* or *slowstands*. When these periods of stasis are followed by an unusually sudden increase in the rate of sea level rise, such cliffs are often overstepped without any significant degree of reworking or breakdown by the transgressive ravinement surface (TRS), a combination of tidal, current and wave erosion. Consequently the post-ravinement transgressive deposits of steeper gradient shelves tend to be considerably thicker above the ravinement surface that may be less well developed than in gentle gradient settings. Cattaneo and Steel (2003) consider the conditions for the drowning of barrier complexes in these circumstances to be unfavourable.

1.5. Shoreline trajectory

A main theory regarding shoreline behaviour during transgression proposes that shoreline trajectory is the primary mechanism governing the amount of erosive ravinement that takes place, and thus the degree of preservation that occurs (e.g. Helland-Hansen and Gjelberg, 1994; Cattaneo and Steel, 2003). Shoreline trajectory is defined as the cross-sectional path of shoreline migration along depositional dip that takes into account relative sea level, sediment supply and antecedent topography (Helland-Hansen and Gjelberg, 1994). The latter takes into account both shoreline gradient and topographic relief.

When shoreline trajectory coincides with or is at a lower angle than the surface being transgressed, erosion predominates and few transgressive deposits will be deposited. This situation occurs when the rates of relative sea-level rise are rapid, when the transgressed topography is of a low gradient or when the rate of sediment supply is low.

Alternatively when a shoreline trajectory is steeper than the transgressed stratigraphy, extensive accumulations of transgressive stratigraphies with high preservation rates are deposited. This is often the case when the rate of relative sea-level rise is gradual, the transgressed topography is steep or under high sediment supply conditions (Cattaneo and Steel, 2003).

1.6. Barrier preservation potential

A number of variables act to determine the preservation potential of a barrier system: that is the extent to which the system is eroded or preserved during transgression. The long-term evolution of coastal barriers and their associated back-barrier environments is dependent upon the *extent of lithification* within the barrier, *barrier volume*, the *energy setting* (wave, current and tide dependent) and the *coastal physiography*. The latter is a function of multiple factors including the *degree of exposure*, *bathymetric relief*, *accommodation space*, the *geometry of the shoreface*, *depth of reworking*, *coastal alignmen*t, *compartmentalisation* and *headland control* (Thompson, 1937; Swift, 1968; Forbes et al., 1990, 1991; Forbes, 1995). The presence or absence of a *sediment lag* mantling the shoreface all contribute to the destruction or preservation of marginal deposits during transgression (Swift, 1968). *Sediment size* is another fundamental variable affecting preservation potential and, accordingly, gravel-dominated barriers possess longer relaxation times and are thus more resilient to relative sea-level rise than their sandy equivalents (Long et al., 2006). Storms et al. (2008) propose that the lower the *tidal range*, the more likely it becomes that a barrier-island will be preserved during overstepping, all other factors being equal. Lastly, Cattaneo and Steel (2003) advocated that under transgressive conditions, the shoreline trajectory may be either steepened or flattened based on the *rate of relative sea-level rise* and this too will implicate upon the evolution and preservation of barrier shoreline systems.

1.7. Seismic stratigraphic nomenclature

The five main stratigraphic surfaces on the mid- to outer continental shelf that are recognisable in seismic surveys include the *sequence boundary* (SB), *transgressive ravinement surface* (TRS), *maximum flooding surface* (MFS), *wave ravinement surface* (wRS) and *tidal ravinement surface* (tiRS):

- **SB:** The sequence boundary is a subaerial unconformity induced by base level fall during a relative sea-level lowstand (Posamentier et al., 1988). It is a high-amplitude reflector associated with fluvial incision and onlap of overlying strata (Catuneanu, 2009).
- **TRS**: The transgressive ravinement surface is an erosional surface that marks the landward passage of the shoreline across the coastal plain (Nordfjord et al., 2009). The TRS is typically a moderate-amplitude reflector formed through a combination of tidal, current and wave erosion that represents the base of the transgressive systems tract (TST) (Cattaneo and Steel, 2003).
- **MFS:** The maximum flooding surface represents the highest level attained by the seafloor during the peak of a transgressive episode and the turnaround from a retrogradational (transgressive) to a progradational (highstand normal regressive) stratal stacking pattern (Cattaneo and Steel, 2003). This typically reflects sediment starvation of the mid-shelf areas and the formation of a condensed section.
- **wRS:** The wave ravinement surface is a highly erosional surface that is formed through the erosion and landward retreat of the shoreface by wave action (Catuneanu, 2006). This is restricted to shallow marine regions above the storm wave base (Cattaneo and Steel, 2003). The wRS tends to separate fine grained non-marine paralic deposits below (e.g. lagoonal muds, peats, washover and flood-tidal delta sands) from marine deposits above (e.g. unconsolidated sand and mud drapes or shoal-retreat massifs) (Reinson, 1992; Snedden and Dalrymple, 1999).
- **tiRS:** For the purposes of this thesis, and to avoid confusion with the transgressive ravinement surface (TRS), the tidal ravinement surface is abbreviated as tiRS. The tiRS results from the landward movement of the zone of maximum tidal scouring (Swift, 1968; Allen and Posamentier, 1993) and tends to be restricted to the thalweg of estuary inlets/mouths, tidal distributary channels and flood-tidal delta channels (Zaitlin et al., 1994) that are dominant along tide-dominated coastlines but are also to

be found along wave-dominated coastlines such as that of South Africa (e.g. Cooper, 1991b).

A conceptual model of unconformities within a transgressive valley fill based on the work of Dalrymple et al. (1992) is provided in Fig. 1.3.

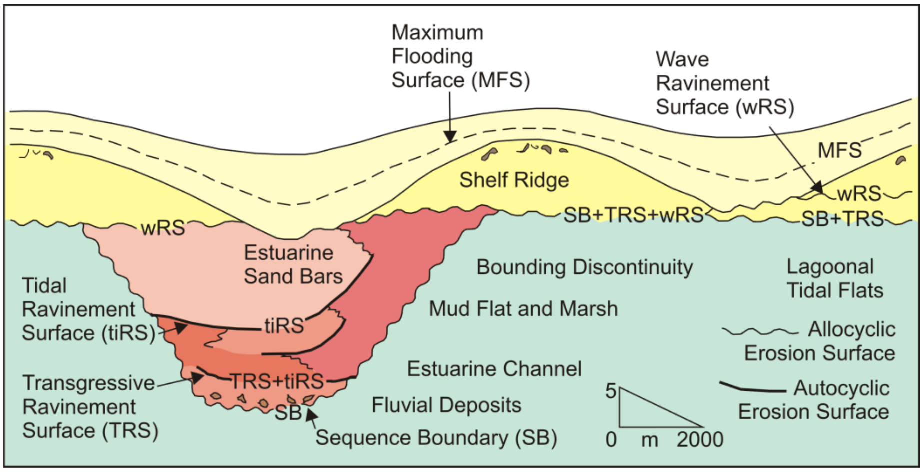

Figure 1.3. Coast-parallel schematic providing nomenclature and facies architecture of a transgressive systems tract in a tide-dominated setting with complete preservation of estuarine deposits. Modified after Dalrymple et al. (1992) and Cattaneo and Steel (2003).

Systems tracts include all "*genetically associated stratigraphic units that were deposited during specific phases of the relative sea-level cycle"* according to Posamentier et al. (1988). These units are visible as three-dimensional facies assemblages in the rock record and include, amongst other less commonly used systems tracts the *falling stage systems tract (FSST), lowstand systems tract (LST), transgressive systems tract (TST), highstand systems tract (HST) and the regressive systems tract* (Van Wagoner et al., 1988):

- **FSST:** comprises all the deposits that accumulated subsequent to the onset of a relative sea-level fall and preceding the next sea-level rise. The FSST is the product of a forced regression rather than a normal regression (Posamentier and Allen, 1999).
- **LST:** comprises deposits that accumulate after the onset of relative sea-level rise. The LST directly overlies the upper surfaces of the FSST and is capped by the transgressive surface (Posamentier and Allen, 1999).
- **TST:** includes all deposits that accumulated subsequent to the onset of transgression until the time of maximum transgression, just prior to the renewed regression of the

HST. The TST lies directly on the TRS and is overlain by the MFS (Posamentier and Allen, 1999).

- **HST:** includes the progradational deposits that form when the rate of sediment accumulation exceeds the rate of creation of accommodation space. The HST comprises the uppermost systems tract of any given stratigraphic sequence; overlies the MFS and is in turn capped by the SB (Posamentier and Allen, 1999).

1.8. Regional setting: The KwaZulu-Natal continental shelf

This study is based within two separate survey areas: one on the mid- to outer- continental shelf of northern KwaZulu-Natal and the other on the middle shelf of central KwaZulu-Natal off north-eastern South Africa (Fig. 1.1). These fall within two of the three greater physiographic subdivisions of Goodlad (1986), who partitioned the local continental shelf into three distinct zones: a narrow zone south of Durban, a wider shelf zone between Durban and Cape St. Lucia (i.e. central KwaZulu-Natal), and a third narrow physiographic coastal zone between Cape St. Lucia and Mozambique to the north (i.e. northern KwaZulu-Natal).

1.8.1. The central KwaZulu-Natal continental shelf

1.8.1.1. Coastal and oceanographic settings

Based on Goodlad's (1986) subdivision of the continental shelf of eastern South Africa, the shelf falls into the wider physiographic zone identified between Durban and Cape St Lucia (Fig. 1.4), characterised by a significant broadening of the shelf. Ignoring broadening of the shelf to the north, this tract of continental shelf is considerably steep (Average gradient: ~1°; maximum gradient: ~3.37°) and narrow (8-15 km) when compared to global values (Martin and Flemming, 1988; Green et al., 2012b; Cawthra et al., 2012). Oceanographically the region is dominated by a high-energy wave regime (Smith et al., 2010) and by a strong western boundary current (the Agulhas Current) that is responsible for the sediment starvation that persists throughout the entire south-eastern margin of Africa (Flemming, 1981; Birch, 1996; Lutjeharms, 2006; Green, 2009a). Average spring tidal range is roughly 2 m (Schumann and Orren, 1980), falling into the high microtidal category of Davies (1964) or low mesotidal category of Hayes (1979).

The study area is located offshore of the Durban Bight in central KwaZulu-Natal in South Africa and spans the midshelf from Durban, through Umdloti Beach to Glenashley Beach (Fig. 8). The inner bight is protected from the local high energy wave- and oceanic current-dominated regime by the Bluff Ridge: a 120 m high linear onshore promontory that forms the entrance to the Durban Harbour and shields the adjacent Durban Bight from the dominant SE approaching swells (Flemming, 1981; Martin and Flemming, 1988; Gründlingh and Pearce, 1990; Cooper, 1991b). To landwards, the Bight coastline is bounded by a narrow coastal plain of sandy beaches backed by a steep hinterland.

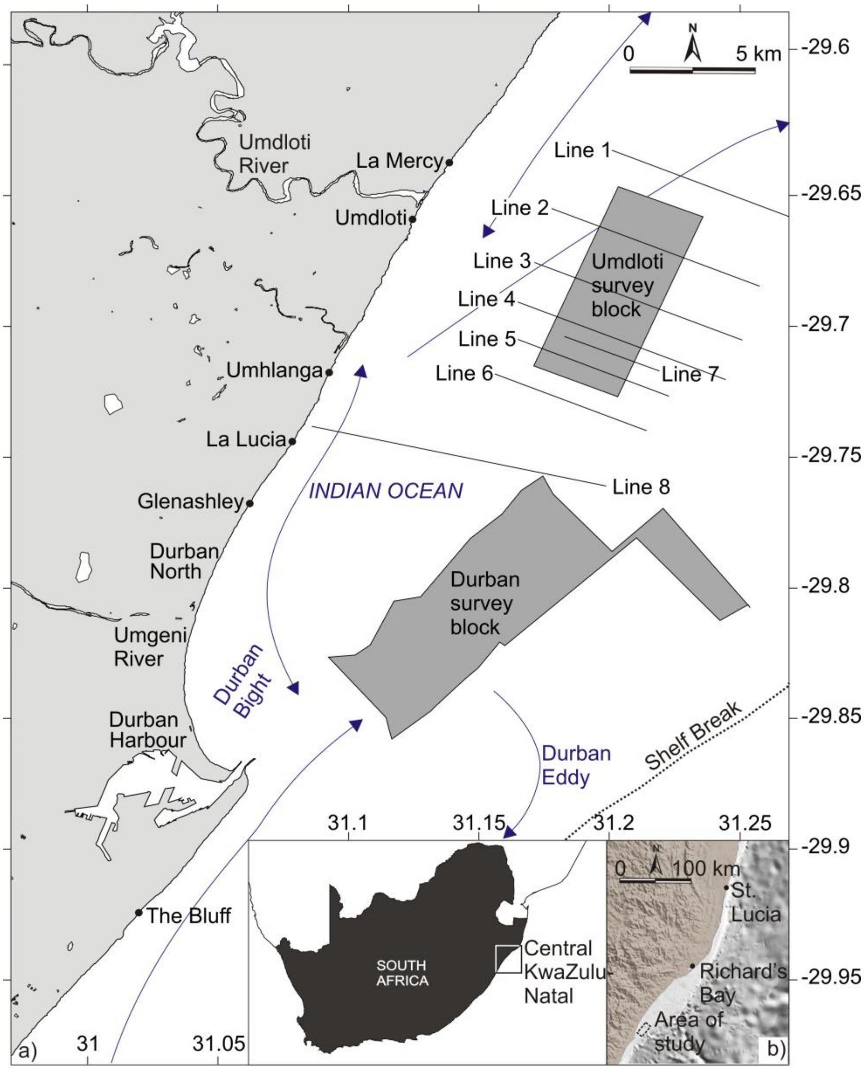

Figure 1.4. Locality map of the central KwaZulu-Natal continental shelf detailing the location of the two bathymetric survey blocks off 1) Umdloti and 2) Durban as well as the location of seismic lines. Blue arrows delineate current paths and eddies on the continental shelf, whilst the blue fonts denote oceanographic features and the dotted line delineates the shelf break. Inset provides the regional context for the study area within the SE African coastline. Co-ordinates are given in decimal degrees.

1.8.1.2. Quaternary lithologies

The shelf comprises an acoustic basement of Cretaceous (generally Lower Santonian to Upper Maastrichtian) aged rocks incised with a number of valley networks formed since early Santonian times (Green and Garlick, 2011; Cawthra et al., 2012; Green et al., 2013b). Overlying this is a number of submerged, coast-parallel, linear ridges or shoals and pronounced changes in slope gradient that have long since been noted on South African shores (Belderson, 1961; Flemming, 1978; Martin and Flemming, 1986, 1987, 1988). These features comprise aeolianites and beachrocks formed within the phreatic zone and represent the cemented cores of drowned barrier shorelines (Ramsay, 1994). These are considered to be Late Pleistocene to Holocene in age (Martin and Flemming, 1988; Bosman et al., 2007). These calcarenite complexes indicate the positions of former minor sea-level stillstands or regression events and are therefore highly useful when reconstructing local relative sea-level curves (Ramsay, 1994; Birch, 1996; Cawthra et al, 2012). These periods of stasis or regression occurred within the greater Flandrian transgression cycle of sea-level rise and their respective deposits are therefore classified as part of the transgressive systems tract (TST) (Green et al., 2012a).

A thin (<20 m) package of unconsolidated Holocene sediment drapes the shelf in the form of a semi-continuous inner- to midshelf wedge (Flemming and Hay, 1988; Birch, 1996). This can be subdivided into a lower transgressive package formed during the early phases of transgression following the Last Glacial Maximum (18 000 yrs BP) separated from an overlying prograding sediment package of modern highstand deposits by a low-amplitude reflector (Green and Garlick, 2011; Green at al., in press). Remnant submerged ridges act as barriers to the offshore and alongshore migration of Holocene sediments, causing sediments to pool on the landward margins of barriers (Flemming, 1981; Birch, 1996).

1.8.1.3. Seismic Stratigraphy

Two previous seismic stratigraphic frameworks have been proposed for the Durban Bight area by Green and Garlick (2011) and Green et al. (2013b). These subdivide the seismic stratigraphy into seismic units A-L based on internal reflector configurations and bounding unconformities (Green and Garlick, 2011, Green et al., 2013b) (Table 1). Of direct interest to the present study are seismic units J, K and L which represent deposits formed within the recent TST and current HST.

Table 1. Established sequence stratigraphy for the central KwaZulu-Natal continental margin based on the previous work of Green and Garlick (2011), Cawthra et al. (2012) and Green et al. (2013b). Simplified descriptions of seismic units, respective lithologies, seismic expressions, ages and interpreted environments of formation are presented.

Seismic Unit	Sub-unit	Underlying surface	Seismic Unit (current study)	Lithology	Seismic expression	Interpreted environment	Age
L	L2	Holocene ravinement surface	U5	Unconsolidated fine sand with minor bioclastics	Low amplitude, weakly layered, small prograding packages; downlap and onlap SB3; separated by flooding unconformities	Holocene inner-shelf wedge	Holocene to Present
	L1	SB3	U1	Unsampled (assumption: typical incised valley fill fines)	Moderate amplitude, chaotic onlapping and lateral accretion fills	Incised valley fill	Late Pleistocene-Early Holocene
SB3				Entire shelf prominent reflector	Undulating, deeply incised surface; erosionally truncates B, J and K; flat interfluves		LGM
J-K		Multiple diachronous surfaces	U2	Quartzitic to shelly sandstone with carbonate cement; only partially sampled	Very high amplitude, unrecognisable reflectors; rugged appearance; welded onto underlying units; stranded outcrops on inner- to outer- shelf	Palaeo-coastlines	Holocene (e.g. Cawthra et al., 2012; Bosman, 2012)
	J1		U3	Unsampled (assumption: typical incised valley fill fines)	Low amplitude drapes within saddles of Unit J	Back-barrier fill	Early Pleistocene-Holocene
F-I		Regional basal surface of forced regression		Very poorly lithified intercalated siltstone and sandstone	Moderate amplitude aggradational/ progradational reflectors; onlap SB	Lowstand shelf edge delta	Latest Pliocene
					Moderate amplitude, chaotic onlapping fills and lateral accretion fills	Isolated incised valley fills	Latest Pliocene
Major hiatus spanning the majority of the Tertiary							

SB2				Entire shelf-prominent reflector	Undulating, non-dipping incised surface; erosionally truncates A, B and C		K/T boundary
E		Maximum surface of forced regression		?	Moderate to high amplitude; parallel to oblique parallel; highly continuous, shallowly SE dipping; downlap MSFR	Outer shelf to shelf edge; deeper marine	Late Maastrichtian
D				?	High opacity, progradational unit	Deep marine	?
C		Subaerial unconformity		?	High amplitude; prograding to parallel to subparallel reflectors; downlap MFS; shallowly SE dipping	Inner shelf to littoral zone	Late Campanian
B	B1-B5	SB1		?	Moderate amplitude; parallel to aggrading subparallel reflectors; highly continuous; shallowly SE dipping	Outer to mid- shelf progradational sequence	Early Santonian
SB1				Mid- to outer- shelf prominent reflector	Shallowly SE dipping, undulating surface; erosionally truncates Unit A		Early Santonian
A				?	Chaotic	n/a	Permian

Units J and K possess strongly chaotic, discontinuous, high-amplitude internal reflectors with rough upper surfaces and a tendency to overlie the SB. These units acoustically mask all underlying strata and are presumed to have formed during periods of minor stasis/regression within the overall transgressive period following the last glacial maximum LGM and which formed the subaerial unconformity SB3 (Green et al., 2013b). Units J and K equate to the calcarenite complexes that predominate the seafloor morphology of the region and routinely crop out at the sea floor (Ramsay, 1994; Bosman et al., 2007). Depressions to landward of the barriers tend to house clay-rich back-barrier deposits interpreted as lagoonal fill (Green and Garlick, 2011).

The uppermost stratigraphic unit is the unconsolidated Unit L which can be subdivided into two facies, both of which are assigned a Late Pleistocene to Holocene age. The lower Facies L1 is located within incised valleys of LGM age, whilst the upper Facies L2 comprises moderate-amplitude, laterally discontinuous reflectors in the form of a shore-attached wedge. This wedge broadly mantles the sea floor except where the Cretaceous basement or cemented calcarenite complexes crop out at the sea floor.

1.8.2. The northern KwaZulu-Natal continental shelf

The northern KwaZulu-Natal shelf (Fig. 1.5) is considered narrow and steep in the global context, ranging in width from 2-4 km with an average gradient of ~2.7° (Martin and Flemming, 1988; Ramsay, 1994). By comparison, the global average shelf width and depth have been estimated at approximately 75 km and 0.116°, respectively (Shepard, 1963). A shallow shelf break at -100 m (Green, 2009a) forms the boundary between very steeply dipping upper slope sediments and relatively flat lying deposits on the shelf (Green, 2011b). The northern KwaZulu-Natal shelf is characterised not only by its narrow width and steep gradients, but also by the presence of a number of coral reefs, large-scale subaqueous dunes and rough, linear shoals (Martin and Flemming, 1988; Ramsay, 1994). These shoal features comprise beachrocks and aeolianites that formed as barrier shorelines through the calcareous cementation of sands within the phreatic zone. Early observations by Ramsay (1994) noted that the surface expression of these barrier shorelines or shoals occurs at depths of 15 to 25 m; 13 to 45 m; 50 to 60 m; and 70 to 95 m. Later examinations by Green (2011b) revealed that the majority of the middle to upper shorelines are submerged beneath unconsolidated Holocene sediments that form the contemporary highstand sediment wedge (Green, 2011b). These barrier cordons are in places partially or fully eroded when intercepted by topographic hollows or indentations in the shelf. This occurs most prominently in the vicinity of the five shelf-indenting canyons, which include from north to south: Mabibi, Sodwana, Diepgat, Leadsman and Leven Canyons (Fig. 1.5).

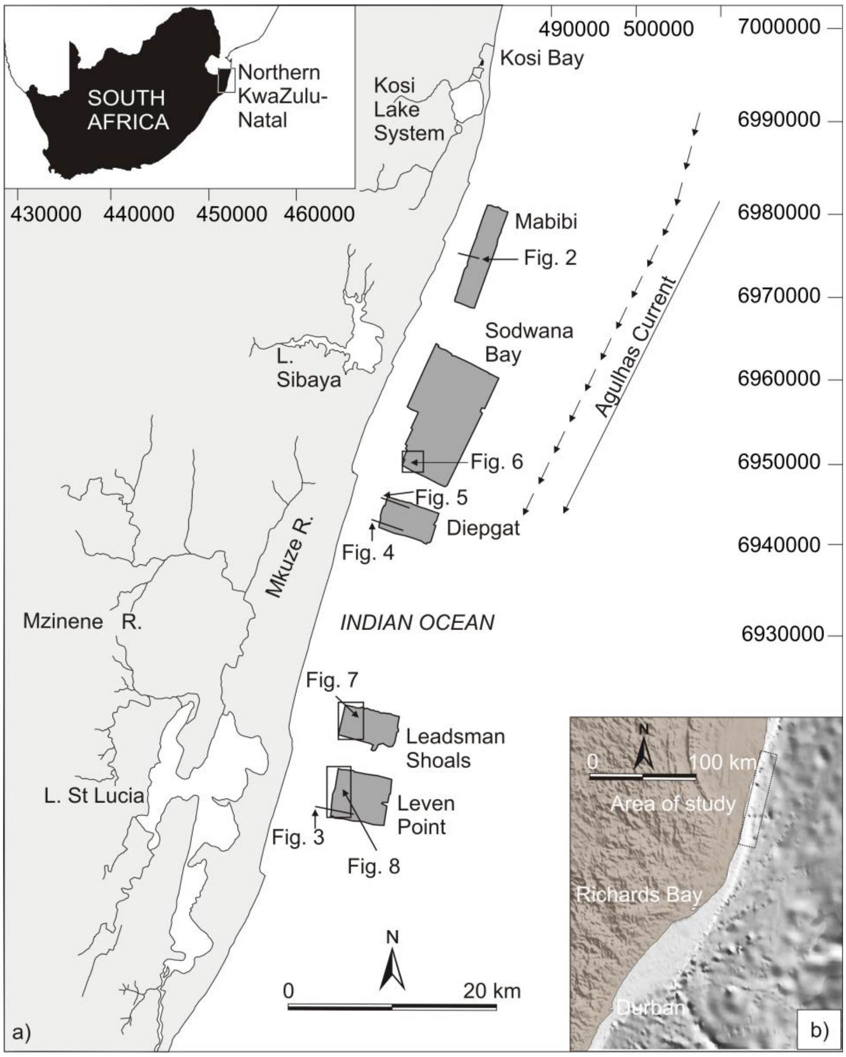

Figure 1.5. Locality map of the northern KwaZulu-Natal study area between Lake St. Lucia and the Kosi Lake system (a). The outlined grey blocks denote areas of multibeam coverage in conjunction with seismic sections and corresponding figure numbers. Northings and eastings are in metres, UTM zone 36S. Inset (b) depicts the shelf break delineated by the -100 m isobath off the KwaZulu-Natal continental shelf derived from the GEBCO dataset. Note the narrow and steep nature of the shelf in the study area (dashed box).

The northern KwaZulu-Natal study area is subject to a high wave energy regime. The wave climate is dominated by long period southerly swell with a subsidiary north-easterly component (HRU, 1968) with significant wave heights for the nearby Richards Bay area averaging 1.59 m (Moes and Rossouw, 2008). The average spring tidal range and the maximum tidal height are 1.84 m and 2.47 m, respectively (Smith et al., 2010), thus falling into the low mesotidal category of Hayes (1979). As a result of its narrowness, the shelf is dominated by the strong poleward flowing Agulhas Current, the core of which overlaps the outer shelf (Flemming, 1981; Green, 2009a). The predominantly sediment starved character of the continental shelf is attributed to this phenomenon (Flemming, 1981; Green, 2009b).

1.8.2.1. Seismic stratigraphy

Green (2011b) provided a sequence stratigraphic framework for the shelf and upper slope comprising several seismic units (A-H) (Table 2). Of these units, only F and G represented Holocene aged deposits. Unit H corresponded to the shoreline complexes identified by Ramsay (1994). These were considered to have formed during stillstands superimposed on an overall regression as sea levels approached the last glacial maximum (LGM) of 18 ka (Ramsay, 1994). However, recent studies by Green et al. (2013a) and Cawthra et al. (2012) consider these to be Holocene in age. Unit G comprises the modern sediment drape which Green (2009b) interpreted as comprising two discrete units; a lower transgressive package and an upper package forming the post-Holocene transgressive ravinement drape. This thesis focuses in detail on these units and their geomorphology.

Table 2. General seismic stratigraphy of the northern KwaZulu-Natal continental margin (simplified from Green, 2011b). The seismic units F and G of Green (2011b) are of direct relevance to this study and correspond to Units 1 and 3 respectively. Unit 2 was not previously recognised.

Seismic Unit	**Sub-unit**	**Underlying Surface**	**Lithology**	**Seismic expression**	**Interpreted environment**	**Age**	**Seismic Unit (this study)**
G	G1	Wave ravinement surface	Unconsolidated fine sand with minor bioclastics	Low-amplitude, low-angle seaward dipping parallel reflectors	Holocene shore-attached wedge	Holocene	Unit 3
	G2	Subaerial unconformity	Unsampled (assumed typical incised valley fill fines)	Onlapping drape fill	Incised valley Fill	Late Pleistocene-Early Holocene	N/a
F		Multiple diachronous surfaces	Quartzitic to shelly sandstone with carbonate cement	Isolated outcrops dispersed from inner to outer shelf	Shoreline deposits	Holocene (e.g. Cawthra et al., 2012)	Unit 1
E		Unknown	Unsampled	High opacity layer	Shoreline deposits	Pleistocene (Shaw, 1998)	N/a
D		Regional basal surface of forced regression	Very poorly lithified silt and sandstone intercalations	High opacity, progradational Unit	Shelf edge wedge	Late Pliocene (Green et al., 2008)	N/a
C		Maximum surface of forced regression	?	Onlapping low amplitude, low continuity reflectors, sheet-like. Not always present	Deeper marine	?	N/a
B		Subaerial unconformity	?	High amplitude oblique parallel–sub parallel clinoforms, high continuity, dip shallowly to SE	Deltaic/ incised valley fill	Middle Maastrichtian (Green, 2011b)	N/a

A		?	?	High amplitude parallel to sub parallel clinoforms, high continuity, dip shallowly to SE, some drape fills	?	Early Maastrichtian (?) (Green, 2011b)	

1.8.3. Quaternary sea-levels in southeastern Africa

Whereas Tertiary sea-levels in South Africa were mainly controlled by tectonic and basin volume changes (tectono-eustacy), Quaternary sea-level changes have been glacio-eustatic in nature and are linked to climatic variations - especially changes in ice volumes in the northern hemisphere (Fig. 1.6) (Tankard et al., 1982; Dawson, 1992; Bradley, 1999; Siegert, 2001; Pillans and Naish, 2004). The melting of icebergs that accompanied the end of the OIS-2 glaciation (~18 000 yrs BP) led to a rise in global sea-levels from as much as 120 m (e.g. Eitner, 1996; Siegert, 2001; Lambeck et al., 2002a; 2002b) to 130 m (e.g. Ramsay and Cooper, 2002).

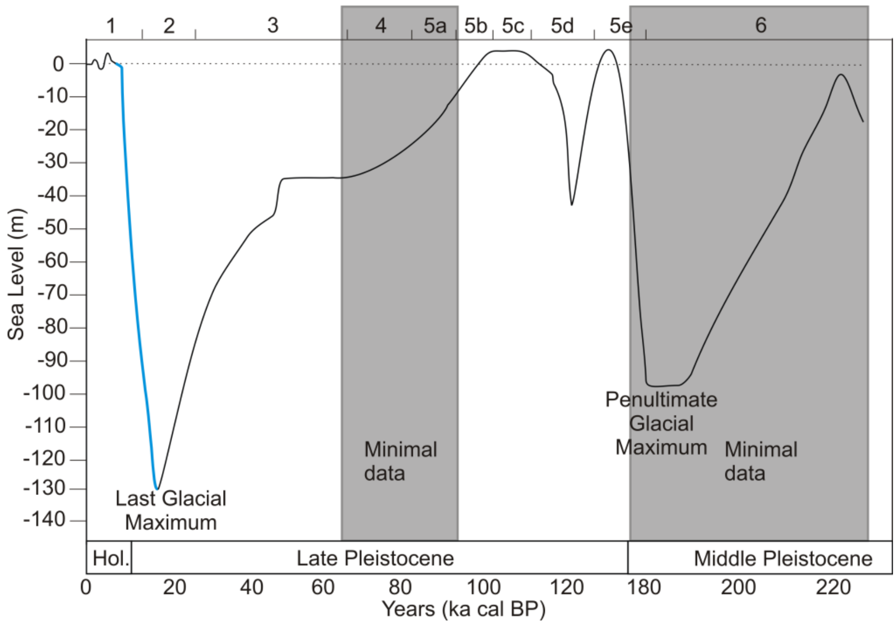

Figure 1.6. Late Pleistocene sea-level curve for the eastern coast of South Africa modified after Ramsay and Cooper (2002). Note the lowstand of -130 m during the LGM followed by the extremely rapid Flandrian transgression (blue line) that ensued during OIS 2 and OIS 1.

On a global scale the Flandrian transgression occurred in a punctuated fashion via several smaller decadal-scale warming events known as Dansgaard-Oescher events, primarily constrained to the northern hemisphere (Bond et al., 1999; Voelker, 2002), and a number of larger high-magnitude meltwater pulse (MWP) events (e.g. Fairbanks, 1989; Bard et al., 1996; Okuno and Nakada, 1999; Liu and Milliman, 2004; Liu et al., 2007). The most pronounced of these is MWP-1A, which spanned depths of between 96-76 m and occurred between 14.3-14.0 ka BP; and MWP-1B during which sea-levels rose from depths of 58-45 m between 11.5-11.2 ka BP (Liu and Milliman, 2004). These correspond with rates of transgression of roughly 60 mm a^{-1} and 43.3 mm a^{-1} respectively (Fig. 1.7.).

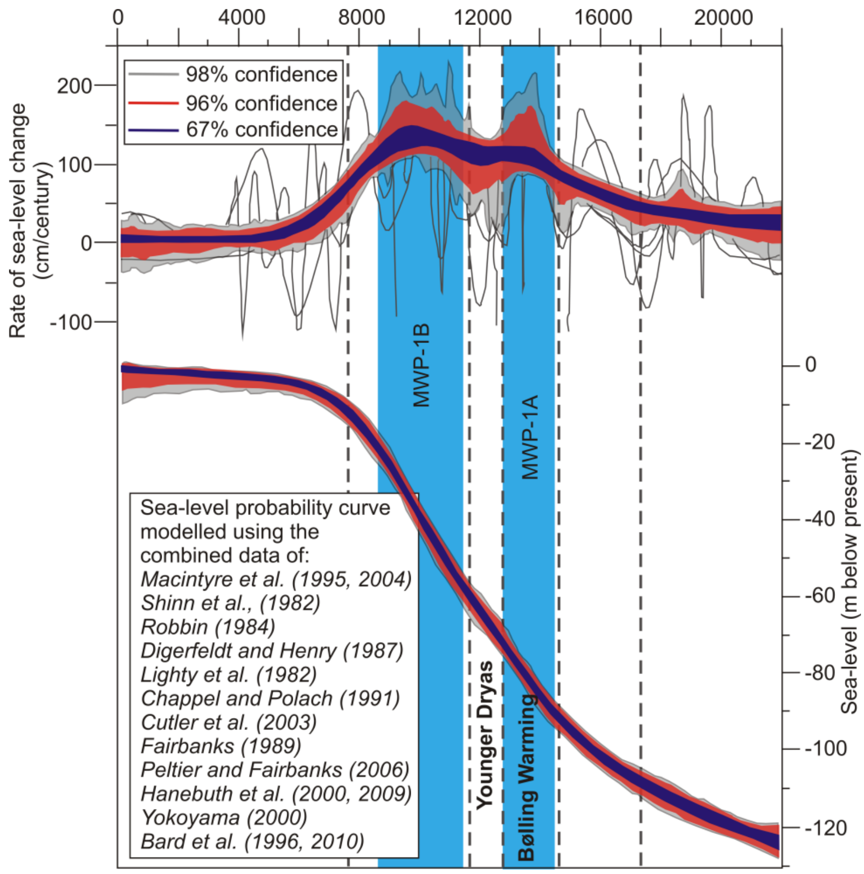

Figure 1.7. Eustatic sea-level curve reconstructed by Stanford et al. (2011) using Monte Carlo simulations and the compiled data of multiple authors (see inset). The lower curve shows sea-level history since just before the LGM until present; the upper curve depicts the first derivative (i.e. the rate) of sea-level change.

These meltwater pulses were interspersed with colder climatic periods of slow or static sea-level known as slowstands (e.g. Kelley et al., 2010) and stillstands. A slowstand associated with the Younger Dryas event occurred from ~12.7-11.6 ka BP in which the rates of RSL rise were notably diminished (Fig. 1.7) (Camoin et al., 2004; Stanford et al., 2011).

In South Africa, the Flandrian transgression occurred between 18 000 and 9 000 yrs BP and caused much of the exposed shelf sands to be eroded before sea level stabilised at its present level between 7 000 to 6 000 yrs BP (Ramsay and Cooper, 2002) (Fig. 1.8). Sea level then rose to +2.75 m for a duration of 2 500 yrs before reaching the mid-Holocene high (mHH) sea-level of +3.5 m approximately 4 500 yrs BP (Ramsay, 1995, 1997). Sea level subsequently subsided to -2 m by ~ 2 000 yrs BP before rising once more to + 1.5 m around 1 610 yrs BP (Ramsay and Cooper, 2002). Finally, the sea level reached its current level approximately 900 yrs ago and appears to be slowly rising as deglaciation continues (Ramsay, 1995; Cooper, 2002)

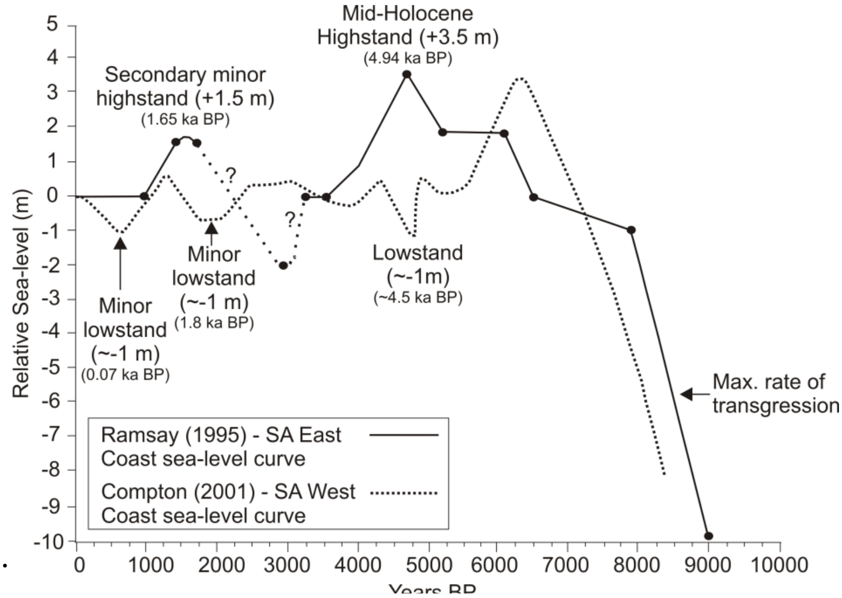

Figure 1.8. Holocene sea-level curve for South Africa adapted from Ramsay (1995) for the east coast and Compton (2001) for the west coast of South Africa. Holocene sea-levels along the East Coast have remained near the present mean sea level with highstands of approximately +2.5, +3.5 and +1.5 m above the present. These were interspersed with a minor lowstand of up to -2 m.

CHAPTER 2

2.1. Seafloor morphology and shallow stratigraphy offshore the Durban area

This chapter presents the results of a seismic and multibeam bathymetric survey that was conducted in order to examine the shallow subsurface architecture and bathymetric expression of the mid-shelf offshore the Durban to Umdloti region. These data are compared to contemporary geomorphic and sedimentological facets of the modern coast in an attempt to correlate offshore morphology and seismic stratigraphic signatures with modern-day features.

2.2. Methods

The seafloor morphology of the mid-shelf offshore Durban to Umdloti was mapped using a Furuno 160-KHz WMB-160F multibeam echo-sounding system. A total of 80 km^2 of bathymetric data were obtained in two separate survey blocks spanning depths of between 28 and 78 m. A Furuno SC30 system provided positions and attitude estimations and corrections were made for tidal variations and variation of sound velocity in the water column.

In order to assess subsurface structure, 100 line km worth of shallow penetration, single-channel seismic data were obtained using a GeoAcoustics Boomer System with a 20-element hydrophone array. A constant power supply of 175 J was utilised for the duration of the survey. Positioning was acquired using a DGPS system capable of sub-metre accuracy. Processing of the raw data involved bandpass filtering (300-1200 Hz), the application of time-varied gains, manual seabed tracking and swell filtering. Sound velocity estimates of 1500 ms^{-1} in water and 1600 ms^{-1} in sediment were applied for all time-depth conversions. All data were finally adjusted for streamer layback and antennae offset.

2.3. Results

2.3.1. Seismic stratigraphy

For a summary of sequence stratigraphic observations and interpretations see the table in Appendix I.

2.3.1.1. Sequence boundary (SB)

This surface occurs as a rugged, high amplitude reflector that truncates steeply-dipping strata within Cretaceous deposits and is ubiquitous across the mid-shelf (Fig. 2.5a). Cretaceous strata are regarded as the *acoustic basement* for the purposes of this study as they form the lowermost and most easily resolvable seismic facies recognised as underlying all seismic lines within the survey area. The high amplitude reflector truncating Cretaceous strata forms multiple incisions into the seismic basement in the form of incised valleys and underlies the TST stratigraphies. Only rarely does this reflector intersect the seafloor. Where it does, this occurs along portions of the mid- to outer shelf (Fig. 2.4c).

2.3.1.2. Unit 1

Unit 1 comprises moderate-amplitude, chaotic, draped reflectors situated within incised valleys onlapping onto the valley walls (Fig. 2.6b) (Figs. 2.1-2.8). Its topmost reflectors are truncated by a low-amplitude, sub-horizontal surface (Fig. 2.3a). Unit 1 forms the lowermost and oldest unit of interest. Such incised valley fills are pervasive throughout the study area and can reach dimensions of over 26 m in valley relief and 1 660 m in width (Fig. 2.6).

2.3.1.3. Unit 2

Unit 2 consists of high-relief pinnacles and ridges comprising high-amplitude reflectors coupled with strong acoustic impedance. Acoustic masking of the underlying stratigraphy is common beneath these features (Figs. 2.1-2.9). Unit 2 takes the form of a series of continuous shore-parallel ridges that are oriented NE-SW, spanning the entire length of the study area. The base of Unit 2 is situated at a consistent depth of ~60 m. Unit 2 has a maximum thickness of 14 m and a maximum width of 2 km. This corresponds with a distinct nick point in the shelf that marks the transition between a lower gradient inner shelf towards a steeper mid- to outer shelf. It is bounded on its lower margin by the SB or by the surface that caps incised valley fills, whilst its upper surface is bounded by a prominent high-amplitude, highly reflective surface (Fig. 2.1a). Unit 2 crops out frequently at the sea floor and is also evident in the multibeam bathymetry dataset offshore of both Durban and Umdloti (Figs. 2.10 and2.11).

2.3.1.4. Unit 3

Unit 3 takes the form of thin (less than 4 m thick) lens-like packages of low-amplitude reflectors of low continuity that onlap the landward edge of Unit 2 and occur within shallow depressions of the SB (Figs. 2.4-2.6; 2.11). Packages of Unit 3 are separated from underlying

Cretaceous units and valley fills by either the SB or by the incised valley fill truncation surface, respectively.

2.3.1.5. Unit 4:

2.3.1.5.1. Unit 4.1

Unit 2 is frequently bounded on its landward margin by an acoustically semi-opaque unit comprising low- to moderate amplitude chaotic reflectors (Unit 4.1). This unit takes the form of a landward pinching wedge that onlaps the landward edge of Unit 2 (Figs. 2.1-2.8) and is ubiquitous throughout the study area. In the central Umdloti area, the same unit can likewise be found onlapping the seaward margin of Unit 2 (Figs. 2.2-2.8). Reflectors display an onlapping relationship with the adjacent Unit 2 and downlapping relationship with the underlying SB, and are themselves capped by the wRS (Fig. 2.1b). Despite their thin nature, deposits of U4.1 can reach up to widths of 4 km along dip.

2.3.1.5.2. Unit 4.2

A further subdivision of Unit 4 (Unit 4.2) may be distinguished at sporadic intervals and as isolated inclusions within the seaward portions of Unit 4 (Figs. 2.2b, 2.4b, 2.7). This facies is distinguished by a highly reflective uppermost surface, whilst internal reflectors appear extremely chaotic, with parabolic forms in the reflector package that mask the underlying units. Occurrences of Unit 4.2 overlie the Cretaceous surface (SB) or incised valley fills (wRS). Only three localities of Unit 4.2 were noted in the study area, each of which was no more than 4.5 m thick and extended up to 500 m down-dip in seismic section.

2.3.1.6. Unit 5:

Unit 5 is an unconsolidated package of sediment that spans the study area and has variable thickness (≤10 m thinning laterally) (Figs. 2.1-2.8). It comprises conformable, low amplitude, parallel reflectors. This unit can be subdivided into a lower and upper package by a low-amplitude, conformable reflector.

2.3.1.6.1. Unit 5.1

The lowermost unit (Unit 5.1) takes the form of a thin (≤6 m), shoreward pinching wedge that tends to thicken against the landward margin of Unit 2 where it onlaps (Figs. 2.1-2.8). Deposits are rarely present on the seaward side of Unit 2 (Figs. 2.1 and 2.6).

2.3.1.6.2. Unit 5.2

Unit 5.2 (U5.2) forms the uppermost and youngest unit and is recognised throughout the study area (Figs. 2.1-2.8). It forms a very thin (≤5 m) sedimentary package comprised of parallel reflectors and fill depressions within saddles of Unit 2 (Fig. 2.3). Unit 5.2 blankets the entire shelf, except where Unit 2 or Cretaceous strata crop out near the shelf edge and thus forms the modern seafloor (Fig. 2.4c; Fig. 2.11).

2.3.1.6.3. Unit 5.3

Two isolated, small-scale valleys (≤120 m in width) in the central study area are incised into the lower and upper unconsolidated units (Units 5.1 and 5.2) (Fig. 2.8a).

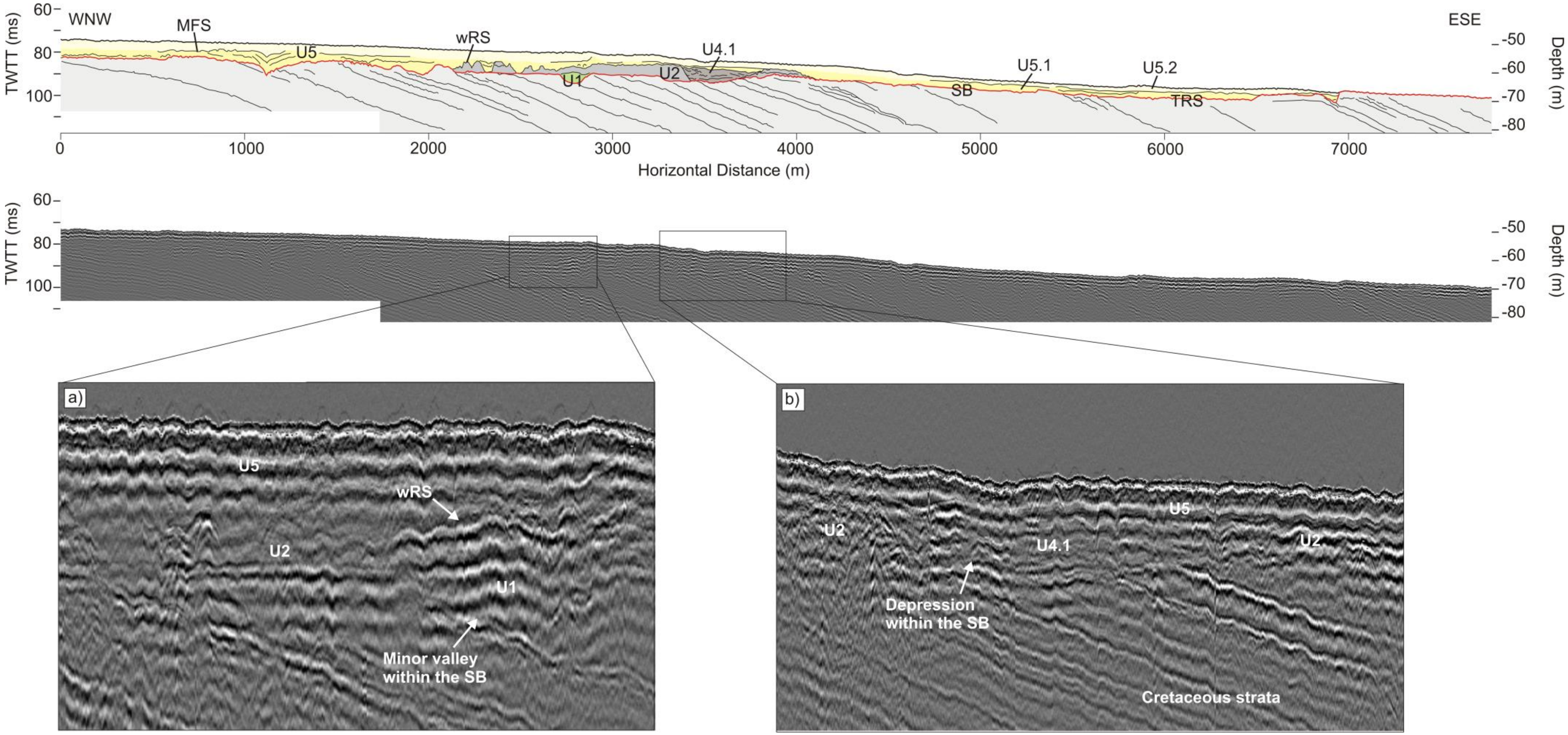

Figure 2.1: Line 1. Shore-perpendicular seismic line and interpretative overlay from the northern Umdloti area (the location of which is depicted in Fig 1.4) showing a well-developed -60 m barrier complex of Unit 2 with U4.1 forming a drape between barrier ridges. Note the thinning of Holocene sediments (yellow) and the exposure of Cretaceous bedrock on the seafloor towards the seaward termination of the seismic line. MFS= maximum flooding surface; SB= sequence boundary; TRS= transgressive ravinement surface; wRS= wave ravinement surface.

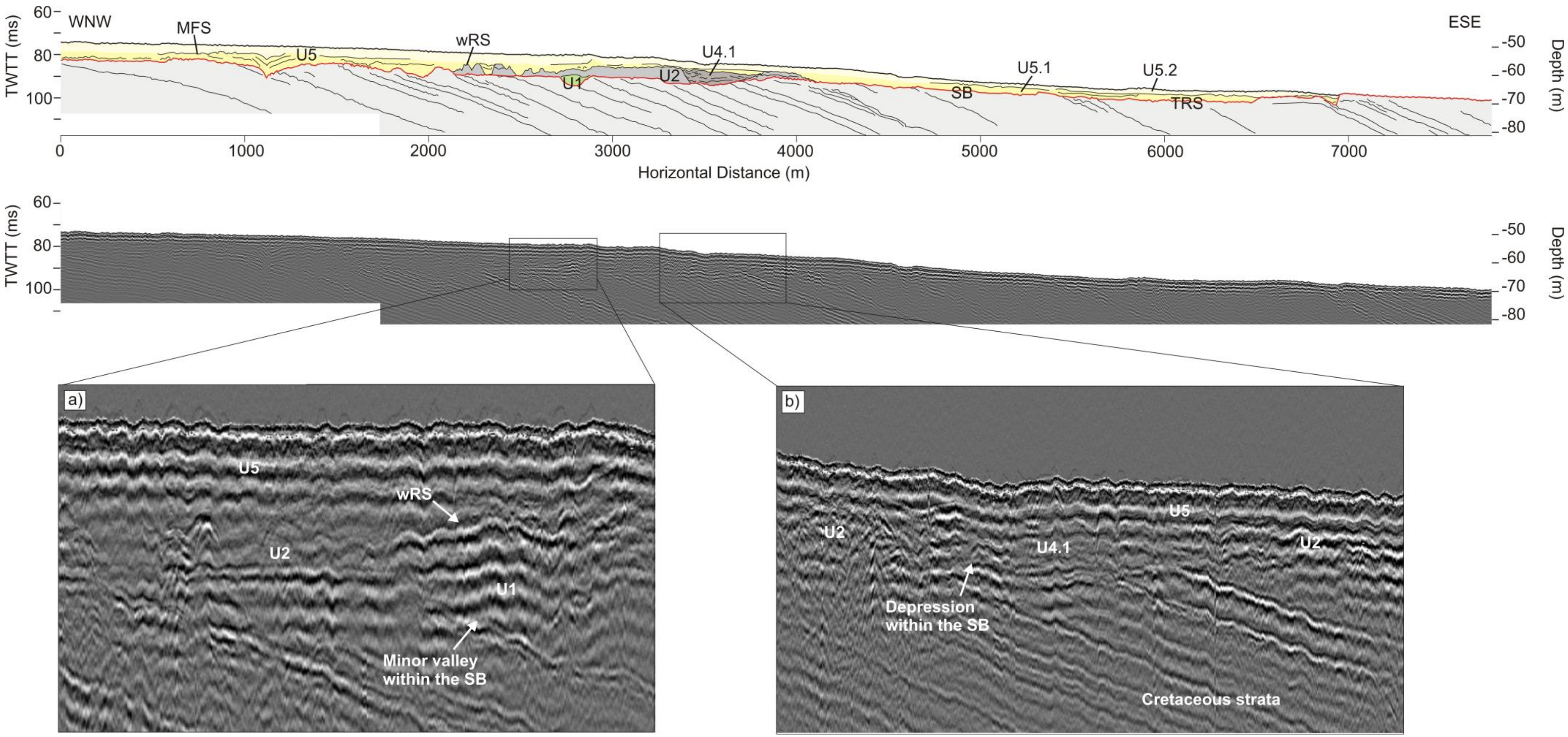

Figure 2.2: Line 2. Shore-perpendicular seismic line and interpretative overlay from the northern Umdloti area (the location of which is depicted in Fig 1.4) showing a well-developed -60 m barrier complex of Unit 2 fronted by a valley (Unit 1) incised into the acoustic basement. Note the damming of unconsolidated sediment in the hinterland of the -60 m barrier as well as the occurrence of the acoustically chaotic U4.2 overlying the incised valley fill. MFS= maximum flooding surface; SB= sequence boundary; wRS= wave ravinement surface; tiRS= tidal ravinement surface.

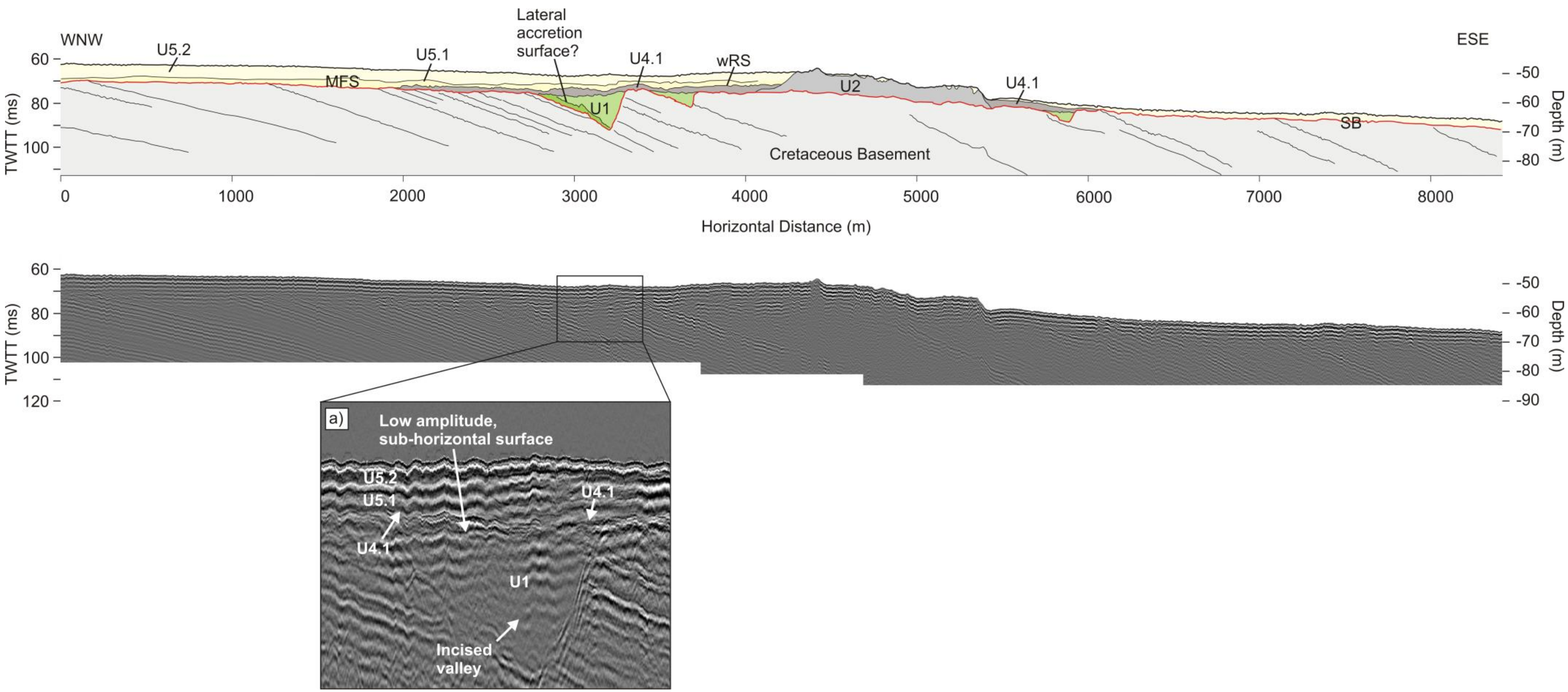

Figure 2.3: Line 3. Shore-perpendicular seismic line and interpretative overlay from the central Umdloti area, the location of which is depicted in Fig 1.4. Unit 5 is almost absent seaward of the barrier whilst Unit 1 incised valleys incise the Cretaceous basement on either side. MFS= maximum flooding surface; SB= sequence boundary; wRS= wave ravinement surface.

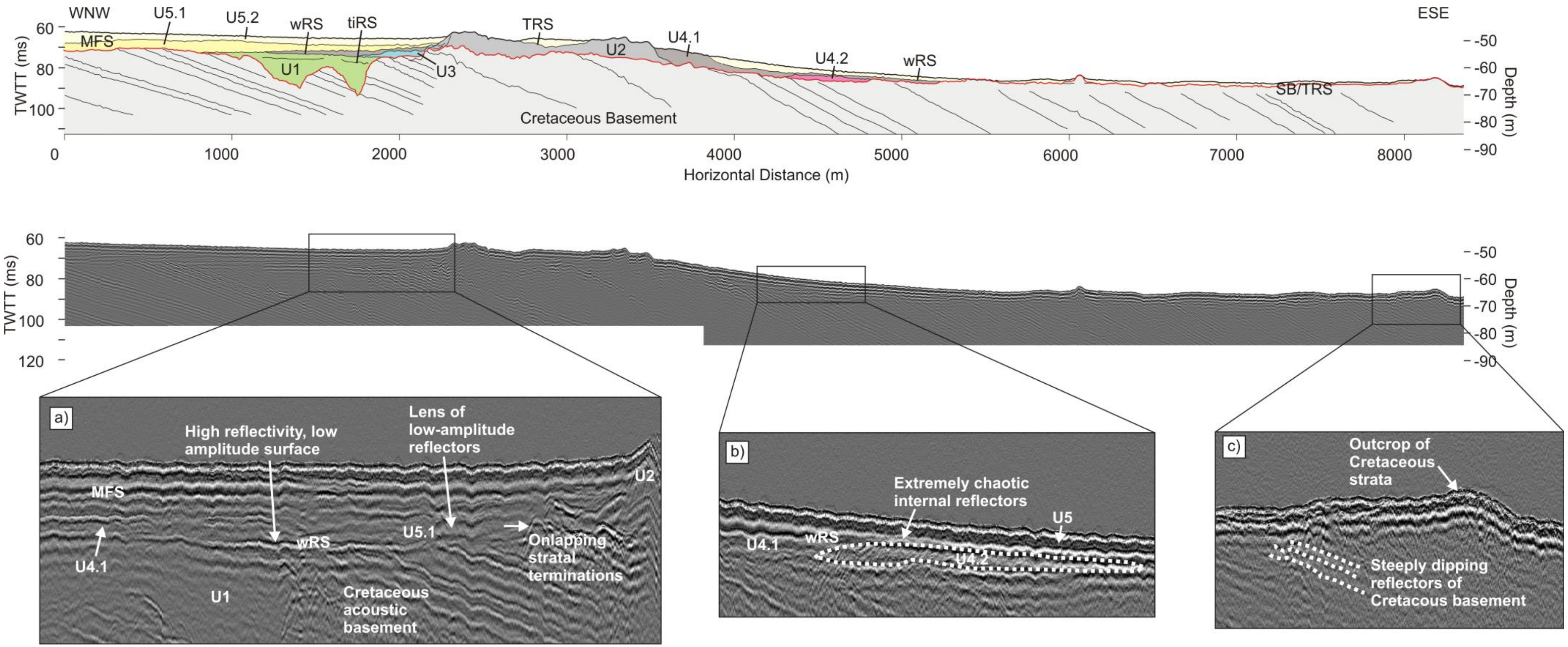

Figure 2.4: Line 4. Shore-perpendicular seismic line and interpretative overlay from the central Umdloti area, the location of which is depicted in Fig 1.4. This depicts a rare occurrence of Unit 3 back-barrier/lagoonal fill (blue) within a depression in the SU. Unit 4.2 (pink) is also present seaward of a double crested barrier complex of Unit 2. MFS= maximum flooding surface; SB= sequence boundary; TRS = transgressive ravinement surface; wRS= wave ravinement surface; tiRS= tidal ravinement surface.

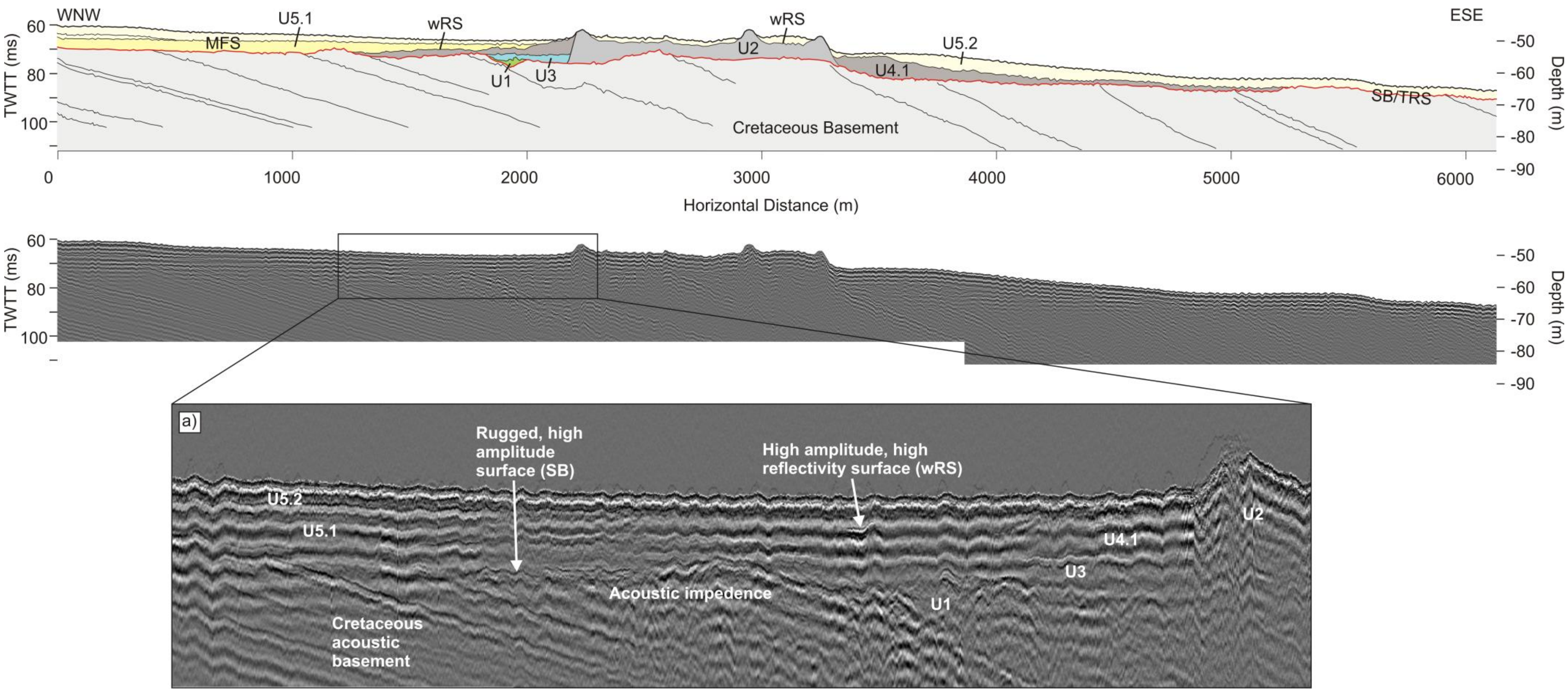

Figure 2.5: Line 5. Shore-perpendicular seismic line and interpretative overlay from the southern Umdloti area, the location of which is depicted in Fig 1.4. Here the -60 m barrier complex of Unit 2 is particularly wide and is bounded in the backshore by a minor incised valley and back-barrier/lagoonal sediments (blue). These are overtopped by the Unit 4.1 calcarenite rubble facies (brown) which pinch away from the barrier complex in either direction. MFS= maximum flooding surface; SB= sequence boundary; TRS= transgressive ravinement surface; wRS= wave ravinement surface.

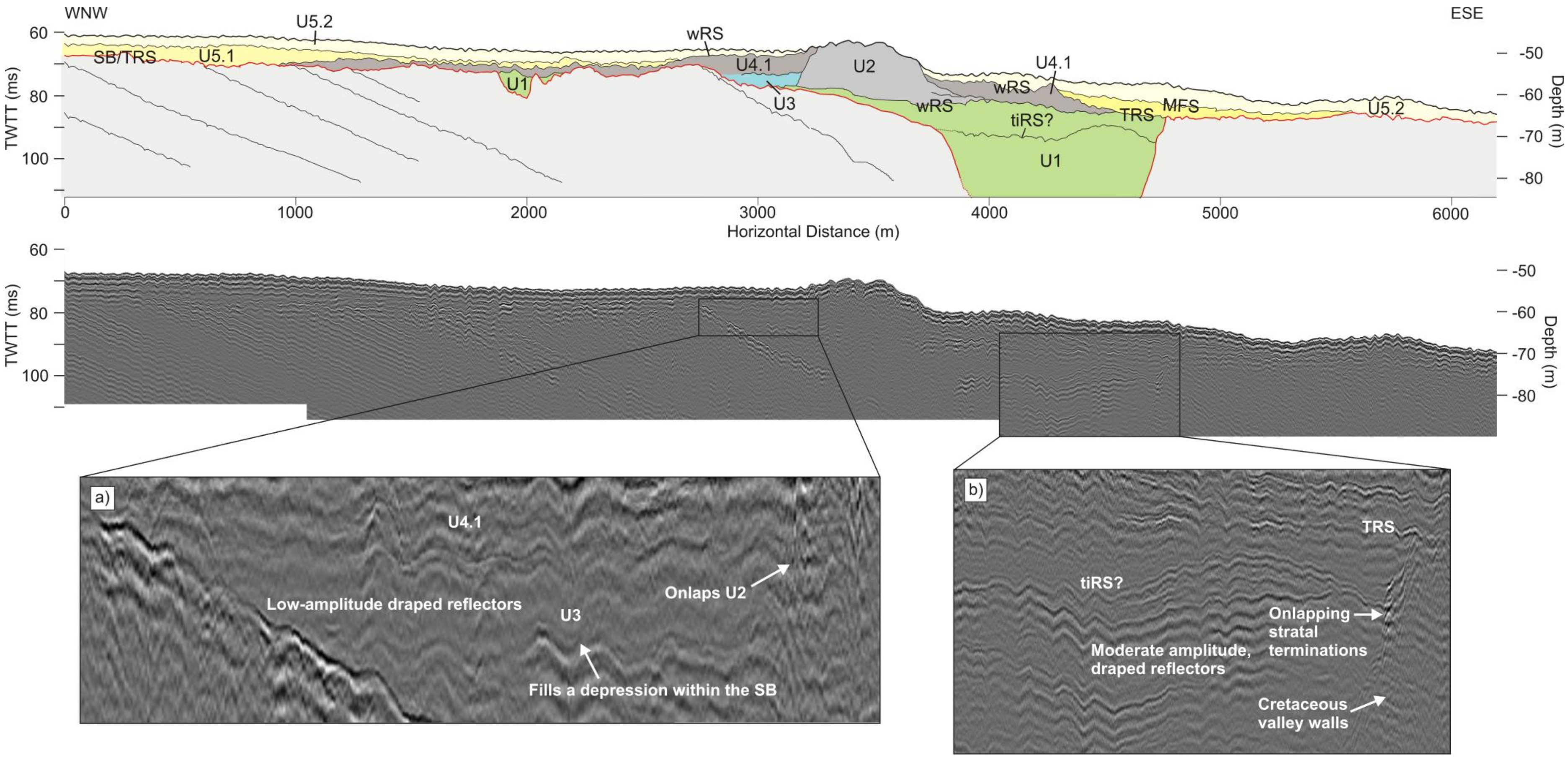

Figure 2.6: Line 6. Shore-perpendicular seismic line and interpretative overlay from the southern Umdloti area, the location of which is depicted in Fig 1.4. A particularly large Unit 1 incised valley exceeding 26 m in depth and 1.6 km in width underlies the Unit 2 barrier in this region. A local deepening in the SB overlying the valley capping causes unconsolidated Holocene sediments (yellow) to be locally thickened in the vicinity. The barrier is also particularly tall (14 m in height) and supports back-barrier deposits (blue) to landward. MFS= maximum flooding surface; SB= sequence boundary; TRS= transgressive ravinement surface; wRS= wave ravinement surface; tiRS= tidal ravinement surface.

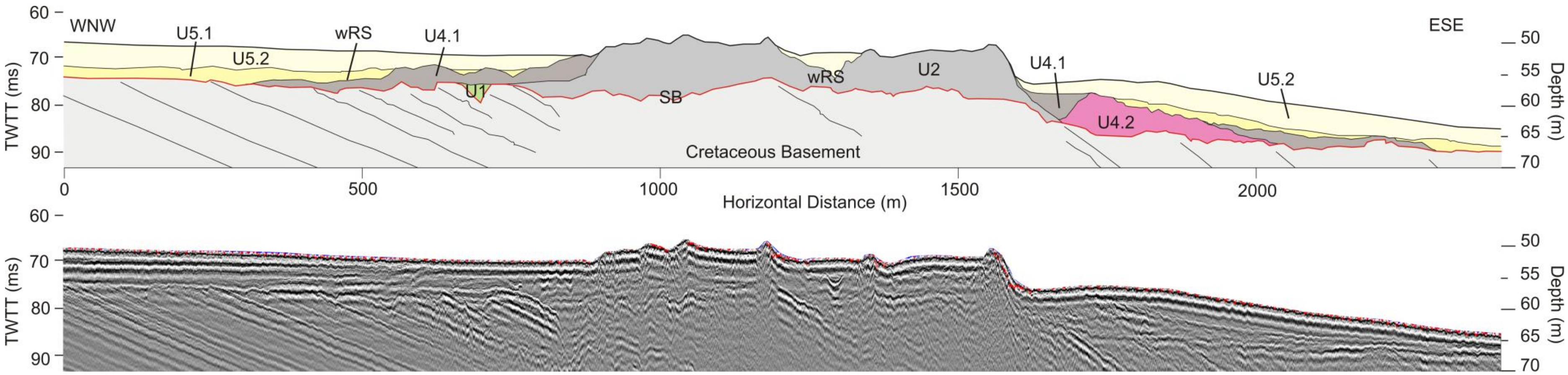

Figure 2.7: Line 7. Shore-perpendicular seismic line and interpretative overlay from the southern Umdloti area, the location of which is depicted in Fig 1.4. Here the Unit 2 barrier complex displays a bifurcating crest and is positioned above a prominent nick point in the shelf. Unit 4.2 (chaotic boulder facies) is locally present. SB= sequence boundary; wRS= wave ravinement surface.

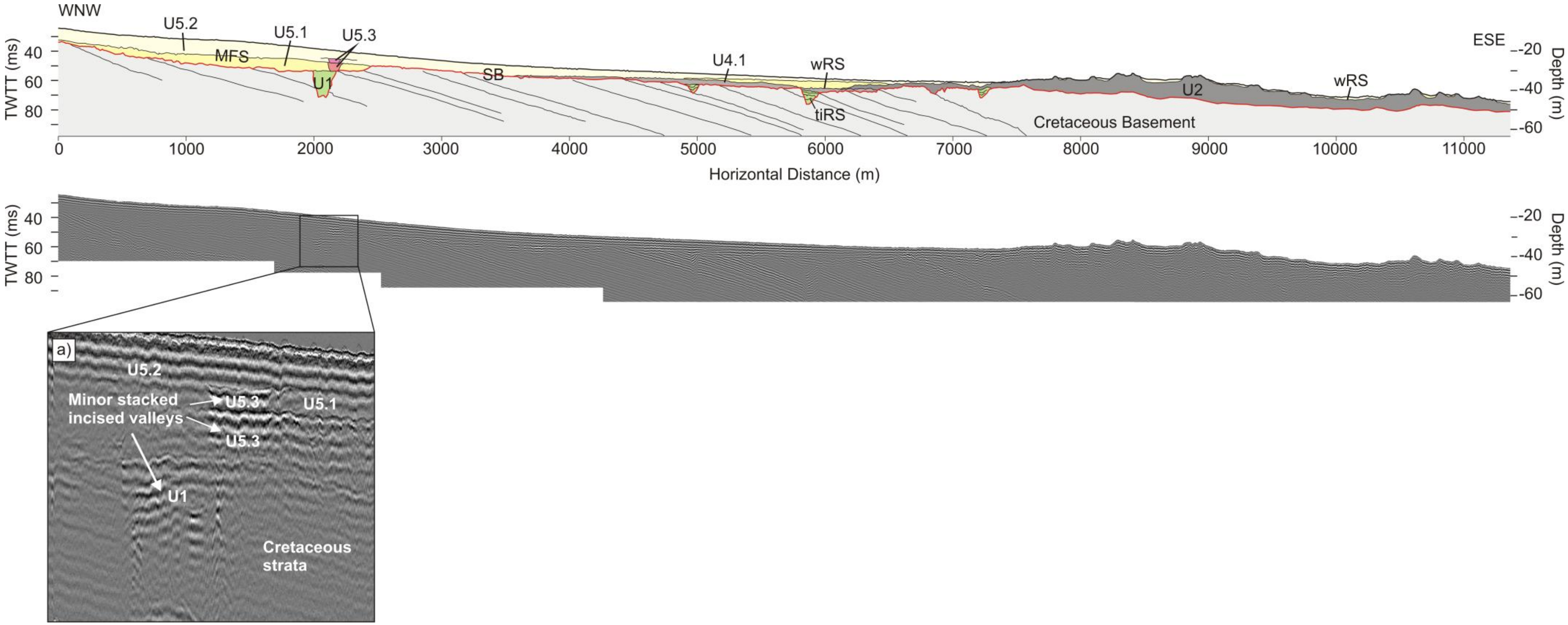

Figure 2.8: Line 8. Shore-perpendicular seismic line and interpretative overlay offshore of La Lucia (seafloor separating the Umdloti and Durban survey blocks as shown in Fig 1.4). The Unit 2 -60 m barrier complex is particularly extensive down-dip and several minor incised valleys are present within the SB up profile. Two vertically stacked incised valleys directly overlie an older incised valley in the SB. MFS= maximum flooding surface; SB= sequence boundary; wRS= wave ravinement surface.

2.3.2. Interpretation of seismic stratigraphy

2.3.2.1. Basal reflector: sequence boundary (SB)

The basal reflector that truncates Cretaceous strata below and separates them from younger, overlying TST and HST stratigraphies is coincident with the surface SB3 of Green et al. (2013b). SB3 is considered to have formed during subaerial exposure of the continental shelf leading up to, and subsequent to, the Last Glacial Maximum (LGM). Disparities exist in the naming of this stratigraphic surface between the central and northern KwaZulu-Natal shelves, with the coeval surface being referred to as a subaerial unconformity in the northern part of the continental shelf.

2.3.2.2. Unit 1: Incised valley fills

Incised valleys within Cretaceous strata and their respective valley fills have been previously documented on the mid-shelf in central KwaZulu-Natal (e.g. Sydow, 1988; Green and Garlick, 2011; Green et al., 2013a) and in northern KwaZulu-Natal (e.g. Green, 2011b). They have been assigned to the late LST and TST with ages spanning the Late Pliocene to latest Pleistocene/Holocene age. The valleys recognised in this study are an extension of those documented by Green et al. (2013b). The strong, sub-horizontal surface truncating valley fills is interpreted as a wRS in accordance with the designations of Dalrymple et al. (1992) and Cattaneo and Steel (2003).

2.3.2.3. Unit 2: Barrier complexes

Unit 2 has been recognised on the continental shelf throughout KwaZulu-Natal. Similar features have been documented from the east coast of South Africa by Flemming (1981), Martin and Flemming (1988), Sydow (1988), Ramsay (1994), Bosman et al. (2007), Green and Garlick (2011), Cawthra et al. (2012) and Green et al (2012a). These “isolated ridge-like features” as described by Green and Garlick (2011) were deposited in the form of coastal dunes and nearshore environments that have subsequently been lithified before subsequent submergence (Martin and Flemming, 1988). The strongly chaotic internal reflector configuration and high degree of acoustic blanking is a typical feature of these calcite-cemented coastal deposits during occupation at or near palaeo-mean sea-level. They thus represent aeolianite/beachrock palaeoshorelines formed during minor stillstands of Late Pleistocene to Holocene age (Martin and Flemming, 1988; Ramsay, 1994; Green et al., 2013a). These resemble modern barrier systems and are accordingly interpreted as submerged barrier complexes. The high-relief upper bounding surface of Unit 2 represents the highly erosive surface formed by wave action (wRS) during transgression over the barrier form.

2.3.2.4. Unit 3: Back-barrier fills

Unit 3 is found within discrete depressions on the landward side of the palaeoshoreline complexes of Unit 2 and possesses the draped, low-amplitude reflectors characteristic of low energy environments. This seismic unit corresponds with the Units J1 and K1 of Green et al. (2013b) who interpreted these deposits as clay-rich back-barrier lagoonal fill on the basis of the draped geometry. Similar deposits were documented in northern KwaZulu-Natal (Chapter 3) onlapping the landward sides of barriers at 100 m and 60 m water depths. Unit 3 is thus considered to have formed in the sheltered back-barrier areas landwards of major barrier complexes that began to form during stillstand conditions (e.g. Green et al., 2013a; Chapter 3), similar to, but on a larger scale than that observed in Figures 2.9a and b.

2.3.2.5. Unit 4: Disaggregated barrier accumulations

2.3.2.5.1. Unit 4.1: Calcarenite rubble facies

The tendency of Unit 4.1 to onlap against the landward and seaward faces of Unit 2 barrier complexes, as well as its propensity to thin laterally away from these barriers, suggests that this unit was deposited after the formation and lithification of the dune cordons against which it abuts. Several onshore calcarenite exposures show evidence for block collapse along the landward edges of these features (Fig. 2.9c). Similarly, blocks that have weathered and collapsed on the seaward margin have been reworked by storms and abut the seaward edges of the calcarenite cordons to form boulder beaches (Figs. 2.9 d, e). The seaward extension of this unit is ascribed to this process. Unit 4.1 thus appears to be a residual deposit of calcarenite (beachrock/aeolianite) rubble derived from the weathering and subsequent reworking of seaward platforms and reefs or from the erosion of the barriers themselves.

Figure 2.9. a) Modern equivalent of a back-barrier setting behind a estuary mouth spit within the Tongati Estuary; **b)** Google Earth image showing an aerial view of the Tongati estuary mouth and bounding back-barrier setting; **c)** Aeolianite features in northern Umdloti showing collapse features on their shoreward margins; **d)** Calcarenite raised shore platform with collapsed blocks at the seaward margin at Isipingo Beach: conditions similar to those that would have led to the development of Unit 4.2 enveloped within Unit 4.1 on the midshelf of central KwaZulu-Natal; **e)** Large storm-reworked boulder accumulations derived from platform remnants on the northern KwaZulu-Natal coast of Mission Rocks. The extremely chaotic acoustic backscatter and parabolic forms of Unit 4.2 offshore of central KwaZulu-Natal are thought to have been created by a similarly coarse and irregular sedimentary package; **f)** Storm reworked boulder accumulations within an alcove at Isipingo Beach,

central KwaZulu-Natal. These are considered to have formed in conditions similar to those having formed Unit 4.2 offshore of central KwaZulu-Natal.

2.3.2.5.2. Unit 4.2: Chaotic boulder facies

Unit 4.2 onlaps the seaward flank of Unit 2 and forms a seaward thinning wedge comprising sporadic and discontinuous chaotic reflectors with small parabolic forms. These suggest high energy conditions (e.g. Nordfjord et al., 2006) that deposited very coarse-grained, loosely packed deposits with a high degree of interstitial void space (e.g. Carter, 1988; Adams and Wesnousky, 1998). In the contemporary coastal setting, storm-deposited boulder beaches that onlap the modern coastal dune cordon are common (Fig. 2.9 e, f) (Salzmann and Green, 2012). These commonly comprise an arrangement of loosely packed, very large boulders (≤5 m in diameter) that overlie shore platforms fronting barriers.

The boulder facies are considered to have formed under the following conditions: boulders were being liberated at the seaward face of a cemented dune that was being undercut by wave action as sea-levels rose and the shoreline was encroached. Cemented blocks were then broken away from the core of the barrier and fell to the platform as collapse features. Storm events acted to rework and reorganise collapsed blocks such that they migrated against the seaward face of the barrier to form an interlocked and stacked pavement of boulders in the form of a *boulder rampart* (Otvos, 2000). The rampart, due to its long relaxation time, exhibited negligible shoreward migration and reworking as sea-levels continued to rise and was fashioned only through the action of extreme swell and storm events of sufficient power to entrain, lift and shuffle blocks within the boulder rampart (e.g. Salzmann and Green, 2012).

2.3.2.6. Unit 5: Unconsolidated Holocene units

Unit 5 coincides with the unconsolidated Holocene sediment prism identified by Birch (1981), Flemming (1981) and Martin and Flemming (1986) and corresponds with similar acoustic units recognised by Green et al. (2012b; 2013a) which they reinterpreted as a progradational highstand wedge formed during the current day HST.

It appears that this package can be further subdivided into lower and upper Holocene unconsolidated sediment packages, Units 5.1 and 5.2 respectively; separated by a weakly reflective reflector which is thought to represent a hiatus in deposition and a change in sedimentation between the TST and the subsequent HST. Supported by observations of retrograding reflectors in the lowermost unit and prograding reflectors in the overlying unit by Green et al. (2012b), it is therefore interpreted as the maximum flooding surface (MFS) as defined by Cattaneo and Steel (2003).

2.3.3. Seafloor morphology

2.3.3.1. Bathymetry of the Umdloti region

A feature comprising outcrop of Unit 2 with a seaward edge situated at -60 m spans the length of the Umdloti study area along strike (9.8 km) (Fig. 2.10). This feature possesses a central ridge of up to 14 m relief that bifurcates, bounded by lower relief outcrop of Unit 2 to landward and by a landward-sloping platform of low gradient (~1.7°) and flat relief to seaward (Fig. 2.10: Cross-sections B and C). The platform is of variable width, widening to a maximum of ~580 m in the northern Umdloti area (Fig. 18: Cross-section A), whilst in the south it is covered by Unit 5 and appears to merge with the core of the main Unit 2 outcrop. The platform terminates in a ledge (~5 m relief) that abruptly deepens toward a flat and featureless seafloor (Fig. 2.10: Cross sections B and C). On the outer shelf, Unit 5 thins such that Cretaceous strata are regularly exposed on the seafloor (Fig. 2.4c; Fig. 2.11).

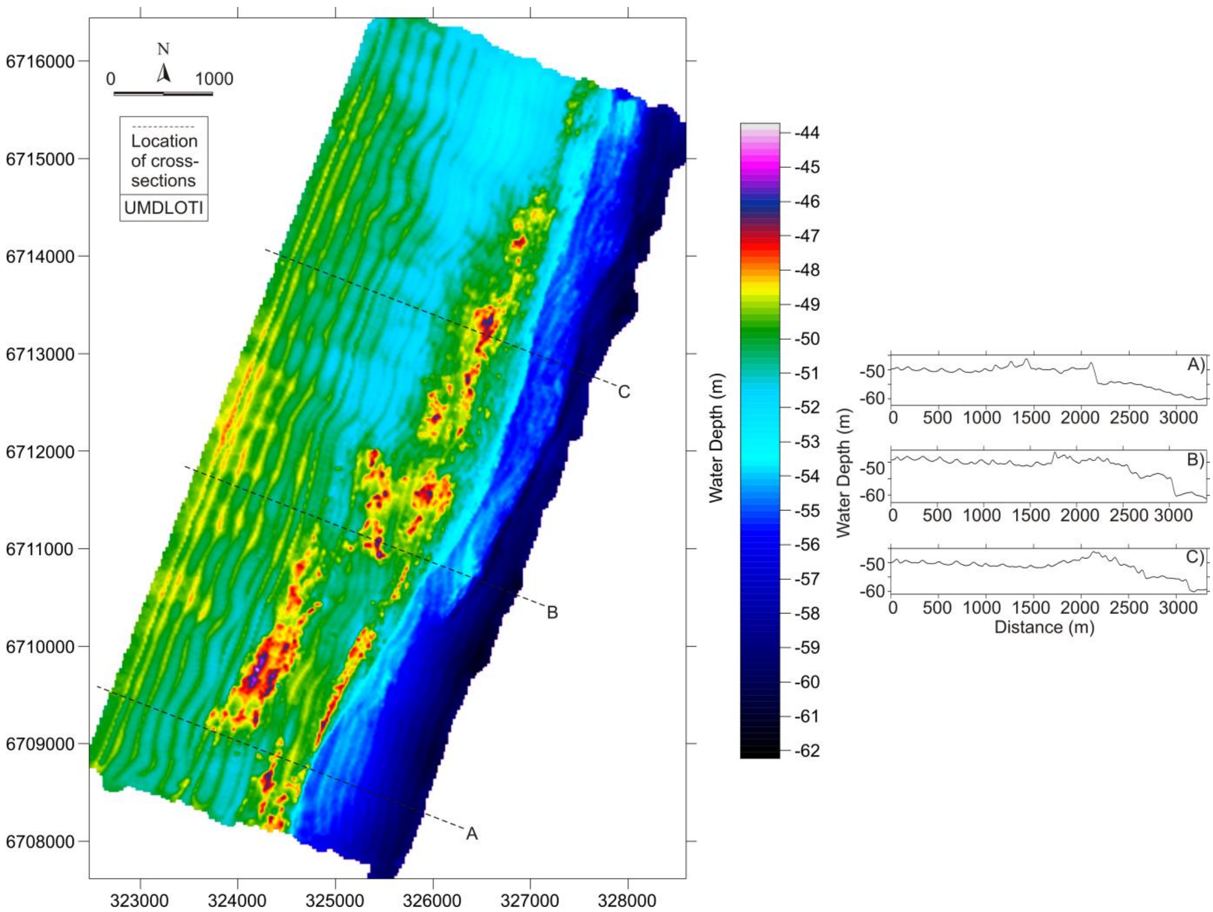

Figure 2.10. Colour-shaded bathymetric image of the mid-shelf inside offshore Umhlanga to La Mercy. The position of the Umdloti survey block with respect to the coastline and adjacent survey areas is provided in Fig. 1.1. Note the presence of the well-developed -60 m outcrop of Unit 2 and hardgrounds cropping out to shorewards of this. A. Topographic profile through the elongate oval; B. Topographic profile intersecting the nothermost edge of the oval depression as well as a number of crests and terraces within the Unit 2 outcrop; C. Topographic profile showing blanketing of seafloor by unconsolidated sediment cover, outcrop of Unit 2 and exposed terraces comprising Unit 2. Northing and eastings are in metres, UTM zone 36 S.

Landward of the -60 m Unit 2 outcrop, the seafloor is punctuated with isolated outcrop of lower relief Unit 2, termed hardgrounds following the usage of Schroeder et al. (1988) and Gardner et al. (2005; 2007). Also present, as confirmed by seismic data (Fig. 2.10: Cross-sections A and B; Fig. 2.11), is an elongate oval shaped depression in the backshore of the Unit 2 outcrop at -60 m within the southern extremity of the Umdloti survey block.

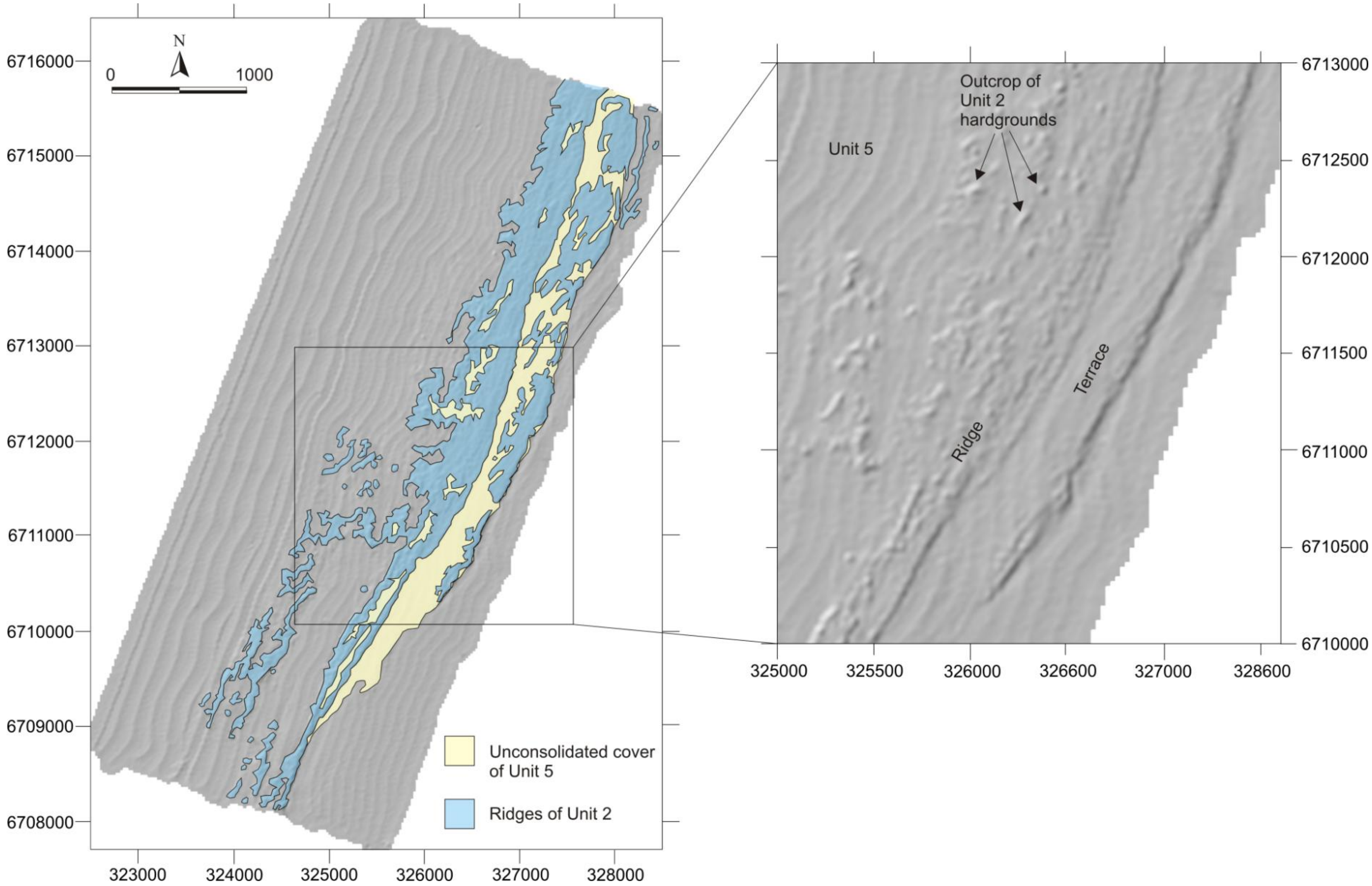

Figure 2.11. Sunshaded bathymetric image of the Umdloti study region with interpretative overlays. Northing and eastings are in metres, UTM zone 36 S. The location of the Umdloti study region is provided in Fig. 1.1 where it is depicted by the northern block within the Central KwaZulu-Natal study region. The northernmost and southernmost extent of the survey area are delimited by La Mercy and Umhlanga onshore, respectively.

2.3.3.2. Bathymetry of the Durban region

The Durban area to the south is likewise dominated by the presence of a laterally continuous, shore-parallel, linear ridge that crops out over a distance of >5 km (Fig. 2.12). This high-relief (~10 m) feature has a seaward edge at approximately 65 m depth, is relatively narrow in width (<100 m) and is fronted on its seaward margin by a shallow gully-like depression (≤2 m deep), similar to the *moats* of Gardner et al. (2005) (Fig. 2.13). The barrier itself flattens towards the north into a near featureless seafloor where it is distinguishable only as a nick point in the shelf gradient (Fig. 2.12: Cross-section F). Landwards of this barrier, a set of semi-circular enclosures bounded by high-relief ridges are present. Green et al (2013b) discuss these in detail and found them to be low-relief depressions no more than 2.5 m in depth and approximately 50 m in width.

Lastly, a broad exposure of hardground comprising rugged outcrop of Unit 2 spans the majority of the shallower seafloor in the Durban area. Here the cover of Unit 5 is so thin that multiple parabolic/arcuate shaped protrusions within Unit 2 crop out at the sea floor (Fig. 2.13) at depths of between 30-50 m. These features are ≤500 m wide, have a relief of up to 8 m above the seafloor and their long axes are orientated NE-SW.

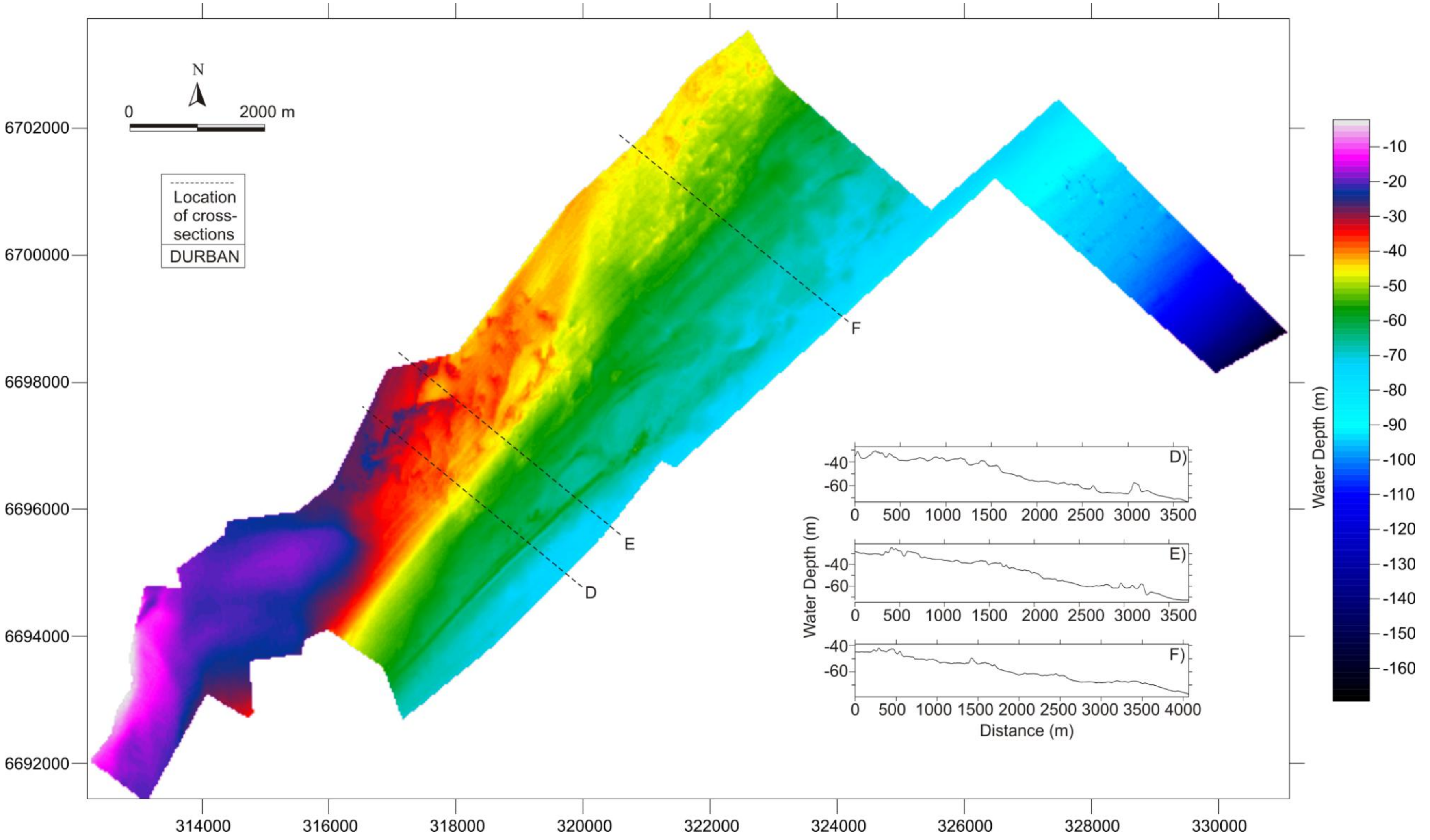

Figure 2.12. Uninterpreted depth-coded bathymetric image of the mid-shelf inside the Durban Bight. The location of the Durban study area with respect to the coastline and surrounding survey areas is depicted in Fig. 1.1. Note the presence of a particularly well-developed and elongate -60 m ridge fronted by a deep gully and backed by exposed remnants of Unit 2 (interpreted as the cores of eroded parabolic dunefields) within the 30 to 50 m depth interval that comprise the hardgrounds in this region. Northing and eastings are in metres, UTM zone 36 S.

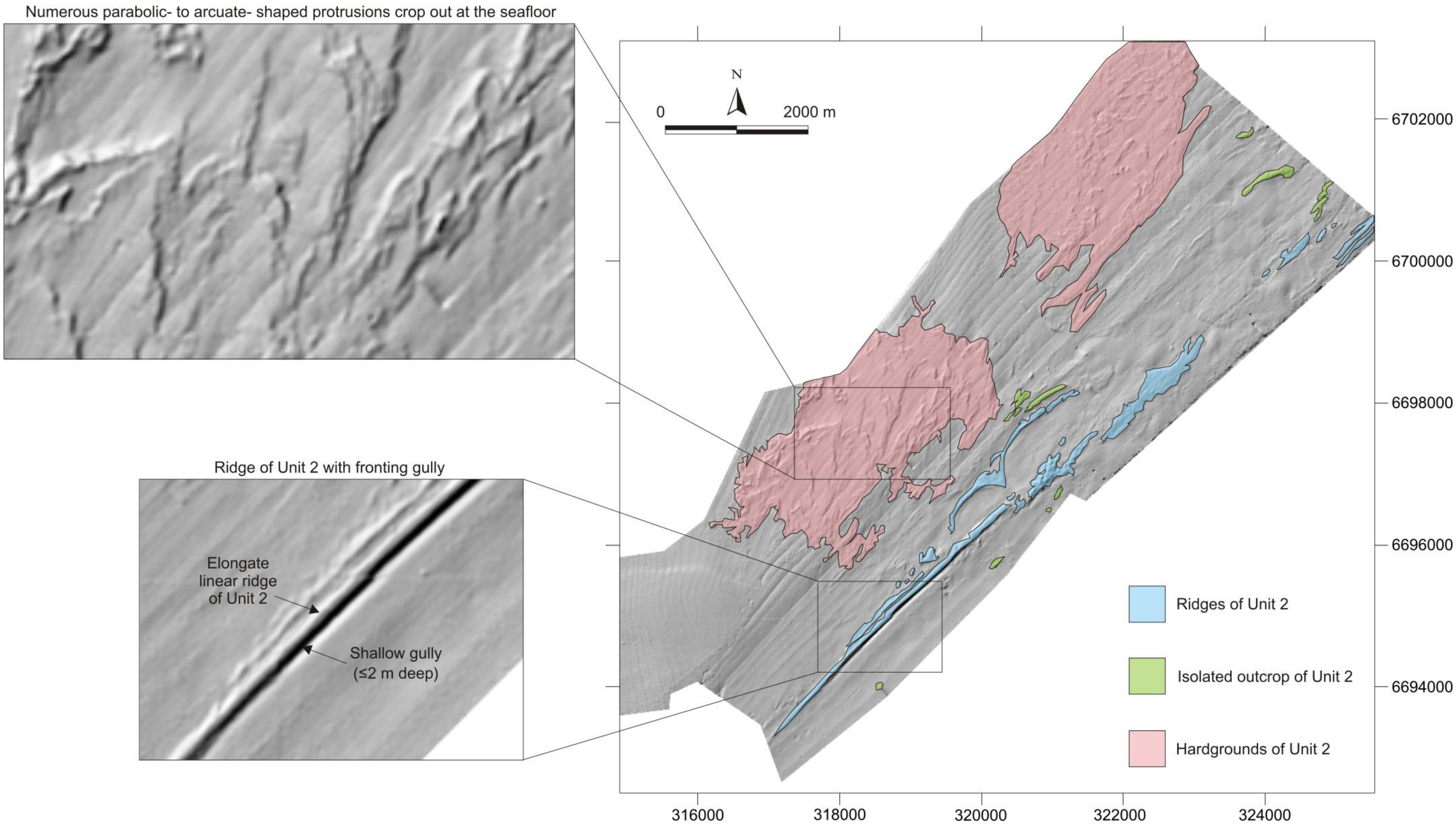

Figure 2.13. Sunshaded bathymetric image of the Durban study region with interpretative overlays. The location of the Durban study area with respect to the coastline and surrounding survey areas is depicted in Fig. 1.1. 3.5x Vertical exaggeration. Northing and eastings are in metres, UTM zone 36 S.

2.3.4. Interpretation

2.3.4.1. Seafloor morphology

2.3.4.2. Major depositional shoreline features and equilibrium characteristics

The outcrop of Unit 2 is consistent in surface morphology (and seismic characteristic) with that of submerged barrier systems elsewhere. A barrier with a base situated at ~60 m depth is a ubiquitous seafloor feature throughout the east coast of South Africa (c.f. Martin and Flemming, 1988; Ramsay and Mason, 1990; Ramsay, 1991, 1994, 1995; Cooper, 1991b). In northern Kwazulu-Natal, a very similar feature, though mostly covered by Holocene sediment, is evident (Ramsay, 1994; Chapter 3). Another similar feature is documented by Green et al. (in press; Appendix III) offshore Richards Bay showing a crenulate bay almost wholly preserved at a similar depth. The barrier complexes show many similar characteristics, namely an evolution to planform equilibrium. These encompass:

1) Segmented lagoonal waterbodies:

The aforementioned arcuate ridges and semi-circular seafloor depressions backing barriers in both the Umdloti and Durban areas were interpreted by Green et al. (2013a) as representing segmented lagoon and lake systems. Nordfjord et al. (2009) noted similar contour-parallel depressions ~10 km in width and ~8 m in depth offshore the New Jersey continental shelf at a similar depth of 50-60 m. These were interpreted as lagoonal or palaeo-estuarine back-barrier topography with filled tidal channels preserved within the depressions. These systems are delimited by an elongate and near continuous barrier situated around the 60 m depth mark, with fronting gully systems and/or platforms on their seaward sides which are thought to have formed coevally with these features. The presence of almost wholly preserved tidal inlets, cuspate spits and prograding ridges surrounding segmented lagoons provide evidence that the shoreline system had reached equilibrium form between sea-level rise, sediment supply and incipient coastal energy (c.f. Zenkovich, 1959; Cooper,1994).

2) Parabolic dune forms:

The parabolic/arcuate depressions within the hardgrounds offshore Durban are of the exact shape and scale as the modern parabolic dunes formed within the coastal dune cordon of KwaZulu-Natal (Hillary, 1947; Maud, 1968; King, 1972; Tinley, 1985). Their arcuate shapes with north-south aligned long axes are in accordance with the northward directed wind direction that predominates in the area at the present time (Lutjeharms, 1981, 2006; Birch, 1996). Gardner et al. (2005) noted similar indentations in the hardgrounds landward of an elongate barrier offshore Florida. They interpreted these as relict parabolic dunes. Green et al. (in press) observed comparable features in a barrier at 100 m water depth offshore Richards Bay which they attributed to relict hairpin blowouts formed within a series of parabolic dunes that were part of a barrier complex.

2.3.4.3. Erosional shoreline features

The flat, semi-horizontal surface that dips gently landwards and terminates against the base of the -60 m barrier is interpreted as a palaeoshore platform. In northern KwaZulu-Natal three similar features are present within the transgressive ravinement surface at depths of 70, 65 and 60 m, each of which are considered to have formed during phases of static or slowly rising sea-level and are interpreted as shore platform equivalents (Chapter 3). The present study area did not extend to sufficient depths to verify whether the deeper platforms are present offshore central Kwazulu-Natal. Examples of an analogous modern shoreline platform from the Umdloti region are provided in Figures 2.14 and 2.15.

Figure 2.14. Raised shore platform similar to the shore platforms observed in seismic section at 60 m depths off the coastline of Umdloti itself as well as at numerous other localities at a concordant depth.

Figure 2.15. Raised shore platform situated slightly seaward of a high-relief (~3.5 m) aeolianite exposure. This is very similar to what is observed in seismic section at 60 m depths offshore the very same locality.

2.4. Discussion

2.4.1. Timing of palaeoshoreline formation

Several examples of palaeoshorelines (barriers, lagoons, terraces, platforms etc.) have been documented in the literature at similar depths in other far-field localities (e.g. Comoro Islands in the western Indian Ocean (Camoin et al., 2004); northeast Gulf of Mexico (Gardner et al., 2007); northern Adriatic shelf in Italy (Storms et al., 2008); western Australia (Nichol and Brooke, 2011); northeast Australia (Abbey et al., 2011)). This strongly suggests that eustatic sea-levels were the dominant drivers in the formation of these features (Green et al., in press). It must be kept in mind that not all shorelines located at the 60 m depth mark are liable to be contemporary in age and that in certain situations local subsidence or uplift is responsible for the positioning of palaeoshorelines at this depth (e.g. Albarracín et al., 2013; Alcántara-Carrió et al., 2013).

In northern and central Kwazulu-Natal the formation of the -60 m barrier complex is attributed to an event of relative sea level stability during the Younger Dryas slowstand. This took place between 12.7-11.6 ka BP at a depth just below 60 m (Camoin et al., 2004). This corresponds favourably with the base of the barriers in the Umdloti and Durban areas.

2.4.2. Preservation

The barrier shoreline and back-barrier stratigraphies appear to have been remarkably well-preserved despite the processes of ravinement that occur when sea-level rises above the shoreline. One such process responsible for this preservation is overstepping, which is usually associated with particularly abrupt phases of sea-level rise. Overstepping of the -60 m barriers both in central and northern Kwazulu-Natal and their fortuitous preservation on the shelf has previously been allotted to meltwater pulses. Green et al. (2013a) ascribes this phenomenon to MWP-1B, a particularly rapid rise in relative sea level that occurred between 11.5 and 11.2 ka BP, shortly after the cessation of the Younger Dryas slowstand, from a depth of about 58 to 45 m (Liu and Milliman, 2004). Chapter 3 deals with submerged shorelines and coeval phases of stasis and overstepping on the northern KwaZulu-Natal shelf. It appears that a similar process would have occurred in the Umdloti area.

Once overstepped (between 58 and 45 m water depths), the shallower portions of the dune fields (≤ 45m depth) landward of the zone of overstepping would have been subject to erosion as sea levels continued to rise, but at a slower rate as the shoreline migrated inland. What is preserved here are the dune cores, as almost certainly most of the dune material would have been removed by wave sculpting during this phase of reduced pace in rising sea level. The fact that the dune cores are still present and have withstood erosion indicates that these were probably fully cemented prior to the process of overstepping.

Although the gradient of the continental shelf in central KwaZulu-Natal is relatively steep, the wave and current energy high and the barrier shoreline systems dominated by sandy sediment, a remarkable degree of preservation of submerged shoreline complexes has occurred. These features have withstood the erosive forces of transgressive ravinement to be enigmatically preserved on the continental shelf. Factors aiding in the unlikely perpetuation of these features include:

- Rapid submergence of the shoreline—presumably at rates of up to 43.3 mm a^{-1} during MWP-1B—allowed the shoreline complex to be overstepped without significant degrees of erosion or reworking (Belknap and Kraft, 1981; Forbes et al., 1995; Storms et al., 2008).
- Cementation of the barriers during a period of prolonged sea-level stasis or slowstand—here attributed to the Younger Dryas slowstand—provided resistance

against the forces of erosion during subsequent overstepping (Forbes et al., 1990, 1991).

- A low tidal range mitigated the effects of tidal scour (hence the almost complete absence of tidal ravinement surfaces in the stratigraphy). This operates more vigorously along macrotidal coastlines where preservation potential would be reduced (Storms et al., 2008).
- The presence of old drainage networks and incised valleys that underlie the barrier complexes. These provided depressions for the enhanced deposition and preservation of overlying transgressive deposits (Hayes, 1979; Helland-Hansen and Gjelberg, 1994).
- A prolonged period of stasis leading to the voluminous build-up of shoreline cordons and the formation of extensive back-barrier morphology. The former, an increased barrier volume, would have lessened the impact of ravinement when the barrier was transgressed (Forbes, 1995) as well as significantly increasing the volume of the back-barrier. The presence of broad lagoonal or estuarine depressions/topographic hollows would have provided a dramatic decrease in slope behind the barrier and a corresponding rapid increase in accommodation space as the barrier was submerged (Mellet et al., 2012). Focused deposition of lagoonal/estuarine deposits would have occurred and their location within deeper waters would have prevented their removal by later wave erosion (Cattaneo and Steel, 2003).
- The near-complete preservation of the -60 m stranded barrier complex, neighbouring lagoons and fronting platforms implies that minimal wave reworking transpired due to an excess of sediment in the system, i.e. that overstepping occurred under *sediment surplus* conditions (Mellet et al., 2012). Essentially, no additional sediment was liberated into the eroding system when sea level overstepped the profile and as such the morphologies remained relatively intact. This is in contrast to the claim of Green et al. (2013a) that the sediment veneer covering transgressive features on the shelf aided in their preservation. Given that transgressive scour would have occurred prior to the deposition of the post-transgressive lag, and given that it would have acted on the very surfaces of these features, it is more likely that adequate sediment in the system prevented the erosion of pre-existing features in order to add to the sedimentary budget.

- Palaeoshoreline features crop out clearly at the seafloor and are well exposed due to the limited blanketing of these features by a thin post-transgressive lag. The thinness of the lag is a result of a minimal degree of erosive scour and sediment liberation from the transgressed shoreline surface as sea levels rose. This is likely due to a combination of factors including: 1) the early cementation of shoreline features, armouring them against significant erosive forces; and 2) a moderately lower gradient (when compared to northern KwaZulu-Natal-chapter 3) of the mid shelf offshore of Durban that would have lent itself to quicker migration of the shoreline for any given increment of sea-level rise and, thus, lessened erosion by wave and tidal ravinement.

CHAPTER 3

3.1. Seafloor morphology and shallow stratigraphy offshore northern KwaZulu-Natal

This chapter documents a series of submerged shorelines preserved on the steep (~2.7°), narrow (2-4 km) and wave-dominated northern KwaZulu-Natal continental shelf, an unlikely setting in which to preserve submerged shoreline sequences. The examination of these features offers a unique opportunity to test the models of shoreline response to RSL rise (as discussed in chapter 1) and to provide alternative scenarios in which submerged shoreline features can either be formed or preserved in seemingly unfavourable settings. This chapter thus aims to identify the mechanisms involved in the development and preservation of these features and relates these to factors that may over-ride those identified as the dominant controls on shoreline preservation during sea-level rise.

3.2. Methods

The continental shelf and upper slope were surveyed between depths of ~30 and 850 m (Fig. 1.5) using a 100 kHz ResonSeabat 8111 ER multibeam echosounder (cf. Ramsay and Miller, 2006). The data obtained resolve vertically to within 30 cm, with the final sounding data output as a 10 × 10 m matrix. Subsurface geology was inspected by means of four hundred line kilometres of single-channel, high-resolution boomer seismic reflection data (Fig. 1.5). Power levels of 500 J were used throughout the study, with a median output frequency of 600 Hz. Raw data were processed, with time-varied gain, bandpass filter (300-1200 Hz), swell filter and manual sea-bed tracking. Streamer layback and antenna offset corrections were applied to all digitised data and constant sound velocities in water (1500 ms^{-1}) and sediment (1600 ms^{-1}) (Shaw, 1998) were used to extrapolate all time-depth conversions. All seismic data have a 1 m vertical resolution, although in certain instances this is reduced to 5 m due to source ringing.

3.3. Results

3.3.1. Seismic stratigraphy

Unit 1 occurs as a series of acoustically opaque, high relief pinnacles and ridges (Fig. 3.1 and 3.2). These form isolated features up to 35 m thick and 200 m wide on the mid- and outer shelf areas. Strong acoustic masking limits observation of the underlying stratigraphy. Where the underlying stratigraphic bounding surface is discernible, it is apparent that this unit is superimposed on a surface within which Green (2009a; 2011b) identified the 18 ka LGM incised valley network (Fig. 3.2; Table 2). In seismic section this surface occurs as a high-amplitude, south-easterly dipping, heavily incised erosional reflector that is laterally continuous along strike (cf. Green, 2009a).

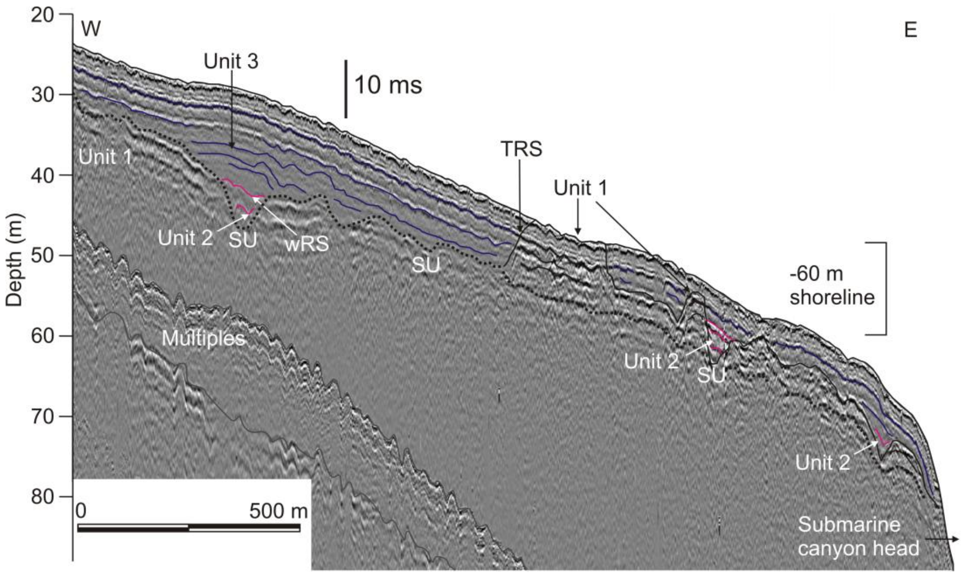

Figure 3.1. Shore perpendicular seismic section and interpretative overlay from the southern Mabibi. Expanded area shows the detailed interpretation of the -60 m barrier complex. SU= subaerial unconformity; TRS= transgressive ravinement surface; wRS= wave ravinement surface.

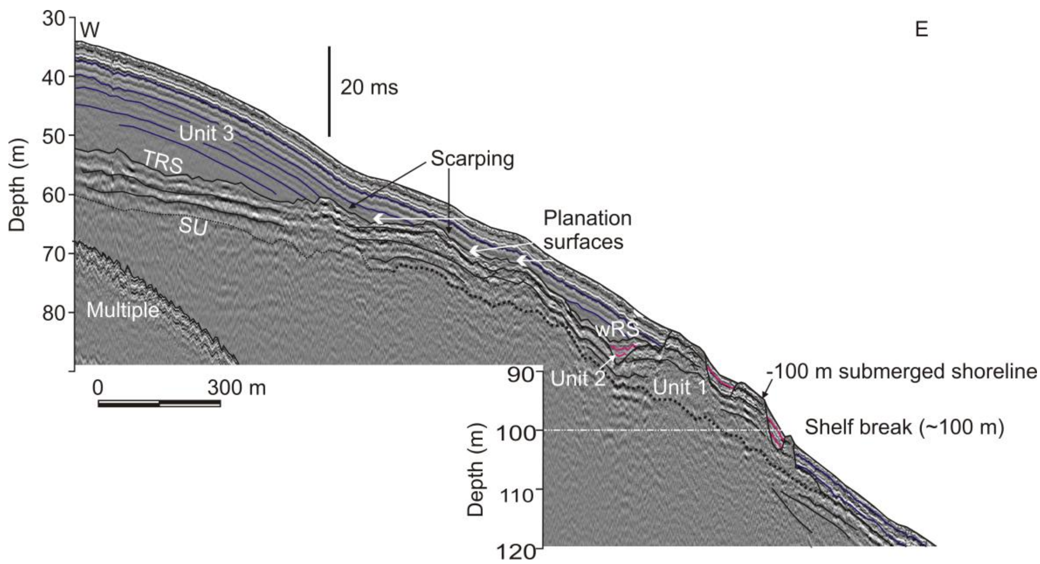

Figure 3.2. Shore perpendicular seismic section and interpretative overlay from the Leven Point area. Note the prominent barrier at 100 m depth with the landward onlapping drape of back-barrier/lagoonal sediments of Unit 2. Also note the absence of barriers at 60 m depth, the presence of scarps in their stead and the presence of well-

developed planation surfaces at -70, -65, and -60 m. SU= subaerial unconformity; TRS= transgressive ravinement surface; wRS= wave ravinement surface.

Unit 2 occurs sporadically throughout the area and comprises a series of low-amplitude, sub-parallel reflectors that form drape fills within the saddles of Unit 1. These infilled depressions trend parallel to the main features of Unit 1 and attain thicknesses of up to 15 m and widths of between 100 and 200 m. Reflectors of Unit 2 onlap the landward margin of Unit 1 and can also onlap the seaward margin of successive landward ridges of Unit 1. Unit 2 may locally pinch landwards forming a seaward thickening wedge (Fig. 3.3 and 3.4).

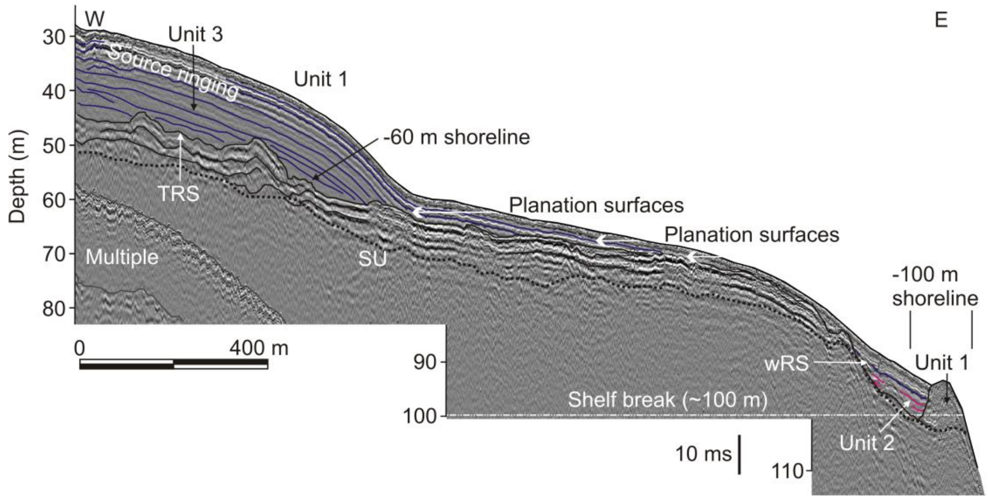

Figure 3.3. Shore-perpendicular seismic section and interpretative overlay from the southern Diepgat area. Note the distinctive -100 m and -60 m barriers, together with the planation surface seaward of the -60 m barrier. SU= subaerial unconformity; TRS= transgressive ravinement surface; wRS= wave ravinement surface.

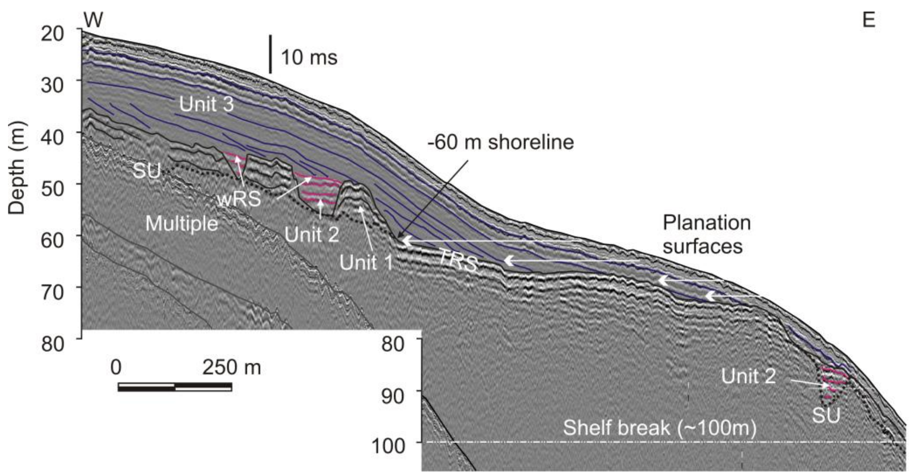

Figure 3.4. Shore-perpendicular seismic line and interpretative overlay from the northern Diepgat area showing a well-developed -60 to -50 m barrier complex with back-barrier Unit 2 sediments draped between the two bifurcated barriers. Note the extensive planation surface that fronts the - 60 m seaward barrier. SU= subaerial unconformity; TRS= transgressive ravinement surface; wRS= wave ravinement surface.

Unit 3 encompasses a series of prograding, low-amplitude reflectors (Figs. 3.2-3.4), but is locally acoustically transparent. Separating Unit 1 and 2 from Unit 3 is a strongly erosional surface (TRS) onto which the reflectors of Unit 3 downlap. Unit 3 attains a maximum thickness of more than 20 m in the inner shelf (Fig. 3.5) and thins towards the shelf break. Where Unit 3 is removed completely, particularly on the outer shelf, the SU may crop out as the surface expression of Unit 1 (Figs. 3.1-3.3).

3.3.2. Interpretation

Substantial outcrops of sandy beachrock and aeolianite have been mapped along the southeast African continental shelf (Flemming, 1981; Martin and Flemming, 1988; Ramsay, 1994; Green, 2009b; Cawthra et al., 2012). Seismic facies within these appear similar to those of Unit 1. Ground-truthing of these features was undertaken by Ramsay (1994) in northern KwaZulu-Natal, confirming their sandy beachrock/aeolianite nature. Beachrock and aeolianite form at or near mean sea level and comprise the beach and dune components of a palaeo-barrier (Vousdoukas et al., 2007).

The very-low-amplitude draped parallel reflectors of Unit 2 point to a low energy environment of deposition. Foyle and Oertel (1997) and Green et al. (2013) consider these to indicate a back-barrier, lagoonal-type environment. An alternative interpretation may be that of a back-barrier tidal channel that has incised Unit 1 and the underlying stratigraphy. Due to the dominant coast-parallel geometry, width of the depression (100 m) and general low-amplitude seismic signature, this interpretation is discarded. Most modern tidal channels on the KwaZulu-Natal coast are narrow (< 25 m wide), orientated normal to the coast and are characterised by high-energy lag deposits (Cooper, 1991b). These would have bright, high amplitude acoustic signatures, with either no clear internal reflector arrangements or lateral accretion packages related to tidal channel migration (e.g. Chaumillon and Weber, 2006). We thus prefer the interpretation of a shallow lagoon-type environment, which is in keeping with the barrier interpretation of the seaward Unit 1 on to which the lagoonal deposits onlap seaward.

Unit 3 encompasses post-transgressive sediments that form a prograding wedge of unconsolidated sediment over the TRS and the underlying stratigraphies of Units 1 and 2. Contrary to the findings of Green (2011), this unit cannot be subdivided into two packages and instead comprises the entire post-ravinement sediment cover.

3.3.2.1. Spatial distribution of barriers

Within the vicinity of Mabibi and Sodwana, a well-developed gully in the TRS is present at a depth of ~60 m (Fig. 3.1). This gully is laterally continuous along strike and is backed landward by a high-relief (≤10 m) linear, shore-parallel ridge of Unit 1 material. In the northernmost portions of the study area, the barriers of Unit 1 are draped by thick Holocene sediments that blanket the shelf, obscuring almost all outcrop (Fig. 3.1 and 3.4). An additional barrier of limited lateral extent (~2 700 m) is present in this region at a depth of -50 m (Figs. 3.1 and 3.5). This appears to be an isolated feature and is absent from seismic and bathymetric sections in the southern Leadsman and Leven Point Areas.

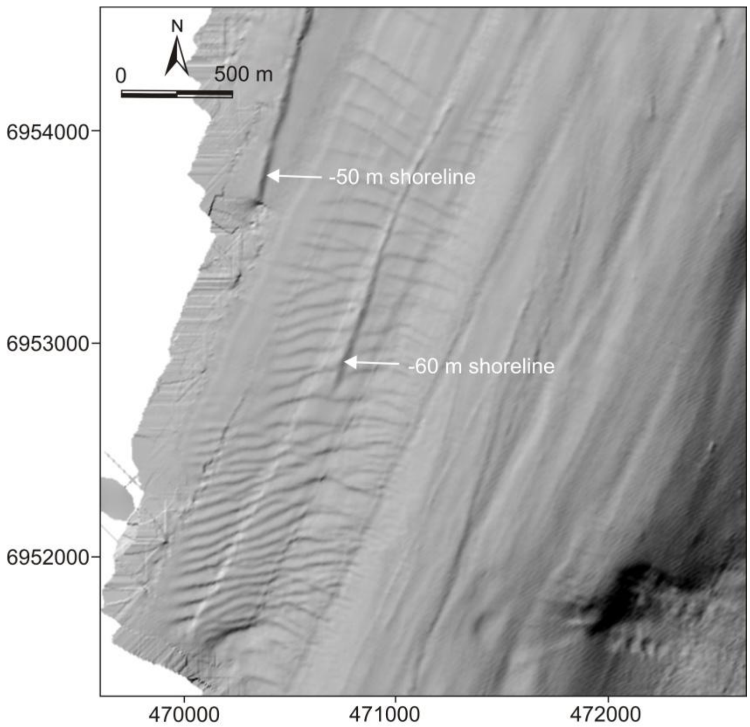

Figure 3.5. Sunshaded bathymetric image of the southern Sodwana area. Note the surface outcrop of the -60 m barrier complex. Northings and eastings are in metres, UTM zone 36 S.

Towards the south of the study area (Diepgat, Leadsman and Leven Point areas), barriers are observed at similar depths. Unlike the Sodwana and Mabibi examples, these divide to form a number of ridges at depths of -55 to -65 m rather than a single feature, and are therefore referred to as *barrier complexes*. Unit 2 forms discrete packages within depressions on the landward sides of these (Fig. 3.4). Barrier complexes with bases at ~ 100 m depth are also present in the southern areas, at or near the shelf break (Figs. 3.3 and 3.7). Relief varies but some, notably in the Diepgat area, are up to 16 m high and extend landwards over significant stretches of seafloor. Accumulations of Unit 2 as back-barrier lagoonal deposits that onlap the seaward barrier are common (Fig. 3.3). A thinner Holocene sediment drape in the southern areas results in local outcrops of the -60 m barriers at the seafloor (Figs. 3.6 and 3.7).

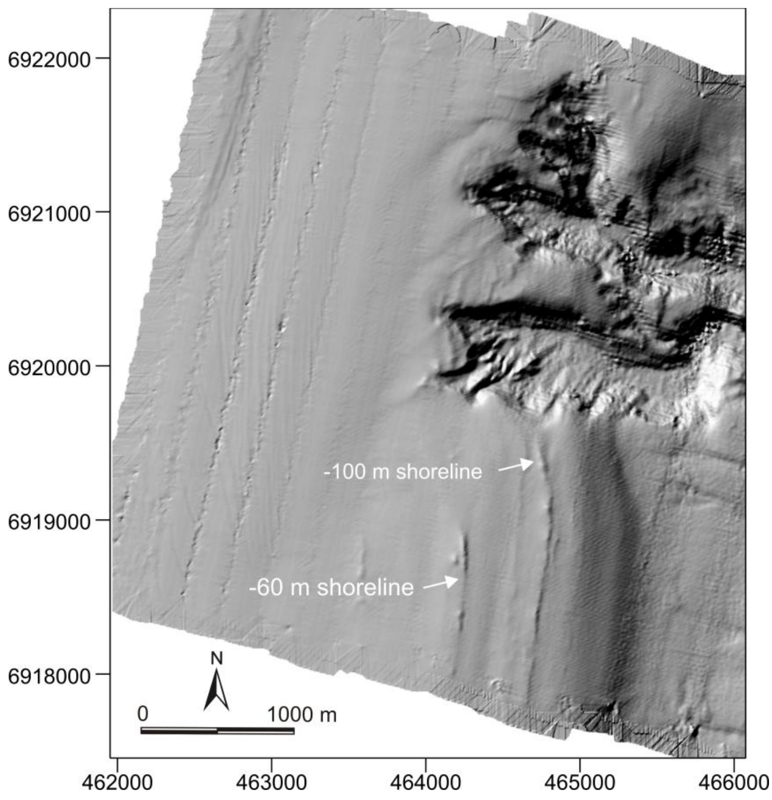

Figure 3.6. Sunshaded bathymetric image of the Leadsman area continental shelf. Note the presence of both the -60 m and -100 m shorelines. Northings and eastings in metres, UTM zone 36S.

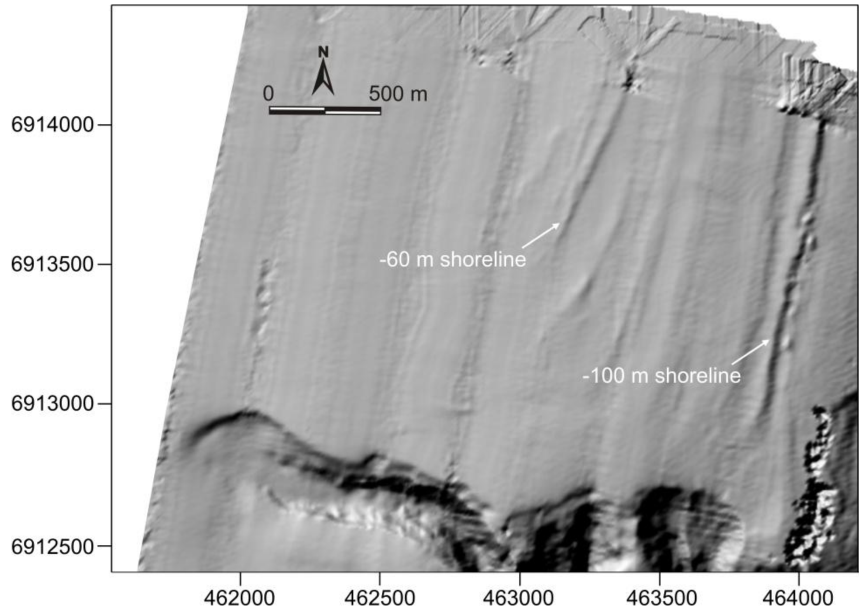

Figure 3.7. Sunshaded bathymetric image of the Leven Point continental shelf illustrating the -60 m and -100 m shorelines. Northings and eastings in metres, UTM zone 36S.

At several depths the TRS is notably flattened, forming a very low-angle, seaward dipping planation surface (Figs. 3.2-3.4) reflected in the topography of the seafloor. A composite planation surface formed of the subaerial unconformity and the ravinement surface caps the underlying unit at depths between 70 and 60 m. This appears to be laterally persistent, spanning the entire study area. Where no barrier forms are present, several scarps and notches are preserved within the TRS (Figs. 3.2 and 3.8). These occur particularly in the northern and central zones of Mabibi, Sodwana and Diepgat and mark major discontinuities in the -60 m barrier along shoreline strike.

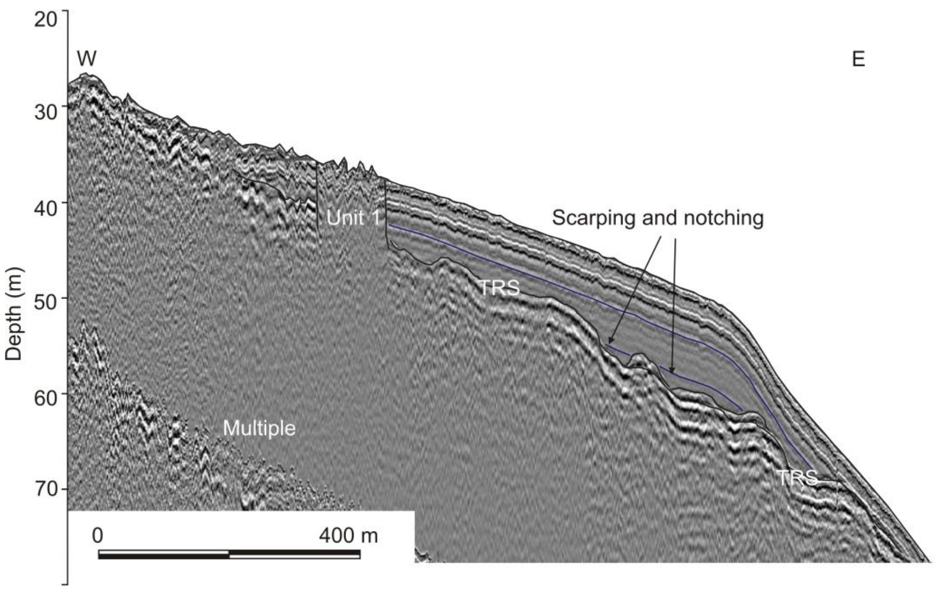

Figure 3.8. Shore-perpendicular seismic line and interpretative overlay from the northern Sodwana Bay area. Note the scarped and stepped profile of the TRS surface at ~ 60 m. TRS= transgressive ravinement surface.

3.4. Discussion

3.4.1. Shoreline occupation and timing of barrier development

Two well-defined high-relief ridges are present at -60 m and -100 m depths, representing barrier shoreline complexes drowned on the shelf. These would initially have developed when sea-level and the associated shoreline was at similar depths. Comparison with global eustatic sea level curves indicates that each shoreline developed during either stillstand or slowstand conditions (Fig. 3.9).

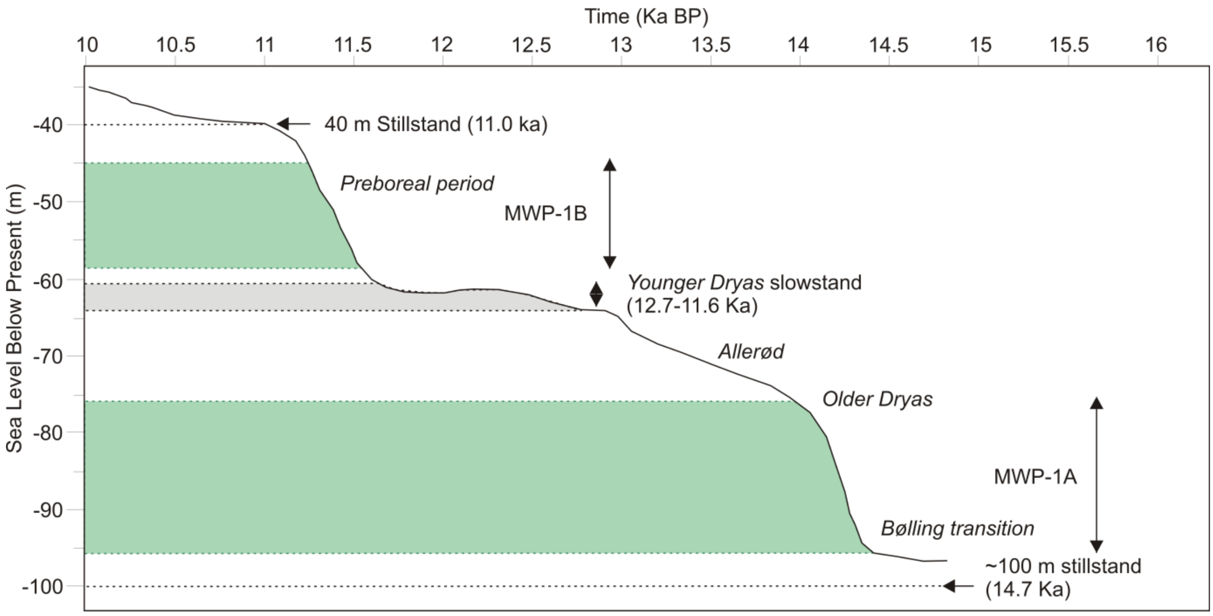

Figure 3.9. Sea-level curve for the period between 10 and 15 ka BP (modified after Liu and Milliman (2004); Camoin et al. (2004); Bard et al. (2010); and Zecchin et al. (2011)). MWP-1A is taken as spanning from -96 to -76 m below mean sea level (14.3-14.0 ka BP; rate of ~60 mm/a), whilst MWP-1B is portrayed between -58 to -45 m below mean sea level (11.5-11.2 ka BP; rate of ~43.3 mm/a).

The -100 m barrier is positioned at the seaward edge of the shelf break. The existence of a barrier at this depth implies that the shoreline occupied that position for some time. The depth corresponds with sea levels of the Bølling-Allerod Interstadial stillstand (Fig. 3.9) of ~ 14.5 ka age.

The -60 m barrier complex occurs extensively throughout the study area (Figs. 3.1 and 3.4), fringed to seaward by a planation surface coinciding with the TRS (Fig. 3.4). Based on observations of contemporary rocky coastlines backed by sandy barriers (as in northern KwaZulu-Natal), the planation surface is interpreted as a shore platform that formed contemporaneously with the sandy barrier. This marks either a period of sea-level stability or a slow rise in RSL. The depth of this platform and the base of the barrier correspond to the observed slowstand of the Younger Dryas event (Fig. 3.9) of 12.7-11.6 ka BP (Camoin et al., 2004).

3.4.2. Preservation of the barrier shorelines

The preservation of barrier forms on a transgressive continental shelf is theoretically rare (cf. Swift and Moslow, 1982; Leatherman et al., 1983), although it may actually reflect a paucity of data. Several factors seemingly militate against the preservation of the submerged barrier shorelines of the northern KwaZulu-Natal. These include:

1) The steep gradient of the shelf. Cattaneo and Steel (2003) showed that the erosion by landward migration of a shoreline across high gradient shelves is more intense than across their lower gradient counterparts. Rate of rise may be constant, but the steeper gradient causes the wave base to occupy the same place for longer periods of time during ravinement (Davis and Clifton, 1987).
2) The sandy nature of the submerged northern KwaZulu-Natal barriers. Sandy barriers are comparatively rarely preserved because their relaxation times are fast compared to those of gravel barrier systems that are better able to survive the translation of the beach-shoreface over the barrier form (Long et al., 2006).
3) The high-energy wave regime, whereby barrier dispersal during wave-ravinement would be exacerbated (Swift et al., 1972).

Despite these impediments, preservation during overstepping of the barrier shoreline must have occurred in order for the submerged barrier forms to exist. Belknap and Kraft (1981), Forbes et al. (1995) and Storms et al. (2008) consider that the rate of sea-level change is a critical factor in the preservation of the barrier form. Rapid sea level rise promotes overstepping and in-place drowning of the shoreline. The most critical factor leading to shoreline preservation, however, is likely to have been early cementation of the barrier prior to inundation by rising sea levels. This would have indurated and armoured the barrier against the erosive forces that predominate during the landward migration of the shoreline.

3.4.3. Rapid rise in RSL and meltwater episodes

The presence of thickly-developed lagoonal deposits landward of both the -100 m and -60 m barriers attests to the rapid creation of accommodation space in the back barrier and a lessening of bay-ravinement as the barrier was submerged (Storms and Swift 2003). The landward-thinning of these deposits further suggests that RSL rose rapidly before decelerating, reducing accommodation space and causing planation by the TRS in the landward extension of the complex. The high gradient of the wRS, bounding the upper surface of lagoonal/back-barrier deposits (Figs. 3.1, 3.2 and 3.4) indicates a steepened shoreline trajectory during overstepping. Possible causes for steepened shoreline trajectories include: high rates of sediment supply, steep transgressed topographies and rapid rates of RSL rise (Cattaneo and Steel, 2003). High sedimentation rates during filling of the back-barrier can be discounted with some certainty on this sediment-starved shelf (cf. Green, 2009b; 2011), and the intrinsic low gradient of back-barrier environments excludes the role of a steepened transgressed topography. Thus, the observed steepening of the wRS-capping the lagoonal deposits and their subsequent overstepping was probably the result of a rapid rate of RSL rise coupled with previous cementation (Cattaneo and Steel, 2003).

Such rapid pulses of RSL rise may be linked to meltwater pulses (MWP's) generated from episodes of particularly rapid ice sheet melting. During MWP-1A, between 14.3 and 14.0 ka BP sea levels rose from -96 m to -76 m (Fairbanks, 1989, Bard et al., 1990). Although less well established in the sea-level record (e.g. Fairbanks, 1989; Bard et al., 1990, Bard et al., 1996; Camoin et al., 2004; Peltier and Fairbanks, 2006), MWP-1B occurred between 11.5 and 11.2 ka BP when RSL rose from -58 to -45 m (Liu and Milliman, 2004). Both MWP-1A and MWP-1B correspond to rapid accelerations in RSL rise after periods of either slowstand or stillstand at levels concomitant with barrier shoreline development along palaeo-coastlines in northern KwaZulu-Natal (Fig. 3.10). It is highly likely that the initial formation of the barriers occurred at -100 m and -60 m; these were overstepped respectively by MWP-1A (-96 m to -76 m) and MWP-1B (-58 to -45 m).

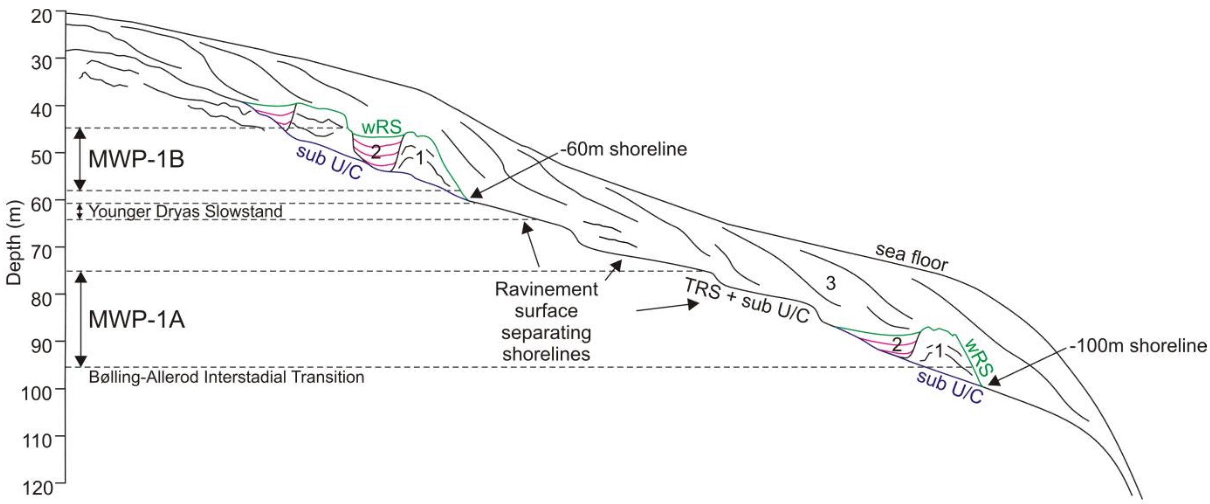

Figure 3.10. Conceptual model of the Holocene stratigraphy of the northern KwaZulu-Natal continental shelf. Note the position of both meltwater pulses (MWP-1A and 1B) bracketing the Younger Dryas slowstand and the Bølling-Allerod Interstadial preceding MWP-1A. Also note the planation in the ravinement surface between these two periods from depths of 78 to 64 m.

In the area between the two barrier systems, at least three low gradient, low relief zones occur within the TRS at depths of roughly -70, -65, and -60 m. (Figs. 3.2-3.4). The overall smooth, platform-like appearance these create is interpreted as the result of extensive ravinement of the surface during periods of slowly rising SL. In terms of the depth of slowstand documented between MWP-1A and 1B, this corresponds neatly with the start and end depths of the TRS platform (Fig. 3.10).

3.4.4. Shoreline Occupation and Early Cementation

The presence of shore platforms seaward of each of the two barrier complexes indicates that there was a lengthy time when sea level either occupied essentially the same position or was rising very slowly. If the -100 m barrier began to form at ~ 14.5 ka and was overstepped at ~ 14.3 ka (Fig. 3.10), this dictates a minimum interval of 200 years for the barrier to have formed. Cowell and Thom (1994) and Stive and de Vriend (1995) assign a 10^2 to 10^3 year time frame for the development of large scale equilibrium in sandy shorelines. Orford et al. (2002) document similar time scales for gravel barrier development. On this basis, the -60 m barrier is interpreted to have formed during the 2.5 ka slowstand preceding MWP-1B (Liu and Milliman, 2004) (Fig. 3.10). Botha and Porat (2007) indicate that the contemporary barrier in northern KwaZulu-Natal formed over a minimum period of ~ 1.5 ka of slow rise or steady sea level.

The rates of shoreline diagenesis in sub-tropical climates can be particularly rapid (Moore, 2001; Vousdoukas et al., 2007). Cawthra and Uken (2012) document the development of beachrock during a similar state of sea-level rise on the contemporary shoreline within a period of ca. 75 yrs. Similar rapid rates of shoreline cementation have been recorded as occurring on a scale of months to years in many areas with warm tropical to sub-tropical climates (e.g. Moresby, 1835; Frankel, 1968; Hopley, 1986). Early cementation of the barrier (as it was forming) prior to overstepping was thus a likely occurrence.

3.4.5. Sediment Deficit Overstepping and Unit 3

A number of incomplete barriers occur as remnant beachrock/aeolianite outcrops separated by bedrock scarps alongshore. These represent the rocky headlands of headland-embayment units. Such areas promote erosion or bypassing of sediment during transgression (e.g. Cattaneo and Steel, 2003) and reflect a reduced sediment supply. In such instances the shoreline transgressed is more likely to be eroded and incorporated into the sediment budget than under surplus conditions where the preservation potential is increased (Mellet et al., 2012). It thus seems likely that sediment deficit conditions prevailed during overstepping and that portions of the -60 m and -100 m barriers were liberated into their respective post-ravinement sediment drapes. The cemented shoreline units that are preserved are therefore likely to represent the cores of indurated coastal dune sands and linear beachrock outcrops that lined former beaches.

Cattaneo and Steel (2003) considered that steep-gradient settings promote erosion such that the TRS is commonly overlain by thick post-ravinement deposits. The thick cover of Unit 3 that blankets the majority of the barriers in the study area is thus likely to be a product of the steep antecedent gradient during overstepping. Deposits that are preserved as Unit 1 are likely to be only the cores of the original barriers. The later draping of these features by Unit 3 may have further increased their potential for preservation by dampening the effect of wave-base erosion as the shoreface transgressed over the barrier core. Ultimately, the lack of surface outcrop of Unit 1 barriers is related to the thick post-ravinement cover and burial of the palaeo-seafloor (Figs. 3.4 and 3.6). This is in direct contrast to gentler gradient and more sediment-rich areas, as off Durban to the south, where similar barrier features crop out (Green et al., 2013).

CHAPTER 4

4.1. The Durban and northern KwaZulu-Natal continental shelves– A Comparison

4.1.1. Oceanography

The Durban and northern KwaZulu-Natal shelves share some similar oceanographic characteristics based on their close proximity along the eastern South African coastline. Both coastlines are dominated by a high energy wave regime (Smith et al., 2010) with an average breaking wave height of ~2.6 m (Dunkley et al., 1998) and by the powerful Agulhas Current, a western boundary current with a core that hugs the shelf break at an average distance of 20-30 km offshore (Pearce, 1974, 1976, 1978; Schumann, 1988). The Agulhas Current impinges on the mid-shelf areas offshore Durban to a lesser extent; these areas are instead controlled more so by the Natal Gyre counter current that is less energetic (Lutjeharms, 2006). Tidal influence is small and a similar spring tidal range of ~1.8 m (Moes and Rossouw, 2008) is experienced in both areas. Except for the Agulhas Current, oceanographic controls thus appear to be fairly uniform from Durban to northern KwaZulu-Natal.

4.1.2. Differing coastal characteristics

In terms of coastal characteristics, central and northern KwaZulu-Natal differ in terms of their shelf gradients, widths, depth of the shelf break and abruptness of the shelf break. Northern KwaZulu-Natal's continental shelf is much steeper (~2.7°) and narrower (2-4 km) than that of central KwaZulu-Natal (~1° and 8-15 km) with a shallower shelf break of -100 m which deepens to -120 m offshore Durban (Goodlad, 1978; Martin and Flemming, 1988; Ramsay, 1994; Green 2009a; Green et al., 2012b). Furthermore, the central KwaZulu-Natal shelf is positioned along a coastal offset that results in a more NE-SW trending coastline when compared to the general NNE-SSW trend that predominates throughout the remainder of the province (Flemming, 1981; Dingle et al., 1983). Finally, the Durban area is underlain by a series of complex drainage networks (Green et al., 2013b), when compared to northern KwaZulu-Natal where the pattern of palaeo-drainage is typically isolated and sparse (Green, 2009a); much like the drainage of the contemporary coastal plain.

4.1.3. Similarities in geomorphic and stratigraphic features

In both the Durban and northern KwaZulu-Natal shelf, a compound barrier occurs at ~ 60 m depths comprising Unit 2 and Unit 1 respectively. The barrier rests on a regionally developed subaerial unconformity into which the LGM drainage network has been incised. The barrier has a high relief (≤14 m) and occurs at a depth of 60 m roughly parallel to the shelf isobaths (Figs. 2.13 and 3.6). In both cases this compound barrier is fronted either by a gully or a shoreline terrace etched into a regionally developed TRS, whilst in the back-barrier a depression in the TRS is filled with a series of fine-grained lagoonal deposits (Unit 3 offshore Durban and Unit 2 of northern KwaZulu-Natal) that onlap the barrier to landwards. The barriers display high degrees of preservation, with the Durban examples appearing to be better preserved, though this may be a function of the thinner surface sediment cover exposing the shoreline features better (discussed below).

4.1.4. Differences in geomorphic and stratigraphic features

Differences in stratigraphic and geomorphic attributes for the two areas include:

- A more complex and differentiated stratigraphy offshore Durban. In addition to the barrier, back-barrier and simple Holocene sedimentary wedge on the mid- to outer-shelf of northern KwaZulu-Natal, the following are additionally present offshore the Durban region:
  - Incised valleys and their respective valley fills (Unit 1) underlying the submerged shorelines (Fig. 2.6)
  - Calcarenite rubble fields onlapping both margins of the barrier complex (Unit 4.1)
  - Chaotic boulder facies scattered on the seaward margin of the barrier complex (Unit 4.2)
  - Differentiation of the unconsolidated Holocene sediment wedge into a lower transgressive (Unit 5.1) and an upper progradational (Unit 5.2) package
  - Minor incised valleys of mid-Holocene age (Unit 5.3)
- The presence of segmented lagoonal systems in the back-barrier at depths of 60 m and less offshore Durban.

- Palaeo-parabolic dune fields developed in the hinterland of major barrier shoreline complexes in central KwaZulu-Natal.
- Scarping and notching within the TRS where barriers have been eroded, as well as the formation of a composite planation surface between -60 m and -70 m. This only occurs offshore northern KwaZulu-Natal.
- A thinner Holocene sediment blanket leading to the exposure of large expanses of hardgrounds on the Durban shelf.
- A greater degree of development and/or preservation of shoreline complexes on the Durban shelf.

4.2. A Comparison between geomorphic regimes

4.2.1. Gradient

According to the shoreline trajectory model of Helland-Hansen and Gjelberg (1994) the generally steep gradient of the KwaZulu-Natal continental shelf (>2°) would have fostered the *deposition* of transgressive stratigraphies during the Flandrian Transgression. This enhanced deposition would have been offset by the enhanced degrees of *erosion* that likewise characterise high gradient settings (Sanders and Kumar, 1975; Davis and Clifton, 1987). This is attributed to the relatively slower landwards migration of shorelines along high gradient coasts for any given increment of sea-level rise.

A greater degree of erosion and ravinement appears to have occurred during transgression along the higher gradient shoreline of northern KwaZulu-Natal. This is in agreement with Cattaneo and Steel (2003), who proposed that transgressions along high gradient shelves (>0.057°) such as those of eastern South Africa, and northern KwaZulu-Natal in particular, involve a greater deal of sediment erosion, reworking and redeposition at the shoreline. This is because the rate of landward migration of the shoreline is slower for any given increment of sea-level rise than on a lower gradient shoreline. The process of ravinement is therefore accentuated and a thicker post-transgressive sediment lag is deposited, as evidenced in thick accumulations of Unit 3 that mostly cover the remnants of the shorelines. High-gradient shorelines are thus considered unlikely candidates/localities for in-place drowning of the shoreline (Sanders and Kumar, 1975). This is evidenced by the simplified stratigraphy in the area (probably due to erosion rather than a lack of formation); notching and scarping in line with eroded portions of the -60 m barrier, a compound platform between 60-70 m depths, and a thickened post-transgressive sediment drape (Chapter 3).

On the Durban shelf, on the other hand, the lower gradient lent itself to the formation and greater degree of preservation of a more complex stratigraphy and more defined coastal features–little changed since being stranded on the continental shelf when overstepped. Green et al. (2013a) note that the widths of the major contemporary submerged barriers of southeast Africa range from 450 m at their thinnest (northern KwaZulu-Natal) to almost 2 km at their widest in southern Mozambique. The barrier core of the segmented lagoonal system at 60 m offshore Durban varies between 100 m and 150 m in width, suggesting that, from a conservative view point, more than half of the system was eroded during ravinement processes (Green et al., 2013a). The other submerged barrier shorelines offshore Durban (Chapter 2) are much wider and reflect an average width of ~ 2 100 m (Appendix II). Off northern KwaZulu-Natal, the width of the submerged barrier shorelines varies more dramatically, averaging from ~ 1 300 m. In keeping with the reasoning that the barrier is reworked and this sediment then deposited as a post-ravinement sand sheet (Chapter 4), the smaller barriers off northern KwaZulu-Natal appear to reflect greater degrees of reworking due to the steeper antecedent topography of the shelf.

4.2.2. Inherited relief

Apart from low gradient, inherited physiography is cited as another leading cause of shoreline preservation. This is particularly applicable to the preservation of back-barrier shoreline facets. The roughness of the terrestrial surface prior to transgression is noted by Cattaneo and Steel (2003) as the supreme control on the nature of transgressive deposits. Where depressions in the terrestrial surface occur, deposition during transgression is focussed and preservation potential is high (e.g. McBride and Moslow, 1991; Snedden and Dalrymple, 1999). This is the case in Durban where numerous pre-existing incised valley networks are present (Green et al., 2013a; b). These provided abundant depressions for the focussed deposition of paralic and other fine-grained deposits as well as providing enhanced accommodation space in the hinterland bordering the shoreline complexes. This may partially explain the greater stratigraphic variation and preservation of a greater variety of transgressive deposits observed off Durban when compared to northern KwaZulu-Natal.

4.2.3. Sediment budget

The greater preservation of transgressive deposits and submerged shoreline complexes in the Durban area is likely due, at least in part, to a difference in sediment supply rates between the two localities at the time of overstepping. The numerous river systems that drain the hinterland into the Durban area (Cooper, 1991b) were likely to have resulted in a *sediment surplus* occurring in this area during overstepping. Owing to the lack of drainage and the protracted sediment starvation of the northern KwaZulu-Natal shelf (Green, 2011b), this area conversely experienced *sediment deficit* conditions. The former is linked to negligible reworking of the shoreline by waves and near-complete preservation of barrier complexes, as observed off Durban. In contrast, the latter tends to cause more significant erosion of barrier complexes, as seen off northern KwaZulu-Natal and discussed by Mellet et al. (2012) for the English Channel.

4.2.4. Summary of coastal variables and outcomes

In summary, the major defining similarities and differences in coastal setting between central and northern KwaZulu-Natal and the morphological variations that have resulted there from are as follows:

	Central KwaZulu-Natal (Durban to Umdloti)	**Northern KwaZulu-Natal (Lake St. Lucia to Kosi Bay)**
Similar Coastal Characteristics	Eustatic sea-level history -Occurrence of prolonged sea-level stasis during barrier development - Occurrence of rapid sea-level rise during the overstepping of barrier shorelines High wave energy Strong Agulhas Current influence Negligible tidal range High gradient continental shelf Narrow shelf width	
Resulting Stratigraphic Similarities	Presence of a -60 barrier complex Presence of fine-grained lagoonal deposits in the backbarrier Early cementation	

	Extremely high degrees of preservation during overstepping	
Differences in Coastal Setting	NE-SW coastal alignment	NNE-SSW coastal alignment
	Gentler shelf gradient (~1°)	Steeper shelf gradient (~2.7°)
	Narrower shelf (2-4 km)	Wider shelf (8-15 km)
	Deeper shelf break (-120 m)	Shallower shelf break (-100 m)
	Larger waves (Hs= 1.8 m)	Smaller waves (Hs= 1.6 m)
	Inherited relief in SB from incised valleys	Little inherited relief in SB
Resultant Stratigraphic Differences	More differentiated transgressive stratigraphy	More simple transgressive stratigraphy
	Higher degree of preservation of palaeoshorelines	Lower degree of preservation of palaeoshorelines
	Pervasive back-barrier morphology	Minor back-barrier morphology
	Widespread dune fields/ hardgrounds	Hardgrounds are absent
	Scarping and notching absent	Scarping and notching within the TRS
	Thinner post-transgressive sediment lag	Thick post-transgressive sediment lag
	More highly evolved or preserved -60 m palaeoshoreline complex	Less developed or preserved -60 m palaeoshoreline

CHAPTER 5

5.1. Conclusions

Research on submerged shoreline deposits and associated transgressive stratigraphies from the last cycle of sea-level rise is useful in better constraining our knowledge of past eustatic sea-level behaviour, in providing oceanographic and palaeo-oceanographic data, and in supplying comprehensive information regarding depositional processes during transgression and relationships with the present-day bathymetry (Cattaneo and Steel, 2003). The variability of transgressive deposits is high, not only for deposits emplaced under different conditions (geological setting, sedimentary basin, varying rates of transgression), but also for coeval deposits within the same sedimentary basin and over short distances (Heward, 1981). This study provides a good example of this variability. The shelves of both central and northern KwaZulu-Natal, despite being relatively proximally spaced along the southeastern coastline of South Africa, possess vastly different transgressive stratigraphies and seafloor morphologies.

Submerged shoreline sequences are located at comparable depths of ~60 m on the continental shelf of Durban and northern KwaZulu-Natal. These represent phases of shoreline building during periods of sea-level stasis where planform equilibrium of the coastline was achieved and barriers were built. A similar shoreline complex exists at a depth of 100 m offshore northern KwaZulu-Natal. This study has not directly recognised the 100 m shoreline offshore Durban, however previous surveys have located a -100 m barrier complex offshore central KwaZulu-Natal (e.g. Martin and Flemming, 1988; Green et al., in press). This also reflects planform equilibrium achieved during a protracted period of sea-level stability.

These reduced rates of sea-level rise would have provided sufficient time for shoreline barriers to aggrade and prograded, as well as to undergo cementation prior to the resumption of transgression. The -100 m barrier is thought to have formed during a period of sea-level stasis during the Bølling-Allerod Interstadial stillstand (~14.5 ka BP) whilst the -60 m barrier is considered to have formed during the Younger Dryas cold period between ~12.7 and 11.6 ka BP. Preservation of the shoreline complexes were facilitated by the rapid overstepping of these indurated features during MWP-1A and -1B which transpired between 14.3 and 14.0 Ka BP and from 11.5-11.2 ka BP, at depths of 96-76 m and 58-45 m, respectively .

The Durban shoreline complex is extremely well preserved and appears to possess a greater abundance of planform equilibrium features as evidenced by more expansive back-barrier features. These comprise a number of segmented lake and lagoon systems. Also present is a pervasive, low-relief platform fronting the barrier complex and a vast dune field in the hinterland of the lake-lagoon system.

The enhanced preservation of transgressive stratigraphies on the mid Durban continental shelf when compared to that of northern KwaZulu-Natal is attributed primarily to the presence of significant pre-existing topographic relief within the transgressed surface due to a number of incised valleys within the sequence boundary (SB); a lower gradient and thus a reduced shoreline residence time (i.e. less time for erosion to act on a stretch of coastline for any given increment of sea-level rise); as well as to relative sediment surplus conditions during overstepping of the -60 m shoreline complex, which resulted in a reduced propensity for sediment liberation from the system during ravinement.

Conditions that would have acted offshore both northern and central KwaZulu-Natal during and prior to overstepping of the complexes to enhance deposition of transgressive stratigraphies and to minimise erosion during transgression include: a prolonged period of stasis leading to significant degrees of volume-building of shoreline complexes through aggradation and progradation; a significant degree of cementation prior to submergence of the shoreline complex; the creation of a back-barrier depression in which to house transgressive stratigraphies and to shelter deposits from transgressive ravinement; sufficiently sediment-scarce conditions such as to prevent the rollover of the barrier up the depositional profile; low tidal range; and rapid rates of relative sea-level rise following cementation of the barriers–leading to overstepping.

Conditions that would have negatively affected the probability of barrier overstepping behaviour and preservation along the KwaZulu-Natal shelf include the high general gradient; high-energy wave regime and short relaxation times of the sandy barriers (if not cemented). The key factors that together contributed to the unexpected preservation of the shoreline in this high-energy setting include the effects of subtropical diagenesis, long periods of stillstand and subsequent drowning by meltwater pulses. It is clear that the governing controls previously considered as important to shoreline preservation can be over-ridden by combinations of local (climatic) and global (eustatic) factors.

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APPENDIX I

Table 3. Seismic stratigraphic observations and interpretations off the Durban and Umdloti continental shelves in central KwaZulu-Natal. Observations are given regarding units, underlying surfaces, seismic characteristics, stratal terminations, positioning of seismic units and the spatial distribution of units within surveyed lines. Units are then related to environment of formation and nomenclature used from previous studies.

Unit	Underlying Surface	Seismic Characteristics	Stratal Terminations	Position	Interpretation	Associated Unit Green et al., 2013
SB	N/A	Rugged, high-amplitude reflector; truncates steeply-dipping Cret. strata; forms incised valleys in basement	Shelf pervasive	Separated steeply dipping Cret. lithologies from overlying TST stratigraphies Outcrops only rarely at the seafloor (>65 m)	SB3 (Green et al., 2013a)	
U1	SB	Moderate-amplitude, chaotic, draped reflectors forming incised valley fills	Onlaps against valley walls	Lowermost unit filling incised v-shaped depressions within the seismic basement; Overlain by units 2-5	Incised valley fills (e.g. Sydow, 1988)	D?
RS1	N/A	Sub-horizontal, low amplitude surface	Onlaps against valley walls	Overlies U1 incised valley fills	wRS	
U2	SB or wRS capping incised valley surfaces	High-amplitude reflectors with strong acoustic impedance; masking of underlying units	Downlaps SB or wRS	Series of continuous, shore-parallel ridges orientated NE-SW; spans entire length of study area; may overlie Cret. strata or U1; outcrops occasionally at seafloor; great lateral variability of height and width	Barrier complex (e.g. Flemming, 1981)	J-K
U3	SB or wRS capping incised valley surfaces	Lens-like packages of low-amplitude, low-continuity, sub-parallel reflectors	Onlaps the landward edge of U2; separated from Cret. strata and U1 by the SB and wRS	Forms within saddles of the SB Terminates laterally against U2 Overlain by U4.1	Back-barrier fill (e.g. Green et al., 2013a)	J1
U4.1	SB or wRS capping incised valley surfaces	Low- to moderate- amplitude, acoustically semi-opaque, chaotic reflectors	Onlaps adjacent U2; downlaps Cret. Units, U1 and U3	Landward pinching wedge; onlaps the landward edge of U2 and the seaward margin of U2 (Umdloti only); pervasive throughout the study area; overlies	Calc-arenite rubble **Not previously documented*	N/A

				SB, U1 and occasionally U3 fills (wRS)		
U4.2	SB or wRS capping incised valley surfaces	Extremely reflective, chaotic internal reflectors; highly reflective uppermost surface; parabolic forms in the reflector package	Downlaps SB or wRS	Occurs at sporadic intervals and as isolated inclusions within seaward portions of U4.1; overlies Cret. surface (SB) or incised valley	Chaotic boulder facies **Not previously documented*	N/A
U5.1	SB, incised valley fills, wRS overlying U2, TRS, U4.1 or U4.2	Conformable, low-amplitude, parallel reflectors	Onlaps against land-ward side of U2	Thin, shoreward-pinching wedge; local thickening against landward margin of U2; thin or absent on seaward side of U2 barriers; overlies the Cret. surface (SB), U1, U2 or U4.1	Lower package within unconsol-idated Holocene sediment wedge	L2
Mid-Holocene reflector		Low-amplitude reflector	Shelf pervasive		First interpreted as: Storm bevelled surface (Green et al., 2012); Reinterpreted as a MFS (current study)	
U5.2	SB, TRS or Holocene reflector	Conformable, low-amplitude, parallel reflectors; more acoustically opaque than underlying U5.1	Onlaps against land-ward side of U2	Uppermost unit blanketing entire shelf, except where U2 or Cret. strata crop out; fills saddles within U2; forms the modern seafloor	Upper package within unconsol-idated Holocene sediment wedge	L2
U5.3	Recent drainage network	Moderate-amplitude, extremely highly reflective discrete packages	Onlap against valley walls (U5.1 and U5.2)	Minor vertically stacked valleys unconsolidated Holocene units (U5.1 and U5.2)	Minor Holocene incised valleys	L1

Abbreviations used: SB= sequence boundary; TST= transgressive systems tract; U= Unit; Cret.= Cretaceous; wRS= wave ravinement surface

APPENDIX II

Table 4. Observations regarding the cross-sectional thicknesses and widths of seismic units within the Durban to Umdloti study mid-continental shelf. Measurements regarding individual lines are provided as well as averages, though it must be noted that the sampling size is small and averages are not statistically robust.

Unit	Present in Lines	Thickness (m)	Width (m)
U1	1	4	184
	2	11	1053
	3	13	920
	4	14	1075
	5	5	162
	6	≥26	1660
	7	4	76
	8	14	150
	Average	**≥11**	**660**
U2	1	6	1985
	2	10	1302
	3	8	1360
	4	8	1422
	5	12	1150
	6	14	824
	7	11	935
	8	12	≥7762
	Average	**10**	**2093**
U3	4	3	446
	5	3	361
	6	4	348
	Average	**3**	**385**
U4.1	1	4	515
	2	6	887
	3	4	2213
	4	6	3967
	5	6	3997
	6	6	3599
	8	3	2499
	Average	**5**	**2525**
U4.2	2	3	496
	4	4	290
	7	7	380
	Average	**5**	**389**
U5.1	1	9	Regional
	2	5	"
	3	4	"
	4	5	"
	5	5	"
	6	5	"
	7	3	"
	8	6	"
	Average	**5**	**Regional**
U5.2	1	4	Regional
	2	4	"
	3	5	"
	4	5	"
	5	5	"
	6	5	"
	7	4	"

	8	8	"
	Average	5	"
U5.3	8	≥4	97
		≥5	119
	Average	**≥5**	**108**

APPENDIX III