

# **Seismic-Stratigraphic Models for Late Pleistocene/Holocene Incised Valley Systems on the Durban Continental Shelf.**

by

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## ABSTRACT

This dissertation examines the Durban continental shelf of the east coast of South Africa from a seismic and sequence stratigraphic perspective. High resolution seismic data reveal eleven seismic Units (A-K) offshore the Durban continental shelf comprising several partially preserved sequences. Unit A is the lower most unit, comprising Permian age shale of the Pietermaritzburg Formation. An early Santonian age is assigned to Unit B. The ages of Units C and D are indeterminate. Unit E is considered late Maastrichtian in age. Units F to I are assigned a late Pliocene age and represent an aggradational progradational shelf-edge wedge. Unit J comprises calcite cemented late Pleistocene/Holocene shoreline deposits which display morphologies similar to planform equilibrium shorelines on modern coasts. Unit K caps the stratigraphy and comprises a seaward thinning, shore-attached wedge of Holocene age. The lower portions of Unit K comprise the fills of an extensive LGM age incised valley network.

A widespread network of incised valley systems on the continental shelf offshore Durban was recognised and examined; the evolution of which were compared over time. These incised valleys represent the shelf extension of the main river systems in the area, namely, the Mgeni, Mhlanga and Mdloti rivers as well as those that drain into the Durban Harbour complex. In the study area late Pleistocene/Holocene aged valleys occur together with a subsidiary series of late Pliocene isolated valleys. Valleys of the last glacial maximum (LGM) of ~ 18 Ka BP exhibit simple fills and have intersected and reworked or completely exhumed the late Pliocene incised valleys. Only isolated examples of these late underlying Pliocene valleys are apparent.

Twenty five prominent incised valleys are recognised within the study area and occur predominantly in the mid-outer shelf. These valleys mainly incise into Cretaceous age rock, except for a few incisions occurring within Permian age shale of the Pietermaritzburg Formation.

Six seismic units (Units 1-6) comprise the infill material within the late Pleistocene/Holocene incised valleys, and on the basis of their architecture are interpreted to correspond with a succession from high energy basal fluvial deposits, low-energy central basin fines, mixed-energy estuarine mouth plug deposits, clay-rich flood deposits through to capping sandy shoreface deposits. The LGM aged fills in particular have volumetrically thick fluvial deposits, the result of increased gradient and stream competence during the LGM. The youngest valleys show a situation of differential evolution along the valley length due to varying rates of sea level rise in the Holocene. Initially, rapid sea level rise caused drowning and overstepping of the outer segment of the incised valley. During the late Holocene, slower rates of sea level rise caused shoreface ravinement of the inner-mid segments of the valley and created an imbalance between accommodation space and sediment supply, producing different facies architectures in the valleys. This differential exposure to accommodation has resulted in a sedimentological partitioning between tide-dominated facies in the outer valley segment and river dominated facies in the inner segment.

Due to significantly wider exposed coastal plain during lowstand intervals, the rivers in the study area avulsed and coalesced on this lowstand surface and thus possess no defined drainage patterns. A crenulate shaped subsurface knickpoint occurs at a depth of ~ 50 m, and is considered to have formed by initial slow ravinement processes that graded the antecedent shelf, followed by overstepping and preservation of the knickpoint during meltwater pulse 1B.

## PREFACE

The work detailed in this dissertation was carried out by the author at the University of KwaZulu-Natal, under the supervision of Dr. Andrew Green.

Parts of this dissertation stemmed from a BSc (Hons) dissertation by the author that addressed five seismic sections from the shelf. This dissertation includes those sections with an additional 18 newly acquired sections for a complete re-interpretation of the data set. Some of these data have appeared as Green, A.N., Dladla, N., Garlick, G.L., 2013. Spatial and temporal variations in incised valley systems from the Durban continental shelf, KwaZulu-Natal, South Africa. *Marine Geology* 335, 148-161. It is from this publication that the majority of this dissertation stems and represents original work by the author, except where suitably acknowledged.

## DECLARATION 1 - PLAGIARISM

I, Nonkululeko Nosipho Dladla, declare that

1. The research reported in this thesis, except where otherwise indicated, is my original research.
2. This thesis has not been submitted for any degree or examination at any other university.
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## **DECLARATION 2 - PUBLICATIONS**

### DETAILS OF CONTRIBUTION TO PUBLICATIONS

#### Publication 1

Green, A.N., Dladla, N., Garlick, G.L., 2013. Spatial and Temporal variations in incised valley systems from the Durban continental shelf, KwaZulu-Natal, South Africa. *Marine Geology* 335, 148-161.

A.N Green: Collated boths sets of data and wrote the portions of the paper concerning the Durban Bight.

N. Dladla: Wrote portions of the paper concerning the data collected from the Glenashley to La Mercy Beach areas, and drafted the related figures.

G.L Garlick: Provided the preliminary interpretations of the Durban Bight data set.

Signed: \_\_\_\_\_

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Appendix A: Additional Strike-parallel seismic records and interpretations from the mid-shelf offshore the Glenashley to La Mercy Beach areas.

Appendix B: Publication entitled “Spatial and Temporal variations in incised valley systems from the Durban continental shelf, KwaZulu-Natal, South Africa” by Green. A.N, Dladla, N. And Garlick, G.L.

## CHAPTER 1

### Introduction

The stratigraphy of incised valleys and their sediment infill has been studied from a variety of settings spanning the Precambrian to modern times (Allen and Posamentier, 1993; Dyson and Von der Borsch, 1994; Talling, 1998; Ardies et al. 2002; Boyd et al., 2006; Dalrymple, 2006; Nordfjord et al., 2006; Flood et al., 2009; Simms et al., 2010). Both ancient and modern examples have proved revealing in the interpretation and discussion surrounding valley positioning, channel geometry and architecture of the infilling deposits of incised valley systems (Dalrymple, 2006). Since the early seismic stratigraphic studies of Payton et al. (1977), the recognition of major erosional unconformities and their stratigraphic significance has driven an almost exponential growth in the number of studies of incised valley systems. In this light, the modern shelf continues to be one of the most revealing settings from which refinements to the models of incised valleys are made (e.g. SEPM Special Publication 85, Incised Valleys in Time and Space). This research examines a series of modern, shelf-hosted incised valleys systems from such a perspective.

The knowledge of the seismic stratigraphy of the shelf offshore the east coast of South Africa is relatively well constrained. Several studies have included Durban (Green and Garlick, 2011; Cawthra et al., 2012), south of Durban (Bosman, 2012) and northern KwaZulu-Natal (Green et al., 2008; Green, 2009; Green 2011). These studies show that deposits at the sequence level are not well preserved and only isolated systems tracts are identifiable. The deposits of transgressive systems tracts are the most isolated of these deposits, preserved only as incised valley fills or thin transgressive sand sheets. This is in agreement with the current thinking that transgressive deposits are typically poorly preserved on continental shelves worldwide (Cattaneo and Steel, 2003).

Despite their poor preservation potential, these systems are fundamental to the identification of major subaerial unconformities (sequence boundaries) and provide evidence of palaeo-flow conditions during intervals of lowered sea level (Nordfjord et al., 2006). As coastal depressions, incised valleys protect sediments from removal by subsequent transgressive erosion, and in particular when referring to the late Quaternary, these systems may very well provide the most complete and only sediment record of lowstand/transgressive intervals (Thomas and Anderson, 1994; Payenberg et al., 2006). They can permit the unravelling of complex sea level and sediment supply relationships during the rising portion of the sea level cycle. The recognition of incised valleys is thus imperative as a tool for the correct subdivision of the stratigraphic record (Zaitlin et al., 1994, Dalrymple, 2006).

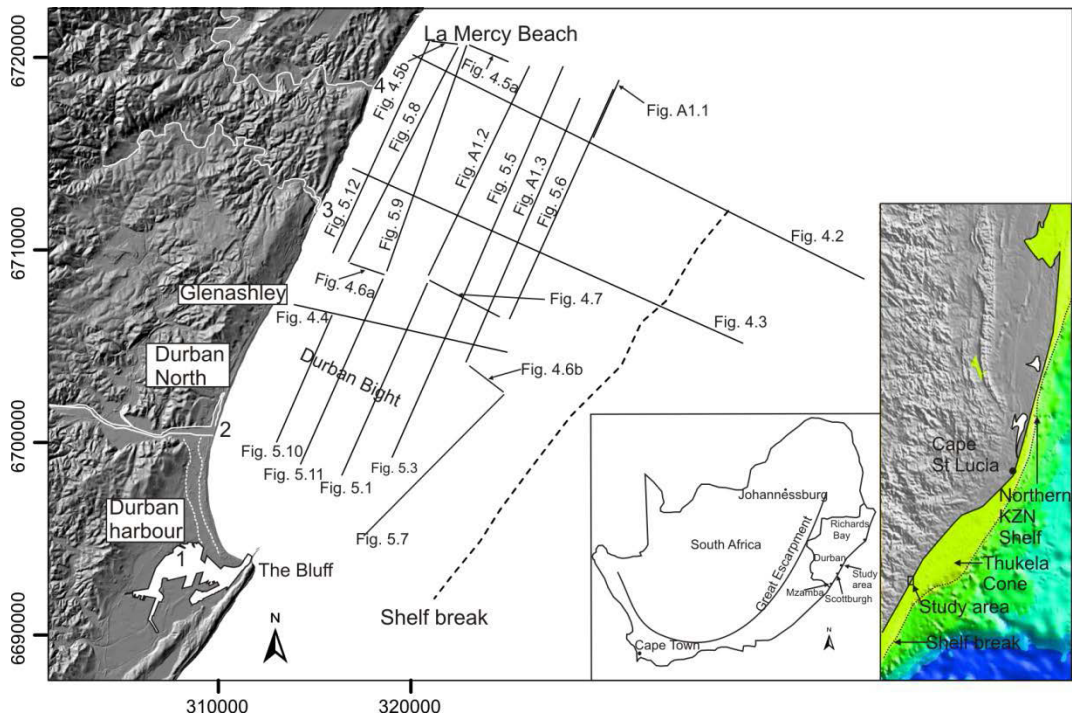
Recent work by Green and Garlick (2011) identified a network of buried incised valleys on the continental shelf of the Durban Bight, KwaZulu-Natal (Fig. 1.1). They proposed that such features acted as conduits for sediment bypass to the fringing deeper basin during times of margin uplift and as such, were key elements in the active evolution of the continental margin during times of base-level fall. This dissertation examines these incised valley systems and their stratigraphic relationships in detail.

### 1.1. Aims and objectives

This dissertation aims to assess the distribution, character and evolution of incised valley systems on the continental shelf offshore Durban. This study focuses on the area spanning the Durban Bight to La Mercy Beach stretch of coastline (Fig. 1.1). The objectives of this study are to:

- (1) Describe more clearly the seismic stratigraphy of the central KwaZulu-Natal continental shelf and to place this within a sequence stratigraphic framework.
- (2) Assess the shallow geomorphology of the study area with respect to incised valley systems, their positioning and the palaeo-drainage characteristics of the shelf.

- (3) Assess the nature of the incised valley fills from a seismic stratigraphic perspective
- (4) Relate these findings to earlier published models of the seismic stratigraphy of incised valley fills and continental shelves.
- (5) Provide a model for the generation and preservation of the incised valley systems.



**Fig. 1.1.** Locality map of the study area detailing the location of the seismic data, the position of the Durban Harbour complex (1) and the Mgeni (2), Mhlanga (3) and Mdloti Rivers (4). The emergent hinterland is shown as a sun-shaded relief map. Northing and Easting co-ordinates in metres, UTM projection. Note the crenulate form of the bay, with the coastline becoming more swash aligned north of the Mgeni River. The inset depicts the regional bathymetry of the SE African continental margin. Note the variation in shelf width.

## CHAPTER 2

### Literature review

#### 2.1. Incised valleys

Zaitlin et al. (1994) define incised valley systems as fluvially- or glacially-eroded, elongated topographic lows characterised by an abrupt basinward shift of depositional facies across a basal sequence boundary of regional extent. These systems form in response to base level fall (exposing the continental shelf to fluvial erosion) and then fill in with the subsequent sea level rise of a transgressive cycle. Incised valleys currently play host to contemporary estuaries that have formed by transgressive infilling since the Oxygen Isotope Stage (OIS) 2-1 (Flandrian) transgression; a phenomenon recognised worldwide. Since the work of Posamentier and Vail (1988), Van Wagoner et al. (1990) and the SEPM Special Publication 51 (Dalrymple et al., 1994), these systems have been of great interest worldwide. As coastal depressions, incised valleys protect sediments from removal by subsequent transgressive erosion and can provide the most complete sedimentary record of lowstand intervals (Thomas and Anderson, 1994; Payenberg et al., 2006).

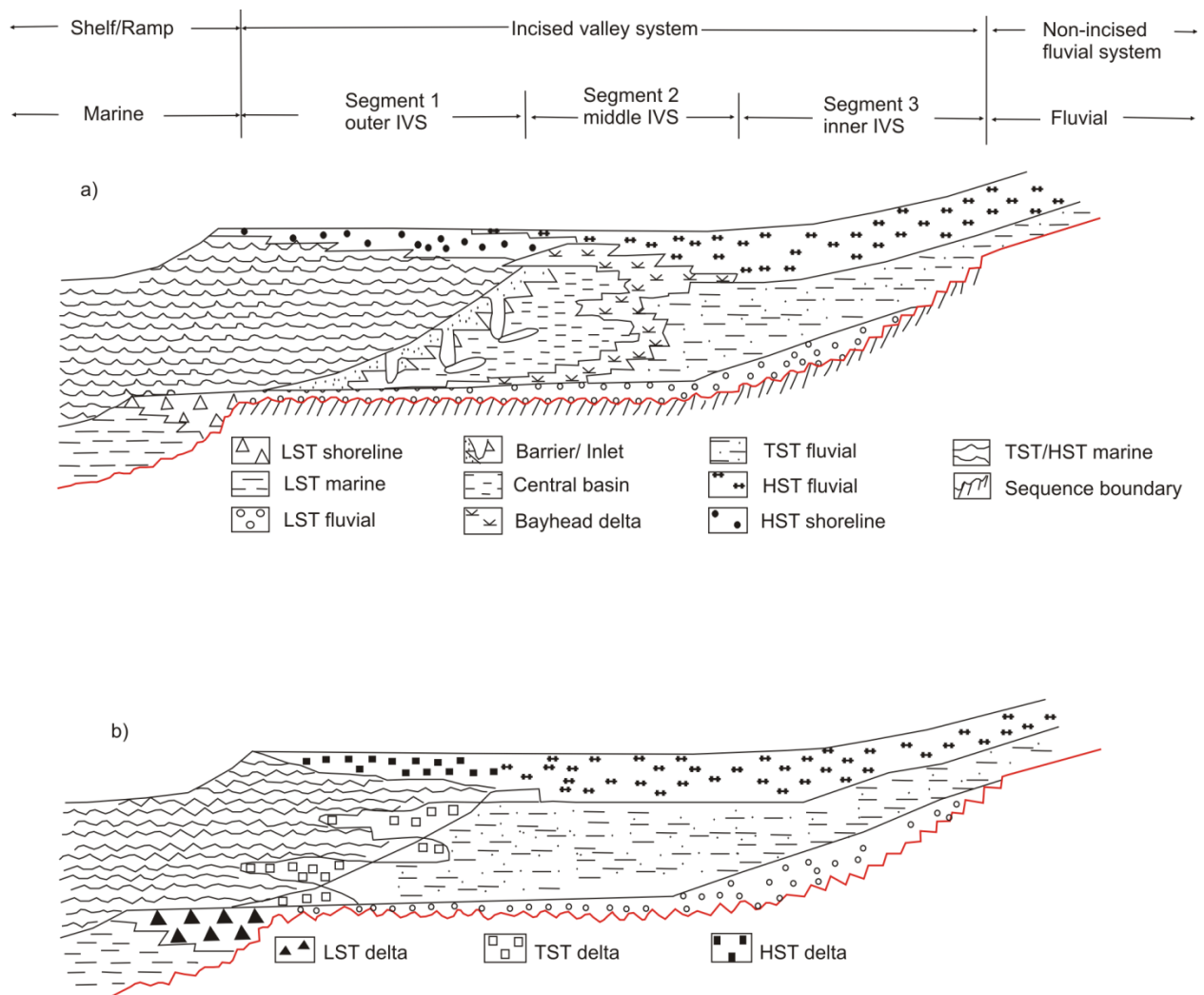
Base level change is a key factor in the development and infilling of incised valleys. Base level change is controlled primarily by two kinds of mechanisms: climatic and tectonic processes (Schumm, 1993; Williams, 1993; Coe et al., 2003; Catuneanu 2006; Tamayo et al., 2008; Catuneanu et al., 2009). Approximately five orders of cycles are recognised in the sedimentary record: first order: c. 50 to c. 200+ Ma; second order: c. 5 to c. 50 Ma; third order: c. 0.2 to c. 5 Ma; fourth order: c. 100 to c. 200 Ka; fifth order: c. 10 to c. 100 Ka (Coe et al., 2003). This dissertation will focus on the latter two cycles with regards incised valley creation and infilling.

The development of incised valleys during the fourth order cycles depends primarily on the rate and amplitude of sea level oscillations (Van Heijst and Postma, 2001). Vail et al. (1984) and Posamentier et al. (1988) propose that fluvial incisions related to Type 1 sequence boundaries (incisions formed when base level falls beyond the shelf-edge) result in the best developed incised valley systems. These incised valleys can extend from a highstand shoreline to the head of a slope canyon (Leeder and Stewart, 1996; Thieler et al., 2007). In some instances, when base level fall does not reach the shelf edge, the incision is then only restricted to a portion of the inner-shelf (Talling, 1998). This leads to the formation of piedmont incised valley systems, as described by Zaitlin et al. (1994), on top of Type 2 sequence boundaries associated only with normal regression. This is elaborated on by Posamentier (2001) who divides these into unincised valleys (when sea level did not fall below the shelf break) and incised valleys implying a drop in sea level below that of the shelf edge.

#### 2.1.1. The tripartite facies model of incised valley systems

Based on earlier facies models of incised valleys and estuaries (Wright, 1980; Rahmani, 1988; Dalrymple et al., 1992; Allen and Posamentier, 1993), Zaitlin et al. (1994) produced the classical model of a simple incised valley fill for both wave and tide-dominated estuarine systems. For the purpose of this dissertation, focus will be given to wave-dominated systems in light of the dearth of tide-dominated estuaries from the KwaZulu-Natal coast (c.f. Cooper, 2001). The original sequence stratigraphic model of a wave-dominated incised valley was based on the tripartite arrangement of facies in an estuary dictated by variations in marine energy (wave dominated zones), mixed fluvial/marine energy (flocculation dominated zones) and fluvial energy. The transgressive arrangement of facies within the incised valley as the estuary form translated landwards would thus produce a predictable succession of facies separated by unconformities formed by transitions between each energy zone. The main facies arrangement followed a coarse-fine-coarse sediment sandwich (cf. Ashley and Sheridan, 1994) representing a basal fluvial package (the bayhead delta), a finely draped central basin package that onlaps the valley sides, and a coarse sandy mouth plug package representing the deposition of barriers, washover fans and flood tide deltas. The main stratigraphic surfaces were considered the bayline (as

formed by the landward retreat of the bayhead delta), the tidal ravinement surface (formed by migration of the tidal channels and/or inlet over the central basin package) and the subaerial unconformity forming the base of the valley (Zaitlin et al., 1994; Ashley and Sheridan, 1994). This fill succession could be capped by shoreface deposits depending on where along the longitudinal valley profile the point is located; separated from the incised valley by a wave ravinement surface (Zaitlin et al., 1994) (Fig. 2.1).



**Fig. 2.1.** Idealised models for the two end-member types of incised valley fills. (a) An underfilled incised valley following the classic model of Zaitlin et al. (1994). (b) An overfilled incised valley of Simms et al. (2006). From Simms et al. (2006).

The model was further extended to include this variability in facies, recognised as discrete segments along the incised valley profile (Fig. 2.1a). Segment 1, is the outer segment (seaward), which extends from the lowstand mouth of the incised valley to the point where the shoreline stabilises at the beginning of highstand progradation. Zaitlin et al. (1994) propose that this segment is characterised by a transgressive succession of fluvial and estuarine facies, overlain by marine sands and shelf muds. Segment 2 (middle segment) is said to represent the area occupied by the drowned–valley estuary at the end of transgression, where lowstand to transgressive fluvial and estuarine facies are overlain by highstand fluvial deposits. The last, landward most segment (Segment 3), is situated between the transgressive marine/estuarine limit and the landward limit of incision (Fig. 2.1a). This segment comprises only fluvial facies. The fluvial style of these may change (they may be braided, meandering, anastomosed and/or straight in character) due to changes in sea level and the rate of accommodation formation (Zaitlin et al., 1994). According to Dalrymple et al. (1994), two classes of incised valleys are recognised; (1) those formed by erosion in response to a fall of relative sea level (i.e., due to a eustatic sea level fall or tectonic uplift of the coastal zone); and (2) those which are not related to sea level change (i.e. erosion is due to tectonic uplift of an inland area, or an increase in fluvial discharge caused by climate change; Schumm et al., 1987; Blum, 1992). The fluvial fill of these erosional valleys may begin to accumulate near the end of the lowstand, but typically contains sediments deposited during subsequent transgression.

### 2.1.2. Revised models

Simms et al. (2006) proposed a revised classification of incised valley systems, using examples of incised valleys along the Texas Coast (Brazos, Colorado, Rio Grande, Trinity, and Baffin Bay incised valley systems (Fig. 2.1b). They base this classification on the proportion of fluvial versus estuarine and marine fill. They suggest an extension of the Zaitlin et al. (1994) model, to include two end members with respect to fluvial sediments; over-filled incised valleys and under-filled incised valleys. Under-filled incised valleys, such as the Trinity and Baffin Bay incised valley systems, are suggested to contain estuarine and marine deposits which fit perfectly with the classic incised valley model (Simms et al., 2006). Over-filled incised valleys, such as

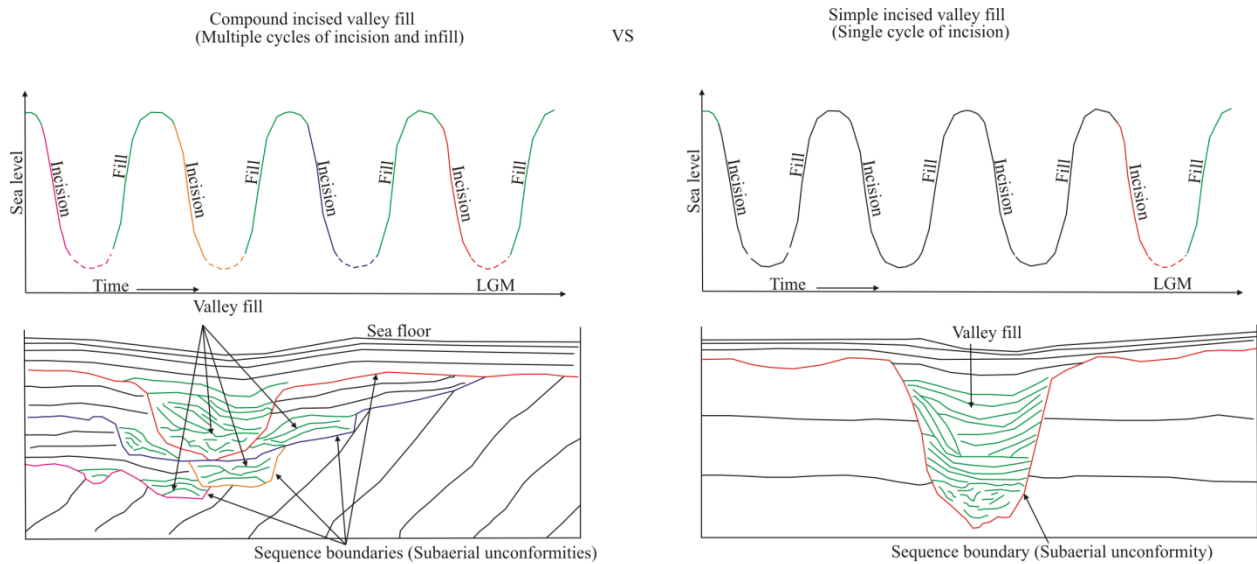
the Brazos and Rio Grande incised valleys, are completely filled with fluvial sediments and do not contain central-basin sediments, and therefore do not fit into the classic incised valley model. They have a fluvial inner segment and a fluvial deltaic outer segment (Simms et al., 2006). Recently Cooper et al. (2012) proposed a new type of incised valley system based on underfilling of the valley form. This type of incised valley system has a limited sediment supply from both the marine and fluvial perspective, has a fill dominated by slumping of the incised valley walls, and a condensed central basin section that reflects the only material deposited by the transgressive systems tract.

From a tectonically active perspective, Wilson et al. (2007) compare Holocene incised valley infill sequences from the Pakarae River (New Zealand) to widely used facies models for estuaries developed exclusively for tectonically stable coastal settings (e.g. Roy, 1984; Dalrymple et al., 1992; Allen and Posamentier, 1993; 1994). These models recognise a fluvial/flood plain environment, a central estuary basin and a barrier environment. The Pakarae River palaeoenvironment facies associations have some similarities with these facies divisions. However, the Pakarae estuarine facies, consisting of silts, sands and occasional thin shelly gravels are generally coarser and more variable than the equivalent facies described by the traditional models. The major difference observed between the Pakarae valley sequence and existing stable-coast models is within the middle part of the infill sequence where the estuarine and fluvial facies alternate at Pakarae instead of displaying deepening central estuary basin facies as proposed in the other models.

### 2.1.3. Compound and simple valley forms

Following Zaitlin et al.'s (1994) subdivision of incised valleys, incised valley systems can either be "simple-fill" or "compound-fill" depending on the number of recorded incision and infilling cycles (Fig. 2.2). A simple incised valley is one that only has one sequence boundary at the base of the fill, whereas a compound incised valley is one that is characterised by more than one sequence boundary, reflecting a polycyclic evolution with multiple cycles of incision and infill driven primarily by repeated base level changes (Zaitlin et al., 1994) (Fig. 2.2).

According to Maselli and Trincardi (2013), most Quaternary examples of incised valley systems are compound in nature and these are often detected on passive continental margins. Examples include the Gulf of Lions (Gensous and Tesson, 1996; Tesson et al., 2011), the Gulf of Mexico (Thomas and Anderson, 1994; Greene et al., 2007), and on strike-slip margins such as the Pacific U.S. coastline (Burger et al., 2001). Incised valley systems that are simple (as opposed to compound) in nature are less common, but have been documented (e.g. Chaumillon et al., 2008; Green, 2009). Maselli and Trincardi (2013) state that these incised valleys can be the result of either base level fall driven by the last glacial-interglacial cycle on active continental margins (Crockett et al., 2008), or can be ascribed to an interval of dramatically increased discharge, typically related to ice melting (Lericolais et al., 2003, Gupta et al., 2007; Thieler et al., 2007).



**Fig. 2.2.** Summary of typical Quaternary incised valley systems. Compound incised valley systems are shown on the left and simple incised valley systems on the right. After Maselli and Trincardi (2013).

#### 2.1.4. Seismic models of incised valley systems

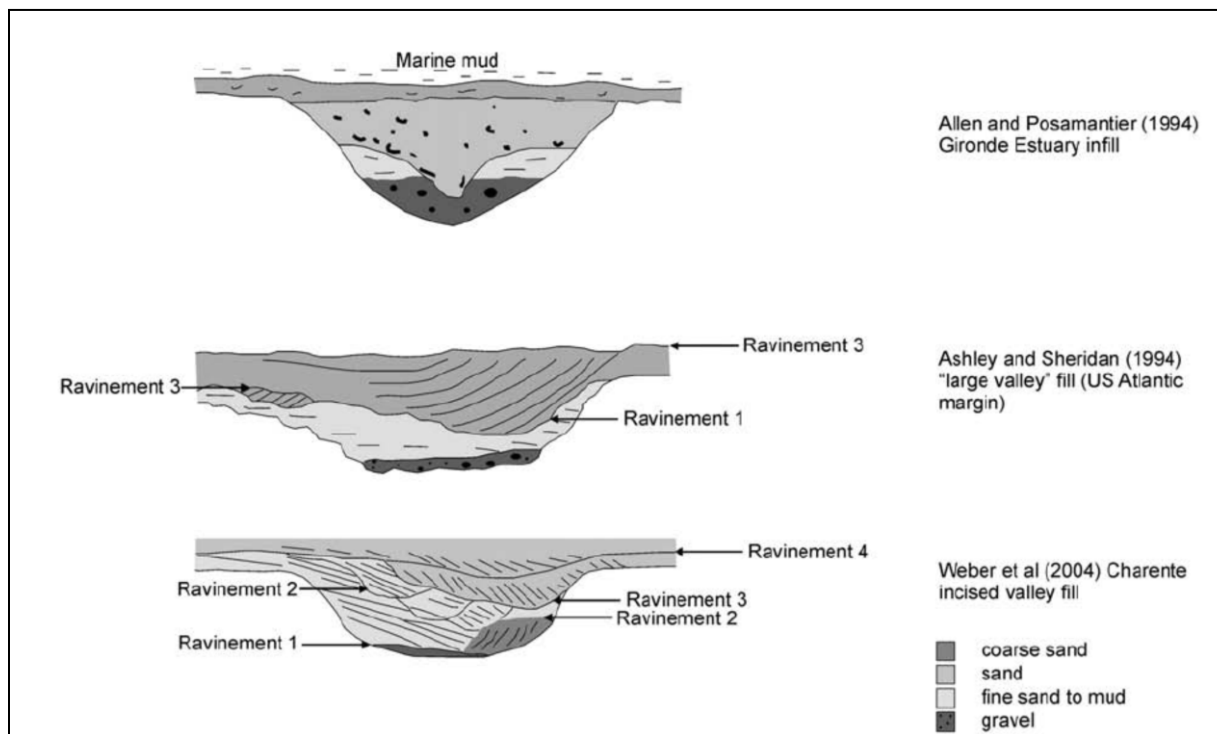
One of the most common means of examining incised valley systems is by seismic reflection survey. One of the most intensively studied shelves is that of New Jersey. Several incised valleys are documented beneath the New Jersey mid-outer shelf (Nordfjord et al., 2006). These incised valleys reveal a retrogradational shift of four seismic facies, preserved only in the stratigraphic record of the latest Quaternary-Holocene drowning and subsequent infilling of fluvial drainage systems. These developed on the shelf at or near the Last Glacial Maximum shoreline (LGM) (Nordfjord et al., 2006) and comprise basal chaotic facies (fluvial lag deposits), variably dipping, moderate amplitude facies (estuarine mixed sand and muds), low amplitude draped facies (central estuarine bay muds) and high angle, variably orientated prograding reflectors (redistributed estuary mouth sands) (Nordfjord et al., 2006).

As with the New Jersey shelf, the French Atlantic coast has been heavily studied from seismic perspectives (cf. Weber et al., 2004; Chaumillon and Weber, 2006; Chaumillon et al., 2008). Weber et al. (2004) recognised a “seismic sandwich” within the fill which they considered the equivalent of Ashley and Sheridan’s (1994) sediment sandwich (Fig. 2.3). These fills comprise high to middle-angle’ reflectors in the basal and uppermost fill units, interposed with low angle draped reflectors in the central portions. Since then many other models have validated these basic arrangement of seismic facies and their equivalent interpretations (e.g. Green, 2009).

#### 2.1.5. Global seismic studies of shelf hosted incised valley systems

The Delaware Bay estuary (Fletcher et al., 1990) shows similar seismic facies to those identified by Nordfjord et al. (2006) and Weber et al. (2004). Here, transgressive flooding of the estuary also occurred during the Holocene as the shoreline moved northwest along a path determined by pre-transgression topography (Fletcher et al., 1990). Transgressive palaeo-valley-fill successions have also been identified on the Virginia inner shelf (Foyle and Oertel, 1997). As with the New

Jersey Systems these incised valleys have been modified during marine transgression, as dendritic riverine drainage basins evolved to become estuaries (Foyle and Oertel, 1997).



**Fig. 2.3.** Schematic models from various studies of incised valley fills. Note the similarity in facies fill, with basal coarse material overlain by flat-lying central basin deposits of an idealised wave-dominated estuary, when compared to the Gironde Estuary infill model from the Atlantic French coast (Allen and Posamentier, 1994) and the large infill model of Ashley and Sheridan (1994) for the US Atlantic coast. The Charente Estuary's incised valley (fringing the French Atlantic coast) is different in that relatively higher angle reflectors comprise the base of the fill, indicating tidal scour and bar fill (From Green, 2009).

The Virginia shelf valley fills were however dominated by estuary-mouth deposits of the outer zone (e.g. Dalrymple et al., 1992; Zaitlin et al., 1994). Interestingly, the fluvial deposits on this shelf are said to be preserved only locally, immediately above the fluvial incision surface. This is different to the observations of Nordfjord et al. (2006) and Chaumillon and Weber (2006), where fluvial deposits are recognised throughout their survey area. Nordfjord et al. (2006) suggested that aggradation of lowstand fluvial lowstand deposits may not have occurred within the Virginia

inner-shelf fluvial valleys during the latest Pleistocene. Instead, higher relief fluvial channels, incising the emerging shelf during regression and lowstand, may have bypassed fluvial sediments seaward, toward the palaeo-shoreline.

Incised valleys mapped offshore the Mobile River in Alabama (Bartek et al., 2004) also appear to be morphologically and stratigraphically similar to New Jersey incised valleys. However, the vertical facies-stacking pattern observed here includes a well-developed, prograding bayhead delta facies, which differs somewhat from the stacking patterns preserved offshore New Jersey (Nordfjord et al., 2006). These incised valley systems offshore Alabama also appear wider, deeper and closer to the shoreline than the New Jersey examples (Bartek et al. 2004).

Liu et al. (2010) describe seismic profiles obtained from the Western Yellow Sea. These were subdivided into seven seismic units by six major seismic surfaces; the incised valley fills beginning with fluvial and the estuarine sediments. These were truncated by a transgressive ravinement surface and capped by transgressive deposits. Liu et al's (2010) model of incised valleys on the Western Yellow Sea conforms well with sedimentological models of contemporary incised valley fills proposed for other shelves, such as those mentioned above, in addition to the Northern KwaZulu-Natal continental shelf (Green, 2009) and the Bay of Biscay (Southwest of France; Lericolais et al., 2001).

#### 2.1.6. Incised valleys and classification schemes from the microtidal KwaZulu-Natal coastline

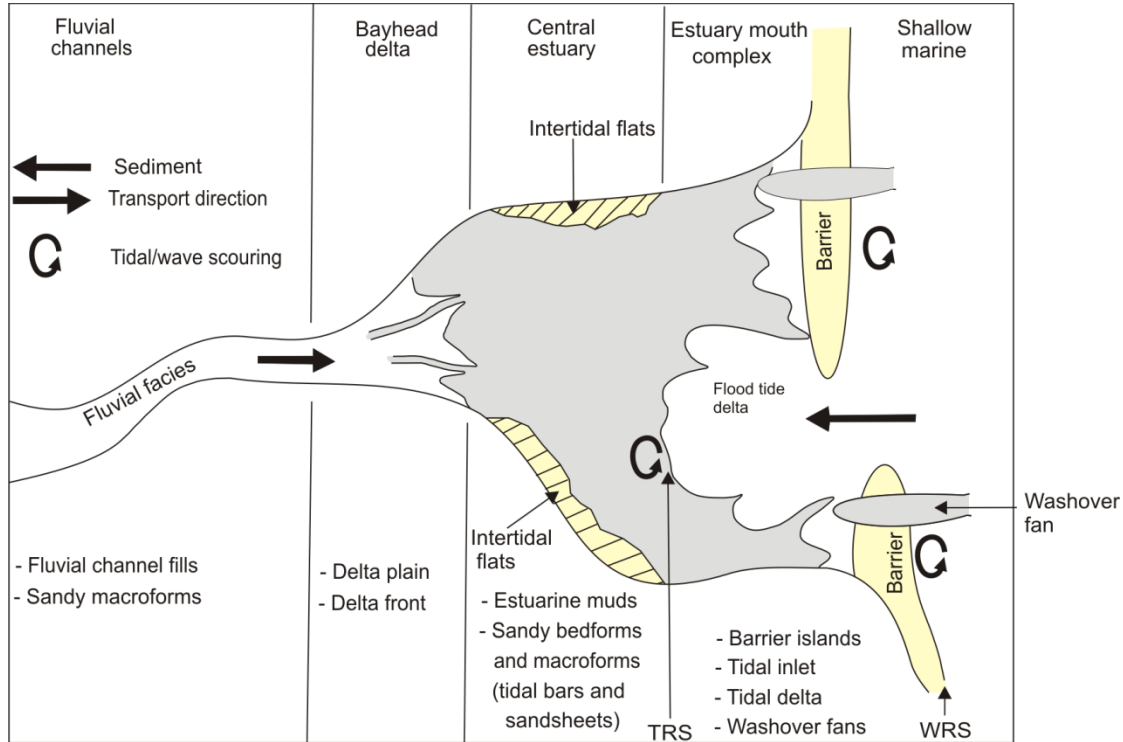
According to Cooper (2001), the South African coast is highly variable both geomorphologically and climatologically. The tidal range around this coast is relatively small when compared with most areas, experiencing a spring tidal range between 1.8 and 2.0 m rendering the coast microtidal (Davies, 1980). More than 300 independent river outlets are present around the microtidal, wave dominated South African coast (Cooper, 2001). Most of these rivers are situated in drowned river valley settings and have obtained their present morphology during the Holocene marine transgression (Cooper, 2001).

#### 2.1.6.1. Estuaries

In a South African context, Day (1980) defines an estuary as ‘a coastal body of water in intermittent contact with the open sea and within which sea water is measurably diluted with fresh water from land drainage’. Geomorphologically, estuaries form between land and sea and act as an interface between terrestrial and marine environments (Fig. 2.4). Estuaries are typically divided into those that are normally open (that maintain a semi-permanent connection with the open sea) and those that are commonly closed by a barrier and which achieve fluvial discharge through barrier seepage and evaporation losses (Cooper, 2001). According to Begg (1984), the coast of KwaZulu-Natal is dominated by open estuaries. Open estuaries include barrier-inlet systems maintained by fluvial discharge (these are termed river dominated estuaries) and tidal discharge (termed tide-dominated estuaries) (Cooper, 2001). Almost all estuaries in South Africa are said to be located in incised bedrock valleys and are thus laterally confined (Cooper, 2001).

##### 2.1.6.1.1. Tide-dominated estuaries

According to Cooper (2001), tide dominated estuaries may be defined as “ those that in spite of their low tidal range have sufficient tidal prism to permit their inlets to be maintained by tidal currents against longshore and cross-shore wave-driven littoral sediment transport”. Cooper (2001) states that these types of estuaries have been studied worldwide (Roy, 1984; Reddering and Esterhuysen, 1987; Cooper, 1993a; Nichol et al., 1994) and are regarded as the typical microtidal estuary. Tide-dominated estuaries commonly display a distinctive tripartite facies arrangement based on marine inputs at the inlet, fluvial inputs at the tidal head, and a quiet water suspension-settling-dominated zone in the middle reaches (Fig. 2.5a). They thus superficially resemble the tripartite model of Zaitlin et al. (1994).

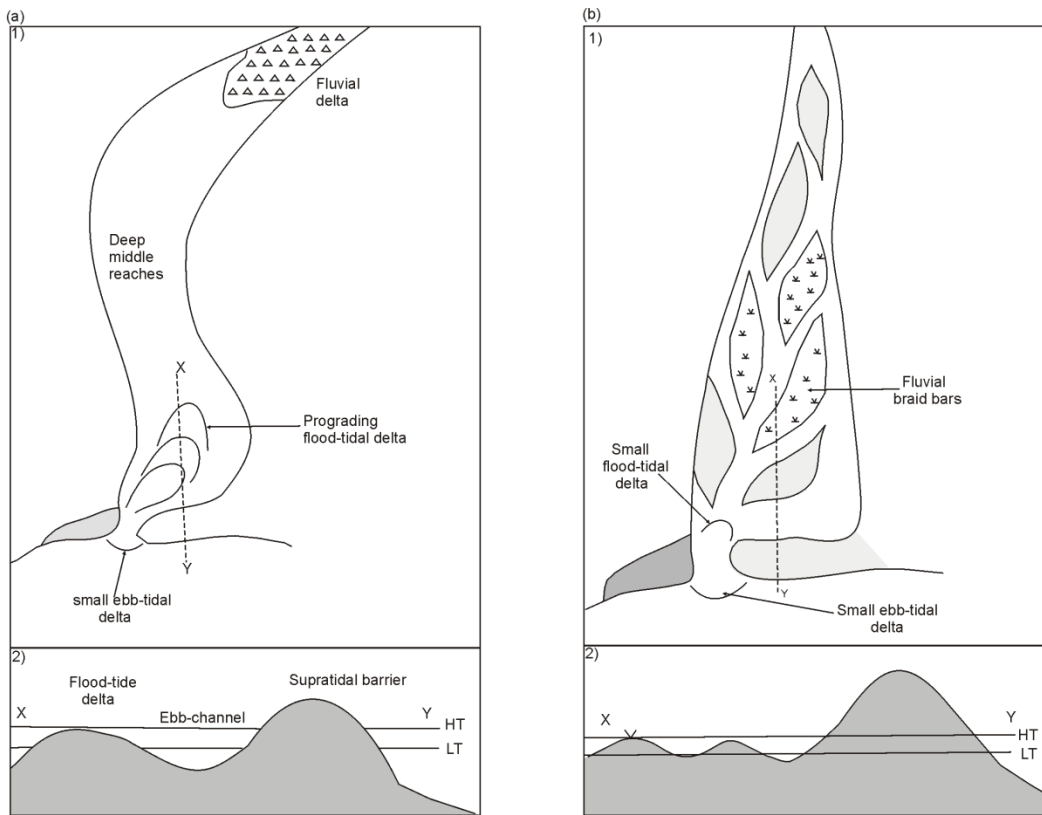


**Fig. 2.4.** Tidal- and wave-ravinement surfaces in a wave dominated estuarine setting (modified from Dalrymple et al., 1992; Zaitlin et al., 1994; Catuneanu, 2006).

#### 2.1.6.1.2. River dominated estuaries

River-dominated estuaries are defined as those in which “an inlet is maintained by fluvial discharge and in which the tidal prism is too small to generate currents adequate to overcome wave-induced sediment transport in the nearshore that acts to close the barrier inlet” (Cooper, 2001). River-dominated estuaries are very well developed in KwaZulu-Natal (Cooper, 1993b, 1994; Cooper et al., 1999). These systems are morphologically different from tide-dominated systems in that flood-tidal deltas are much reduced in size or completely absent (Cooper, 2001). Such estuaries are characterised by shallow or intertidally exposed back-barrier areas in which fluvial sediment extends close to or directly to the landward margin of the estuary barrier (Fig. 2.5b) (Cooper, 2001). Cooper (2001) attributes this to high fluvial sediment supply from a steep hinterland and deeply eroded catchments. Cooper (2001) further suggests that ebb-tidal deltas are relatively poorly developed or absent due to strong wave energy and flood-tidal deltas are small or absent due to weak tidal currents and lack of accommodation space in the sediment-filled

channel. A small flood-tidal delta was recorded in the Mgeni estuary (Cooper, 1988) (Fig. 1.1), while no flood-tide delta is present in the Mvoti estuary, 30 km north of it.



**Fig. 2.5.** (a) Generalised morphology of tide-dominated estuaries in plan (1a) and cross-section (2a). Note the flood-tidal deltas which may also show landward progradation and the small ebb-tidal delta which is confined by high wave energy. The fluvial delta marks the downstream limit of coarse-grained riverine sediments. (b) Generalised morphology of river-dominated estuaries in plan (1b) and cross-section (2b). Note the extension of riverine bars to the barrier and the small extent of flood- and ebb-tidal deltas. Figures modified from Cooper (2001).

### 2.1.7. Sequence stratigraphic framework and nomenclature

Catuneanu (2006) stated that sequence stratigraphy, in the simplest sense, deals with the sedimentary response to base level changes, which can be analysed from the scale of individual depositional systems to the scale of the entire basin. It emphasises facies relationships and strata architecture within a chronological framework (Catuneanu et al., 2009). Historically, sequence

stratigraphy is regarded as having stemmed from the seismic stratigraphy of the 1970s (Catuneanu, 2006).

#### 2.1.7.1. Systems tracts

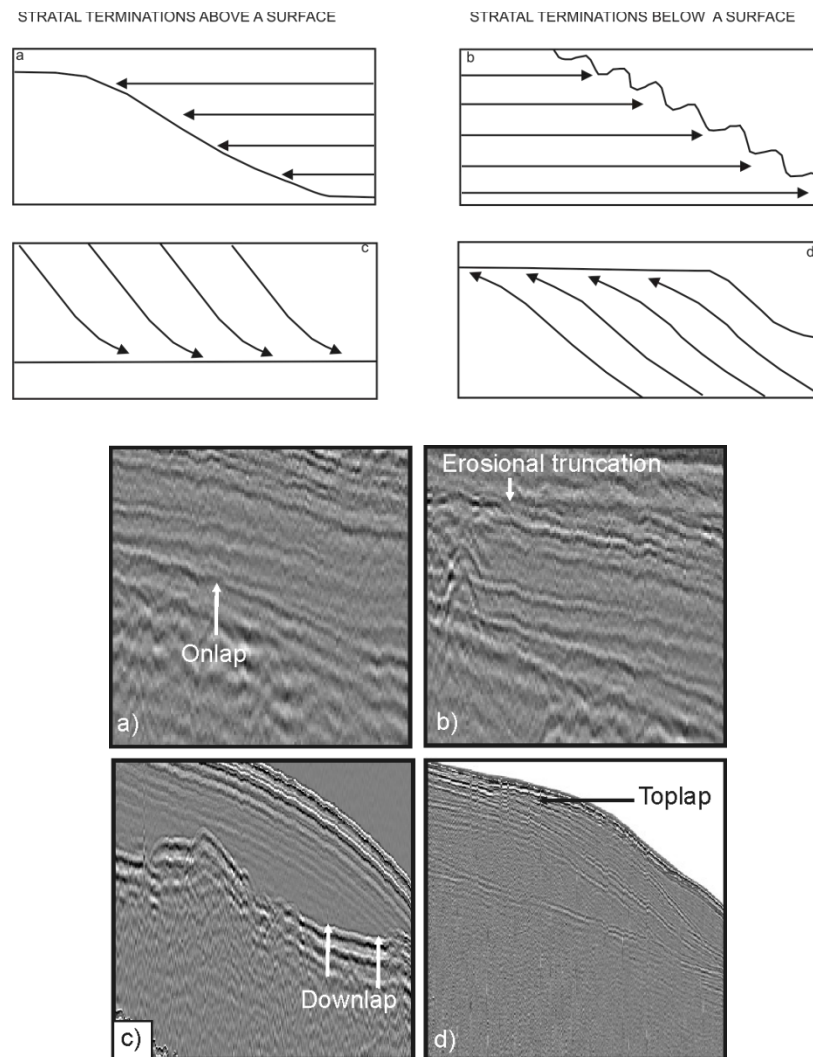
This dissertation recognises four systems tracts in each complete sequence: the falling stage systems tract (FSST), the lowstand systems tract (LST), the transgressive systems tract (TST) and the highstand systems tract (HST). The FSST represents periods of sea level lowering, starting at the point of maximum sea level and ending at the point of minimum sea level. Though controversial, Catuneanu (2006) interprets the FSST as consisting primarily of shallow-and deep-water facies, which accumulate at the same time with the formation of the subaerial unconformity in the non-marine portion of the basin. The sequence boundary is considered to form by subaerial erosion, normally associated with stream downcutting, basinward shift in facies and onlap of overlying strata (Catuneanu, 2006). This separates the FSST and LST deposits and usually occurs at the top of the FSST, though it may bind the HST in the proximal portions. The LST represents periods where sea level begins to slowly rise from its minimum level to the point where the rate of sea level rise begins to increase rapidly. Sediment at this stage is therefore deposited in a progradational-aggradational manner, as the rate of increase in accommodation space and the rate of sediment supply are balanced. The TST occurs once the rate of sea level rise is stabilised and ends where the rate of sea level rise begins to decrease. This point is marked by the regional development of a maximum flooding surface (MFS), indicating widespread proximal drowning and the onset of shallow marine sediment starvation. The LST and TST represent periods of time where the topography that was exposed or eroded during sea level lowering was subsequently infilled. The HST occurs when the rates of sea level rise drop below the sedimentation rates, thus sediment supply rates exceeds the rate of accommodation space creation. In this case, deposition trends and stacking patterns are dominated by a combination of aggradational and progradational processes.

#### 2.1.7.2. Stratigraphic surfaces

Zaitlin et al. (1994) suggest that the infill of incised valley system is characterised by numerous stratigraphically important surfaces. The sequence boundary is the surface that defines the valley form and is the most extensive surface of all, forming through a combination of fluvial incision within the valley form and subaerial exposure of the interfluves (Zaitlin et al., 1994). According to Catuneanu (2006), transgressive ravinement surfaces are scours formed by tides and/ or waves during the landward shift of the shoreline. The tidal ravinement surface is produced by erosion in the base of the deepest tidal inlet or other tidal channel (Zaitlin et al., 1994). Zaitlin et al. (1994) suggests that these channels are typically associated with the estuary mouth, barrier/flood tidal delta complex of wave-dominated estuaries or with sand bars and flats which extend along the entire length of tide-dominated estuaries. According to Dalrymple et al. (1992) and Harris (1994), in tide-dominated shelf settings, tidal ravinement may also take place on the shelf itself. The maximum flooding surface (MFS) (Frazier, 1974; Posamentier et al., 1988; Van Wagoner et al., 1988; Galloway, 1989) corresponds to the time of maximum transgression. This surface is said to separate retrograding strata below from prograding strata above (Catuneanu, 2006).

#### 2.1.7.3. Stratal terminations

“Stratal terminations are defined by the geometric relationship between strata and the stratigraphic surface against which they terminate” (Catuneanu, 2006). The main types of stratal terminations include truncation, onlap, downlap, toplap and offlap (Fig. 2.6). Catuneanu (2006) states that apart from truncation; these stratal terminations were introduced as early as the 1970’s by authors such as Mitchum and Vail (1977) with the development of seismic stratigraphy to define the architecture of seismic reflectors. These were later adopted for sequence stratigraphic purposes (e.g. Posamentier et al., 1988; Van Wagoner et al., 1988).



**Fig. 2.6.** Types of stratal terminations above and below a surface (modified from Emery and Myers, 1996) with seismic images depicting actual examples. (a) onlap, (b) truncation, (c) downlap and (d) toplap.

## CHAPTER 3

### Regional setting

#### 3.1. Regional setting

The continental shelf of the Durban area is relatively narrow (~ 18 km) when compared to the global average of ~ 50 km (Shepard, 1963). The shelf is considered to be one of the World's narrowest (Martin and Flemming, 1988). Cawthra et al. (2012) states that areas with similar shelf widths include central Brazil (Natal-Salvador), the African northwest coast (Western Sahara to Morocco), the east coast of Japan, the west coast of North America (near California) and the east coast of New Zealand. Based on Goodlad's (1986) subdivision of the continental shelf of eastern South Africa, the shelf is divided into the wider physiographic zone identified between Durban and Cape St. Lucia, though the shelf is significantly narrower than that of the Thukela Cone (~ 45 km) to the north (Goodlad, 1986) (Fig. 1.1). The shelf break occurs at a depth of ~ 100 m, 20 m above the last glacial maximum (LGM) shoreline of ~ 18000 BP (Ramsay and Cooper, 2002). Morphologically, the Durban Bight is dominated by a large crenulate bay at its southernmost point (the Bluff) (Fig. 1.1), straightening towards the Mgeni River. Thereafter, the shoreline comprises a straight swash-aligned planform with a very narrow (< 1 km) coastal plain (Fig. 1.1).

#### 3.2. Hinterland topography and drainage

KwaZulu-Natal is situated on the eastern side of the Great Escarpment of South Africa (Fig.1.1). The Great Escarpment rises to over 3300 m above sea level, and is situated approximately 230 km from the coast (Cooper, 1991). The hinterland gradient is thus steep and drainage systems are comparatively short, characterised by high flow velocities and large volumes of sediment transported to the coastline (Cooper, 1991). These rivers are restricted to individual catchments with steep divides. Together with the extremely narrow coastal plain in the study area, these factors foster the development of discrete inlets at the coast with little to no overlap of the systems (Cooper, 2001). Onshore from the study area, three main rivers drain the hinterland and

reach the coastline. These are from south to north: the Mgeni, Mhlanga and Mdloti Rivers (Fig. 1.1). The Mgeni River is the largest river in the Durban area. It spans a length of ~ 232 km with a catchment area of ~ 4500 km<sup>2</sup> making it the fourth largest river to discharge into the Indian Ocean offshore KwaZulu-Natal (Badenhorst et al., 1989). It originates in the foothills of the Drakensberg Mountains at an elevation of 1889 m (Tinmouth, 2010) and drains a variable series of geological units, most notably the granites and gneisses of the Natal Metamorphic Province (Johnson et al., 2006). Comparably, the Mhlanga and Mdloti Rivers are much smaller. The Umdloti River drains a catchment of ~ 484 km<sup>2</sup> and has an estimated length ranging from 74-88 km (Begg, 1978). The Mhlanga River is the smallest of the three; possessing a catchment area of ~ 80 km<sup>2</sup> and a river length of 28 km (Begg, 1978).

### 3.3. Oceanography and shelf sedimentology

High wave activity dominates the east coast of South Africa (Smith et al., 2010). Here, the Agulhas Current, a coast parallel western boundary current which sweeps polewards with a core generally just offshore the shelf break, impinges on the continental shelf (Schumann, 1988). According to Lutjeharms (2006) where the shelf is narrow, this current can reach a mean speed of 2 m.s<sup>-1</sup>. The Agulhas Current influences both the physical and biological processes on the continental shelf and is thus responsible for the range of sedimentological and biological features found therein (Ramsay, 1994). Large-scale subaqueous dunes are generated in the unconsolidated shelf sediment under the influence of strong Agulhas Current flow, with a dominantly south easterly transport direction (Flemming 1978, Flemming 1981; Flemming and Hay, 1988, Ramsay, 1994 and Ramsay et al., 1996). It must however be mentioned that in isolated areas, the shelf is dominated by the influence of a clockwise gyre, resulting in sediment being transported towards the north (evident from northward-migrating dune fields) (Ramsay, 1994).

### 3.4. Regional geology

The study area's shelf forms part of the Durban Basin, a complex Mesozoic rifted feature which originated during the early phase of extension along the east African continental plate prior to the breakup of Gondwana (Dingle and Scrutton, 1974; Dingle et al., 1983; Broad et al., 2006). Goodlad (1986) describes the Thukela Cone (Fig. 1.1) as a deep-water fan complex, located seaward of the continental shelf. It began prograding into the Natal Valley area of the Mozambique Channel in the early Cretaceous (Goodlad, 1986). According to Dingle and Scrutton (1974); Dingle et al., 1983; and Goodlad (1986), the Natal Valley formed from the withdrawal of the Falkland Plateau, and its proximity has resulted in a narrow (~ 15 km) continental shelf and a steep continental slope. This resulted in limited preservation of post-Cretaceous sedimentation on this portion of the continental shelf, with most of the sediments having been transported offshore into the deep marine environment (Dingle et al., 1983; Green and Garlick, 2011).

The early Cretaceous drift succession is very localized (McMillan, 2003). Sedimentation patterns during this period were almost entirely controlled by the relative availability of accommodation space (caused by sea-floor subsidence, still-stand or uplift of different parts of the southern African continental margin) (McMillan, 2003). Rocks of the drift succession comprise shelfal claystones and siltstones of late Barremian to early Aptian age (McMillan, 2003). Drift sedimentation was episodic (McMillan, 2003), marked by deposition during the early Santonian and late Campanian with several hiatuses. Subsequently, depocentre amalgamation was accompanied by deposition of thick (>900 m) successions of marine claystones of late Campanian to late Maastrichtian age. These conform to the Mzinene and St. Lucia Formations respectively (Kennedy and Klinger, 1972; Dingle et al., 1983; Shone, 2006). The study area is underlain mostly by early Santonian age rocks upon which a thin veneer of Pleistocene and Holocene sediment rests (Green and Garlick, 2011). Pleistocene age material occurs mostly as remnant onshore palaeo-dune cordons, while offshore equivalents formed during lower sea level stillstands. Cemented portions of these are preserved as coast-parallel, submerged reef systems (Martin and Flemming, 1988; Ramsay, 1994; Bosman et al., 2007). Around Durban partially

cemented calcareous sandstones and unconsolidated clay-rich sands are preserved as the a) Berea and Bluff Ridges, and b) the Isipingo Formation (Anderson, 1906; Krige, 1932; King, 1962a, b; McCarthy, 1967; Dingle et al., 1983; Martin and Flemming, 1988; Roberts et al., 2006).

Holocene sediments are restricted to the modern day progradational highstand sediment prism on the shelf and to unconsolidated muddy deposits in the swampy backbarrier areas of the Durban coastline and adjacent estuaries such as the Mgeni, Mhlanga and Mdloti Estuaries (McCarthy, 1967). Tertiary aged deposits are considered absent from the coastal plain and shelf of the study area (Dingle et al., 1983). According to many authors (e.g. Wigley and Compton, 2006; Compton and Wiltshire, 2009), during the Neogene period both the western and eastern margins of South Africa were characterised by major uplift induced cycles of erosion (Partridge and Maud, 1987) prompting large portions of the Tertiary successions to be eroded. However, Green and Garlick (2011) recognised thin, isolated incised valley fills of suspected latest Pliocene/early Pleistocene age within the shelf stratigraphy.

### 3.5. Regional seismic stratigraphic models

#### 3.5.1. Green and Garlick's (2011) regional seismic stratigraphy

Green and Garlick (2011) represent the results of the first high resolution single-channel seismic survey undertaken across the continental shelf offshore Durban (Durban Bight area), providing an integrated study with published onshore and offshore lithostratigraphic data from the area. Seven seismic units (A to G) were resolved beneath the continental shelf offshore Durban, identified on the basis of seismic impedance, reflection termination patterns, internal-reflection configuration and bounding acoustic reflectors. These are presented in table 3.1 and summarised here:

- Unit A, a retrograding, early Santonian package of sedimentary rocks representative of a transgressive systems tract.

- Unit B, a prograding /aggrading (normal regressive) highstand systems tract (HST) wedge of a suspected late Campanian age.
- Unit C, a late Maastrichtian age shelf prograding wedge of falling stage systems tract (FSST) origin.
- Unit D, isolated laterally discontinuous incised valley fills.
- Unit E and F, acoustically opaque ridge-like drowned shoreline deposits.
- Unit G, the contemporary HST Holocene wedge, the basal most portions of which comprise lowstand systems tract (LST) and transgressive systems tract (TST) incised valley fills.

### 3.5.2. Cawthra et al.'s (2012) regional seismic stratigraphy

Cawthra et al. (2012) recognised eight seismic units (A-G) offshore south of Durban (Bluff area). Cawthra et al.'s (2012) interpretations of the seismic units are similar to those of Birch (1996) and Martin and Flemming (1986; 1988), but are considerably more detailed. Cawthra et al.'s (2012) study recognises regional Sequence Boundaries (SB1, 2 and 3), Maximum Flooding Surfaces (MFS1 and 2) and Wave Ravinement Surfaces (WRS 1 and 2). These are presented in table 3.2 and summarised here:

- Units A to C define the late Cretaceous drift sequence from the Upper Santonian to the late Maastrichtian.
- Unit D is interpreted as late Pliocene in age with a basal facies indicative of basinward advance related to early Pliocene regression. This is overlain by Upper Pliocene deposits, shaped by the transgression which marked the subsequent onset of the Quaternary period.
- Units E and F represent Quaternary deposits (cordons of aeolianite and interdune deposits of the Pleistocene).
- Unit G represents the Holocene sediment wedge, characterised by relict and modern shoreface-attached ridges.

### 3.5.3. Green's (2011) regional seismic stratigraphy

According to Green (2011), high resolution single-channel seismic data reveal seven seismic units (A–G) from the narrow and steep upper portions of the sheared passive continental margin of northern KwaZulu-Natal. These are presented in table 3.3 and summarised here:

- Unit A comprises an aggradational/progradational unit of suspected middle Maastrichtian age. Separated from the overlying unit by a subaerial unconformity surface SB1. Forms sequence 1.
- Units B (progradational) and C (onlapping, sheet like) form sequence two and span the late Cretaceous (late Maastrichtian) to mid-late Palaeocene times.
- Unit D are aggradational to progradational deposits, deposited during shelf margin advance linked to hinterland uplift.
- Unit E is an assortment of aggradational progradational shelf-edge and shelf margin reflectors. The age of unit E is late Pliocene (Green et al., 2008).
- Unit F represents a series of shorelines formed during Oxygen Isotope Stage (OIS) 5a to 2 on the regressive and transgressive limbs preceding and following the Last Glacial Maximum (LGM).
- Unit G, the uppermost unit, formed during the OIS 2 transgression to present mean sea level and reflects the subsequent development of the contemporary highstand wedge.

Seismic-Stratigraphic Models for Late Pleistocene/Holocene Incised Valley Systems on the Durban Continental Shelf.

Underlying horizon	Seismic Unit/Surface	Seismic Facies	Modern Description	Thickness	Stratal Characteristics	Interpreted Depositional Environment	Systems Tract	Sequence	Age
-	A	SF1-6A, separated by reflectors a-e	Outer to mid-shelf retrograding parasequence. Subordinate incisions and fills	>20 m	Moderate amplitude parallel to sub-parallel, high continuity, dip shallowly to SE	Outer to mid-shelf	Early TST	1	Early Santonian
	MFS		Condensed horizon		Very high amplitude smooth planar surface, dipping shallowly to SE	Outer-mid shelf	Maximum Flooding Surface	1	
MFS	B		Inner shelf aggradational to progradational parasequence	>55 m	High amplitude parallel to sub-parallel, high continuity, dip shallowly to SE, downlap MFS	Inner shelf to littoral zone	HST	1	Late Campanian
	SB1		Outer to mid-shelf prominent reflector		Erosional truncation of B, undulating surface, dipping shallowly SE		Sequence Boundary		
MSFR	C		Outer shelf prograding wedge	>18 m	Moderate to high amplitude parallel to oblique parallel, high continuity, dipping shallowly SE, downlap MSFR	Outer shelf to shelf edge	FSST	1	Late Maastrichtian
	SB1		Entire shelf prominent reflector		Erosional truncation of A, B and C, undulating incised surface, no dip		Sequence Boundary		K/T boundary
Major hiatus spanning most of the Tertiary									
SB1	D		Isolated, laterally discontinuous incised valley fill		Moderate amplitude, chaotic, onlapping and lateral accretion fills	Incised valley fill	Late LST-TST	?	Latest Pliocene
	E		Inner-outer shelf stranded sediment outcrop	8 m	Very high amplitude, unrecognisable reflectors, very rugged appearance, welded onto underlying unit	Late Pliocene palaeo-coastline	Stillstand	2	Early Pleistocene
	E	SF1Ei	Fill within saddles of Unit E		Low amplitude drapes	Backbarrier fill	TST	2	Early Pleistocene
	F		Mid-outer shelf stranded sediment outcrop	5-12 m	Very high amplitude, unrecognisable reflectors, very rugged appearance, welded onto underlying unit	Late Pleistocene palaeo-coastline	Stillstand	3	Late Pleistocene
	SB2		Entire shelf prominent reflector		Erosional truncation of A, E and F, undulating deeply incised surface, flat interfluvial		Sequence Boundary		LGM
SB2	G	SF1Gi	Incised valley fill		Moderate amplitude, chaotic, onlapping and lateral accretion fills	Incised valley fill	Late LST-TST		Late Pleistocene/Holocene
	G	SF1-4G separated by reflectors f-h	Seaward thinning shore attached wedge.	10 m	Low amplitude, weakly layered reflectors, downlap and onlap SB3. Small prograding packages, separated by flooding unconformities. Overall retrogradational stacking.	Holocene innershelf wedge	TST	4	Holocene to Present

**Table 3.1.** Seismic stratigraphic units, facies, bounding surfaces and stratal characteristics of the Durban Bight continental shelf. Included here are the interpreted environment of deposition, systems tract and age (Green and Garlick, 2011).

## Seismic-Stratigraphic Models for Late Pleistocene/Holocene Incised Valley Systems on the Durban Continental Shelf.

Underlying Horizon	Seismic Unit/	Seismic facies/	Modern description	Thickness	Strata characteristics	Interpreted depositional environment	Systems tract	Sequence	Age
Reflector g	G	G2	Shore attached prograding wedge	<12 m	Acoustically transparent, Low amplitude divergent reflectors	Inner to mid-shelf sediment wedge	LST-TST	5	Holocene
WRS 2		G1		<10 m					
SB3		WRS 2	Stranded sediment outcrops of the inner shelf			Marine Flooding Surface reworked by transgressive wave base migration	Wave Ravinement Surface	5	
		SB3	Extensive reflector spanning the entire shelf		Erosional truncation of Units E and F, low angle, incised, planar surface	Pleistocene-Holocene boundary	Sequence boundary	4	LGM
SB 2/ E	F2		Inner-shelf: associated with E	2-5 m	Acoustically semi-transparent or transparent, adjacent to, capping or intercalated deposit associated with E	Unconsolidated Aeolian material;	LST	4	Pleistocene
	F1			1-3 m		Back-barrier interdune deposits			
SB2	E		Inner to outer-shelf isolated ridges	< 19	High acoustic impedance of chaotic internal configuration. Rests on SB2	Aeolianite/beachrock palaeoshorelines	LST-TST-HST-FSST	4	Pleistocene
		MFS 2	Prevalent surface on shelf edge, grades into SB2		Capping of underlying transgressive sediments	Late Pliocene-early Pleistocene boundary	Maximum Flooding Surface	3	Late Pliocene-early Pleistocene
WRS 1	D	SFD2	Retrograding wedge on upper slope	5 m	Low amplitude oblique reflectors, onlapping WRS1	Shelf-edge progradation during sea level rise	TST	3	Pliocene
Reflector f					Erosional truncation of D1				
		WRS 1	Thinly developed retrograding unit		High angle prograding reflectors onlapping SB2	Marine Flooding Surface reworked by wave base migration	Transgressive Ravinement Surface		
			Buried slope prograding wedge			Outer-shelf aggradation and progradation during relative sea level fall			
SB2		SFD1		7 m			FRST		
SB2		SB2	Extensive reflector spanning the entire shelf		Erosional truncation of Units A, B and C, incised, planar surface	Cretaceous-Tertiary boundary	Sequence Boundary		Cretaceous-Tertiary

**Table 3.2.** Seismic stratigraphic units, seismic facies, bounding surfaces, stratal characteristics of the Durban Bluff (Cawthra (2010); Cawthra et al. (2012)). Included here are the interpreted environments of deposition, systems tract, age and sequences to which each belong.

Seismic-Stratigraphic Models for Late Pleistocene/Holocene Incised Valley Systems on the Durban Continental Shelf.

SB1	C	SB1	Moderate amplitude, parallel to sub-parallel sigmoidal reflectors	48 m	Oblique progradation of reflectors	Shelf-edge aggradation and progradation	FRST-FSST		Late Maastrichtian
SB1		SB1	Prominent reflector of the outer-shelf		Erosional truncation of Unit B, planar surface	Steeply dipping Surface of the outer shelf forming the upper continental slope	Sequence Boundary; Correlative Boundary	2	Late Campanian-early Maastrichtian
Reflector e		SFB3	Outer-shelf aggradational to progradational parasequence; subordinate incisions on upper boundary	22m	High amplitude reflectors. Toplap SB1	Littoral zone (end of transgression)	Late HST	1	
Reflector d	B	SFB2	Mid- to outer-shelf aggradational to progradational parasequence; subordinate incisions on lower boundary	5 m	Moderate amplitude sub-parallel reflectors. Downlap reflector d	Inner-shelf shallow marine (decelerating base-level rise)	Mid HST	1	Campanian
MFS 1		SFB1	Mid-shelf aggradational to progradational parasequence	44 m	Moderate amplitude oblique reflectors. Onlap and downlap MFS1	Inner-shelf (decelerating base-level rise)	Early HST	1	
		MFS 1	Condensed horizon		Planar surface dipping up to 10° to the east	Late Santonian- early Campanian boundary	Maximum flooding surface	1	Late Santonian-early Campanian
Reflector c		SFA4	Mid-outer shelf retrograding parasequences	5 m	Moderate amplitude parallel to sub-parallel reflectors	Inner-shelf (transgression rapidly ensued)	Late TST	1	
Reflector b		SFA3	Mid-outer shelf retrograding parasequence; Subordinate incisions on upper boundary	17 m	High amplitude divergent reflectors. Onlap and downlap reflector b	Mid-to inner-shelf (transgression ensued less rapidly)	Mid-late TST	1	Early Santonian
Reflector a	A	SFA2	Inner-outer shelf retrograding parasequence; Subordinate incisions on upper boundary	19 m	Moderate amplitude divergent reflectors. Onlap and downlap reflector a	Mid-shelf (transgression ensued less rapidly)	Early-mid TST	1	
Boulder bed		SFA1	Inner-shelf aggrading parasequences	>27 m	Moderate amplitude parallel reflectors	Outer-shelf (transgression ensued rapidly)	Early TST	1	

**Table 3.2.** Seismic stratigraphic units, seismic facies, bounding surfaces, stratal characteristics of the Durban Bluff (Cawthra (2010); Cawthra et al. (2012)). Included here are the interpreted environments of deposition, systems tract, age and sequences to which each belong.

Seismic-Stratigraphic Models for Late Pleistocene/Holocene Incised Valley Systems on the Durban Continental Shelf.

Underlying horizon	Seismic Unit	Seismic Facies	Modern Description	Thickness	Stratal Relationship	Interpreted Depositional Environment	Systems Tract	Sequence
-	A	A1	Mid-upper slope prograding acoustic basement. Subordinate incision	> 110 m	High amp. parallel to sub parallel clinoforms, high continuity, dip shallowly to SE		FSST (?)	1
		A2	Mid slope incised channel fill	10-20 m	Onlapping lateral accretion fill	Estuarine	Late FSST	
		A3	Mid slope incised channel fill	10-20 m	Onlapping drape fill	Abandoned estuarine/ fluvial channel	Late FSST	
Surface of subaerial erosion SB1			Mid to upper slope prominent reflector		Erosional truncation of A, incised undulating surface, dip towards SE		Sequence Boundary	
SB1	B	B1	Inner shelf connected aggradational/progradational wedge	> 110 m	High amp. oblique parallel-sub parallel clinoforms, high continuity, dip shallowly to SE, onlap SB1, may downlap SB1 in deeper sections	Marine deltaic	LST	2
		B2	Mid-upper slope incised channel fill	< 35 m	Onlapping drape fill	Incised valley fill	LST	
Maximum surface of regression (MR1)	C	C	Mid slope, thinly developed retrogradational unit	< 20 m	Onlapping low amplitude, low continuity reflectors. Not always present	Deeper marine sequence	TST	2
Major erosional hiatus-spanning ~Late Cretaceous-Miocene "Angus"								
Major erosional hiatus- spanning the Mid Pliocene "Jimmy" (Dingle et al, 1978)								
BSF	D	D1	Landward unit at base of shelf edge wedge		Low amp. high continuity oblique sigmoidal to tangential clinoforms. Downlaps MFS.	Shelf margin clinoform	FSST	3
Flooding surface		D2	Buried mid slope retrograding wedge		Low amp. high continuity oblique parallel clinoforms. Onlap successively more distal and deeper, downlap BSF and/or MR1.	Shelf margin clinoforms	FSST	
Subaerial unconformity/correlative conformity SB2		D3	Mid-upper slope retrograding wedge		Low amp. high continuity sigmoid oblique clinoforms, onlap the subaerial u/c in proximal sections, downlap MR1 and/or BSF	Shelf edge delta aggradation progradation during SL rise	LST	4
Subaerial unconformity SB2		D4	Incised channel fill	< 10 m	Onlapping drape fill	Delta top distributary channel infill	LST	
		E4	Outer-mid shelf landward extent of self-edge wedge	Obscured by multiple	Low amp, low continuity, irregular reflectors. Onlaps SB2/RS1 (?) grades into E1-3. Toplaps E3.	Shelf aggradation and retrogradation during relative SL rise.	HST	

**Table 3.3.** Summary table of Green's (2011) stratigraphic units A-G and subordinate facies, interl reflectr geometry, unit thickness bounding surfaces, interpreted environment of deposition, systems tract and sequence number.

Seismic-Stratigraphic Models for Late Pleistocene/Holocene Incised Valley Systems on the Durban Continental Shelf.

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Major erosional hiatus-spanning Late Pliocene-Early Pleistocene (?)								
Unknown	E	E	Inner-outer shelf attached wedge	< 25 m	Channelled internal reflection config. High acoustic impedance. Truncates topsets of D3 and incises into D4	Shallow marine nearshore facies	?	?
Multiple surfaces as G is diachronous	F	F	Inner-outer shelf stranded sediment outcrop	< 35 m	High acoustic impedance, rests erosionally on E/D3-4/D1. Truncates topsets of D3 and incises into D4	Late Pleistocene Aeolianite/beachrock. Palaeoshoreline.	Any sea level cycle?	?
Subaerial unconformity SB3	G	G1	Shore connected prograding wedge	< 50 m	Acoustically transparent, low amplitude obliquely divergent reflectors, downlaps SB2 and wave ravinement surface of underlying valley fill	Holocene inner shelf wedge	HST	5
Subaerial unconformity SB3		G2	Incised valley fill	< 80 m	Onlapping drape fill	Transgressive fill of incised river valley	LST-TST	

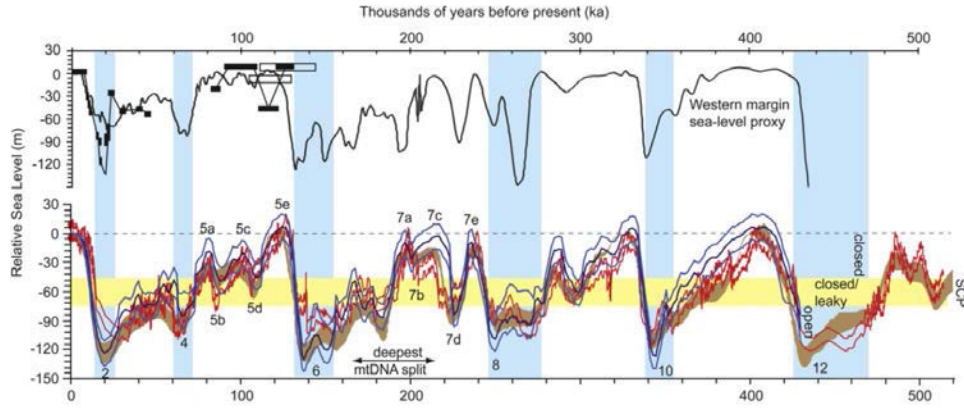
**Table 3.3.** Summary table of Green's (2011) stratigraphic units A-G and subordinate facies, internal reflector geometry, unit thickness, bounding surfaces, interpreted environment of deposition, systems tract and sequence number.

### 3.6. Sea level changes

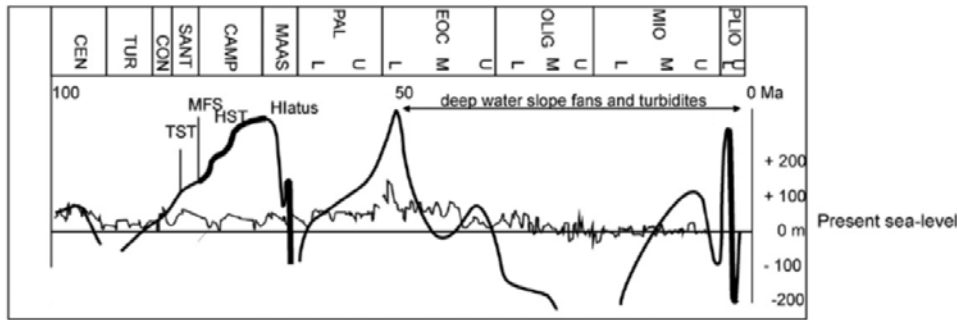
Local changes in sea level along the coastal plain of South Africa may have been influenced by tectonic uplift or subsidence (Compton, 2011). However, these factors are assumed to have been insignificant for the coastline in comparison to the larger amplitude variations in global sea level on glacial to interglacial cycles (Compton, 2011). This assumption is corroborated by the sea level curves derived for the South African margin which show general agreement with global records since the Last Interglacial (Ramsay and Cooper, 2002; Carr et al., 2010) and for the timing of sea level fluctuations since 440 Ka (Compton and Wiltshire, 2009). The composite global relative sea level curve of Waelbroeck et al. (2002) spans the last 450 000 years to present (Fig. 3.1), the compilation of which is based on statistical comparison between relative sea level (RSL) estimates derived from corals and other evidences and high-resolution  $\delta^{18}\text{O}$  records.

#### 3.6.1. Cretaceous to Tertiary Sea level Variations

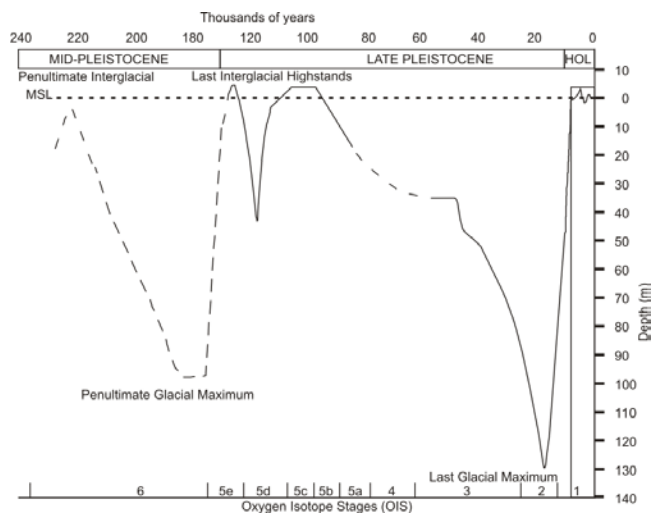
The end of the Cretaceous signifies a major change in global climates, with Tertiary climates being characterised by a progressive and sometimes erratic decline in temperature (Dingle et al., 1983; Partridge and Maud, 1987; 2000). This period was characterised by major eustatic sea level variations (Fig. 3.2), with the major regressions accompanied by hiatuses in the sedimentary record (Dingle et al., 1983). The late Cretaceous transgression, peaking in the Maastrichtian, was followed by a major late Maastrichtian to early Palaeocene regression (Dingle et al., 1983). This regression was followed by a regional late Palaeocene – early Eocene transgression (Dingle et al., 1983). A major mid Tertiary regression spans most of the Oligocene with sea levels reaching a maximum of ~530 m below present levels (Dingle et al., 1983). Following the Oligocene regression and associated hiatus was a mid to late Miocene transgression (+ 100 m above present sea level) which was interrupted by a brief latest Miocene regressive pulse (~ 100 m below present sea level) before reaching its peak in the early Pliocene (Dingle et al., 1983; Visser, 1998). A major lowering of sea level marked the late Pliocene before the more regular fluctuations of sea level of the Pleistocene commenced.



**Fig. 3.1.** Sea level curves of Waelbroeck et al. (2002) in blue, Rohling et al. (2009) in red and Bintanja et al. (2005) in brown (From Compton, 2011).



**Fig. 3.2.** Sea level variations since the mid-Cretaceous (modified from Dingle et al., 1983) and superimposed with the global eustatic curve of Miller et al. (2005). Note the rapid late Maastrichtian-early Palaeocene, late Pliocene, and suspected late Miocene sea level regressions (From Green and Garlick, 2011).



**Fig. 3.3.** Late Pleistocene sea level curve for the east coast of South Africa (after Ramsay and Cooper, 2002). Note the rapid transgression during deglaciation in the latest Pleistocene/ early Holocene followed by slowing rates of sea level rise in the Late Holocene

### 3.6.2. Quaternary sea level variations in South Africa

According to Norström et al. (2012), several proxy data have been used to reconstruct past sea levels in southern Africa, mainly radiocarbon or OSL dating of exposures of marine facies or shoreline indicators (e.g. Ramsay, 1995; Compton, 2006; Carr et al., 2010) as well as palaeo-environmental indicators in lagoon and estuary sediments (e.g. Baxter and Meadows, 1999). Sea level has fluctuated no more than 3 m over periods of hundreds of years on the southern African coast during the last 7000 yr (Miller et al., 1993, Ramsay, 1995; Baxter and Meadows, 1999; Compton, 2001), compared to sea level fluctuations of more than 100 m over periods of thousands of years during glacial to interglacial cycles (Ramsay and Cooper, 2002; Cutler et al., 2003). However, these subtle Holocene variations in sea level have had a large impact on the evolution of coastal environments (e.g. Compton and Franceschini, 2005; Wright et al., 1999).

Ramsay and Cooper (2002) integrated all sea level data along the south and east coast of South Africa during the late Quaternary, and focused mainly on the late Pleistocene to Holocene time periods (Fig. 3.3). During the last interglacial (OIS 5c and 5e), sea level in South Africa was approximately 6 to 8 m higher than present day (Ramsay et al., 1993). Between 95 Ka and 45 000 Ka BP (OIS 5b to 3) sea levels regressed to about -50 m followed by a subsequent transgression to -25 m at 25 Ka BP. The last interglacial was followed by a prolonged regression, occurring over the next 7000 years that ended in the Last Glacial Maximum (LGM) lowstand of -125 m below Mean Sea Level (MSL) (Green and Uken, 2005). This eustatic lowstand was then followed by the Flandrian Transgression (18 Ka to 9 Ka BP), which saw sea level rise rapidly to the contemporary MSL (Ramsay and Cooper, 2002). The subsequent Holocene Epoch saw sea levels gently fluctuate around the elevation of present day MSL (Ramsay, 1995).

Norström et al. (2012) stated that in the early Holocene, the global sea level rose in response to increasing temperatures, glacial melting and larger volumes of water within the world's oceans. Norström et al. (2012) further suggested that the available sea level curves in the southern African region place the Holocene sea level maximum between 6500 cal BP (Miller et al., 1993;

Compton 2006) and 5000 cal BP (Ramsay, 1995; Baxter and Meadows, 1999; Ramsay and Cooper, 2002) with an elevation of ~2 to 5 m above MSL.

### 3.6.3. Melt Water Pulses and the global eustatic record

Meltwater pulses (MWP), representing stages of increased melting during the deglaciation period marked by the Flandrian transgression, allow for a sudden increase in sea level. These meltwater pulses create ideal conditions for the enhanced preservation of the shoreline by overstepping (Storms et al., 2008; Zecchin et al., 2011; Salzmann et al., 2013).

The timing and existence of meltwater pulses is very controversial (Okuno and Nakada, 1999; Peltier, 2005; Peltier and Fairbanks, 2006; Stanford et al., 2006). MWP1A is said to have begun ~14.6 Ka yr BP when global eustatic levels were ~100 m below present mean sea level (MSL) during the Bølling-Allerød interstadial (Fairbanks et al., 2005). During MWP1A sea level rose ~16 m (at 26-53 mm/yr) with a peak at about 13.8 Ka yr BP (Stanford et al., 2011). Significant debate still exists regarding the timing and existence of MWP1B. Liu and Milliman (2004) describe a distinct acceleration in sea level rise from -58 to 45 m ~11 Ka yr BP from sites in Barbados following the Younger Dryas cold period. This is consistent with rates of 13 to 15 mm/yr during meltwater pulse 1B (MWP1B). To date this has not been substantiated by evidence from South Pacific coral reefs (Bard et al., 2010).

## CHAPTER 4

### Regional seismic stratigraphy

#### 4.1. Methods

##### 4.1.1. Data collection

220 km of very high resolution single-channel seismic data were collected from the study area, covering an overall area of  $\sim 300 \text{ km}^2$ . The seismic data collected comprised a grid of thirteen coast parallel and eight coast perpendicular lines (Fig. 1.1) Two long, coast-perpendicular lines (Fig. 4.1 and 4.2) were collected with the specific intent of intersecting the shelf break and to provide tie-lines for the coast-parallel stratigraphic interpretations. As the main focus of this study is concerned with incised valley systems, the emphasis was placed on the collection of coast parallel seismic data that would best reveal these features.

The single-channel seismic data were collected using a Design Projects boomer system and a 20-element hydrophone array. The data were recorded via an Octopus 360 acquisition system or using the Hypack <sup>TM</sup> hydrographic software package coupled to a National Instruments Digital-Analogue converter. Power levels of 200 J were used throughout the study. Positioning was achieved using a DGPS of approximately 1 m accuracy, corrected to the Durban Harbour MSK base station (Fig. 1.1).

##### 4.1.2. Data processing

Raw data were processed using an in-house designed software package. Time-varied gains, bandpass filtering (300-1200 Hz), swell filtering and manual sea-bed tracking were applied to all the data, in addition to streamer layback and antennae offset corrections. Constant sound velocities in water (1500 m/s) and sediment ( $1600 \text{ ms}^{-1}$ ) were used to extrapolate all time-depth conversions. Depth to reflector maps were produced by exporting the digitised data as ASCII

text files into Surfer 9 and interpolating the data sets using the Kriging method. The final images were produced as colour coded image plots showing horizon depth relative to MSL.

#### 4.2. Results

Data interpreted from three down dip seismic images, acquired from the Glenashley to the La Mercy Beach area, reveal that the continental shelf of Durban is characterised by several seismic units (A-K), classified on the basis of the internal reflector geometry and bounding acoustic reflectors (e.g. Fig. 4.1 and 4.6). The seismic facies recognised within each unit were assigned numbers e.g. Seismic Facies 1 of Unit B (SF1B) (Table 4.1). A number of these units comprise incised valley features infilled with younger material, the sequence stratigraphy of which is examined in detail in chapter 5 of this dissertation.

#### 4.3. Unit A

Unit A is the oldest unit resolved, occurring only in the landward most portions of the study area. It is characterised by very high amplitude chaotic reflectors. From seismic records acquired from the La Mercy Beach area, these reflectors show no apparent reflection termination patterns or internal-reflection configuration (Fig. 4.2 and 4.4). However, they become more oblique parallel toward the Glenashley area (Fig. 4.3). Unit A is separated from the overlying Unit B by a distinct, high amplitude erosional surface (SB1).

#### 4.4. Unit B

Unit B forms a landward pinching wedge, appearing only in the landward most portions of the survey area. It may be divided into two seismic facies, namely seismic facies 1B (SF1B) and seismic facies 2B (SF2B) (Fig. 4.2). This unit comprises moderate to high amplitude, sigmoid oblique, progradational reflectors. SF1B toplaps reflector 1 which separates SFB1 from SFB2. The most proximal reflectors of SF2B either onlap SB1 (Fig. 4.2 and 4.4) or are truncated by the

upper boundary SB3 (Fig. 4.4). Unit B is separated from Unit C by a moderate to high amplitude surface (Surface 1).

#### 4.5. Unit C

Unit C is an inner to mid-shelf landward thinning unit, characterised by high amplitude, sigmoid progradational reflectors. These both onlap (Fig. 4.3 and 4.4) and downlap (Fig. 4.2 and 4.4) Surface 1 and are truncated by SB3 mid-shelf (Fig. 4.3 and 4.4). Where Unit C pinches out, surface 1 and SB3 almost merge (Fig. 4.2). Unit C is separated from Unit D by an irregular, high amplitude surface (Surface 2). This surface truncates the reflectors of Unit C to seaward (Fig. 4.2).

#### 4.6. Unit D

Unit D occurs in the mid-shelf of the study area and comprises moderate to low amplitude, oblique-parallel to hummocky reflectors. These reflectors both onlap and downlap the underlying erosional surface (Surface 2) and are erosionally truncated by Surface 3, the most seaward bounding surface (Fig. 4.2). The stacking pattern of the reflectors is undefined due to the overlying Unit J which hampered the signal penetration during data collection.

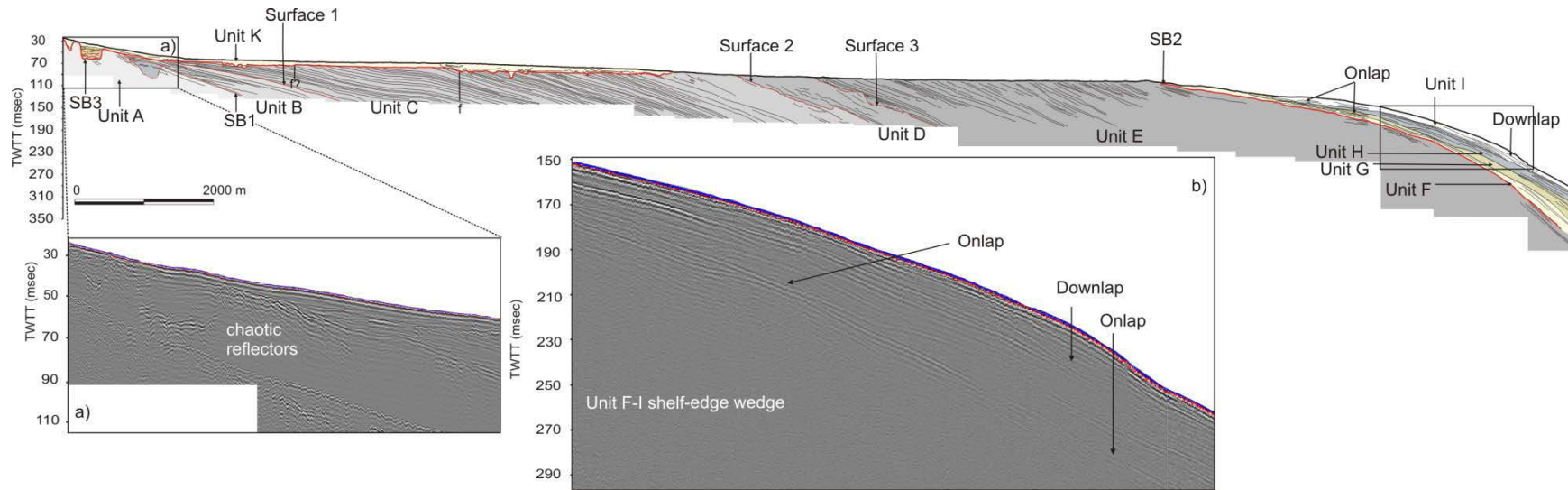
#### 4.7. Unit E

Unit E is characterised by prograding moderate to low amplitude sigmoid oblique to oblique-parallel reflectors. The landward most clinofolds are truncated by SB3. Where Unit E crops out in the mid- to outer shelf, it appears to be truncated by the sea floor. The seaward most reflectors are concordant with the upper erosional surface (SB2) (Fig. 4.1 and 4.2).

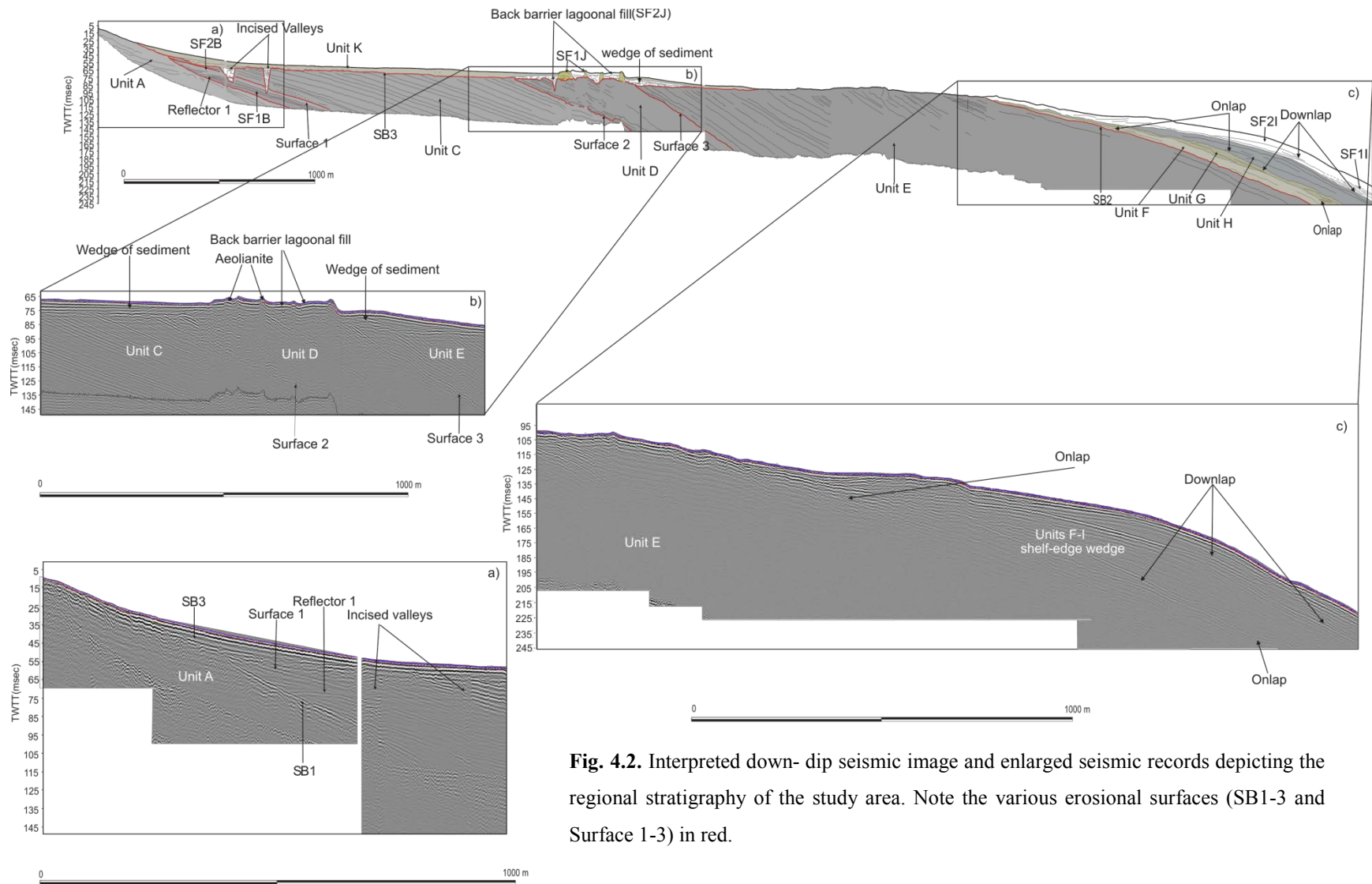
## Seismic-Stratigraphic Models for Late Pleistocene/Holocene Incised Valley Systems on the Durban Continental Shelf.

Underlying horizon	Seismic unit/surface	Sub-unit	Green and Garlick's (2011) unit	Modern description	Thickness	Characteristics	Interpreted depositional environment	Systems tract	Age
-	A	n/a	Not recognised	Pietermaritzburg Formation shales		Chaotic	n/a	n/a	Permian
	SB1			Outer to mid-shelf prominent reflector		Erosional truncation of A, undulating surface, dipping shallowly to SE		Sequence boundary	
SB1	B	B1 and B2, Reflector 1	A	Outer to mid- shelf prograding package	>20 m	Parallel to sub parallel, sigmoid oblique, moderate to high amplitude, high continuity reflectors, dipping shallowly SE	Outer to mid-shelf	HST	Early Santonian
Surface 1	C		B	Inner shelf aggradational to progradational reflectors	>100 m	Sigmoid parallel , parallel to sub-parallel, high amplitude, high continuity reflectors, dip shallowly SE	Inner shelf littoral zone	HST	Late Campanian?
Rugged horizon, Surface 2	D		Not recognised		>50 m				?
Surface 3	E		C		>18 m	Parallel to oblique parallel moderate to high amplitude, high continuity reflectors, dipping shallowly SE	Outer shelf to shelf edge	FSST	Late Maastrichtian
Major hiatus spanning most of the Tertiary									
	SB2			Entire shelf prominent reflector				Sequence boundary	K/T boundary
SB2	F-I		Not recognised	Shelf-edge wedge		Aggradation/progradational moderate amplitude reflectors, onlaps SB2	Lowstand shelf edge delta	LST	Latest Pliocene
SB2	Coeval with wedge, not apparent in the northern study area		D	Isolated, laterally discontinuous incised valley fill		Onlapping and lateral accretion fills, moderate to high amplitude, chaotic reflectors	Incised valley fill	Late LST-TST	Latest Pliocene
	SB3			Entire shelf prominent reflector		Erosional truncation of A, B, C,D, Pliocene valleys, undulating, deeply incised surface, flat interfluvies		Sequence boundary	LGM
SB3	J	J1	E-F	Inner-outer shelf stranded sediment outcrop	8m	Welded onto underlying surface SB3, very rugged appearance. Very high amplitude, unrecognisable reflectors	Palaeo-coastlines	Stillstand	Late Pleistocene/Holocene
SB3		J2		Fill within saddles of Unit J		Drape, low amplitude	Backbarrier fill	TST	Late Pleistocene/Holocene
	K	K1	G	Incised valley fill		Onlapping and lateral accretion fills, chaotic, moderate amplitude reflectors	Incised valley fill	Late LST-TST	Late Pleistocene/Holocene
SB3									
Holocene Ravinement		K2		Seaward thinning shore attached wedge	10 m	Downlap and onlap SB3. Small progradational packages separated by flooding unconformities. Weakly layered, low amplitude reflectors	Holocene inner shelf wedge	TST	Holocene to present

**Table 4.1.** Simplified stratigraphic framework for the continental shelf of Durban, describing seismic units, the age of each unit, and the interpreted depositional environments. The age of the units is based on Green (2011) and Green and Garlick (2011).



**Fig. 4.1.** Interpreted down- dip seismic image and enlarged seismic records depicting the regional stratigraphy of the study area. Unit J is not present but is shown in subsequent along strike figures. Note the various erosional surfaces (SB1-3 and Surface 1-3) in red.



**Fig. 4.2.** Interpreted down- dip seismic image and enlarged seismic records depicting the regional stratigraphy of the study area. Note the various erosional surfaces (SB1-3 and Surface 1-3) in red.

#### 4.8. Units F, G, H and I

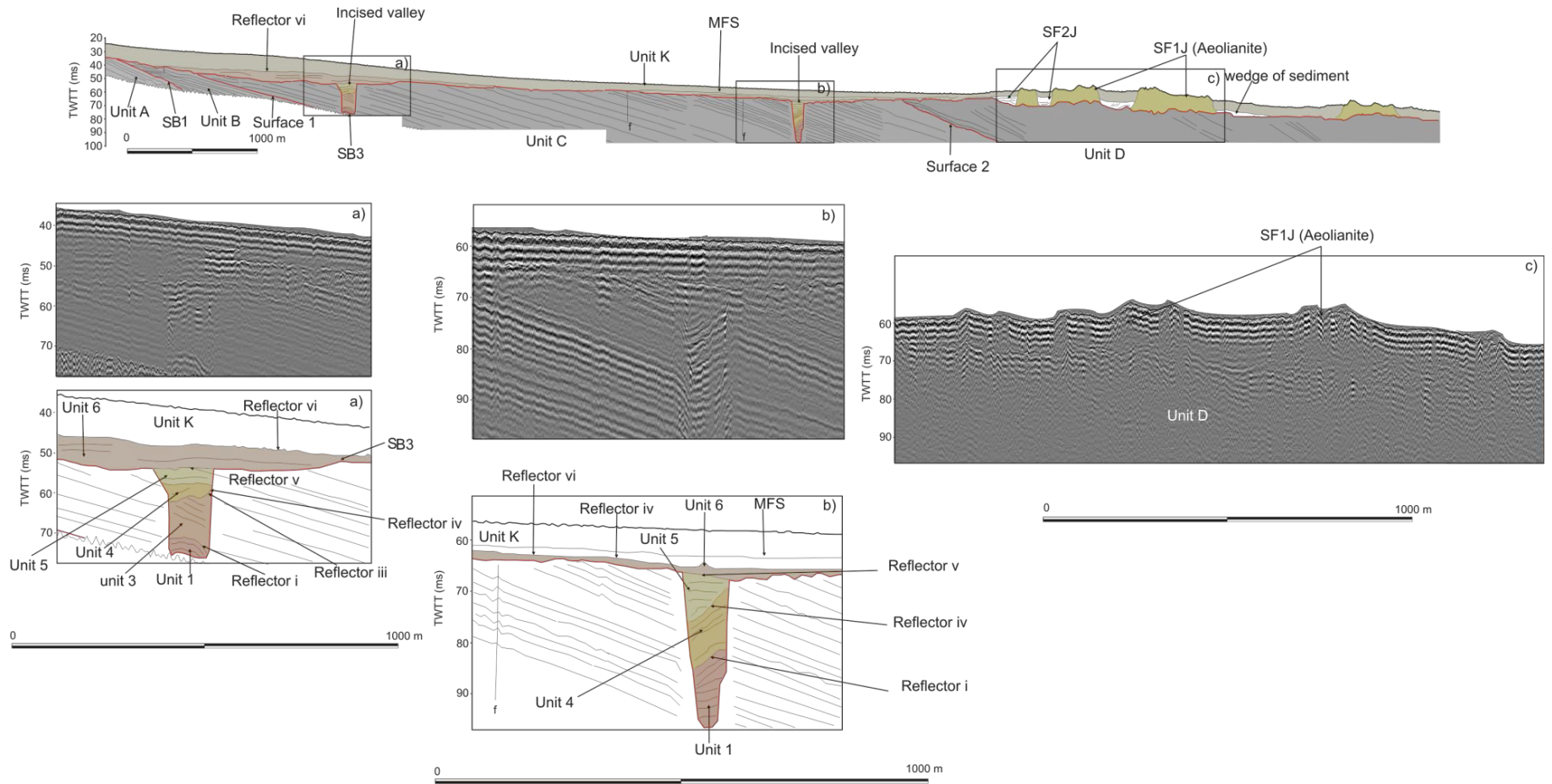
Units F-I are characterised by aggradational-progradational, moderate to low amplitude or moderate to high amplitude sigmoid-oblique to oblique parallel reflectors forming a landward thinning composite shelf-edge wedge (Fig. 4.1 and 4.2). This wedge is separated from Cretaceous deposits by the erosional surface SB2. The lower unit, Unit F, onlaps SB2 and where it pinches out, Unit G directly overlies SB2. Unit G both onlaps and downlaps the underlying Unit F. Unit H onlaps Unit G and thins landward, eventually pinching out. Beyond this point reflectors of Unit I onlap directly on Unit G. Unit I appears to be divided into two facies, namely SF1I and SF2I, which both onlap and downlap the underlying bounding surfaces and each other.

#### 4.9. Unit J

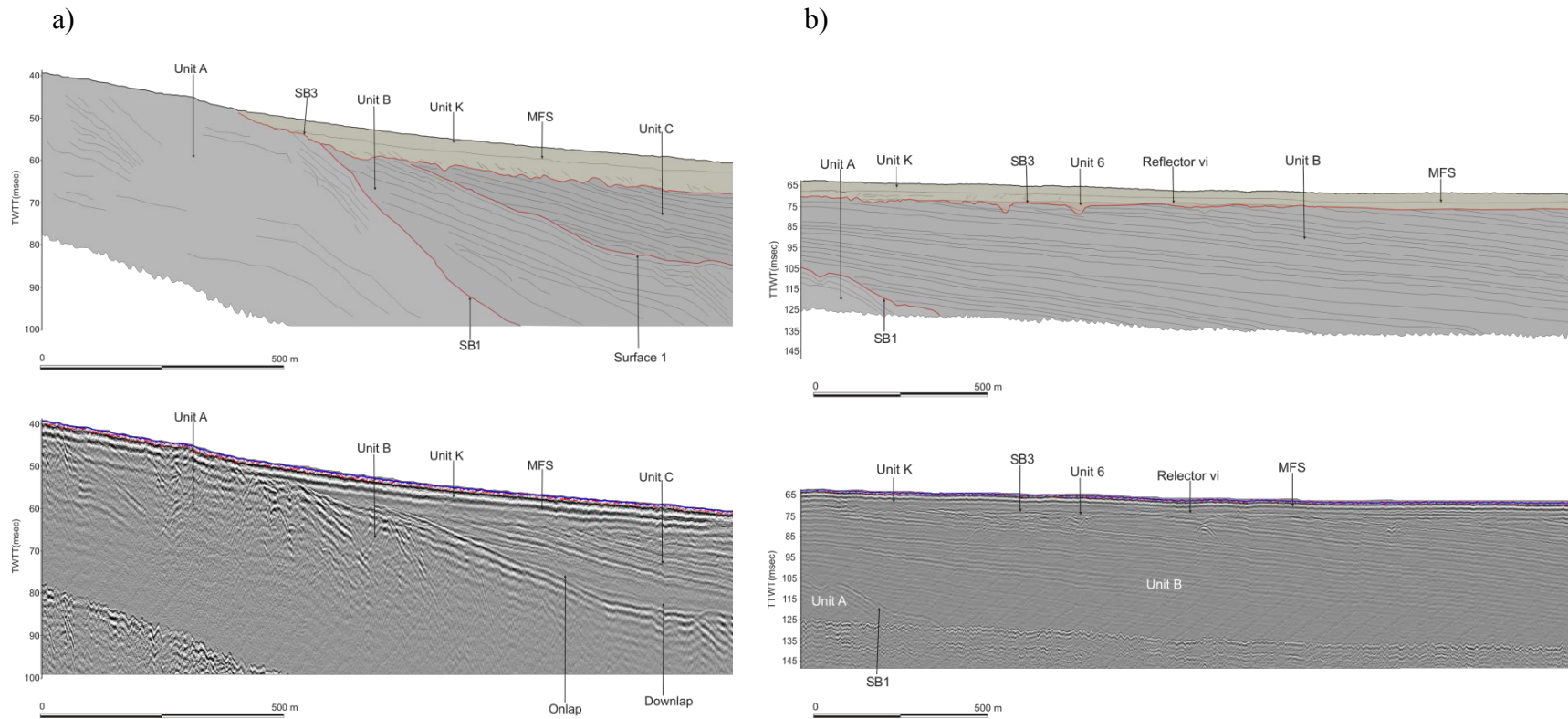
Unit J is observed on the inner- to mid-shelf portions of the survey area. This unit is made up of two seismic facies, namely, SF1J and SF2J (e.g. Fig. 4.1 to 5.3). It is characterised by a rugged appearance and appears to rest upon the underlying SB3. SFJ1 forms ridge-like structures which crop out on the sea floor and are characterised by high amplitude, chaotic reflectors.

#### 4.10. Unit K

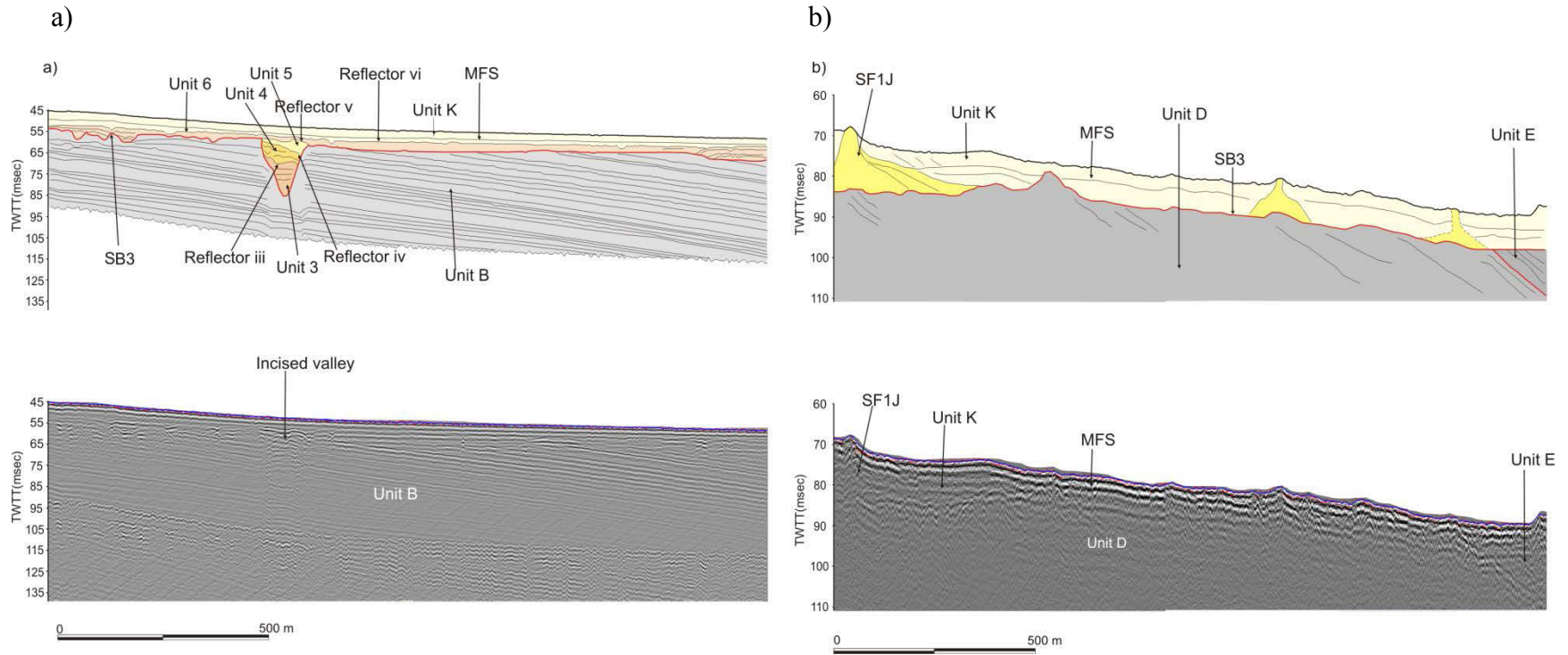
Unit K caps the stratigraphy, and forms a shore-attached prograding wedge (SF2K) comprising low to moderate amplitude discontinuous reflectors. The lower portions of Unit K (SF1K) comprise the fills of the ~18000 BP LGM incised valley network. The wedge attains a maximum thickness of ~11 m. The lower most portions of Unit K comprise semi-transparent to low amplitude, sigmoid continuous reflectors which overlie Reflector vi. These may also drape SB3 where Reflector vi merges with SB3 or Unit K coalesces with Unit 6 (Fig. 5.2) (in this case, the prograding sand body forms the capping fill of the SB3 incised valleys). This lower portion of Unit K is best represented in Fig. 5.1, and occurs as a thin veneer in the other seismic sections. The top of this unit is generally the modern day sea floor, except where units C and D crop out in the mid shelf evident in the northernmost coast perpendicular seismic records (Fig. 4.1).



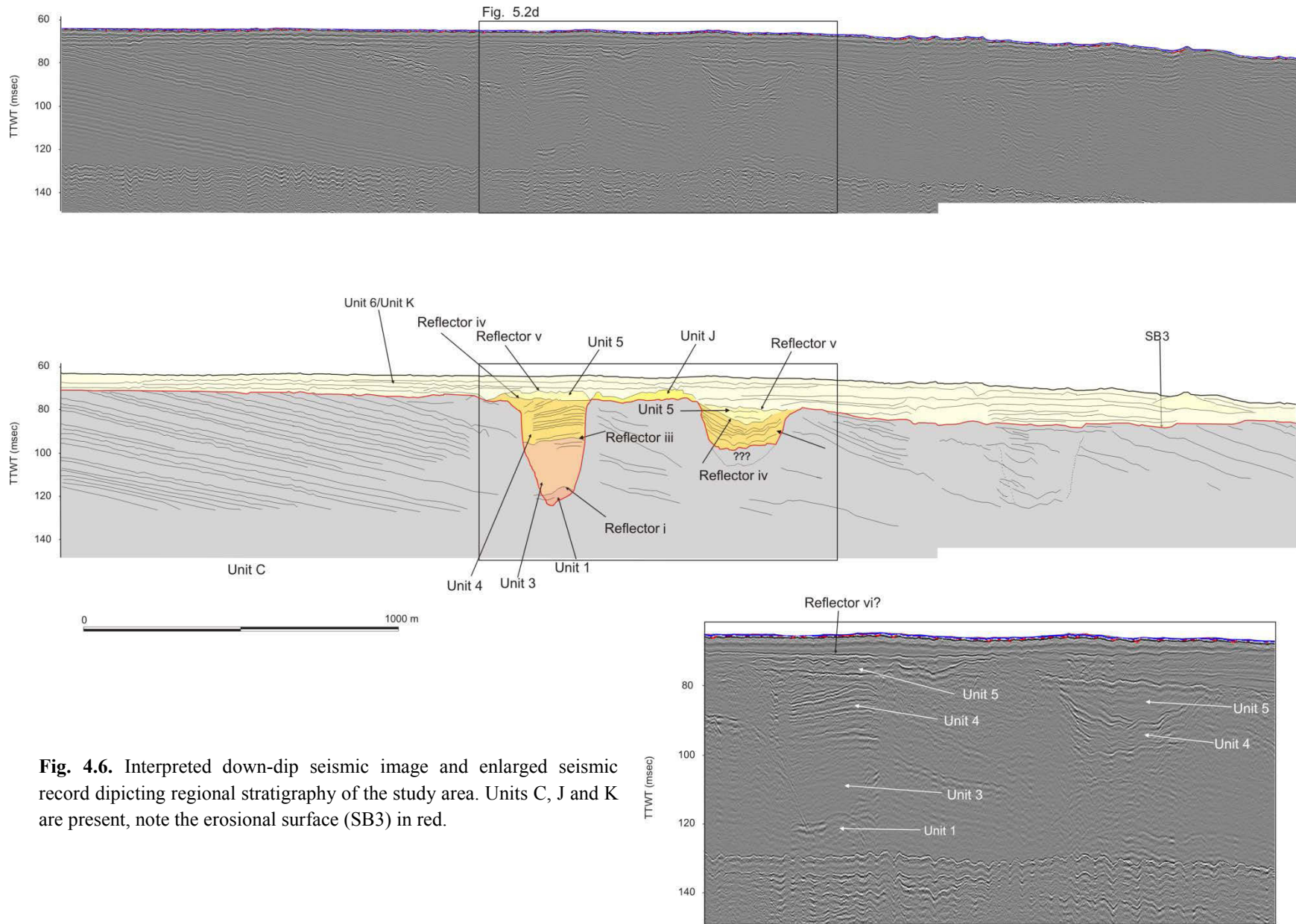
**Fig. 4.3.** Interpreted down- dip seismic image and enlarged seismic records depicting the regional stratigraphy of the study area. Unit A-D and Unit K are present. Note the various erosional surfaces (SB1 and 2, Surface 1 and 2) in red.



**Fig. 4.4.** Interpreted down-dip seismic images depicting the inner-shelf regional stratigraphy of the study area. Units A-C and K are present, note the various erosional surfaces (SB1, SB3 and Surface 1), the maximum flooding surface (MFS) and the rugged appearance of SB3.



**Fig. 4.5.** Interpreted down-dip seismic images. Units B, D, J and K are present. Note the rugged appearance of SB3 and the presence of the MFS.



**Fig. 4.6.** Interpreted down-dip seismic image and enlarged seismic record depicting regional stratigraphy of the study area. Units C, J and K are present, note the erosional surface (SB3) in red.

#### 4.11. Discussion

Based on similar observations by Cawthra (2010) and Cawthra et al. (2012) for the Blood Reef area, Green and Garlick (2011) for the neighbouring Durban Bight, and Green (2011) for the northern KwaZulu-Natal shelf, a sequence stratigraphic framework for the study area can be constructed. This can be further refined when compared to previously published accounts of the local onshore (McCarthy, 1967; Roberts et al., 2006) and offshore geology (Dingle et al., 1983; Martin and Flemming, 1988; Richardson, 2005), major tectonically induced hinterland erosion cycles (Partridge et al., 2006) and post-Gondwana depositional events (Dingle et al., 1983; McMillan, 2003; Partridge et al., 2006; Roberts et al., 2006).

##### 4.11.1. Acoustic basement

Observations of the coastal outcrop in the northernmost portions of the study area, in addition to diver observations in the nearshore environment (Green pers.comm) reveal that Unit A crops out and comprises finely laminated shales with occasional silt partings. These shales form part of the Permian age Pietermaritzburg Formation (SACS, 1980) and comprise the surface against which the younger Cretaceous strata onlap. The unit is truncated by a rugged surface against which the younger strata onlap as coastal onlap (cf. McMillan, 2003).

##### 4.11.2. Cretaceous age units

In accordance with Green and Garlick (2011), Unit B is considered as early Santonian in age. This unit can be traced along strike for ~ 26 km from the Durban harbour where it is intersected by boreholes (McMillan, 2003). It was deposited during gradually rising sea levels reported in the Durban Basin during the Santonian (Dingle et al., 1983) (Fig. 3.2), but with a high rate of sediment supply that would foster the development of the sigmoid prograding seismic architecture. Green and Garlick (2011) and Cawthra (2010) describe this unit as having an overall retrograding package, which is at odds with the prograding facies described here.

Green and Garlick (2011) attribute this difference in facies architecture to a differential rate in (a) sediment supply or (b) subsidence along strike (*sensu* Catuneanu, 2006). The prograding reflectors north of their study area are attributed to either lower subsidence rates or higher sedimentation rates- which would foster conditions of normal regression. Towards the south however, either reduced sedimentation rates or faster rates of subsidence would cause these areas to go through relative deepening, leading to the retrogradation of reflectors. This local variation in the stratigraphic architecture of the transgressive and highstand systems tract remains an important question in explaining the variability of coevally deposited sequence stratigraphic units within a basin (Catuneanu, 2006). Unit B is capped by surface 1, the equivalent of Green and Garlick's (2011) Maximum Flooding Surface which they related to an early Campanian period of sediment starvation and current smoothing.

The ages of Unit C and Unit D are indeterminable. Unit D is only recognised in profiles from this study area, and was not recognised by Green (2011) on the northern KwaZulu-Natal continental shelf or by Green and Garlick (2011) south of the study area (Durban Bight). Owing to the very similar reflector packages of Green and Garlick's (2011) highstand Unit B, it is assigned a late Campanian age. Dingle et al. (1983) and McMillan (2003) considered a continued sea level rise from early Santonian until a maximum sea level was reached during late Campanian (76.5–72.5 Ma) (Fig. 3.2). Shelly glauconitic limestones and sandy claystones exposed onshore just south of the Mzamba area on the KwaZulu-Natal South Coast (Fig. 1.1) have been age constrained to the late Campanian to earliest Maastrichtian (McMillan, 2003). This unit is thus tentatively linked to these sedimentary rocks.

The overall seismic architecture of Unit E, resembles the acoustic basement identified by Sydow (1988) and Green (2011) on the northern KwaZulu-Natal continental margin; as well as Green and Garlick (2011) further south in the Durban Bight. These authors consider this unit to be late Maastrichtian in age. The prograding nature of this unit suggests a general basinward advance of sediment supply due to sea level lowering (e.g. Osterberg, 2006); thus comprising part of a shelf

preserved falling stage systems tract. The overall preservation of this systems tract on the shelf is a rarity (Catuneanu, 2006) and indicates that sufficient accommodation space existed on the palaeo-shelf for the accumulation of these sedimentary rocks. In addition, their subsequent preservation from ravinement in the ensuing cycle of sea level rise is likely a response of rapid rise in sea level and a steep landward shoreline trajectory (e.g. Cattaneo and Steel, 2003). Unfortunately, the sea level history of the area is so poorly constrained (cf. McMillan, 2003) that this cannot be proved or disproved.

#### 4.11.3. Neogene deposition at the shelf edge

Units F-I have a striking resemblance to the forced regressive-lowstand shelf-edge wedge described by Green et al. (2008) and Green (2011) for the northern KwaZulu-Natal margin, as well as Cawthra (2010) and Cawthra et al. (2012) for the Blood Reef area. These authors assigned a late Pliocene age to the wedge. Martin and Flemming (1988) also recognised a similar arrangement of prograding shelf-edge facies to which they assigned a Pliocene age. On this basis units F-I are accordingly assigned in a similar manner.

The dominantly aggrading-prograding reflectors of Units F, G, H and I are indicative of normal regression, usually associated with static or slowly rising sea levels where sediment supply rates outbalance the available accommodation space (e.g. Catuneanu, 2006). The overall aggrading-prograding stacking pattern of the shelf-edge wedge may be assigned to the lowstand systems tract (LST) based on this architecture. In this light, this low stand shelf-edge wedge is similar to that recognised by Green (2011) for the northern KwaZulu-Natal continental shelf, though volumetrically greater. This difference in volume can be attributed namely to differences in shelf physiography. The northern KwaZulu-Natal continental shelf is significantly steeper and narrower with a far more abrupt shelf break (Martin and Flemming, 1988) when compared to Durban. This physiography is a product of continuing uplift in the Neogene (Dingle et al., 1983; Partridge and Maud, 1987; Green, 2011) that promoted sediment bypass. The result in northern KwaZulu-Natal is that most of the sediments would be deposited in the distal basin floor as

slope-floor fans (Green, 2011). In Durban, the wider shelf with gentler shelf break would foster less bypass of sediment and enhance the preservation potential of a shelf-edge delta at lowstand (e.g. Porebsky and Steel, 2003).

This shelf edge-delta marks the end of the hinterland uplift of the late Pliocene (e.g. Partridge and Maud, 1987) (Fig. 3.2) that was marked by widespread instability on both east and west coasts (Wigley and Compton, 2006; Green, 2011). This period would have been characterised by fluvial incision and bypass of sediment across the shelf through a series of valleys. Subordinate, isolated fills of the latest Pliocene age are recognised from the shelf in the study area (Chapter 5) as well as in Durban Bight (Green and Garlick, 2011). The concept that these may have fed the shelf-edge wedge at lowstand is further discussed in chapter 5.

#### 4.11.4. Shoreline deposits

Unit J displays similar features to units described by Green (2011) on the northern KwaZulu-Natal continental shelf, Green and Garlick (2011) from the Durban Bight, and Cawthra (2010) from offshore the Bluff area. Green et al. (2013a) and Green et al. (in press) have recently confirmed these as calcite cemented shoreline deposits that crop out and exhibit morphologies similar to planform equilibrium shorelines on modern coasts. This unit is thus equivalent to the coast-parallel calcarenite reef system of Martin and Flemming (1988), Ramsay (1994) and Bosman et al. (2007).

The drapes (SFJ2) within the saddles of SFJ1 are similar to those described by Green and Garlick (2011) and Salzmann et al. (2013), which they interpret as back barrier lagoonal fill. Similar interpretations of identical seismic units have been made by Foyle and Oertel (1997) and Osterberg (2006). These are considered to have formed on a transgressive cycle after the formation of the aeolianites, when conditions were most favourable to the formation, drowning and preservation of more tranquil back-barrier sediments (Green and Garlick, 2011). Green et al. (in press) consider these to have been formed in the late Pleistocene and early

Holocene and preserved in response to the rapid drowning of the shorelines by meltwater pulses 1A and 1B (cf. Liu and Milliman, 2004; Bard et al., 2010).

#### 4.11.5. Unconsolidated Holocene highstand wedge

Unit K, a shore-attached prograding Pleistocene/Holocene wedge, was also identified by Martin (1984), Martin and Flemming (1986), Martin and Flemming (1988), Birch (1996) and Green and Garlick (2011). According to Ramsay and Cooper (2002), Unit K (SFK2) accrued as a shore attached prograding wedge during the transgression following the LGM. The general progradational seismic character of this unit points to a more recent Holocene age as sea level rise slowed down and normal regression occurred (Fig. 3.3). The thin nature of the wedge (~ 11 m) is attributed to a period of low sediment supply due to the prevailing isolated and poor drainage network in the area (see Chapter 5).

The geometry of the lower portions of Unit K is that of a prograding shore-attached sediment body (Fig. 5.1). Bosman (2012) states that similar deposits are recognised south of the study area, forming part of a large aggrading and prograding unconsolidated sediment deposit previously termed a 'submerged spit bar' (Martin and Flemming, 1986). Martin and Flemming (1986) suggested that this shore-attached prograding sediment depocentre formed at the convergence of sediment paths generated by the Agulhas Current, the counter current and longshore drift from sediment supplied by local rivers and northward littoral drift. They further suggest that upward sediment accumulation is limited by the prevailing swell energy consequently forcing progradation onto the open shelf. Martin and Flemming (1986) base their classification of this sediment body as a submerged spit bar on its progradational nature, depth of occurrence and resemblance to subaerial sand spits.

Goff and Duncan (2012) also describe similar facies on the middle and outer New Jersey shelf. They describe these facies as prograding sand-ridges, comprising numerous low amplitude seaward dipping reflectors. Similar to this study, this prograding Holocene sand body lies above the Holocene transgressive ravinement surface. These ridges are said to have formed initially in the shoreface, subsequent sea level rise having brought them into the deeper water environments, where they continue to be modified or may become inactive in response to less vigorous bottom currents (Goff and Duncan, 2012). Goff et al. (1999), suggest that sand-ridges in the mid-shelf water depths (~20-50 m) of their study area are still being modified in a lee/stoss relationship (erosion on the stoss side and deposition in the lee side) to a modern day, predominantly westerly bottom current. In outer-shelf water depths (~50-120 m), Goff et al. (1999) concluded that sand ridges are moribund, but modified at basins and flanks by recent and/or modern erosion.

#### 4.11.6. Regionally developed sequence boundaries

Three sequence boundaries are developed on the continental shelf of Durban, namely, SB1, SB2 and SB3. SB1 is the oldest boundary, separating the Permian age deposits from the overlying Cretaceous age deposits. SB2 is interpreted as a sequence boundary occurring above the basinward prograding deposits of the Cretaceous from the overlying Tertiary lowstand shelf-edge wedge. According to Catuneanu (2006), this surface is considered to form by subaerial erosion, normally associated with downstream downcutting, basinward shift in facies and onlap of overlying strata. SB3 is the uppermost sequence boundary observed in the study area, and is a regionally extensive surface spanning the entire shelf, separating Quaternary deposits from the underlying older deposits. The last recorded lowstand record was ~18 000 BP, marked as the last glacial maximum (LGM) (Ramsay and Cooper, 2002) when sea level fell to ~ 130 m below present (Fig. 3.3), well past the shelf break (Green and Garlick, 2011). The timing and depth of this lowstand is similarly recognised in global eustatic records (Compton, 2011). This study associates SB3 with this drop in sea level towards the LGM. In this study area, no apparent incisions associated with SB1 have been recognised, however, several incised valley systems are characteristic within SB3 and isolated valleys are apparent in SB2 (Chapter 5).

## CHAPTER 5

### Incised valley systems: geomorphology and stratigraphy

#### 5.1. Introduction

Several incised valley systems are present offshore Durban and are summarily documented in this chapter (Figs. 5.1 to 5.12). This chapter documents the occurrence of large late Pleistocene/Holocene aged valleys (SB3 associated), together with a subsidiary series of isolated late Pliocene aged valleys (SB2 associated). SB3 valleys exhibit simple fills and have intersected and reworked many of the late Pliocene incised valleys. Only isolated examples of these late underlying Pliocene valleys are apparent (Fig. 5.1 and 5.3).

Incised valleys developed in the SB3 (e.g. Fig. 5.1 and 5.2) surface may comprise up to six seismic units (Table 5.1). These units may not always be present in all the incised valleys, but occur in some combination throughout the study area. Isolated late Pliocene examples comprise two seismic units (Fig. 5.1). Irrespective of age or location, the lower two seismic units of each valley fill display similar acoustic characteristics and are grouped accordingly.

#### 5.2. Valley fill seismic stratigraphy

##### 5.2.1. Unit 1

Unit 1, the lowermost seismic unit, is bound at its base by the subaerial unconformity (SB3) (e.g. Fig. 5.2 and 5.4). High amplitude, wavy to chaotic (sometimes concave upward) reflectors are characteristic of this basal unit. The erosional upper boundary (Reflector i) separates it from the overlying Unit 2 (e.g. Fig. 5.4).

### 5.2.2. Unit 2

Unit 2 comprises moderate to high amplitude steeply dipping, prograding sigmoid reflectors. These reflectors onlap valley flanks and downlap the erosional boundary, Reflector iii, forming mounds (Fig. 5.4). They may also terminate against their bounding erosional boundary, Reflector ii (Fig. 5.4c). Unit 2 is either attached to one (Fig. 5.4c and d) or both valley sides (Fig. 5.4 b).

### 5.2.3. Unit 3

Unit 3 occurs as a thickly developed drape package of low to very low amplitude, sub-parallel to oblique parallel (in LGM age examples) (e.g. Figs. 5.2 to 5.4 and 5.7) and concave upward (in late Pliocene examples) (Fig. 5.1) reflectors. Where oblique parallel, these reflectors may onlap or downlap valley flanks, downlap the underlying Reflector i (Fig. 5.4d) and toplap Reflector iii (Fig. 5.3 and 5.7a).

### 5.2.4. Unit 4

Unit 4 is characterised by reflectors of varying amplitude (moderate to very high). These form a wavy sub-parallel to oblique- parallel or steeply dipping package of aggrading (Fig. 5.2c), prograding (Fig. 5.2b) or mixed aggradational/progradational (Fig. 5.2d) reflectors. These reflectors onlap (e.g. Fig. 5.4b and f) or downlap (e.g. Fig. 5.4d and f) reflector ii. Where unit 3 is eroded, these reflectors onlap the valley flanks (Fig. 5.4a). Unit 4 is bound at its base by a very high amplitude, erosional boundary (Reflector iii), separating it from the underlying Unit 3 in all incised valleys (e.g. Figs. 5.4, 5.8 and 5.9).

#### 5.2.5. Unit 5

Unit 5 occurs as a sheet-like body which either drapes the underlying high amplitude Reflector iv (e.g. Fig. 5.2 b) or onlaps it (where Reflector iv is inclined- Fig. 5.4a) and terminates against Reflector ii (Fig. 5.4c). This unit comprises wavy parallel to sub-parallel, prograding reflectors of varying amplitude. It is capped by a rugged high amplitude erosional surface (reflector v) that extends along the entire study area of the shelf. Where Unit 5 is absent, Unit 6 directly overlies the underlying Units.

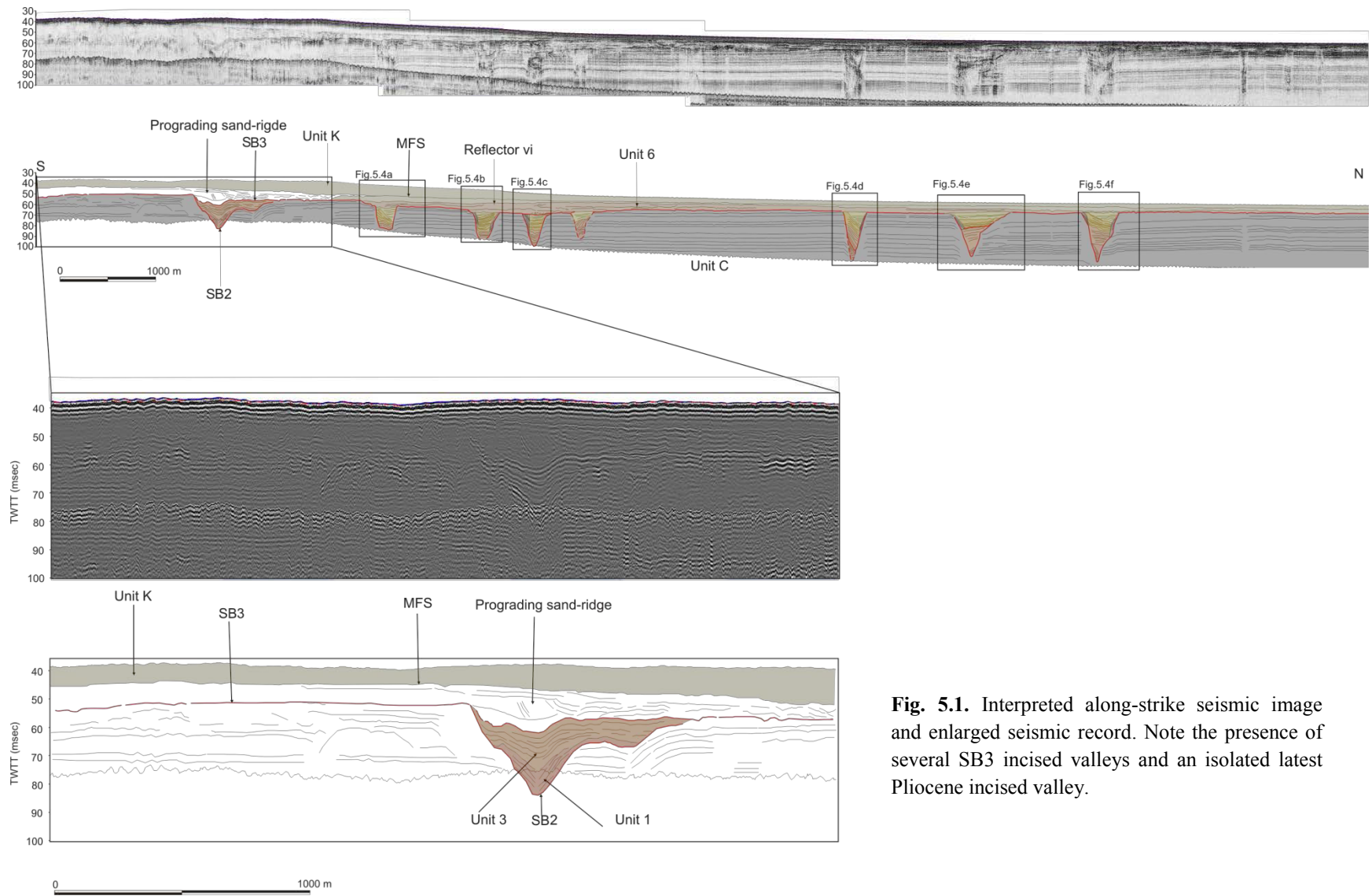
#### 5.2.6. Unit 6

Capping the valley fill in almost all valleys is Unit 6, a laterally extensive unit comprising a wavy parallel or wavy-to-oblique parallel prograding set of reflectors of varying amplitude. These may either drape or downlap underlying high amplitude rugged erosional surface (Reflector v) and if the underlying units have been eroded these reflectors may also downlap valley sides. In some areas, Unit 6 may be acoustically transparent. Reflector vi separates Unit 6 from the overlying unit L, the clinofolds of which drape upon Unit 6. Where unit 6 has been eroded (or coalesces with Unit L), Unit L caps the incised valleys (Fig. 5.2d).

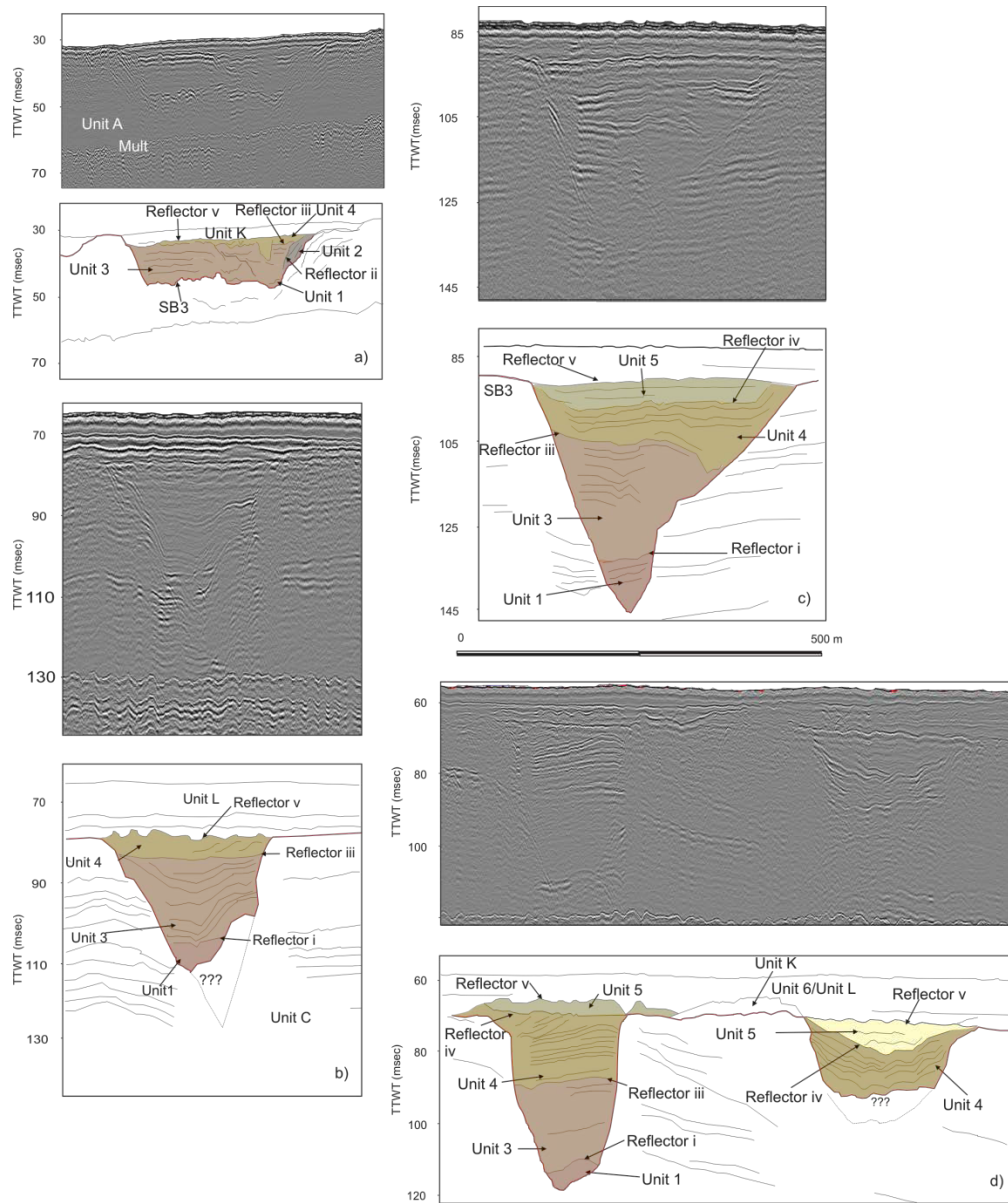
Seismic-Stratigraphic Models for Late Pleistocene/Holocene Incised Valley Systems on the Durban Continental Shelf.

Stratigraphic surface	Seismic Unit	Description	Thickness	Stratal relationship	Interpreted depositional environment
Reflector vi		Holocene ravinement surface		Erosional	
	Unit 6		< 4 m	Wavy- to oblique-parallel, prograding low amplitude reflectors	Post-wave ravinement sediment.
Reflector v		Wave ravinement surface		Erosional	
	Unit 5		2-4 m	High amplitude, sub-parallel to wavy parallel continuous reflectors	Flood deposit
Reflector iv		Catastrophic flood surface		Erosional	
	Unit 4		>15 m	Sub-parallel to oblique parallel, variable amplitude reflectors	Barrier/flood tide deltaic/estuarine mouth plug/shoreface
Reflector iii		Tidal ravinement surface		Erosional	
	Unit 3	Central drape	>15 m	Onlap other units, drape fill of low angle, sub-parallel, low amplitude reflectors	Central basin estuarine deposits
Reflector ii					
	Unit 2	Valley flank-attached packages	4-6 m	Onlap and downlap subaerial u/c, sigmoid progradational moderate amplitude reflectors	Fluvial point bar
Reflector i		Bay ravinement surface		Non-depositional	
	Unit 1	Basal unit of most valleys	<11 m thick	Downlap subaerial u/c, wavy to chaotic, high amplitude reflectors	Fluvial LST
SB3				Erosion surface	

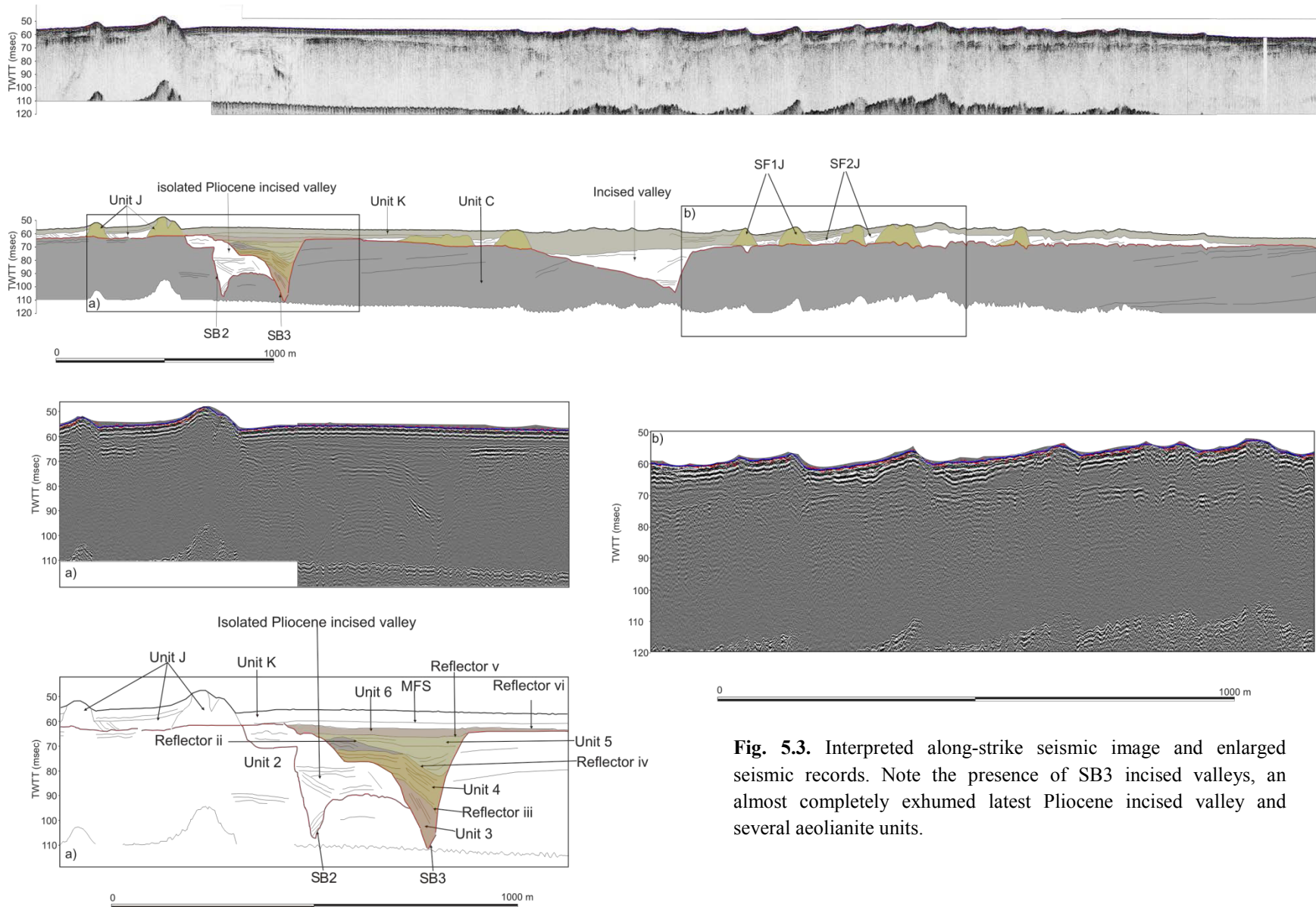
**Table 5.1.** Bounding unconformity surfaces, seismic units, stratal relationships and interpretive environments of both SB2 and SB3 incised valley fills.



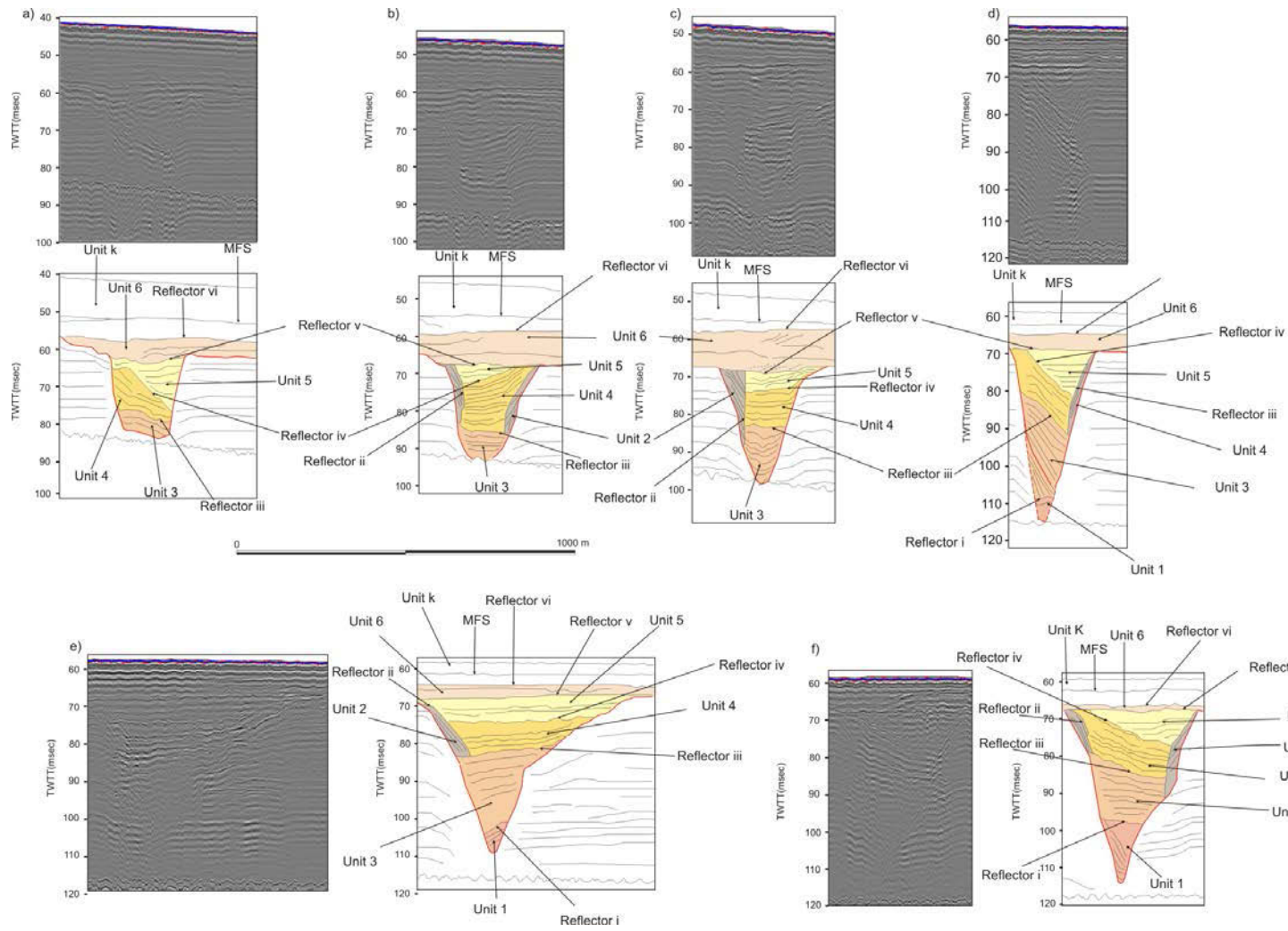
**Fig. 5.1.** Interpreted along-strike seismic image and enlarged seismic record. Note the presence of several SB3 incised valleys and an isolated latest Pliocene incised valley.



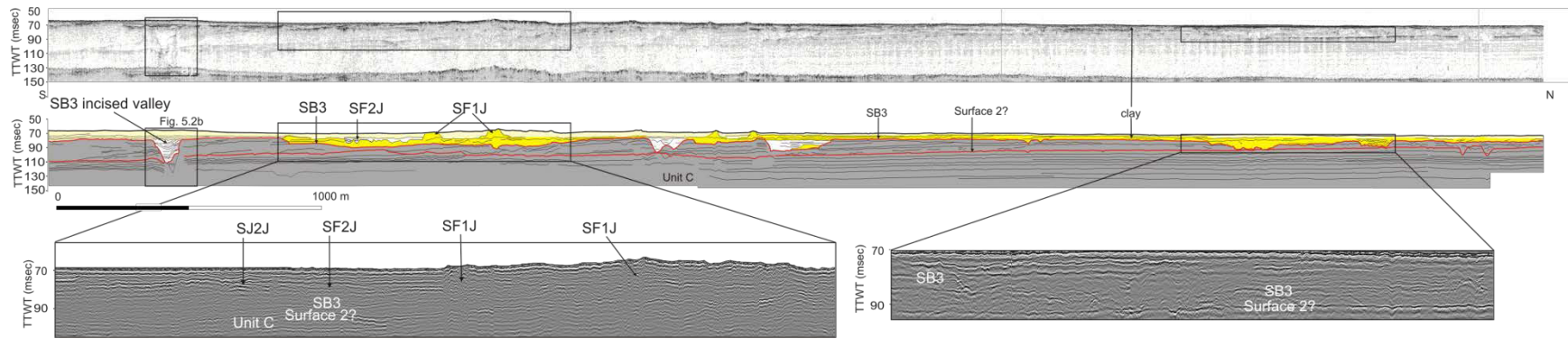
**Fig. 5.2.** Incised and filled valleys within SB3 from Glenashley Beach to La Mercy Beach. (a) The most proximally imaged incised valley offshore the Mdloti River. (b) Mid-shelf located incised valley related to the Mhlanga River. (c) Mid/outer-shelf located incised valley related to the Mhlanga River. (d) Down dip seismic section intersecting a bend of the Mhlanga River’s incised valley. Not the general seaward thickening of Units 1 and 4, the well-developed drapes of Unit 3 and the erosional nature of Reflector v.



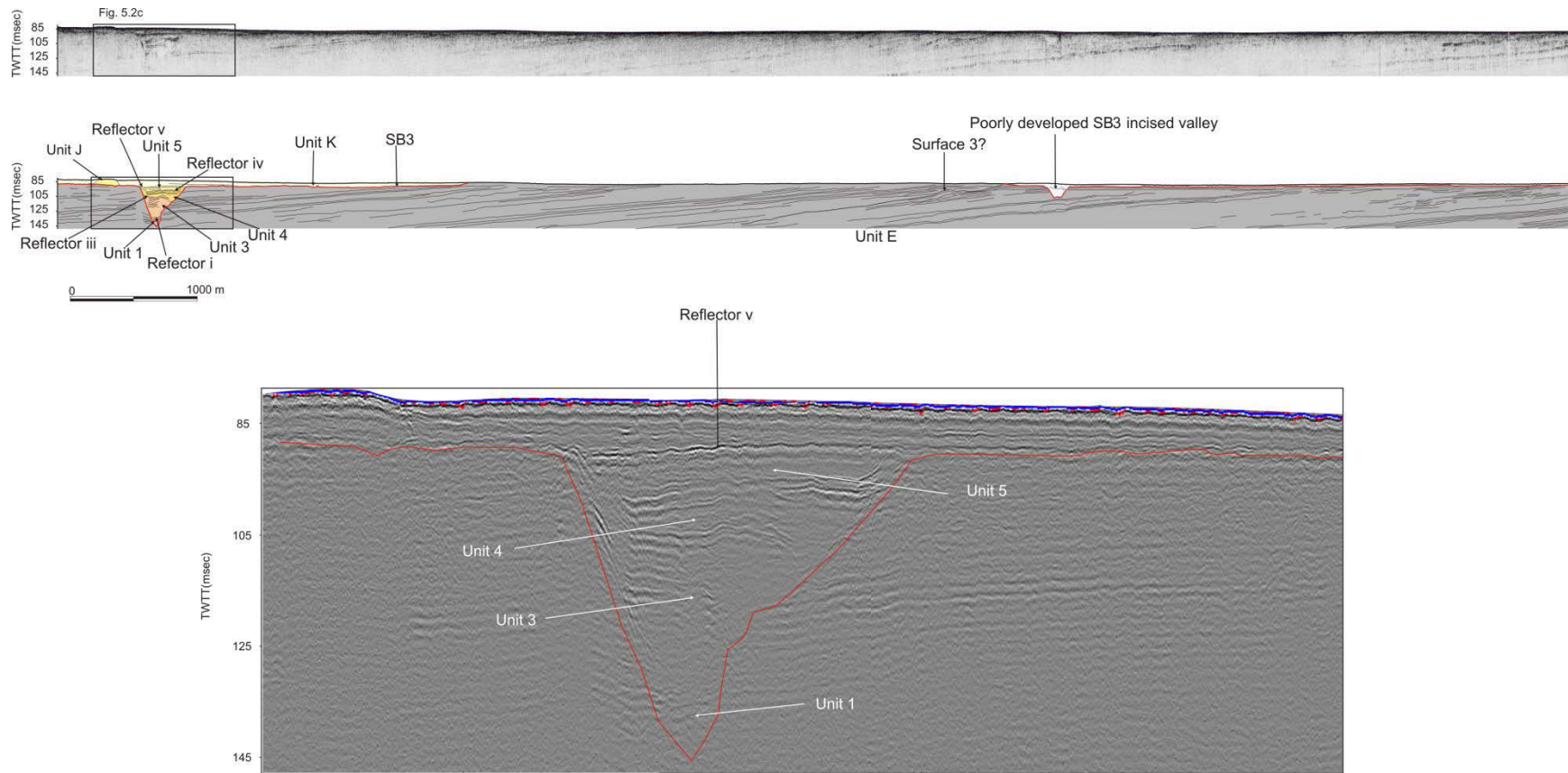
**Fig. 5.3.** Interpreted along-strike seismic image and enlarged seismic records. Note the presence of SB3 incised valleys, an almost completely exhumed latest Pliocene incised valley and several aeolianite units.



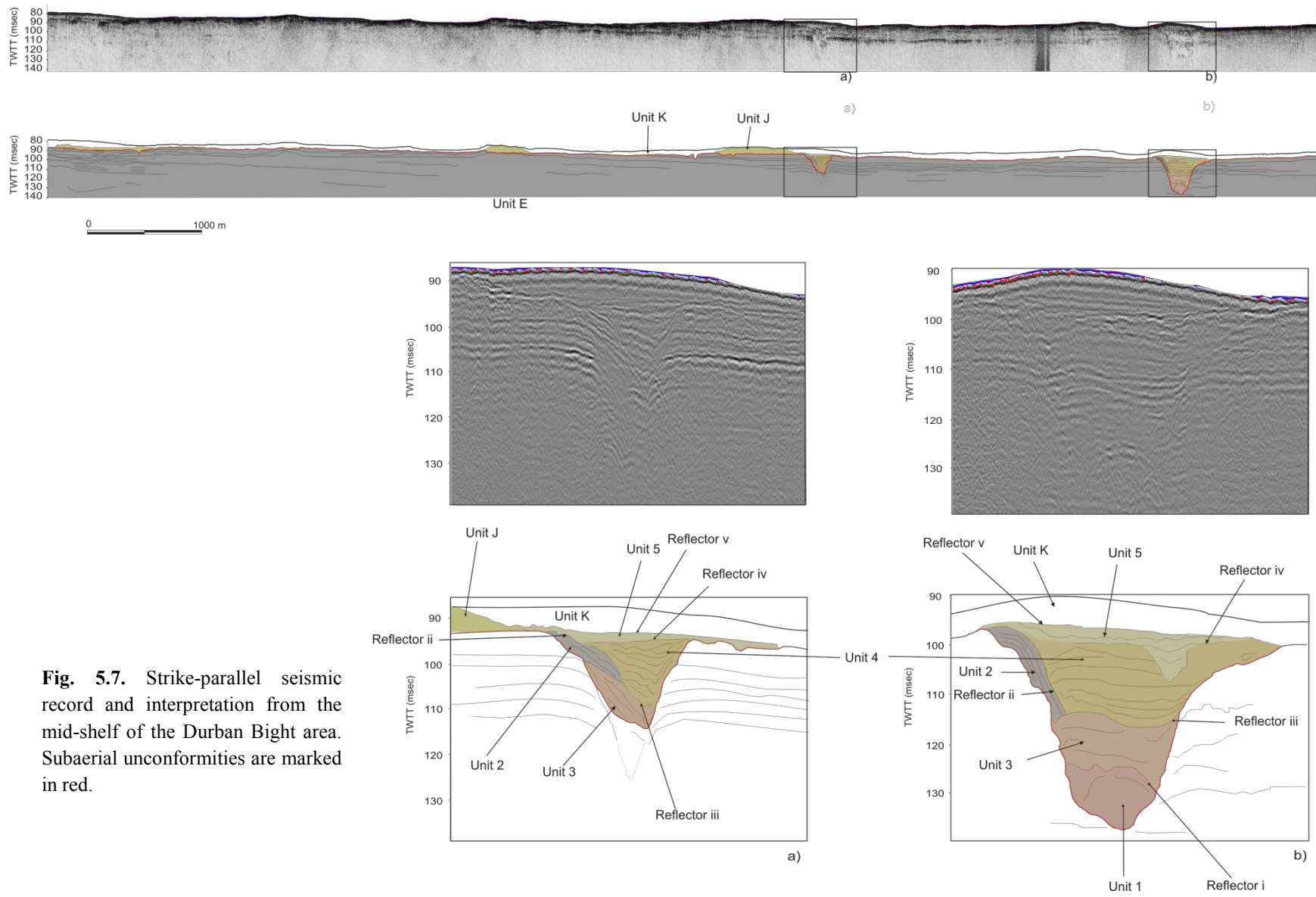
**Fig. 5.4.** Incised and filled valleys within SB3 from mid-shelf offshore Glenashley. ( a, b and c), south of Glenashley. ( d, e and f) and north of Glenashley. Note the better preservation of Unit 1 in V-shaped valleys north of Glenashley.



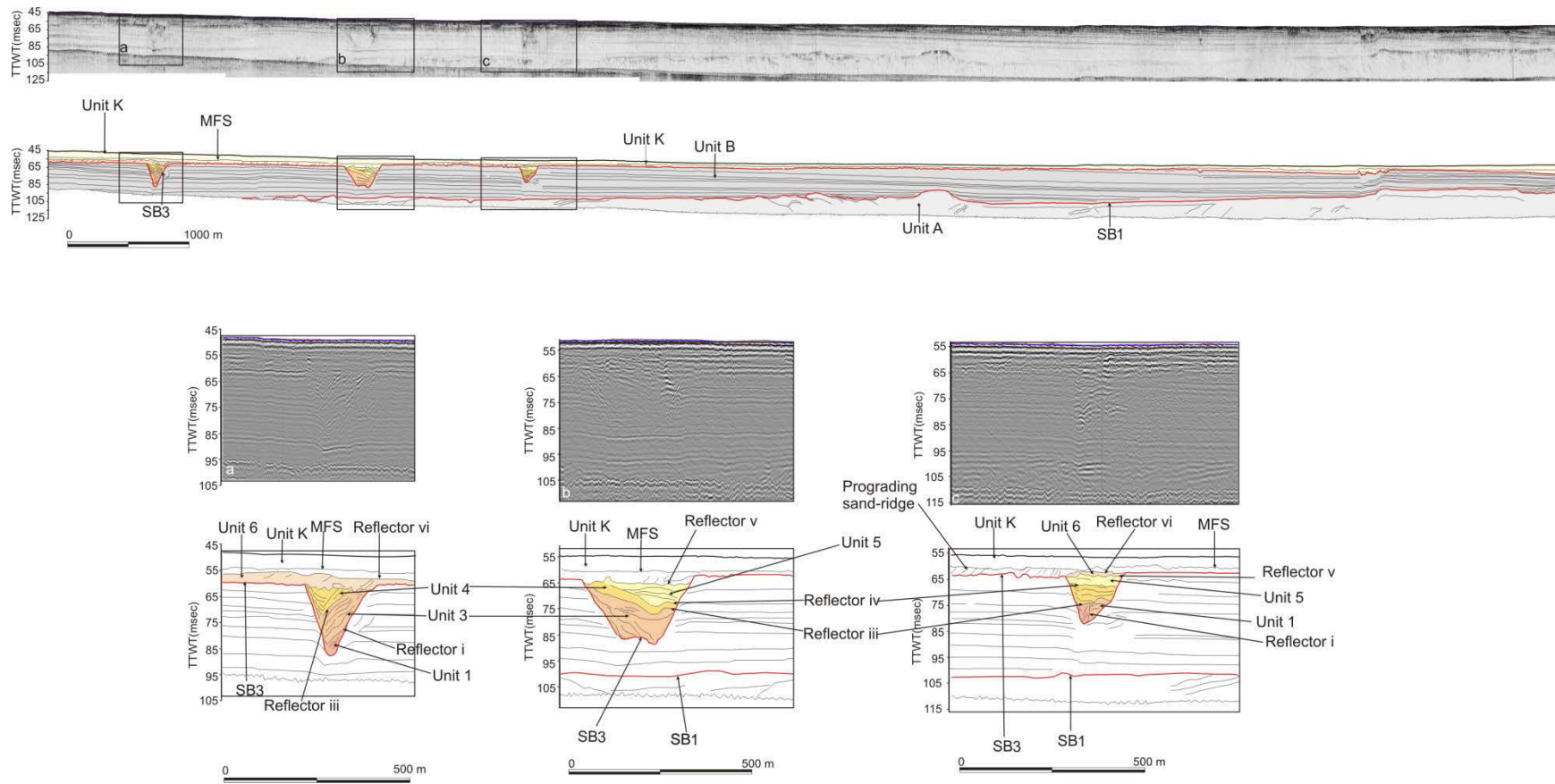
**Fig. 5.5.** Strike-parallel seismic record and interpretation from the mid-shelf of the Glenashely Beach to La Mercy Beach area. Subaerial unconformities are marked in red, incised valley fills are depicted in white. Note the single incised valley intersected by the line, offshore the Mhlanga River. Enlarged seismic sections detail the aeolianites of Unit J, and the rugged relief of SB3.



**Fig. 5.6.** Mid-shelf strike-parallel seismic interpretation depicting Units E, J and K. Note the presence of a single well developed SB3 incised valley and a poorly developed SB3 incised valley.



**Fig. 5.7.** Strike-parallel seismic record and interpretation from the mid-shelf of the Durban Bight area. Subaerial unconformities are marked in red.



**Fig. 5.8.** Strike-parallel seismic record and interpretation from the inner-shelf offshore the Mhlanga and Mdloti estuaries. Subaerial unconformities are marked in red.

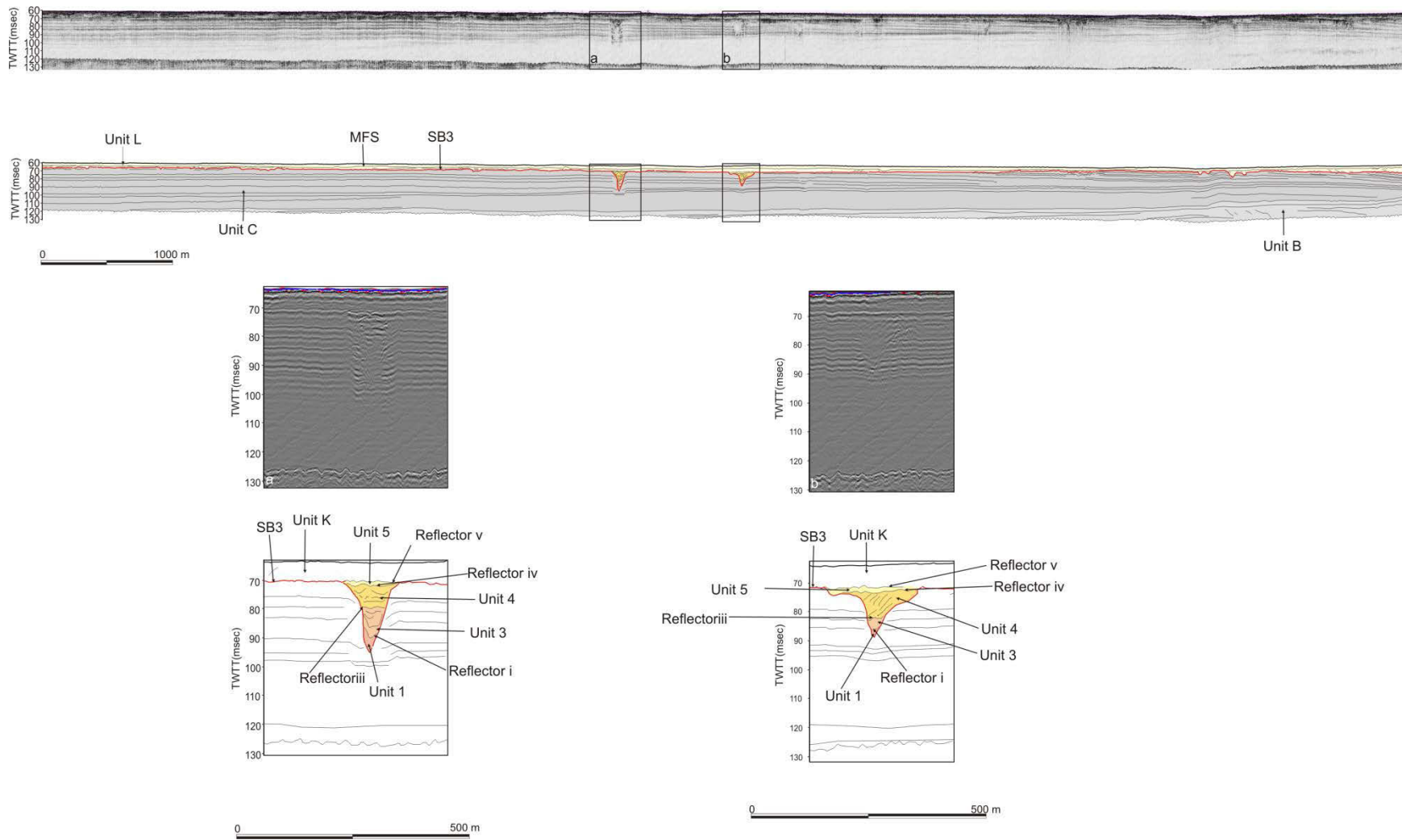
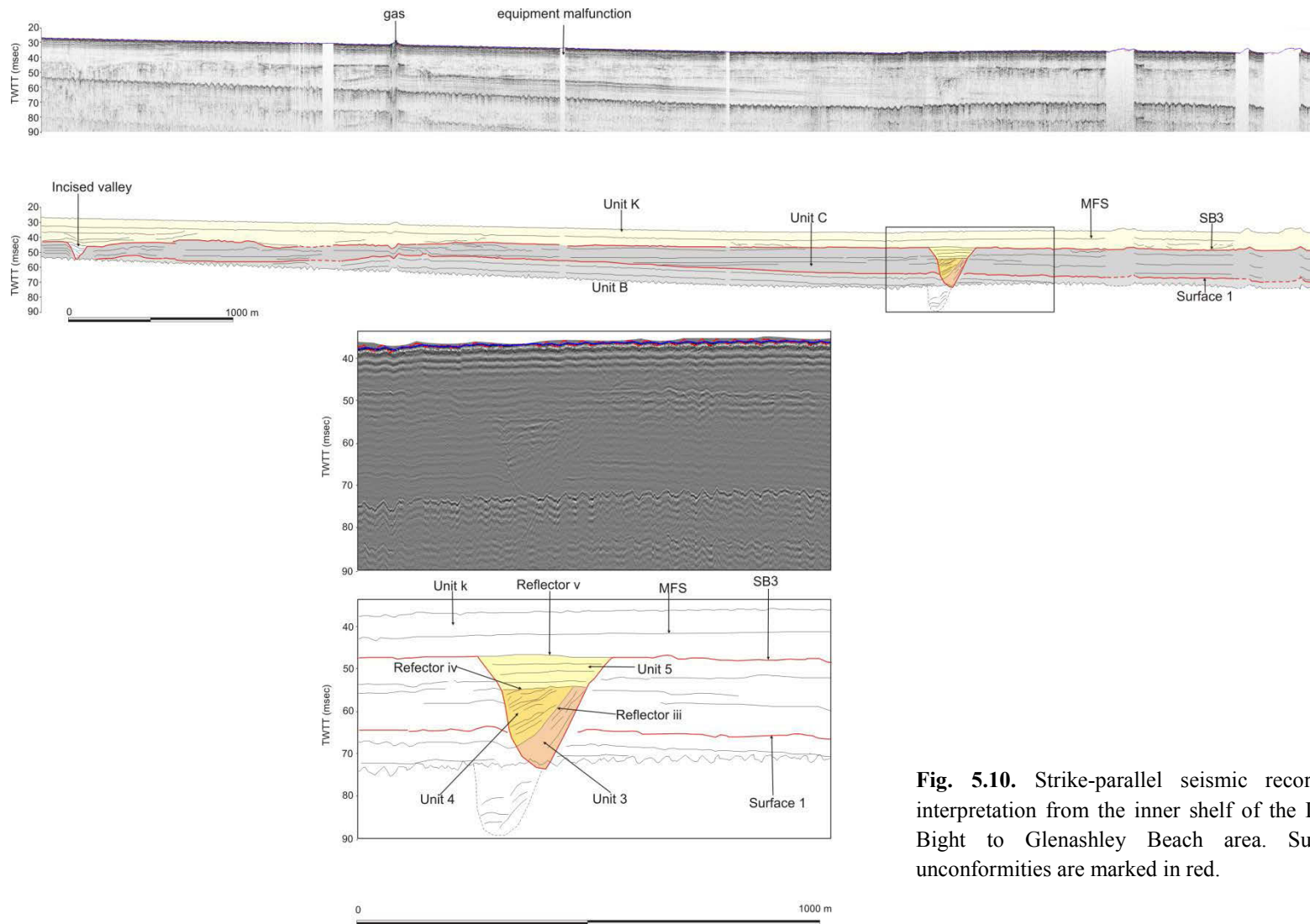
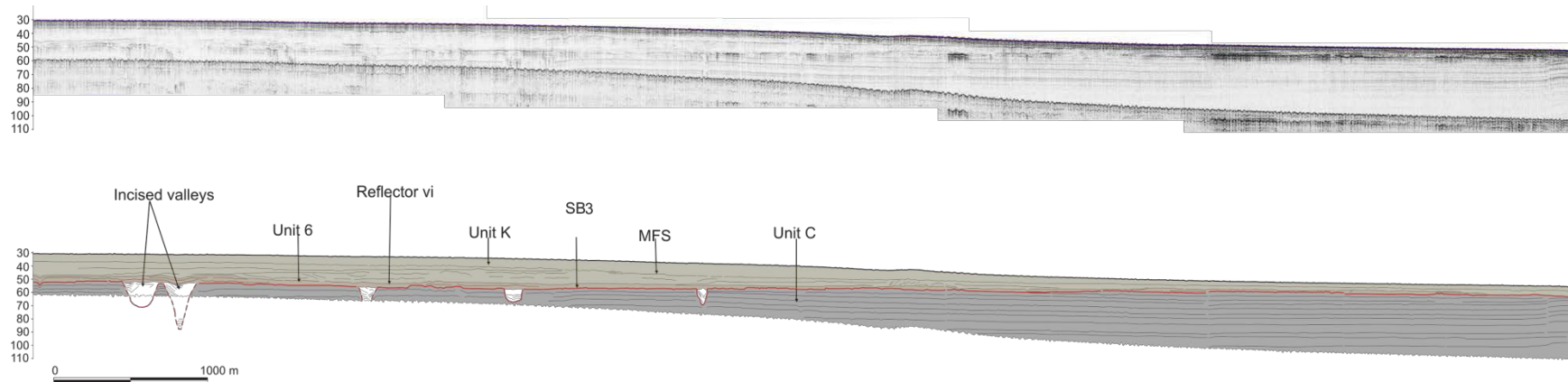


Fig. 5.9. Strike-parallel seismic record and interpretation from the inner-shelf offshore the Mhlanga and Mdloti estuaries. Subaerial unconformities are marked in red.



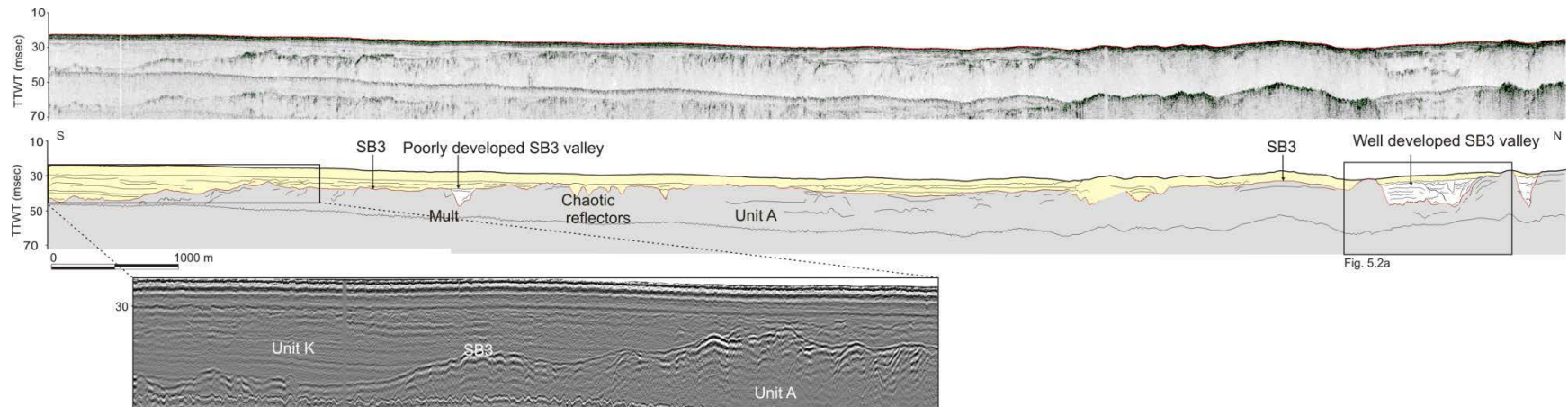
**Fig. 5.10.** Strike-parallel seismic record and interpretation from the inner shelf of the Durban Bight to Glenashley Beach area. Subaerial unconformities are marked in red.



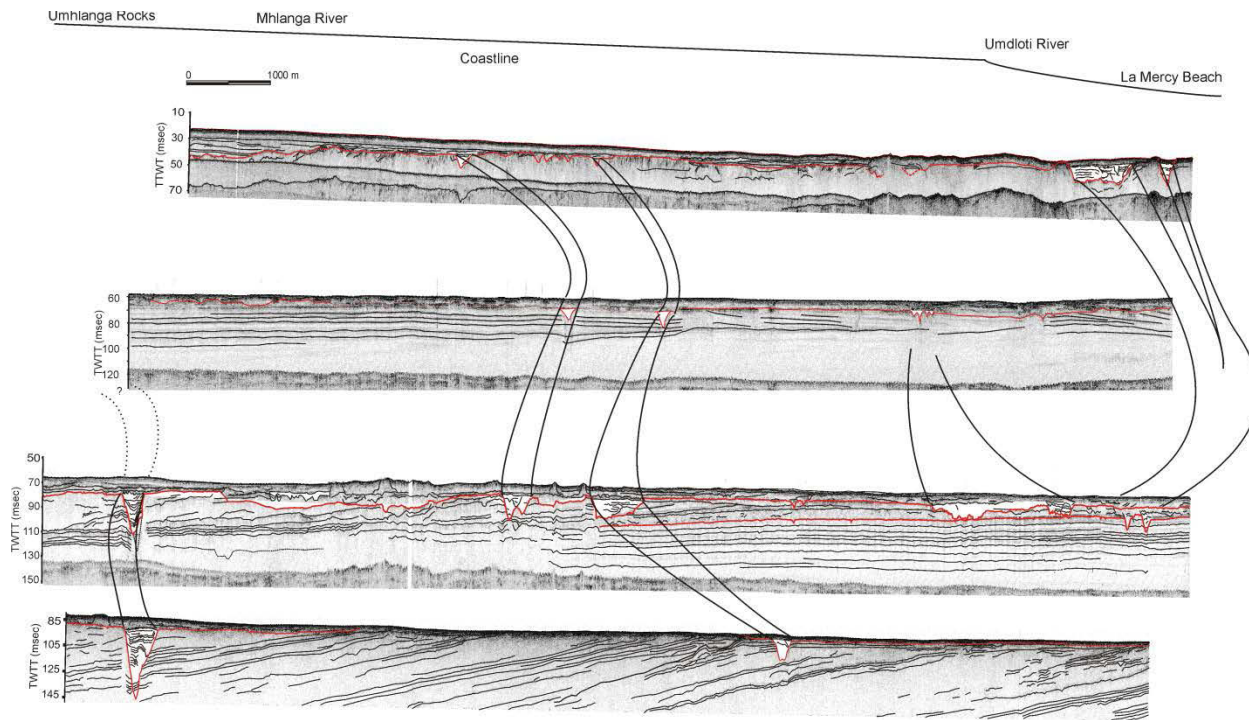
**Fig. 5.11.** Strike-parallel seismic record and interpretation from the inner-shelf of the Durban Bight area to Glenashely Beach area. Subaerial unconformities are marked in red, incised valleys are depicted in white.

### 5.3. Incised valley location and geomorphology

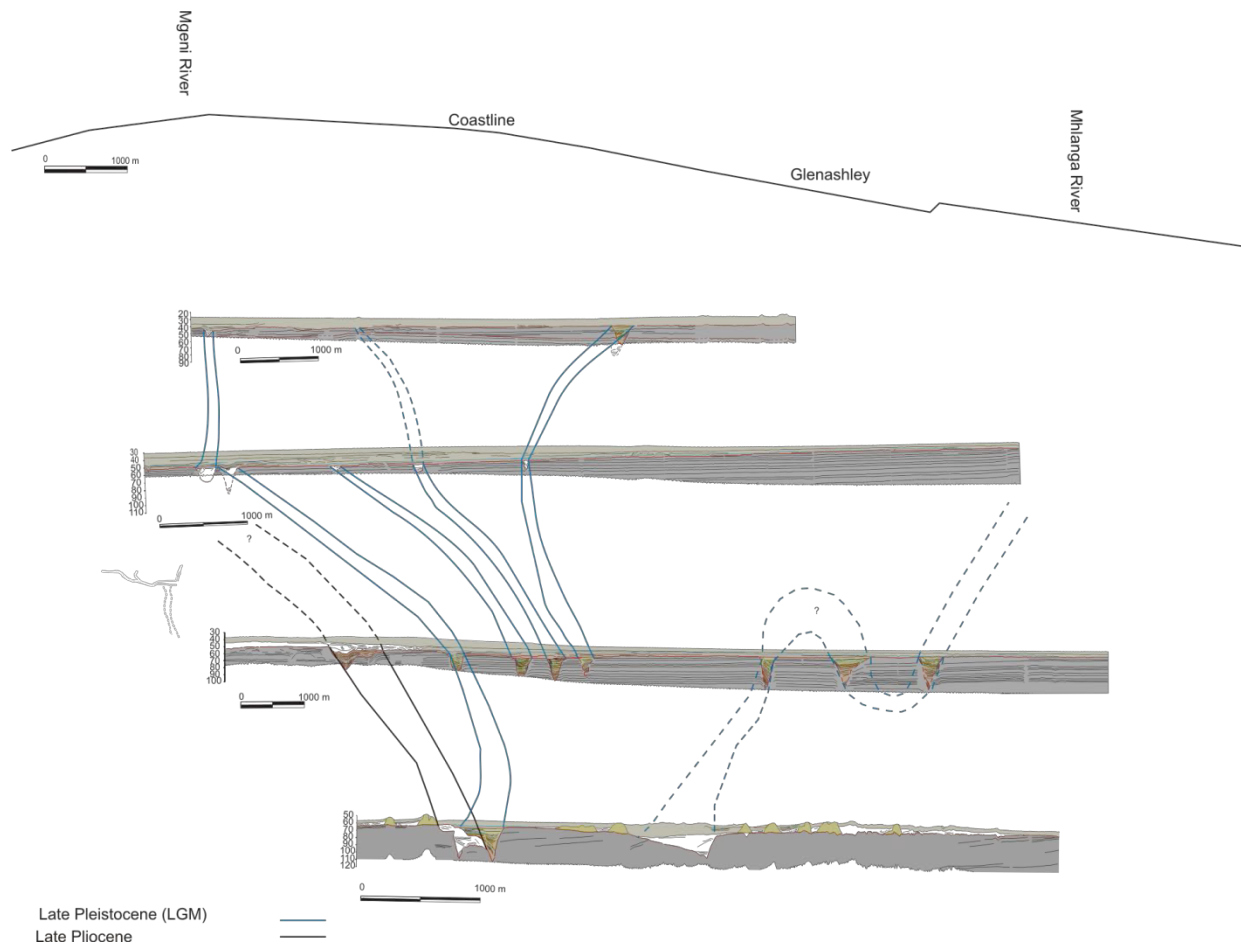
Overall, twenty five prominent incised valley systems are documented in this dissertation, from offshore the Mgeni River to La Mercy beach. Several more incised valleys are also observed in the study area, but due to the indistinguishable nature of their facies, they are not documented further (e.g. Fig. 5.11). To the north of the Glenashely Beach area, incised valleys are more isolated when compared to those found to the south (compare Fig. 5.1 with Fig. 5.6 and 5.12). Apart from the isolated examples of latest Pliocene age incised valleys, only one set of incised valleys occurs in the study area; those occurring within incisions of SB3. Throughout the study area, the LGM age valleys exhibit simple fills. The isolated latest Pliocene examples are only apparent in the Durban Bight area, where they appear to have been intersected and reworked by the younger LGM age incised valleys forming a compound fill arrangement (Fig. 5.1 and 5.3). The largest incised valley (75 m wide and 30 m deep) in the northern portion of the study area occurs 1 km north of the Mdloti River in the inner shelf (Fig. 5.13). Some incised valleys are apparent in the mid-outer shelf offshore the Mhlanga River (Fig. 5.13), yet no major network occurs in close proximity to the modern Mhlanga River course. Throughout the study area, there is a general absence of both LGM age and late Pliocene incised valleys in the inner shelf when compared to the mid to outer shelf (Figs. 5.13 and 5.14). Interestingly the LGM incised valleys tend to widen and deepen with distance from the shoreline (e.g. Fig. 5.2). These valleys are typically both U- and V- shaped.



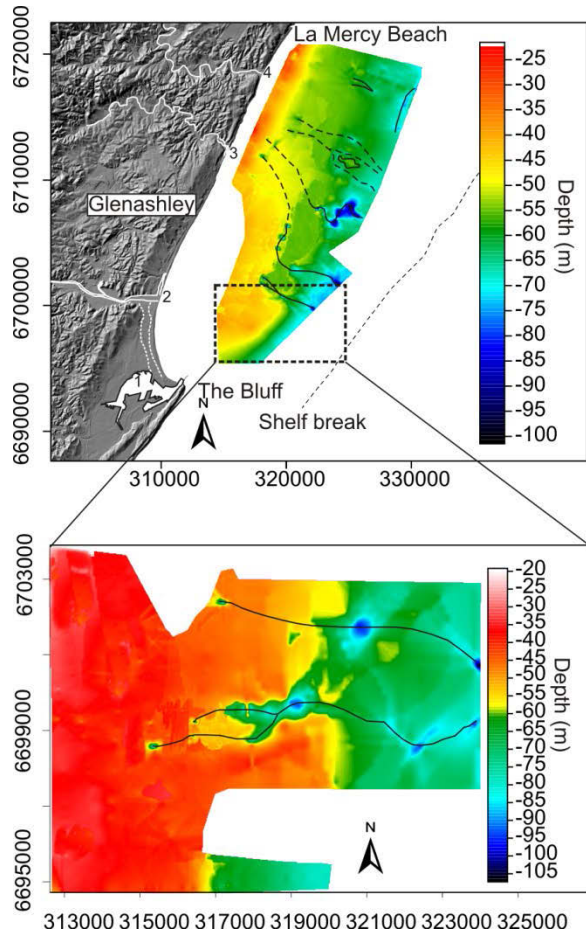
**Fig. 5.12.** Strike-parallel seismic record and interpretation from the inner-shelf of the Glenashley Beach to La Mercy Beach area. Subaerial unconformities are marked in red, incised valley fills are depicted in white. Note the single occurrence of an incised valley offshore the Mdloti River.



**Fig. 5.13.** Fence diagram of the seismic data and interpretive overlays for the Glenashely Beach to La Mercy Beach area. Note the development of only one network of incised valleys (SB3) and the absence of prominent incised valleys in proximal areas.



**Fig. 5.14.** Fence diagram of seismic data and interpretive overlays for the Durban Bight to Glenashely area. Note the presence of isolated latest Pliocene valleys (SB2) as well as SB3 valleys. Note the absence of prominent incised valleys in the inner-shelf when compared to the mid and outer shelf. Incised valleys tend to deepen and widen with distance from the shoreline. Note the meandering river pattern in the mid-shelf.



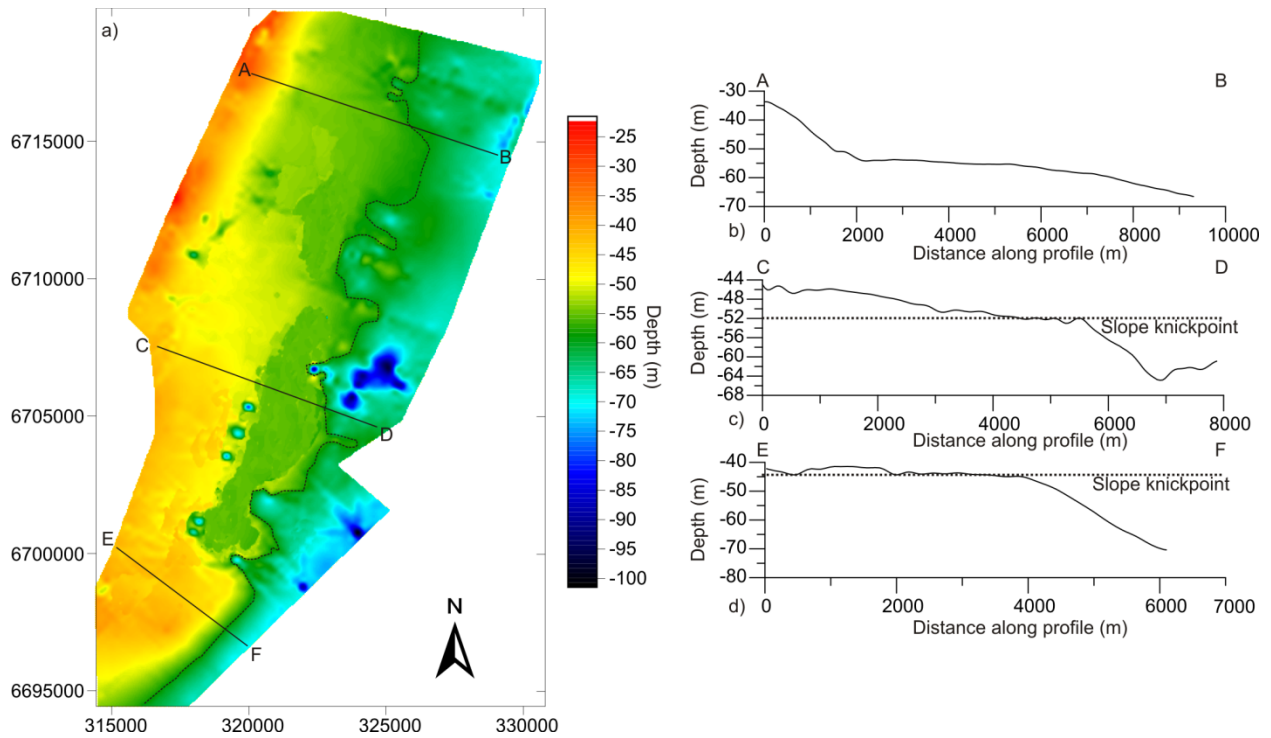
**Fig. 5.15.** Sub-surface geomorphology and drainage pattern offshore the Durban continental shelf, from Durban Bight to La Mercy Beach (data from Green and Garlick, 2011) incorporated into the gridded data set.

### 5.3.1. Drainage patterns and subsurface geomorphology

Rivers in the study area appear to have avulsed throughout the study area and show no specific drainage pattern (Fig. 5.15). In the northern parts of the study area, these rivers seem to meander in the mid-outer shelf offshore the Mhlanga River. Offshore the Mgeni River, in the mid-shelf, a dendritic pattern of valleys is evident but no single clear river system can be delineated. In both areas a clear subsurface slope knickpoint is apparent at between 45 m and 50 m depth. The knickpoint has a crenulate shape forming a series of embayments bounded by cusped features (Fig. 5.16). The knick point becomes more prominent from north to south in the Study area (Fig. 5.16b to d). In cross section C-D, the slope knick point occurs at a depth of -52 m, ~ 5500 m along profile (Fig. 5.16 c). In cross section E-F, the slope knick point occurs at a depth of ~ 45 m, ~4000 m along profile (Fig. 5.16d).

### 5.4. Spatial variation of infilling and fill architecture

The SB3 incised valleys in the study area show a variegated fill succession. Unit 1 is typically better preserved in the V-shaped valleys and toward the north of the study area (e.g. Fig. 5.4). This Unit tends to become better developed with distance from the shoreline and with increasing valley relief (Fig. 5.2 a-d). Unit 4 thickens in a similar fashion. From the Glenashley/La Mercy Beach area, Unit 2 is best preserved in the inner shelf and is absent in the mid-outer shelf. Conversely, in the southern study area, this unit is absent in the inner shelf and is instead best preserved in mid- outer shelf, and seems to increase in volume from the north to south (Fig. 5.4). Units 5 and 6 are preserved in all incised valleys, from the inner-outer shelf.



**Fig. 5.16.** Subsurface geomorphology and the subsurface knick point. (a) location of the cross section lines. (b) cross section through point A-B. (c) cross section through points C-D. (d) cross section through points E-F.

## CHAPTER 6

### Discussion

Six seismic units are evident as infill material within incised valleys found in the study area. The interpretations of Units 1-4 are based on other authors' interpretations of similar seismic units (e.g., Nordfjord et al., 2006; Green, 2009). The fill of the valleys throughout the study area is similar to the typical infilling response to transgressive flooding of Ashley and Sheridan (1994) and Zaitlin et al. (1994).

#### 6.1. Depositional trend of the incised valley fills

##### 6.1.1. Unit 1 Fluvial lag deposits

Based on the high amplitude, wavy to chaotic nature of the reflectors characterizing Unit 1, and its position directly above the regional basal incision surface (SB3), this unit is interpreted as a higher energy, late lowstand fluvial lag deposit (cf. Zaitlin et al., 1994).

##### 6.1.2. Unit 2 Central basin deposits

On the basis of its low amplitude and draped nature, Unit 2 may be considered as the central basin-type fill for wave dominated (cf. Zaitlin et al., 1994) and mixed wave and tide dominated (Allen and Posamentier, 1994) estuaries. Such seismic units are recognised as such in many similar seismic studies of incised valley systems (Weber et al., 2004; Chaumillon and Weber, 2006; Nordfjord et al., 2006; Green, 2009; Tesson et al., 2011).

### 6.1.3. Unit 3 Progradational fluvial point bars

Unit 3 appears as a valley flank attached seismic package. Based on this attached nature to the valley margins, Unit 3 may be considered a tidal-flat type environment. Nordfjord et al. (2006) suggests that such deposits were deposited as Holocene transgression began to backfill incised valleys. The higher amplitude and progradational arrangement of the reflectors suggests coarser-grained sediment (e.g. Foyle and Oertel, 1997) which is typical of modern day estuarine tidal flats on the east coast of South Africa (Cooper, 2001). Alternatively this unit may be interpreted as a series of fluvial point bars (e.g. Weber et al. 2004) which would better match the seismic sandwich model presented by Weber et al. (2004). In keeping with the progradational arrangement of reflectors, this argument seems more likely.

### 6.1.4. Unit 4 Estuary-Mouth complex deposits

Unit 4 may be interpreted as a product of barrier/ flood tide deltaic/ estuarine mouth plug and shoreface deposits based on the variable amplitude and often mixed arrangement of the reflectors therein. According to Nordfjord et al. (2006) such deposits reflect deposition under complex and highly energetic wave and current conditions. The mixture of small aggrading and prograding high amplitude reflectors may represent prograding dunes, linear shoals, or tidal bars fed by longshore drift (e.g. Nordfjord et al., 2006). The high angle dipping reflectors are considered bedding generated by the lateral migration of the inlet (e.g. Chaumillon and Weber, 2006). This is consistent with the modern day inlet behaviour on the KwaZulu-Natal coast (Cooper, 2001).

### 6.1.5. Unit 5 Flood deposit?

Unit 5 is atypical from most other seismic or sedimentological models proposed for incised valley systems (e.g. Allen and Posamentier, 1994; Ashley and Sheridan, 1994; Zaitlin et al., 1994; Weber et al., 2004; Nordfjord et al., 2006; Tesson et al., 2011). Coring in the Durban Harbour within related incised valley systems revealed that similar seismic units are comprised of well stratified moderately-stiff clays. Unit 5 is interpreted as a flood deposit, only locally

developed, that resulted from suspension fallout after flood peak. Similar features are well known from the contemporary wave-dominated Mgeni Estuary. These formed after catastrophic flooding of the estuary resulted in a thick developed stiff clay covering most of the central estuarine basin (Cooper, 1988; Cooper et al., 1990). An extensive mud belt has been documented offshore the Gironde Estuary (Lesueur et al., 1996). This formed due to periods of episodic transport to the shelf. Unit 5 appears to be the more proximal portion of such a deposit, preserved within the valley form that provided shelter from wave reworking.

Green et al. (2013a) provide an alternative hypothesis for the development of similar looking seismic facies in an overstepped lagoon formed offshore Durban. They interpreted this facies as representing the more distal portions of Zaitlin et al.'s (1994) baymouth sandplug. These areas are characterised by back-barrier muddy material interspersed with coarser grained packages that have been introduced by barrier washover. Dabrio et al. (2000) describe similar types of distal-proximal mouth plug geometries from incised valleys of the Gulf of Cadiz. Here muddy deposits of the transgressive distal backbarrier (Unit 4) are overlain by sandy barrier equivalents (Unit 5), separated by a tidal ravinement surface. The surface underlying Unit 4 is thus accordingly interpreted as such. Localised scours that truncate the upper reflectors of Unit 4 (Fig. 5.7) are suggestive of local scale tidal scouring within the inlet complex itself (Reflector iii). Consequently this Reflector iii is interpreted as a minor tidal ravinement surface formed by inlet migration during transgression.

#### 6.1.6. Unit 6 Post oceanic ravinement sediment

The capping unit, Unit 6 that overlies the incised valley succession is interpreted as the post-oceanic ravinement (Reflector v) sediment drape.

#### 6.1.6.1. The infilling of incised valleys by migrating dunes/ shelf sand-ridges

The seismic data reveal that in some instances, Unit K and Unit 6 are indivisible. This suggests that the SB3 incised valleys offshore Durban were at times filled by migrating shelf dunes such as in the underfilled incisions of Hervey Bay, Australia (Payenberg et al., 2006). According to Payenberg et al. (2006), the valley fill identified here is not typical of incised valleys that contain sediments deposited in wave-dominated drowned river-valley estuaries. The subaqueous dunes/prograding sand-ridges currently infilling parts of the incised valley are evidence for strong northward-directed currents on the shelf (Boyd et al., 2004). In this study, LGM age incised valleys may have been largely infilled during ensuing sea level rise, but the presence of sand dunes capping the succession suggests that they were underfilled during transgression and that were subsequently filled by the current-reworked post-transgressive sand drape (e.g. Payenberg et al., 2006). In either case, the accommodation left within the partially filled valley is now being filled by sediment migrated by tidal and ocean currents during sea level highstand conditions.

#### 6.2. Bounding Surfaces

Reflector i is a low relief reflector of low to moderate amplitude, separating the Fluvial lag deposits from the overlying central basin deposits. This reflector is interpreted as a bayline erosion surface formed during the landward transition of a bayhead delta during the early transgressive systems tract (Zaitlin et al., 1994). Localised scours at the base of Unit 4 are suggestive of local scale scouring within the inlet complex itself (Reflector iii). Reflector iii shows a similar seismic expression to that observed by Zaitlin et al. (1994) and Nordfjord et al. (2006), which they interpreted as a tidal ravinement surface. In Accordance this reflector is considered as such. The oceanic transgressive ravinement surface is formed by landward movement of the shoreface during rising sea level (Swift, 1968) Seismic reflector v is thus interpreted as a wave ravinement surface. This surface is also recognised by Nordfjord et al. (2006).

### 6.3. Spatial and temporal differences in incised valley development

Isolated incised valleys of the latest Pliocene age are recognised in this study and are similar to those described by Green and Garlick (2011). These authors suggest that these incised valleys show that there was an active drainage network at this time in the Durban Bight area. In keeping with this thinking, this dissertation also suggests that there was an active drainage network operating at this time in the study area. Where these latest Pliocene valleys have been re-incised by LGM age valleys, it is clear that the antecedent topography created a topographic low that would later be exploited during subsequent valley incision (e.g. Posamentier, 2001).

Green and Garlick (2011) recognised a number of stacked Cretaceous age networks in the Durban Bight. The valley networks documented here do not show such complexity in their stacking arrangements and lack any Cretaceous aged examples. Incised valleys systems are isolated, simple (as opposed to very clearly compound) in nature (see Green et al., 2013b), and are much larger than those of the Cretaceous age network of recognised by Green and Garlick (2011).

These differences have several implications for the development of the continental shelf of the area. This dissertation suggests that fluvial influences reduced northwards of the Durban Bight. In this case, rivers either did not incise (the unincised lowstand valleys of Posamentier, 2001) or there was a complete absence of rivers from this area during Cretaceous times. Given that the distance separating the two areas is ~30 km and uplift occurred along the entire length of the east coast of southern Africa (Walford et al., 2005; Moore and Blenkinsop, 2006) the latter argument is more likely; that active drainage had not yet evolved. Schumm and Ethridge (1994) show that a strong correlation exists between valley age and valley dimension; fluvial valleys typically widen and deepen with time. The smaller nature of the SB3 valleys north of the Durban Bight signifies that even when drainage (in the form of the palaeo-Mhlanga and Mdloti Rivers) did evolve; it was far smaller in size than that of the Durban Bight drainage which appears to have been dominated by the palaeo-Mgeni River since early Santonian times (Green et al., 2013b).

It is likely that the smaller Mhlanga and Mdloti Rivers only evolved during the base level fall associated with the late Pliocene uplift. Other isolated remnants of this Pliocene aged grouping of incised valleys occur to the south in the Durban Bight (Green and Garlick, 2011). These were fortuitously preserved from later re-incision and reworking by younger Pleistocene incisions by the inception of the Bluff dune ridge that would have diverted palaeo-drainage accordingly. In the northern study area, it is considered that these incised valleys are similarly compound valleys, yet the underlying Pliocene valleys were completely exhumed or modified during the Pleistocene glaciations, explaining the apparent dominance of simple incised valleys in the area. The persistent development of incised, rather than unincised river valleys (cf. Posamentier, 2001) since the early Pleistocene would promote the re-incision and reworking of these younger features inherited for their antecedent topography.

#### 6.4. Palaeodrainage patterns

The continental shelf offshore Durban is characterised by a poorly defined drainage pattern (Fig. 5.15). Due to the steep coastal hinterland and the much gentler and narrow coastal plain, the rivers draining from the hinterland changed their fluvial style when they intersected the exposed palaeo-coastal plain when sea level was lowered. This resulted in the meandering of rivers and the coalescence of several channels during avulsion processes. This avulsion is related to slow and steady rates of shelf uplift since the Neogene (Green, 2011) that may have caused constant channel shifting and thus a less ordered channel pattern.

#### 6.5. Spatial Variation of infilling and fill architecture

On the whole, these SB3 fills conform loosely to those fills recognised by other authors for the outer segments of wave-dominated incised valley systems (e.g. Zaitlin et al., 1994; Nordfjord et al., 2006) and to mixed wave and tide-dominated systems (Chaumillon et al., 2008). The variation in seismic unit distribution within these fills is considered to be a function of either the valley depth (and consequently accommodation and exposure to ravinement processes) or to

rapid infilling (e.g. Cooper, 1991). It is most likely that in the outer segment of the incised valley system, rapid drowning in the early Holocene (Ramsay and Cooper, 2002), possibly by MWP 1B (e.g. Green et al., in press) would cause an abrupt change in facies with the effects of the associated wave ravinement thus lessened.

The seaward thickening of the estuarine mouth plug deposits is likely to be associated with these valleys acting as updrift traps of littoral drift (e.g. Chaumillon and Weber, 2006; Chaumillon et al., 2008). Modern littoral drift in the study area migrates from south-to north, and results in modern estuaries along the KwaZulu-Natal coast possessing well developed barrier/inlet systems updrift of littoral drift sources (Cooper, 2002). Valley positioning relative to littoral drift has some control on the internal facies architecture too, though not to the extent that the entire fill is sand-dominated such as those of the Lay-Sèvre incised valley complex of the Bay of Biscay (Chaumillon et al., 2008) or the tide-dominated estuaries of the Eastern Cape of South Africa (Cooper, 2002).

It is interesting to compare the fills of the LGM aged valleys to the relative influences of tide-vs-river dominance in an overall wave-dominated setting (e.g. Cooper, 2001). In the outer portions of the studied valley systems, these valleys are most similar to those of Cooper's (2001) tide dominated examples. Fluvial sediment supply was comparatively low, central basin deposits are prominent and flood tide-deltas, washovers and barriers are present. In comparison, the inner portions appear to be related to river-dominance, where flood tide deltas are small or absent, with side attached bars (of sandy fluvial sediment) common. Such a change can be explained from the perspective of changing rates of relative sea level rise over time. The initial rapid rise in sea level following the LGM (Fig. 7.2a) would foster rapid drowning of the outer segments, lower rates of fluvial sediment supply and general dominance of the central basin and mouth plug deposits (Fig. 7.2c). The gradual slowing of relative sea level rise in the late Holocene (Fig. 7.2a and c) (Ramsay and Cooper, 2002) would conversely cause the proximal inner segments of the systems to behave in a river-dominated manner; a greater degree of fluvial infilling and lesser degree of marine infilling the result (Fig. 7.2c). The coastward younging of the valley fills thus means that

the outer portions would behave in a tide-dominated manner, whereas the inner sections would possess the characteristics of the contemporary, river-dominated estuaries of the KwaZulu-Natal coastline (e.g. Cooper, 2001).

There is a comparative absence of proximal incised valleys on the shelf in the study area. Instead of well-preserved valleys extending directly offshore of the modern day river mouths, incised valleys become progressively better preserved in the mid-shelf (apart from the Mdloti River). This could be the product of 1) differential subsidence along a shelf/coastal plain hinge line (sensu Labaune et al., 2010); 2) the shelf morphology (Lericolais et al., 2001; Chaumillon et al., 2008); or 3) removal of the valleys by ravinement processes during the late transgressive systems tract. The KwaZulu-Natal coastline in this case is shown to be rising slightly (Mather, 2011) and as such it appears that the first argument is not applicable. The second situation occurs when the shelf gradient shallows towards the shelf break and as such causes a reduction in the incision depth.

The wedging out of incision depths (Fig. 5.15) is most likely a factor of the latter two scenarios. Nordfjord et al. (2004) show a similar style of erosion; deglaciation in the post LGM period caused the development of a ravinement surface that removed most of the proximal portions of fluvially incised valleys on the New Jersey shelf, yet not to the extent that has occurred in this study. In the examples documented here, there is a disconnect between the inner and outer segments of the incised valley systems. Distal overstepping during transgression in the early Holocene and proximal erosion by ravinement during the slower transgression in the late Holocene would produce such morphology (Fig. 7.2c). An extensive, well-preserved barrier and back barrier complex is recognised in the mid-shelf of the study area (Green et al., 2013a; Green et al., in press) and confirms that rising sea level overstepped rather than eroded the shelf in this part of the study area.

## 6.6. Knickpoint significance

According to Green et al. (2013a), the Durban continental shelf is characterised by a series of closely spaced drowned aeolianite barriers at depths between 65 and 50 m. The depths of these drowned shorelines coincide with eustatic sea levels immediately preceding MWPs 1A and 1B, the surface preserved seaward of these features representing a ravinement surface formed during slow sea level rise (Green et al, 2013b). The knickpoint has a similar shape to the contemporary headland bound bays of KwaZulu-Natal and occurs at depths slightly shallower than the barriers documented. This knickpoint reflects differential rates of ravinement during sea level rise preceding and after MWP1B. Prior to MWP1B, slow sea level rise associated with intense ravinement of the palaeo-shelf had occurred (cf. Salzmann et al., 2013), forming a gentler topography. The steepening in topography is related to sudden in place drowning of the shelf that preserved this steepened topography, followed by slow rise in sea level and the resumption of intense ravinement processes and palaeo-shelf flattening. This flattening matches the ~ 48 m depth recorded by Liu and Milliman (2004) as the end of the meltwater pulse episode. A similar example is documented by Zecchin et al. (2011) from the Calabrian margin where they examine cliffs that have been overstepped in a similar manner.

## CHAPTER 7

### Conclusions

#### 7.1. Regional seismic stratigraphy

The regional seismic stratigraphy reveals several incomplete sequences spanning the Permian period through early Santonian times to present day. Pietermaritzburg Formation shales form the acoustic basement and are onlapped by early Santonian aged rocks deposited during a sea level highstand. Several new seismic units are revealed in this study and comprise thick packages of sigmoid prograding reflectors that onlap and downlap the erosion surface capping the acoustic basement. These are interpreted as normal regressive deposits formed during a late Campanian highstand, capped by a regional Maximum Flooding Surface. These are unconformably overlain by a strongly basinward prograding forced regressive wedge interpreted as late Maastrichtian in age. A major hiatus occurred and culminated in the incision of a major subaerial unconformity within which several isolated incised valleys are preserved. These are considered as late Pliocene in age. Onlapping this surface is a well-developed shelf edge wedge comprising normal regressive parasequence sets of the lowstand systems tract. This wedge is considered latest Pliocene in age and represents the emergence of shelf edge deltas after a prolonged period of sea level fall associated with hinterland uplift and incised valley formation. It is likely that the incised valley network fed the shelf edge wedge during the lowstand interval. These were re-incised by several valleys that formed during sea level fall towards the LGM. The subaerial unconformity has reworked the upper surfaces of every unit that subcrops the shelf and overprinted most of the late Pliocene incised valleys. Several late Pleistocene/Holocene submerged shoreline complexes are evident in the mid-shelf region and are associated with sea level stillstands superimposed on the Flandrian transgression after the LGM. The preservation of both the barrier shorelines and their backbarrier lagoonal fills is related to the abrupt overstepping of these features during MWP1A and MWP1B. The infilling of the LGM aged valleys occurred during this transgression and was followed by the development of the modern Holocene sediment wedge that formed as sea levels stabilised towards the mid Holocene.

## 7.2. Incised valleys

Two networks of incised valleys encompassing late Pliocene and late Pleistocene ages are documented. The older incised valley networks are associated with the development of small, incipient fluvial systems during phases of uplift that established a cross shelf sediment transport network to the shelf edge.

The incised valley fills appear to conform to fairly standard stratigraphic successions as recognised by many other authors. However, the dominant allocyclic controls on infilling appear to be a combination of glacio-eustasy, available accommodation, degree of exposure to later ravinement (a function of valley depth and rapid deglaciation in the early Holocene) and valley positioning relative to littoral sediment supply. The capping valley fill (Unit 6/Unit K) suggests that the incised valleys off Durban were at times filled by migrating sediment waves, evident of strong northward flowing bottom currents on the shelf. This is atypical of incised valleys that contain sediments deposited in wave-dominated incised valley systems.

The valleys associated with the Last Glacial Maximum had sufficient accommodation space to preserve a full suite of units associated with a lowstand-highstand sea level cycle. In these cases, this dissertation shows evidence, to a lesser degree, of control on the infilling succession by the updrift trapping of longshore drift (thickening of the barrier/mouth plug deposits northwards along drift direction). The change in fill character between proximal and distal valley fills reflects a change from a tide to river-dominated setting related to the slowing of the rate of sea level rise towards the mid Holocene.

Initial tectonic controls dictated to some extent the positioning of the early subaerial unconformities. The development of the late Pliocene age incised valleys was a function of hinterland uplift and influenced the evolution of later incised valley networks by the creation of an antecedent topography that would be inherited by successive incision phases. The LGM

channel geomorphology appears to be controlled by the changing style of fluvial systems at lowstand, a factor of the suddenly increased width in coastal plain and the amalgamation of channels during avulsion.

The examples presented in this dissertation document the evolution of a network of incised valleys from a tectonically dominated perspective to one influenced primarily by glacio-eustasy and antecedent topography. The models presented here may thus be extended to other shelves that have been exposed to intermittent uplift in their evolutionary history, superimposed by glacio-eustatic fluctuation.

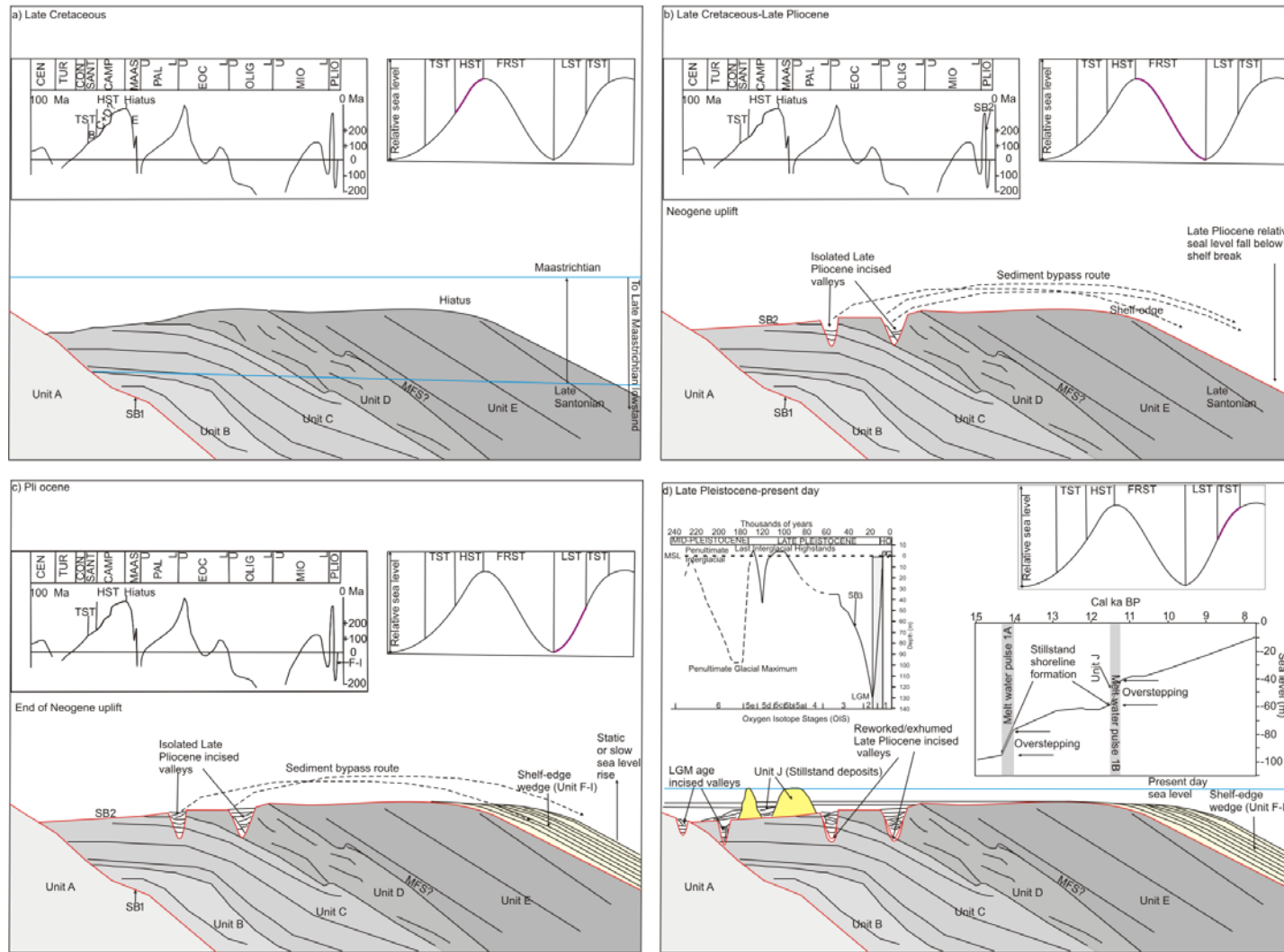
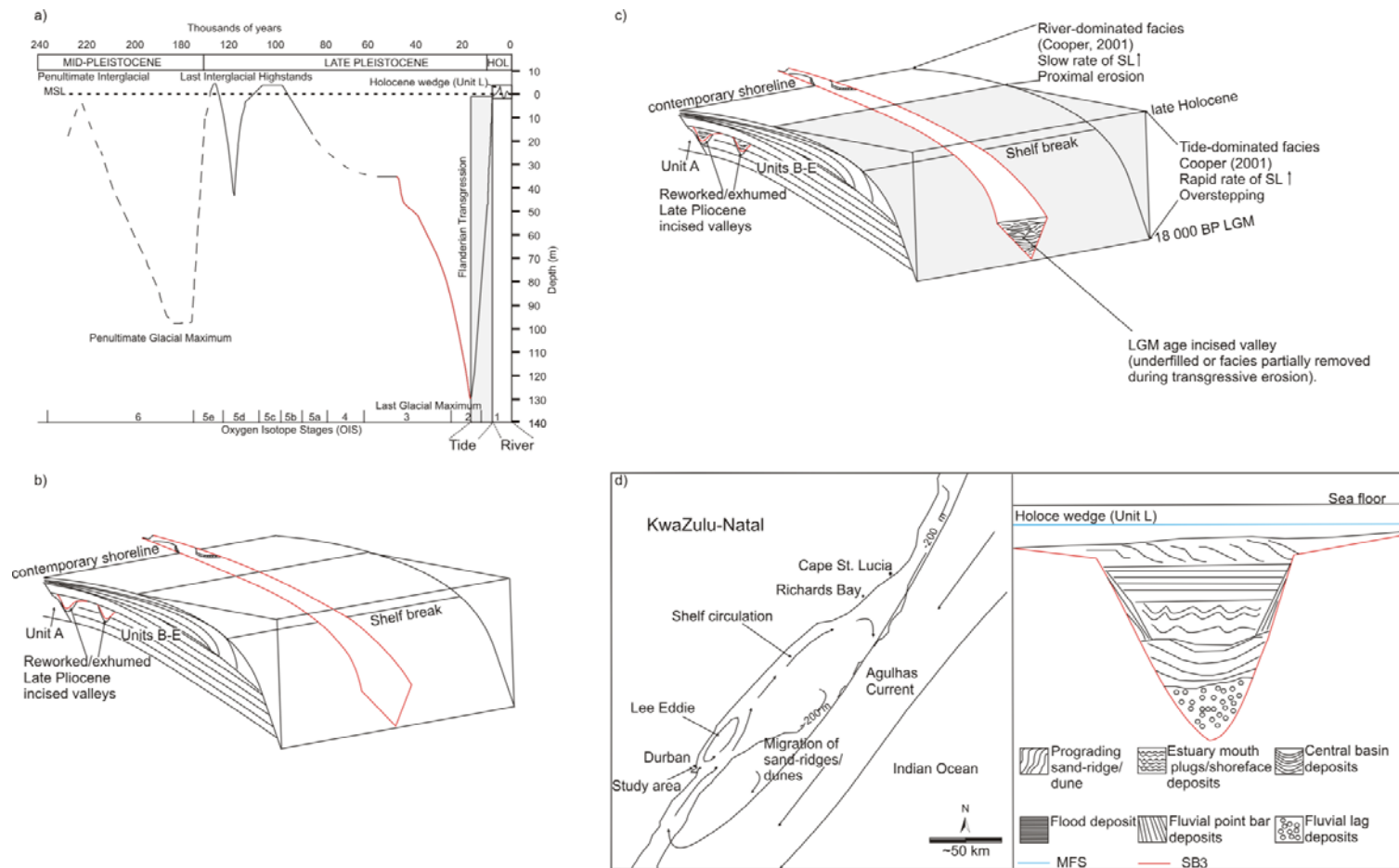


Fig. 7.1. A model of the evolution of the regional seismic stratigraphy off Durban. See text for discussion.



**Fig. 7.2.** A model for the development of the incised valleys offshore Durban. (a) Late Pleistocene sea level curve for the east coast of South Africa (after Ramsay and Cooper, 2002). Note the rapid transgression during deglaciation in the latest Pleistocene/ early Holocene followed by slowing rates of sea level rise in the late Holocene. (b) Formation of incised valleys during transgression (c) Partitioning of the incised valleys into mid-outer segment tide-dominated and inner segment river dominated systems. Such partitioning is related to the differential influence of rate of sea level rise along the profile of each valley segment. (d) The shelf circulation as related to a typical incised valley fill with a capping of prograding dune facies.

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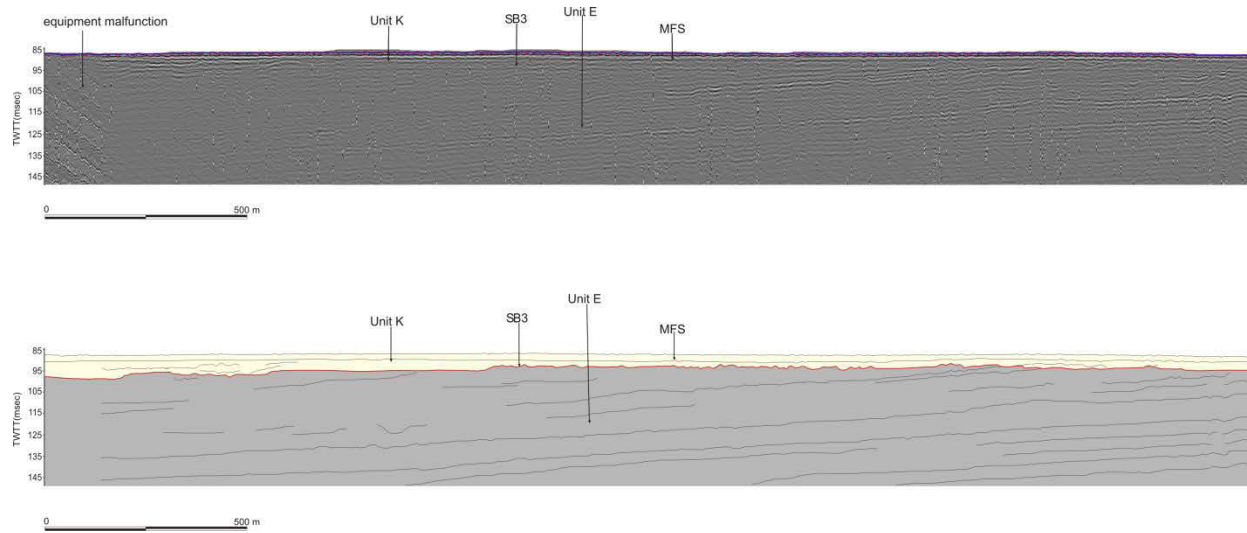
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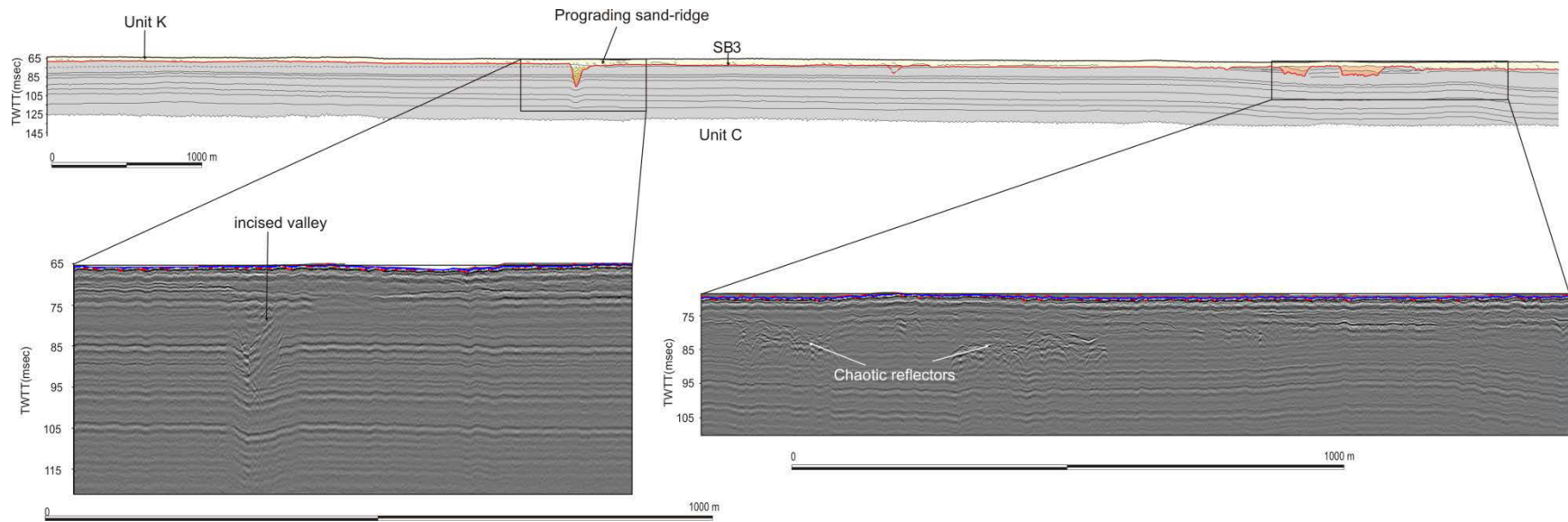
Dr. A.N Green (2013).

## Appendix A

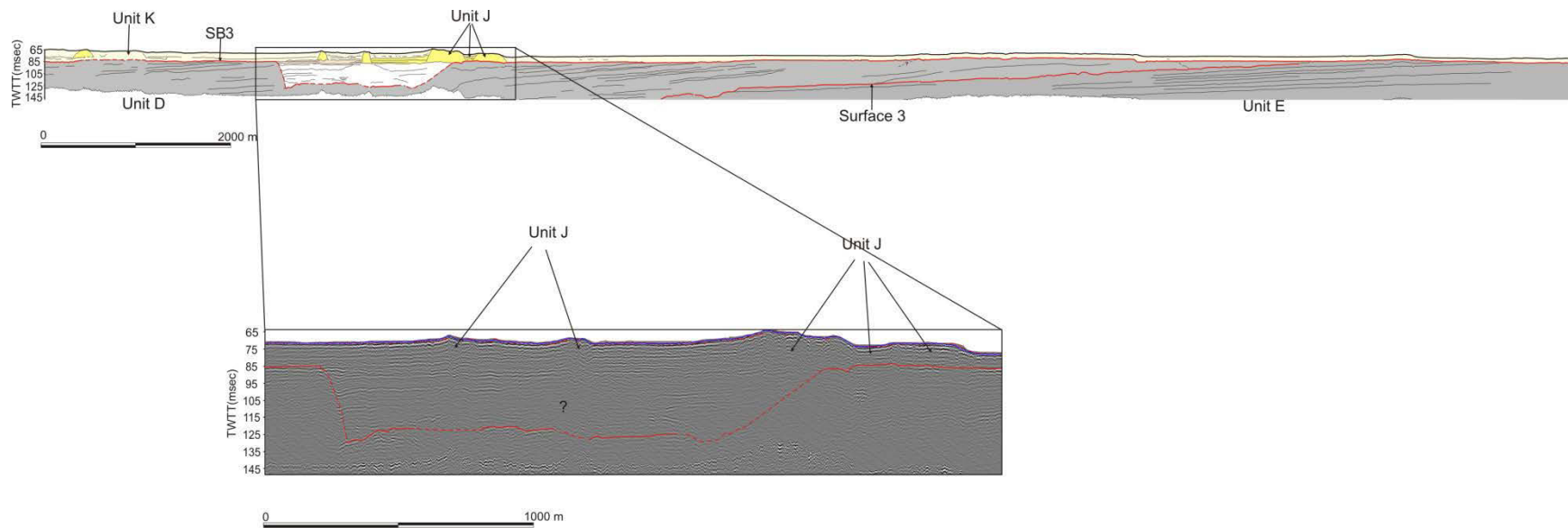
Additional Strike-parallel seismic records and interpretations from the mid-shelf offshore the Glenashley to La Mercy Beach areas.



**Fig. 8.1.** Strike-parallel seismic record and interpretation from the mid- to outer-shelf offshore La Mercy Beach area.



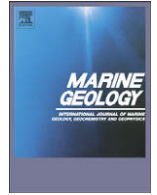
**Fig. 8.2.** Strike-parallel seismic record and interpretation from the mid-shelf offshore the Mhlanga and Mdloti estuaries. Subaerial unconformities are marked in red.



**Fig. 8.3.** Strike-parallel seismic record and interpretation from the mid-shelf of the Glenashley to La Mercy Beach areas. Subaerial unconformities are marked in red.

## Appendix B

Publication entitled “Spatial and Temporal variations in incised valley systems from the Durban continental shelf, KwaZulu-Natal, South Africa” by Green. A.N, Dladla, N. And Garlick, G.L.



# Spatial and temporal variations in incised valley systems from the Durban continental shelf, KwaZulu-Natal, South Africa

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## ABSTRACT

The evolution of several incised valley systems from the KwaZulu-Natal shelf is compared over time. These represent the shelf extension of the collective Durban Harbour drainage system, and the Mgeni, Mhlanga, and Mdloti Rivers. Two main ages of incision are apparent; early Santonian (Cretaceous), and late Pleistocene/Holocene. The early valleys formed by tectonic controls, namely phases of higher frequency base level fall superimposed on lower frequency, higher order transgression. The results are complex networks of stacked compound valleys that have been exploited by some of the younger networks formed by glacio-eustatic fall prior to the last glacial maximum (LGM) of ~18 Ka BP. The valley fills have evolved from high energy basal fluvial deposits, low-energy central basin fines, mixed-energy estuarine mouth plug deposits, clay-rich flood deposits through capping sandy shoreface deposits. The earliest fills are dominated by central basin deposits and were underfilled as a result of low gradient and limited sediment supply. The more recent late Pleistocene/Holocene fills have significantly thicker fluvial deposits as a result of increased gradient and stream competence during the later stages of valley and shelf evolution. The youngest valleys show a situation of differential evolution along the valley length due to varying rates of sea level rise in the Holocene. Initial rapid sea level rise caused drowning and overstepping of the outer segment of the incised valley, whereas slower rates of sea level rise in the late Holocene caused shoreface ravinement of the inner-mid segments of the valley. This differential exposure to accommodation has resulted in a sedimentological partitioning between tide-dominated facies in the outer valley segment and river-dominated facies in the inner segment (cf. Cooper, 2001).

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## 1. Introduction

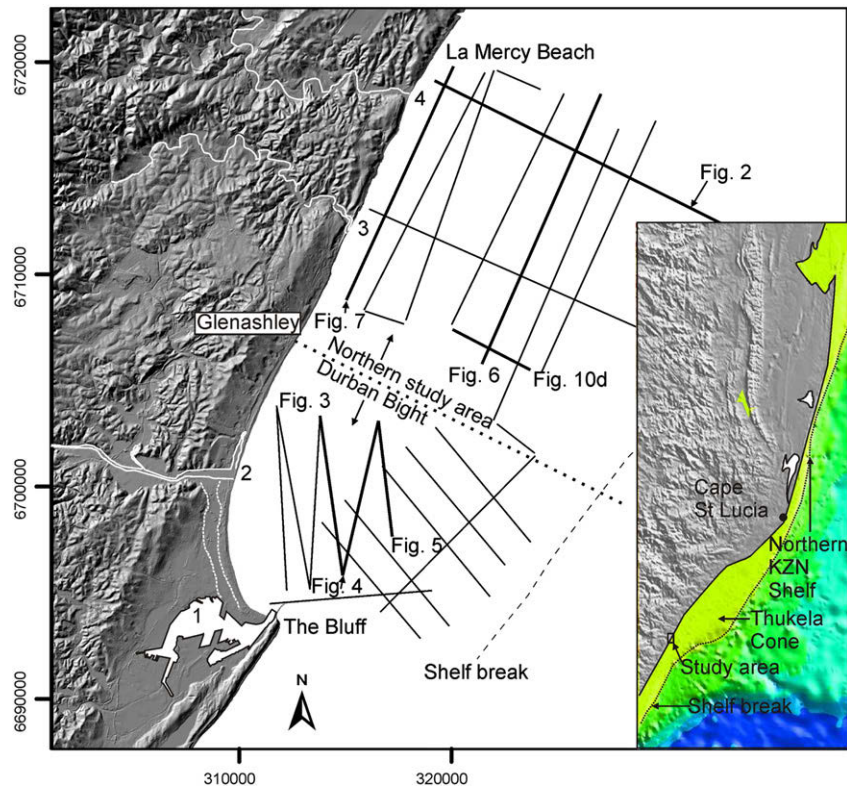
Incised valley systems (i.e. themselves, the drainage networks, and the infilling sediment) are important stratigraphic elements on continental shelves. They provide preferential accommodation for elements of the transgressive systems tract that are elsewhere removed by wave and shoreline erosion during the last phases of transgression in a sea-level cycle (Weber et al., 2004; Nordfjord et al., 2006; Tesson et al., 2011). Additionally, the lower surface of the valleys (the subaerial unconformity-or sequence boundary) is an important surface that represents base-level fall and the extension of drainage systems out onto the exposed continental shelf (Nordfjord et al., 2004). Recent work by Green and Garlick (2011) identified a network of buried palaeo-drainage (incised valleys) on the continental shelf of the Durban Bight, KwaZulu-Natal. They proposed that such features acted as conduits for sediment bypass to the fringing deeper basin during times of margin uplift and as such, were key elements in the active evolution of the continental margin during times of base-level fall. Using additional seismic data, we examine a widespread network of incised valley systems on the continental shelf offshore

Durban with the aim of examining the controls on the morphology, infilling and positioning of these systems.

## 2. Regional setting

The continental shelf of the Durban Bight and adjacent areas is narrow (~18 km) when compared to the global average of ~50 km (Shepard, 1963). 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), though the shelf is significantly narrower than that of the Thukela Cone (~45 km) to the north (Goodlad, 1986). The shelf break occurs at a depth of ~100 m, 20 m above the last glacial maximum (LGM) shoreline of ~18000 BP (Ramsay and Cooper, 2002). Oceanographically, the shelf is dominated by waves (Smith et al., 2010) and the poleward-flowing western boundary Agulhas Current. This current is particularly vigorous and has been attributed to the scouring of the south east African continental shelf (Flemming, 1981; Green, 2009). Tidal ranges average 2 m (SAN, 2009), and is thus in the upper microtidal category. Morphologically, the Durban Bight is dominated by a large crenulate bay at its southernmost point (the Bluff) (Fig. 1), straightening somewhat towards the Mgeni River. Thereafter, the shoreline comprises a straight swash-aligned planform with a very narrow (>1 km) coastal plain (Fig. 1).

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**Fig. 1.** Locality map detailing location of the seismic data used in this study, the position of the Durban Harbour complex (1) and the Mgeni (2), Mhlanga (3) and Mloti Rivers (4). The fluvial drainage patterns and emergent hinterland are shown as a sun-shaded relief map. Northing and easting co-ordinates in metres, UTM projection. Note the log-spiral form of the bay, with the coastline becoming more swash-aligned north of the Mgeni River. Inset depicts the regional bathymetry of the SE African continental margin. Note the variation in shelf width.

The study area's shelf forms part of the Durban Basin, a complex Mesozoic rifted feature which originated during the early phase of extension along the east African continental plate prior to the break-up of Gondwana (Dingle and Scrutton, 1974; Dingle et al., 1983; Broad et al., 2006). Rocks of the drift succession comprise shelfal claystones and siltstones of Late Barremian to Early Aptian age (McMillan, 2003). Drift sedimentation was episodic (McMillan, 2003), marked by deposition during the Early Santonian and Late Campanian with several hiatuses. Subsequently, depocentre amalgamation was accompanied by deposition of thick (>900 m) successions of marine claystones of Late Campanian to Late Maastrichtian age. These conform to the Mzinene and St. Lucia Formation respectively (Kennedy and Klinger, 1972; Dingle et al., 1983; Shone, 2006). The study area is underlain mostly by Early Santonian age rocks upon which a thin veneer of Pleistocene and Holocene sediment rests (Green and Garlick, 2011). Pleistocene age material occurs mostly as remnant onshore palaeo-dune cordons, while offshore equivalents formed during lower sea level stillstands. Cemented portions of these are preserved as coast-parallel, submerged reef systems (Martin and Flemming, 1988; Ramsay, 1994; Bosman et al., 2007). Around Durban partially cemented calcareous sandstones and unconsolidated clay-rich sands are preserved as the a) Berea and Bluff Ridges, and b) the Isipingo Formation (Anderson, 1906; Krige, 1932; King, 1962a,b; McCarthy, 1967; Dingle et al., 1983; Martin and Flemming, 1988; Roberts et al., 2006). Holocene sediments are restricted to the modern day progradational highstand sediment prism on the shelf and to unconsolidated muddy deposits in the swampy backbarrier areas of the Durban coastline and adjacent estuaries such as the Mgeni, Mhlanga and Mloti Estuaries (McCarthy, 1967).

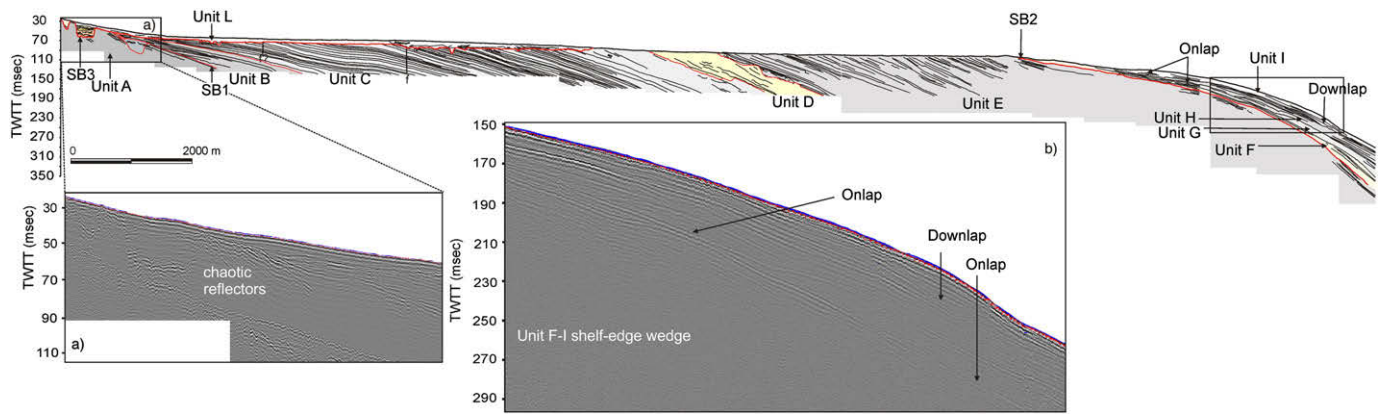
Tertiary aged deposits are considered absent from the coastal plain and shelf of the study area (Dingle et al., 1983). According to many authors (e.g. Wigley and Compton, 2006; Compton and Wiltshire, 2009), during the Neogene period both the western and

eastern margins of South Africa were characterized by major uplift induced cycles of erosion (Partridge and Maud, 1987) prompting large portions of the Tertiary successions to be eroded. However, Green and Garlick (2011) recognise thin, isolated incised valley fills of suspected Latest Pliocene/Early Pleistocene age.

### 3. Regional seismic stratigraphy

The regional seismic stratigraphy is best presented by 18 km long down-dip seismic records acquired from the La Mercy Beach area (Fig. 2). The shelf consists of several seismic units (A–L), delineated on the basis of the internal reflector geometry and bounding unconformity surfaces (Table 1). The acoustically incoherent Unit A comprises the acoustic basement of the northern study area, where it crops out on the beach as shale of the Permian age Pietermaritzburg Formation (SACS, 1980). Units B–E are strongly sigmoid progradational units, separated by minor unconformity surfaces. A notable exception is the boundary between units C and D which resolves as a high amplitude, rugged relief surface. Unit B is early Santonian in age, C and D are indeterminate and E is considered late Maastrichtian in age (Green and Garlick, 2011).

Units F–I depart from the sigmoid oblique pattern and instead comprise aggradational-progradational, moderate to low amplitude sigmoid-oblique to oblique parallel reflectors that form an onlapping-offlapping shelf edge wedge (Table 1). These have a striking resemblance to the forced regressive-lowstand shelf-edge wedge described by Green et al. (2008) and Green (2011) for the northern KwaZulu-Natal margin. These authors assigned a Late Pliocene age to the wedge; on this basis we accordingly assign units F–I in a similar manner. They are formed by hinterland uplift during the late Pliocene (e.g. Partridge and Maud, 1987). Subordinate, isolated incised valley fills of latest Pliocene age are also recognised from the shelf in the Durban Bight (Green and Garlick, 2011).



**Fig. 2.** Interpreted down-dip seismic image and enlarged seismic records depicting the regional stratigraphy of the study area. Units A–I and Unit L are present but are shown in subsequent along-strike figures. Note the various erosional surfaces (SB1–3) in red.

Units J and K commonly occur in the inner to mid-shelf portions of the survey area as two similar units of chaotic, very high amplitude internal reflector configuration (Figs. 3–7). These units have rugged appearances and often appear to rest upon the underlying SB3. This unit is equivalent to the coast-parallel calc-arenite reef systems of Martin and Flemming (1988), Ramsay (1994) and Bosman et al. (2007). Small drape and lateral accretion fills (Facies J1 and K1) (Fig. 3) within the saddles formed by this unit commonly occur as a back-barrier, clay-rich lagoonal fill (Green and Garlick, 2011).

Capping the stratigraphy is the late Pleistocene/Holocene Unit L (Figs. 2 and 3). This forms a shore-attached prograding wedge (Facies L2) comprising low to moderate amplitude discontinuous reflectors. The lower portions of unit L (Facies L1) comprises fills of the ~18000 BP LGM incised valley network (Figs. 4–7). The wedge attains a maximum thickness of ~11 m. Its lower boundary is marked by a high amplitude undulating surface (SB3). The top of the unit is the modern day sea-floor, except where units C and D crop out in the mid shelf.

#### 4. Methods

We examine the subsurface geomorphology and seismic structure by single-channel seismic profiling. Single-channel seismic data were collected using a boomer system and a 20-element array hydrophone. Power levels of 200 J were used throughout the survey. Positioning was achieved using a DGPS of ~1 m accuracy. Raw data were processed using an in-house designed software package. Time-varied gains, bandpass filtering (300–1200 Hz), swell filtering and manual sea-bed tracking were applied to all data. Streamer layback and antenna offset corrections were applied to the digitised data set and constant sound velocities in water (1500 m/s) and sediment ( $1600 \text{ ms}^{-1}$ ) were used to extrapolate all time-depth conversions. All seismic data have 3 m vertical resolution as a result of source ringing during data acquisition. Seismic data form part of a grid spanning ~300 line km (Fig. 1).

#### 5. Results

##### 5.1. Incised valleys

Within the early Santonian Unit B, several incised valley systems are apparent in the Durban Bight (Figs. 3–5). These form a series of compound valleys (valleys B1–B3) that display a nested stacking pattern forming complex drainage patterns between the Durban Harbour and Mgeni River area (Fig. 1). These valleys are typically

both U- and V-shaped and range from 100 to 200 m wide and 15 to 30 m deep (Figs. 3 to 5).

The largest incised valley in the Durban Bight occurs in the incisions of SB3 (Fig. 5). This is filled by Facies L1 and forms a large scale valley, up to 1.2 km wide and up to 30 m deep. This appears to have intersected and reworked the lower incised valley units within Unit B and some of the late Pliocene incised valleys of Green and Garlick (2011) (Fig. 5). Compared to the widespread underlying incised valley networks in Unit B, the valleys incised into SB3 are restricted in distribution and are typically centred offshore of the Durban Harbour (Fig. 6).

From north of the Mgeni River (Glenashley Beach to La Mercy Beach), only one set of incised valleys is present; those occurring within incisions of SB3 (Figs. 7 and 8). These appear as narrow, isolated features that exhibit simple (as opposed to compound) fills. The largest incised valley (75 m wide, 30 m deep) occurs 1 km north of the Mdloti River in the inner shelf (Fig. 9). Some incised valleys are apparent in the mid-shelf offshore of the Mhlanga River (Fig. 9), yet no major network occurs in close proximity to the modern Mhlanga River course. Incised valleys typically incise deeper with distance from the coast (Fig. 9).

Several common features occur throughout the study area. These are:

- 1) a comparative absence of incised valleys in the inner shelf, compared to the mid-outer shelf (Figs. 6 and 9). In almost all instances, depth of incision increases with distance from the shoreline.
- 2) a similar series of seismic units that occur within the fill successions of the SB3 network of incised valleys (Figs. 10 and 11).

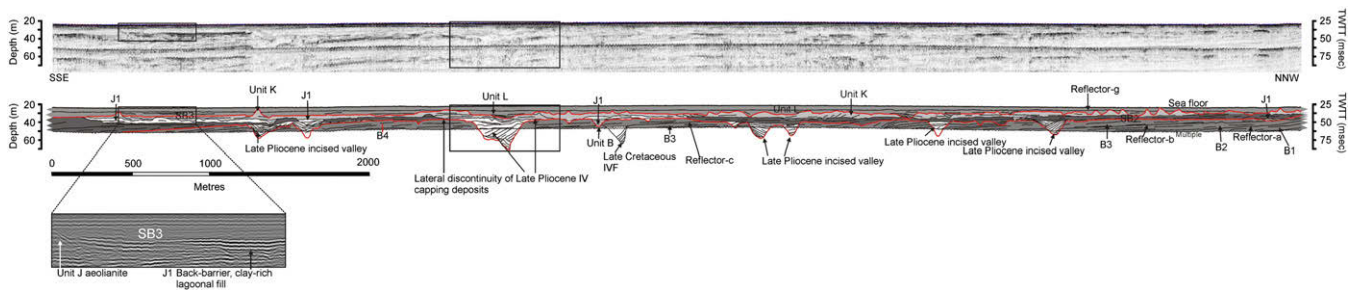
##### 5.2. Valley fill seismic stratigraphy

Incised valley fills within Unit B (Fig. 10a and b) comprise up to five seismic units (Table 2) while incised valleys developed in the SB3 surface (Figs. 10c; 11a–d) comprise up to six units (Table 2). Irrespective of location or age, the lower four seismic units of each valley fill exhibit similar acoustic characteristics and are grouped accordingly.

Unit 1, the lowermost valley fill, is bound at its base by the subaerial unconformity and has an erosional upper boundary (Reflector i). The internal reflector geometry comprises high amplitude, wavy to chaotic reflectors. Reflectors of Unit 2 onlap the valley sides and downlap Reflector i forming mounds. These comprise steeply dipping prograding sigmoid reflectors of moderate amplitude. Onlapping the valley sides and capped by an erosional reflector (Reflector iii), Unit 3 occurs as a thickly developed drape package of low angle sub-parallel, low amplitude reflectors. Reflectors of Unit 4 onlap Reflector iii and terminate against an erosive upper surface (Reflector iv). These form a sub-parallel to steeply

**Table 1**  
Simplified sequence stratigraphic framework for the northern KwaZulu-Natal continental margin, describing seismic units, bounding surfaces, the age of each unit and the interpreted depositional environments. Age of units based on Green (2011) and Green and Garlick (2011).

Underlying horizon	Seismic unit/surface	Sub-unit	Green and Garlick's (2011) unit	Modern description	Thickness	Characteristics	Interpreted depositional environment	Systems tract	Age
-	A	n/a	Not recognised	Pietermaritzburg Formation Shales		Chaotic	n/a	n/a	Permian
	SB1			Outer to mid-shelf prominent reflector		Erosional truncation of A, undulating surface, dipping shallowly SE		Sequence boundary	
SB1	B	B1-5, marked by incised valley subaerial u/c surfaces a-e	A	Outer to mid-shelf retrograding package.	> 20 m	Parallel to sub-parallel reflectors, moderate amplitude, high continuity, dip shallowly to SE	Outer to mid-shelf	Early TST	Early Santonian
	C		B	Inner shelf aggradational to progradational reflectors	> 100 m	Parallel to sub-parallel, high amplitude high continuity reflectors, dip shallowly to SE	Inner shelf to littoral zone	HST	Late Campanian
Rugged horizon	D		Not recognised		~50 m				?
	E		C		> 18 m	Parallel to oblique parallel moderate to high amplitude, high continuity reflectors, dipping shallowly SE,	Outer shelf to shelf edge	FSST	Late Maastrichtian
<i>Major hiatus spanning most of the Tertiary</i>									
	SB2			Entire shelf prominent reflector		Erosional truncation of A, B and C, undulating incised surface, no dip		Sequence Boundary	K/T boundary
SB2	F-I		Not recognised	Shelf-edge wedge		Aggradational/progradational moderate amplitude reflectors, onlap SB3	Lowstand shelf edge delta	LST	Latest Pliocene
SB2	Coeval with wedge, not apparent in the northern study area J-K		D	Isolated, laterally discontinuous incised valley fill		Onlapping and lateral accretion fills, moderate amplitude, chaotic reflectors	Incised valley fill	Late LST-TST	Latest Pliocene
			E-F	Inner-outer shelf stranded sediment outcrop	8 m	Welded onto underlying unit, very rugged appearance. Very high amplitude, unrecognisable reflectors	Palaeo-coastlines	Stillstand	Early to late Pleistocene
		J1		Fill within saddles of Unit J		Drapes, low amplitude	Backbarrier fill	TST	Early to late Pleistocene
	SB3			Entire shelf prominent reflector		Erosional truncation of B, J and K, undulating deeply incised surface, flat interfluvial		Sequence Boundary	LGM
SB3	L	L1	G	Incised valley fill		Onlapping and lateral accretion fills, chaotic, moderate amplitude reflectors	Incised valley fill	Late LST-TST	Late Pleistocene/Holocene
Holocene ravinement		L2		Seaward thinning shore attached wedge.	10 m	Downlap and onlap SB3. Small prograding packages, separated by flooding unconformities. Weakly layered, low amplitude reflectors.	Holocene inner-shelf wedge	TST	Holocene to present



**Fig. 3.** Strike-parallel seismic record and interpretation from the mid-shelf of the Durban Bight. Subaerial unconformities are marked in red, incised valley fills are depicted in white. Enlarged seismic record shows the rugged high amplitude surface SB3, with associated back-barrier clay drapes (Facies J1). IVF = incised valley fill.

dipping, oblique-parallel package of aggrading (Fig. 11c), prograding (Fig. 11b) or mixed aggradational/progradational (Fig. 11d) reflectors.

Unit 5 occurs only in SB3 valleys and drapes Reflector iv (Fig. 11b). This unit is erosionally truncated by Reflector v, a rugged moderate amplitude erosional surface that extends along the entire study area of the shelf. This may merge with Reflector iv if Unit 5 is eroded. Unit 5 comprises a sheet-like body of wavy-to-oblique parallel prograding reflectors of varying amplitude. Unit 6 forms the capping valley fill in all valleys. Unit 6 may downlap Reflector iv or if the underlying units have been eroded, Unit 6 may downlap the valley sides. Its upper surface marks the contemporary seafloor. This unit comprises a laterally extensive, wavy- to oblique parallel prograding set of reflectors of varying amplitudes. In some areas Unit 6 may be acoustically transparent.

In terms of volume, the valley fills within Unit B are overwhelmingly dominated by Unit 3. Subordinate and thinly developed packages of Unit 1 are evident, and occur only in the upper sequence of fills within the stacked arrangement (Fig. 10a and b). Similarly, Unit 2 occurs only very occasionally in the fill succession of the Unit B networks when compared to the SB3 network. There is far less variation in the valley fill material of the Unit B networks. The typical successions show sharp transitions between Unit 3 and the occasionally encountered Unit 4, but are typically associated with monotonous packages of drape fills.

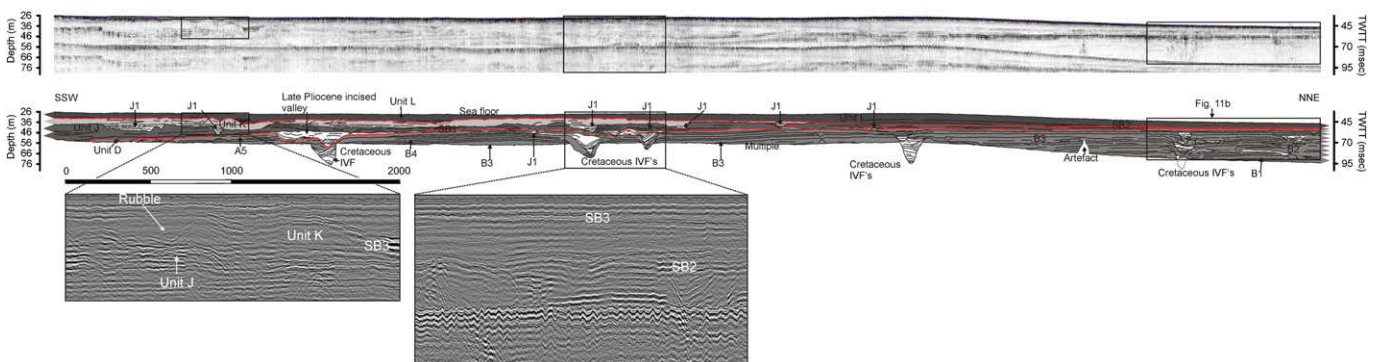
Valleys within SB3 contain a more variegated fill succession. Unit 1 tends to become better developed with distance from the shoreline and with increasing valley relief (Fig. 11a–d). Unit 4 thickens in a similar fashion. Unit 2 conversely is best preserved in the inner shelf and is absent from the mid-outer shelf (Fig. 11a–d) in all of the imaged systems, apart from a single occurrence in the Durban Bight area (Fig. 10c).

## 6. Discussion

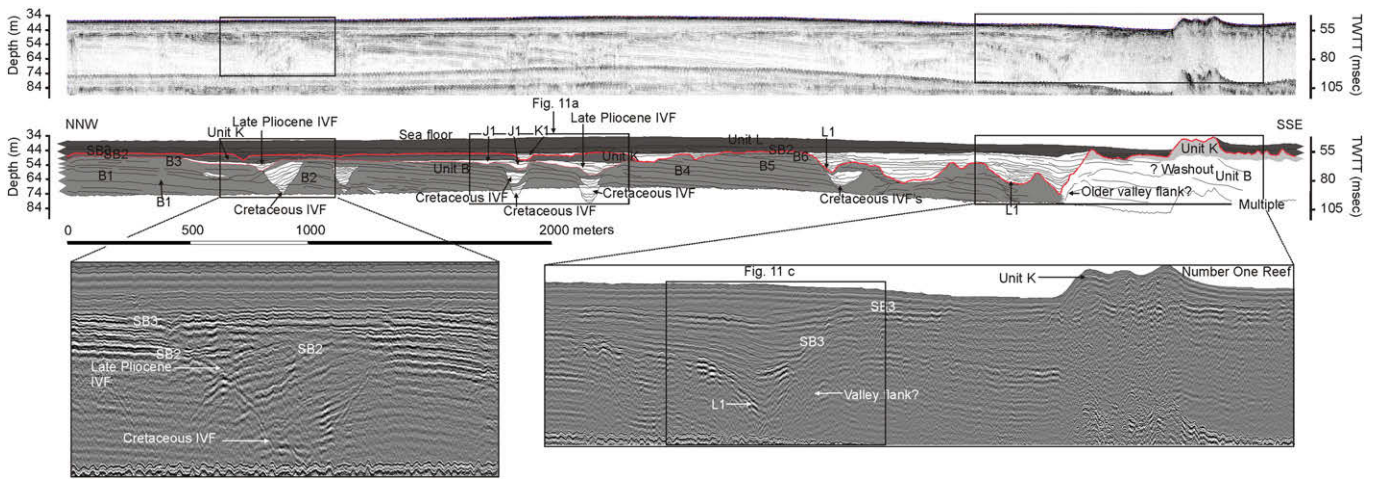
### 6.1. Overall depositional trend of incised valley fills

We consider the fill of both sets of valleys throughout the entire study area as similar to the typical infilling response to transgressive flooding of Ashley and Sheridan (1994) and Zaitlin et al. (1994). Our interpretations of Units 1–4 are based on other authors' interpretations of similar seismic units (e.g. Nordfjord et al., 2006; Green, 2009) we thus make similar interpretations of the fills for Units 1–4. Unit 1 is interpreted as a higher energy, late lowstand fluvial lag (cf. Zaitlin et al., 1994) as manifested in the chaotic and high amplitude reflector arrangement. We accordingly interpret Reflector i as a bayline erosion surface formed during the landward translation of a bayhead delta during the early transgressive systems tract (Zaitlin et al., 1994). Unit 2 may be considered a tidal-flat type environment, based on its attached nature to the valley margins. The higher amplitude and progradational arrangement of the reflectors suggest coarser-grained sediment (e.g. Foyle and Oertel, 1997) which is typical of modern day estuarine tidal flats on the east coast of South Africa (Cooper, 2001). Alternatively Unit 2 may be interpreted as a series of fluvial point bars (e.g. Weber et al., 2004) which would better match the seismic sandwich model presented by Weber et al. (2004). In keeping with the progradational arrangement of reflectors, this argument seems more likely.

On the basis of its low-amplitude, draped nature, Unit 3 is considered as the muddy central basin-type fill for wave-dominated and (cf. Zaitlin et al., 1994) mixed wave and tide-dominated (Allen and Posamentier, 1994) estuaries. Such seismic units are recognised as such in many similar seismic studies of incised valley systems (e.g. Weber et al., 2004;



**Fig. 4.** Strike-parallel seismic record and interpretation from the mid-shelf of the Durban Bight. Subaerial unconformities are marked in red, incised valley fills are depicted in white. Enlarged seismic records detail nested Cretaceous age incised valley systems within Unit B, truncated by the late Pliocene surface SB2.



**Fig. 5.** Strike-parallel seismic record and interpretation from the mid/outer-shelf of the Durban Bight. Subaerial unconformities are marked in red, incised valley fills are depicted in white. Note the late Pliocene aged incised valley system developed within SB2, in addition to the well-developed SB3 incised valley system situated landward of the Number One Reef.

Chaumillon and Weber, 2006; Nordfjord et al., 2006; Tesson et al., 2011). The variable amplitude and often mixed arrangement of reflectors of the overlying Unit 4 we interpret to be the product of barrier/flood tide deltaic/estuarine mouth plug and shoreface deposits. The mixture of small aggrading and prograding high amplitude reflectors suggests the presence of prograding flood tide deltas or small shoals fed by longshore drift (e.g. Nordfjord et al., 2006). The high angle dipping reflectors are considered bedding generated by the lateral migration of the inlet (e.g. Chaumillon and Weber, 2006). This is consistent with the modern day inlet behaviour on the KwaZulu-Natal coast (Cooper, 2001). Localised scours at the base of the unit (Fig. 11a) are suggestive of local scale tidal scouring within the inlet complex itself (Reflector iii). In accordance we consider this reflector a tidal ravinement surface.

Unit 5, which is present only in SB3 valleys, we consider atypical from most other seismic or sedimentological models proposed for incised valley systems (e.g. Allen and Posamentier, 1994; Ashley and Sheridan, 1994; Zaitlin et al., 1994; Weber et al., 2004; Nordfjord et al., 2006; Tesson et al., 2011). Coring in Durban Harbour within related incised valley systems revealed that similar seismic units are comprised of well stratified moderately-stiff clays (Miller, W, pers. comm.). We interpret this unit as a flood deposit, only locally developed, that resulted from suspension fallout after the flood peak. Similar features are well known from the contemporary wave-dominated Mgeni Estuary. These formed after catastrophic flooding of the estuary resulted in a thickly developed stiff clay covering most of the central estuarine basin (Cooper, 1988; Cooper et al., 1990). An extensive mudbelt has been documented offshore the Gironde Estuary (Lesueur et al., 1996). This formed due to periods of episodic transport of mud to the shelf. Unit 5 appears to be the more proximal portion of such a deposit, preserved within the valley form that provided shelter from wave reworking.

Unit 6 is interpreted as the post-oceanic ravinement sediment overlying Reflector v, the oceanic ravinement surface (cf. Catuneanu, 2006). This comprises the upper sections of the modern day highstand wedge.

## 6.2. Spatial and temporal differences in incised valley development

### 6.2.1. Durban Bight (southern study area)

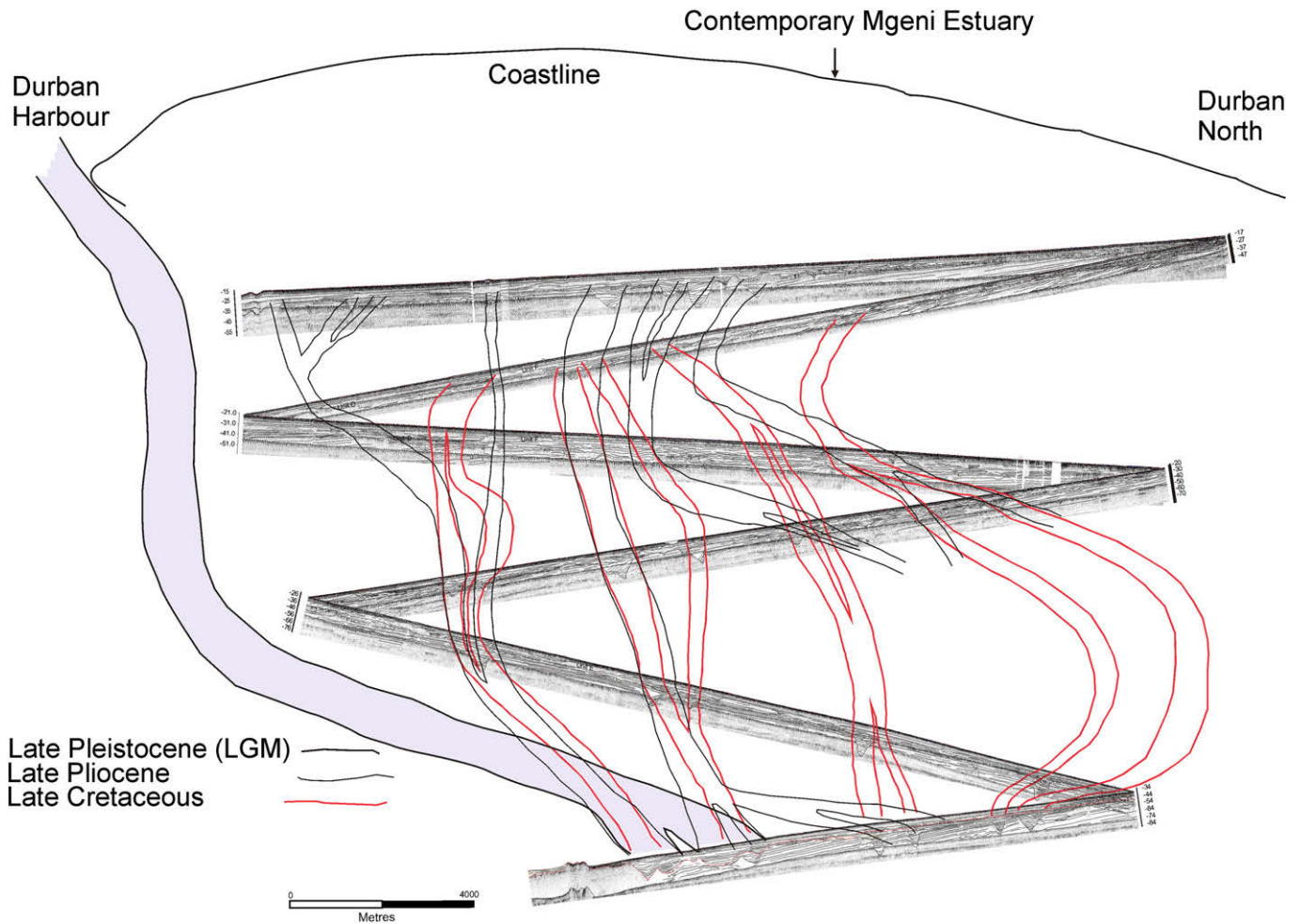
A large proportion of the incised valleys of the Durban Bight occur within early Santonian age rocks (Unit B). The erosional surfaces between the stacked incised valleys were attributed by Green and Garlick (2011) to short-lived, higher frequency forced regressive conditions superimposed on the higher order transgression recognised by Dingle et al. (1983) and Miller et al. (2005) for this time period. In effect, base

level rise was overprinted by pulses of hinterland uplift in the Mid-Cretaceous (cf. Walford et al., 2005; Moore and Blenkinsop, 2006; Moore et al., 2009) which caused river rejuvenation and the formation of sub-aerial unconformities. Transgressive infilling of these surfaces was never completed, and with each stage of base level fall, these features were re-incised, but never completely exhumed by the next stage of drainage evolution. The overall small amounts of base level lowering would create a situation of flatter topography (less knickpoint migration in the rivers) and lower levels of sediment supply to the shelf edge.

The isolated incised valleys of latest Pliocene age recognised by Green and Garlick (2011) show that there was an active drainage network at this time in the Durban Bight area. Where these have been re-incised during Quaternary lowstands, it is clear that the antecedent topography created a topographic low that would be exploited during subsequent valley incision (e.g. Posamentier, 2001). It is noteworthy that earlier Pleistocene stages of valley development are not preserved, despite sea level having fallen past the 100 m shelf break numerous times (Waelbroeck et al., 2002; Rohling et al., 2009). The Mgeni incised valley in SB3 is the only notable exception to this.

The LGM-associated drainage is typically restricted to the area offshore the Durban Harbour (Fig. 6). This is a puzzling trend in that the present Mgeni River course, some 10 km north of the harbour, is underlain by a deep valley incised into Gondwana-aged rocks that trends roughly coast perpendicular (Orme, 1975), extending to ~0.5 km landwards of the modern coastline. Logically, a direct offshore extension of the lowstand river during the LGM (or any other Pleistocene lowstand for that matter) would be expected. Borehole data indicate that throughout the coastal plain, a clay-rich horizon overlies the Cretaceous bedrock but does not extend to the Mgeni Estuary (Cooper, 1991). This is radio carbon dated at between 24 950 and 48 000 BP and is overlain by fluvial, feldspathic sands similar to the modern Mgeni River gravels at approximately – 15 m below MSL (Cooper, 1991). These sands indicate that the palaeo-Mgeni River flowed in a coast parallel manner, toward the Durban Harbour (Fig. 1). The harbour itself is underlain by several large LGM aged channels (our unpublished data) that extend out towards our large LGM shelf hosted network (Figs. 3, 4 and 6). The lowstand Mgeni River incised valley thus took a pronounced bend to the south towards the harbour and then returned northwards as seen from the offshore seismic data set.

It appears that since the early Pleistocene the lowstand course of the Mgeni River has followed a similar, shore-parallel course. Such constraint of river bends during sea-level fall indicates a strong structural control on fluvial patterns and the influence of antecedent channel morphology on subsequent incision. Although seismic data presented here,



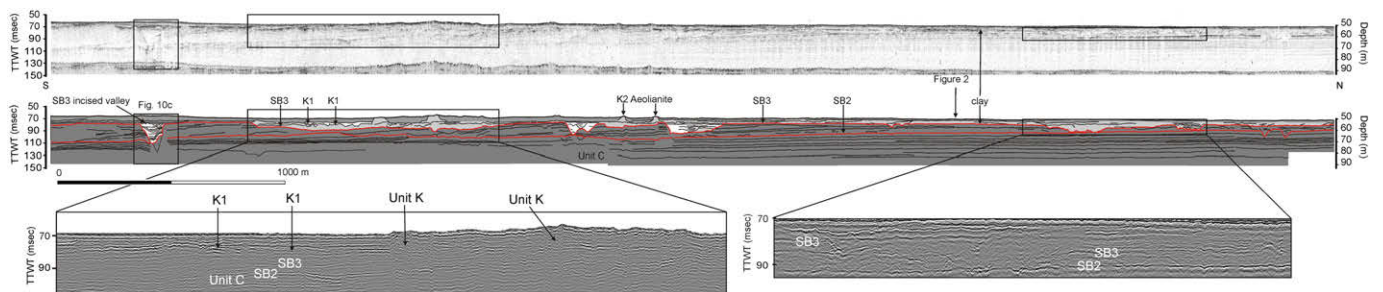
**Fig. 6.** Fence diagram of seismic data and interpretive overlays for the Durban Bight area. Note the dense network of Unit B hosted incised valleys. Late Pliocene valleys are also prominent, SB3 valleys are restricted to a single occurrence offshore the Durban Harbour. There is no direct LGM extension offshore of the contemporary Mgeni River mouth.

and in Green and Garlick (2011), do not recognise prominent faulting in the Cretaceous aged units; several coast-parallel faults have been recognised from the KwaZulu-Natal coast and attributed to Gondwana break-up (Watkeys and Sokoutis, 1998). It is possible that as river competence was reduced at lowstand intervals, the Mgeni River began meandering on the palaeo-coastal plain and these meanders were constrained by these faults. Such basement control on incised valley placement is well documented in the literature (e.g. Menier et al., 2006; Chaumillon and Weber, 2006; Menier et al., 2010). In addition, based on the global sea-level curves (Waelbroeck et al., 2002; Rohling et al., 2009), it appears that lowstands of the Pleistocene have consistently reached depths exceeding the 100 m shelf break. In this case,

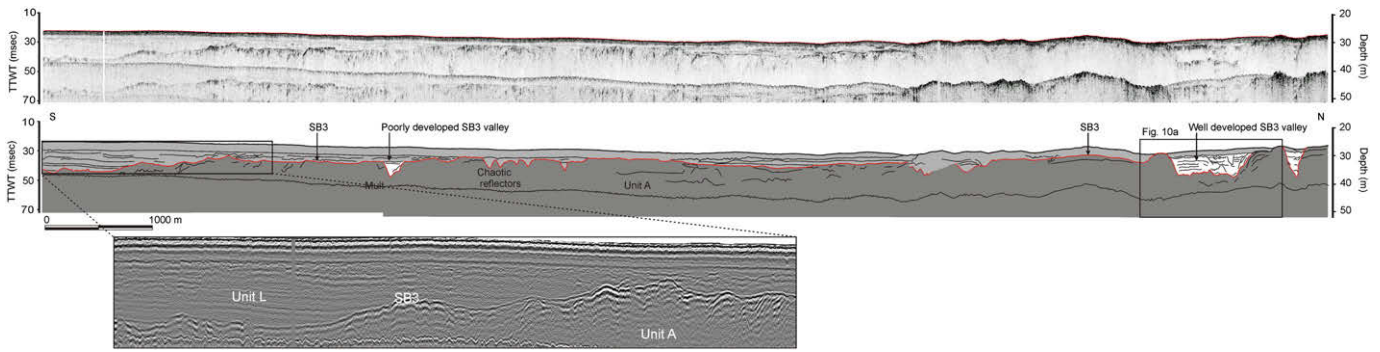
these valleys have re-incised the same course, consistently inheriting this meander pattern (cf. Posamentier, 2001) and accounting for the lack of a direct proximal extension of the lowstand Mgeni River. Interestingly, as competence was further decreased during the following transgression, the course remained constrained in this similar manner. Low lying muddy lagoonal deposits follow a similar trend (Cooper, 1991) and point to a control of the older incised valley form on sedimentation throughout the transgressive sea level cycle.

6.2.2. Glenashley Beach to La Mercy Beach (northern study area)

Palaeo-drainage is comparatively simple in the northern parts of the study area compared to the Durban Bight. Differences are namely



**Fig. 7.** Strike-parallel seismic record and interpretation from the mid-shelf of the Glenashley Beach to La Mercy Beach area. Subaerial unconformities are marked in red, incised valley fills are depicted in white. Note the single incised valley intersected by the line, offshore the Mhlanga River. Enlarged seismic sections detail the aeolianites of Unit K, and the rugged, relief of SB3.



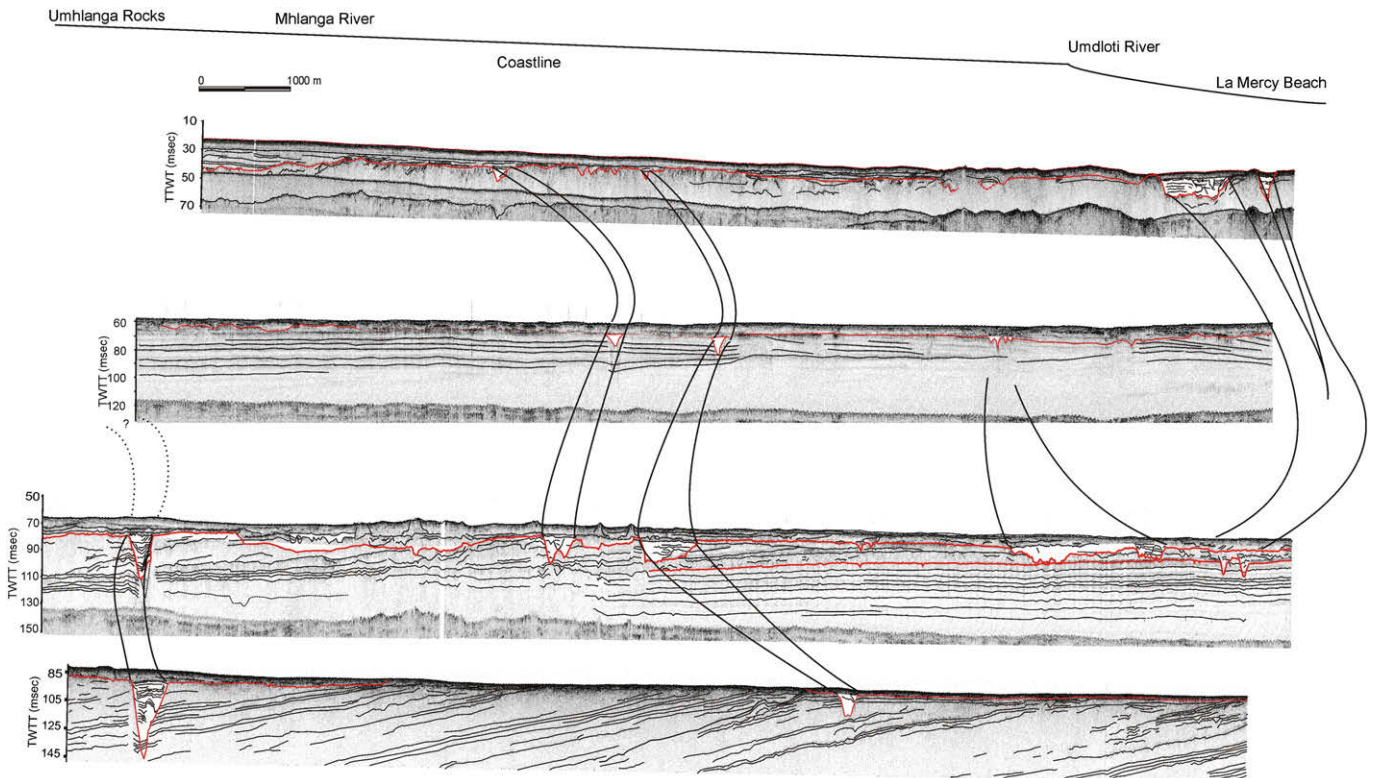
**Fig. 8.** Strike-parallel seismic record and interpretation from the inner shelf of the Glenashley Beach to La Mercy Beach area. Subaerial unconformities are marked in red, incised valley fills are depicted in white. Note the single occurrence of an incised valley offshore the Mdloti River.

in the isolated, larger, yet simpler forms of all incised valleys and the absence of a stacked network of incised valleys in the Cretaceous units (Units B–E).

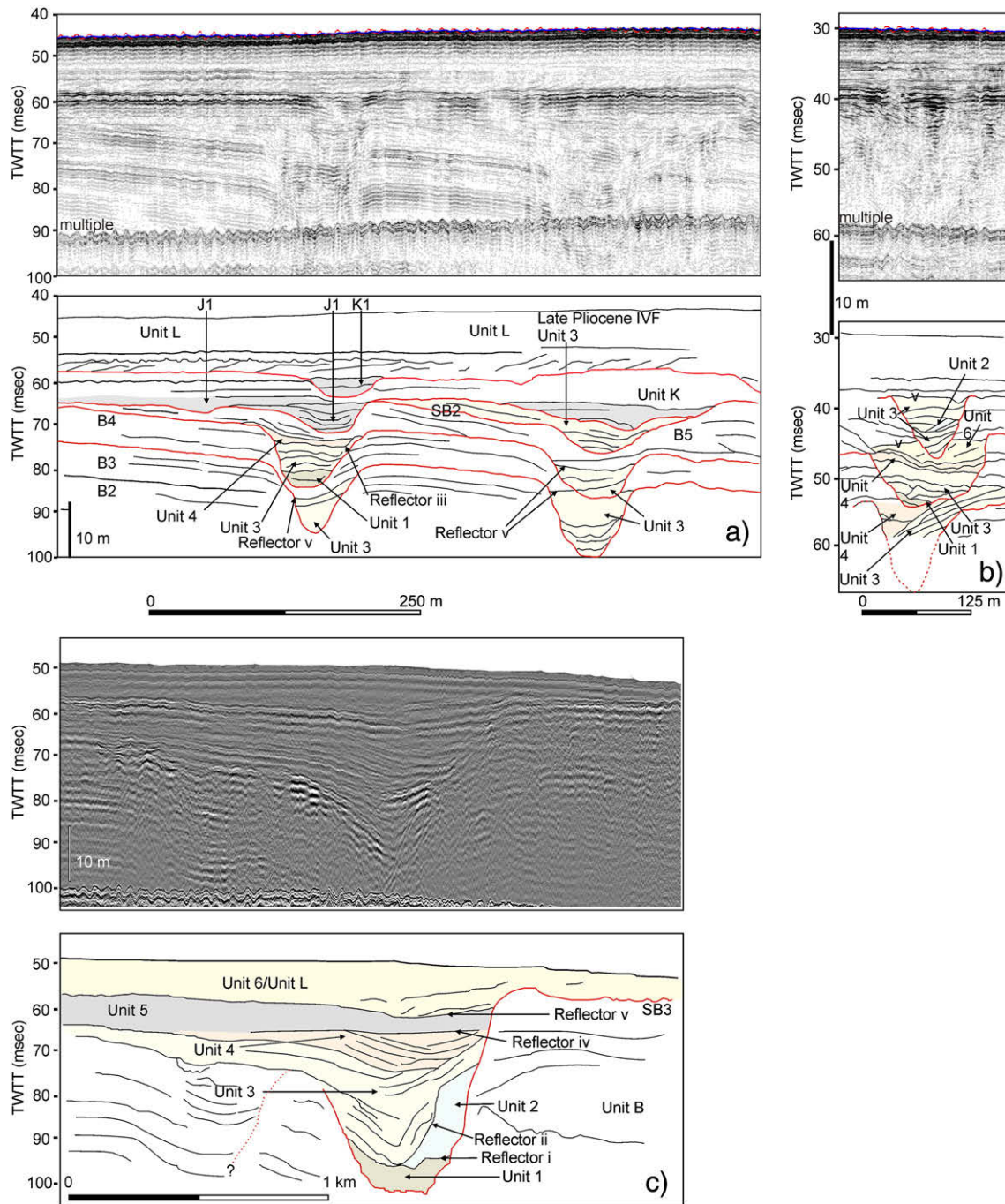
These differences have several implications for the development of the continental shelf of the area. We posit that fluvial influences reduced northwards of the Durban Bight. In this case, rivers either did not incise (the unincised lowstand valleys of Posamentier, 2001) or there was a complete absence of rivers from this area during Cretaceous times. Given that the distance separating the two areas is ~30 km and uplift occurred along the entire length of the east coast of southern Africa (Walford et al., 2005; Moore and Blenkinsop, 2006) we prefer the latter argument; that active drainage had not yet evolved. The palaeo/Cretaceous Mgeni River was thus the major contributor of

sediment to this portion of shelf during the early drift stage of margin evolution.

Schumm and Ethridge (1994) show that a strong correlation exists between valley age and valley dimension; fluvial valleys typically widen and deepen with time. The smaller nature of the SB3 valleys north of the Durban Bight signifies that even when drainage (in the form of the palaeo-Mhlanga and Mdloti Rivers) did evolve; it was far smaller in size than that of the Durban Bight drainage which was dominated by the palaeo-Mgeni River since early Santonian times. It is likely that these smaller rivers only evolved during the base level fall associated with the late Pliocene uplift. Other isolated remnants of this grouping of incised valleys occur to the south in the Durban Bight. These were fortuitously preserved from later re-incision and



**Fig. 9.** Fence diagram of seismic data and interpretive overlays for the Glenashley Beach to La Mercy Beach area. Note the development of only one network of incised valleys (SB3) and the absence of prominent incised valleys in the proximal areas.

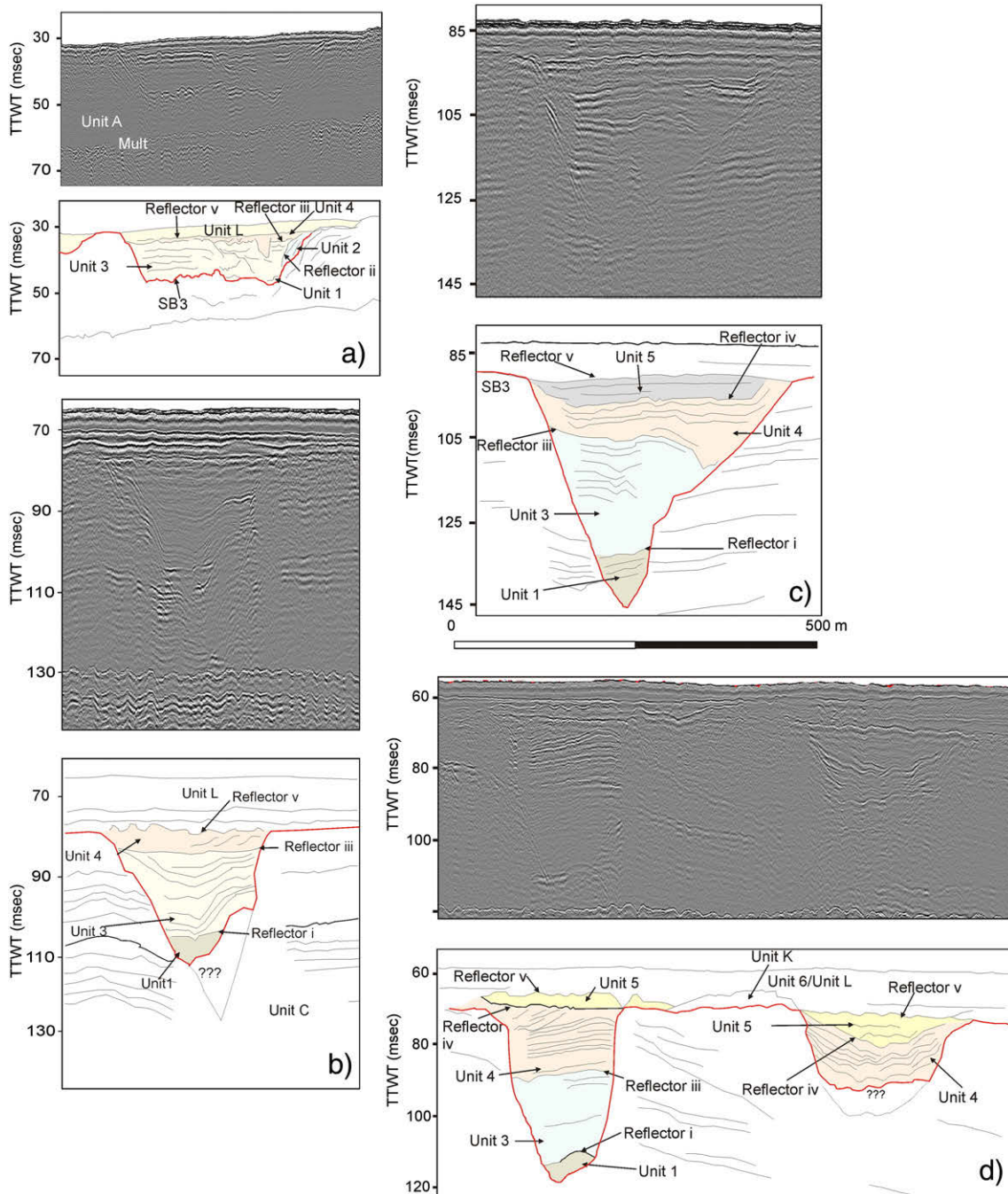


**Fig. 10.** a and b. Compound incised valley systems from the Durban Bight occurring within Unit A. Note the stacked nature of the subaerial unconformities and the dominance of Unit 3 within the fills. c. Incised and infilled valley within SB3 offshore the Durban Harbour. Note the more variegated fill when compared to the Unit B examples. It appears that the SB3 incised valley has incised and reworked a late Pliocene incised valley system.

reworking by younger Pleistocene incisions by the inception of the Bluff dune ridge that would have diverted palaeo-drainage accordingly. In the northern study area, we consider that these incised valleys are similarly compound valleys, yet the underlying Pliocene valleys were completely exhumed or modified during the Pleistocene glaciations, explaining the apparent simple incised valleys in the area. The persistent development of incised, rather than unincised river valleys (cf. Posamentier, 2001) since the early Pleistocene would promote the re-incision and reworking of these younger features inherited for their antecedent topography.

### 6.3. Spatial variation of infilling and fill architecture

Some models of transgressive infilling of incised valleys consider large, high-accommodation valleys, or valleys connected to large rivers as having a higher propensity for fluvial fill in the mid-upper segment of the valley (e.g. Nichol et al., 1994). We show clearly that the early Santonian (Unit B) network has little to no basal facies that can be interpreted as fluvial material i.e. the wavy-chaotic, high amplitude reflectors of Nordfjord et al. (2006) or the disconnected high-angle and high amplitude reflectors of Weber et al. (2004). The lower



**Fig. 11.** Incised and filled valleys within SB3 from Glenashley Beach to La Mercy Beach. a. The most proximally imaged incised valley, offshore the Mdloti River. b. Mid-shelf located incised valley related to the Mhlanga River. c. Mid/outer-shelf located incised valley related to the Mhlanga River. d. Down dip seismic section intersecting a bend of the Mhlanga River's incised valley (location in Fig. 1). Note the general seaward thickening of Units 1 and 4, the well developed drape of Unit 3 and the erosional nature of Reflector v.

sequences and their fills are instead dominated by central basin drapes, with only the uppermost sequences possessing higher energy deposits in the form of estuarine mouth plugs. Such an absence is unsurprising considering the small scale, and thus low accommodation of the incised valleys in Unit B. Additionally, their compound nature indicates a propensity to occupy the same channel throughout the entire sea level cycle and thus bypass larger quantities of sediment to the lowstand shelf and deeper basin (e.g. [Chaumillon and Weber, 2006](#)). In any case, a low sediment supply is indicated by the underfilled valleys. Either gradient was low, inhibiting the deposition of gravely facies or the

sediment supply was fine-grained, a product of the silty Cretaceous sedimentary rocks reworked during sub-aerial exposure.

These fills are truncated by a series of oceanic ravinement surfaces (Reflector v) which are in turn separated by thick shoreface deposits. On the whole, these resemble the mixed-sand and mud dominated Charente incised valley ([Chaumillon and Weber, 2006](#)), but lacking a lowstand systems tract, gravely component. We consider the absence of better developed estuarine mouth plug deposits to be a function of subsequent hydrodynamics. Especially in the outer segment of these valleys, wave-ravinement across an exposed shelf would have removed the

**Table 2**  
Bounding unconformity surfaces, seismic units, stratal relationships and interpretative environments of both Unit B and SB3 incised valley fills.

Stratigraphic surface	Seismic unit	Description	Thickness	Stratal relationship	Interpreted depositional environment
	Unit 6/unit L in SB3 valleys		<15 m	Wavy- to oblique parallel prograding low amplitude reflectors, acoustically transparent	Post-wave ravinement shelf deposits
Reflector v	Unit 5	Wave ravinement surface	2–4 m	Erosional High amplitude, sub-parallel, continuous reflectors	Flood deposit
Reflector iv	Unit 4	Catastrophic flood surface	> 15 m	Erosional Sub-parallel to oblique-parallel, variable amplitude reflectors	Barrier/flood tide deltaic/ estuarine mouth plug/ shoreface
Reflector iii	Unit 3	Tidal ravinement surface	> 15 m	Erosional Onlap other units, drape fill of low angle, sub-parallel, low amplitude reflectors	Central basin estuarine deposits
Reflector ii	Unit 2	Valley flank-attached packages	4–6 m	– Onlap and downlap subaerial u/c, sigmoid progradational moderate amplitude reflectors	Fluvial point bar
Reflector i	Unit 1	Bay ravinement surface Basal unit of most valleys, uncommon in Unit B valleys	<11 m thick	Non-depositional Downlap subaerial u/c, wavy to chaotic, high amplitude reflectors	Fluvial LST
Late Cretaceous subaerial u/c's; SB3					

upper portions of any fill and modified the upper portions of the valley form. This is recognised by the strong erosional truncation of the upper fills by Reflector v.

In stark contrast, the significant increase in the basal fluvial component within fills of the SB3 (LGM age) incised valleys points to changes in both accommodation setting and base level fluctuation. These are significantly larger valleys that appear to have been subject to a greater degree of fluctuation in base level during the glacial-interglacial sea level cycle compared to their Cretaceous age counterparts (cf. Green and Garlick, 2011). This would certainly foster the development and preservation of a full suite of lowstand to highstand transgressive systems tract deposits as recognised by Zaitlin et al. (1994). The LGM examples documented here also reflect a probable steeper gradient than that of the Cretaceous examples. Sediment supply in this case would be abundant, the systems now having a greater capacity to both incise and transport coarser sediment.

On the whole, these SB3 fills conform loosely to those fills recognised by other authors for the outer segments of wave-dominated incised valley systems (e.g. Zaitlin et al., 1994; Nordfjord et al., 2006) and to mixed wave and tide-dominated systems (Chaumillon et al., 2008). The variation in seismic unit distribution within these fills we consider to be a function of the either the valley depth (and consequently accommodation and exposure to ravinement processes) or to rapid infilling (e.g. Cooper, 1991). It is most likely that in the outer segment of the incised valley system, rapid drowning in the early Holocene (Ramsay and Cooper, 2002) would cause an abrupt change in facies with the effects of the associated wave ravinement thus lessened.

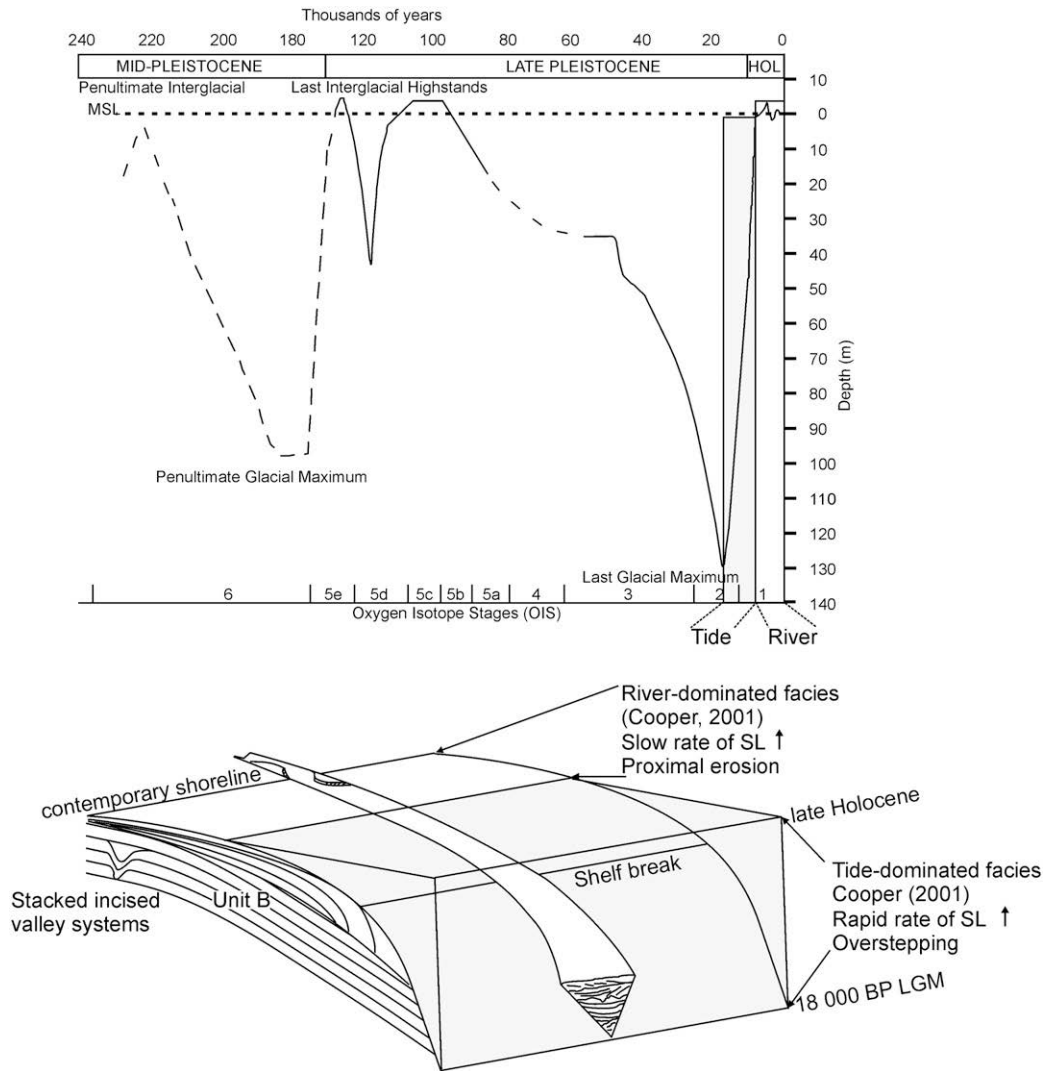
The seaward thickening of the estuarine mouth plug deposits is likely to be associated with these valleys acting as updrift traps of littoral drift (e.g. Chaumillon and Weber, 2006; Chaumillon et al., 2008). Modern littoral drift in the study area migrates from south-to north, and results in modern estuaries along the KwaZulu-Natal coast possessing well developed barrier/inlet systems updrift of littoral drift sources (Cooper, 2002). Valley positioning relative to littoral drift has some control on the internal facies architecture too, though not to the extent that the entire fill is sand-dominated such as those of the Lay-Sèvre incised valley complex of the Bay of Biscay (Chaumillon et al., 2008) or the tide-dominated estuaries of the Eastern Cape of South Africa (Cooper, 2002).

We compare the fills of the SB3 valleys to the relative influences of tide-vs.-river dominance in an overall wave-dominated setting (e.g. Cooper, 2001). In the outer portions of the studied valley systems,

we consider these valleys to be most similar to those of Cooper's (2001) tide dominated examples. Fluvial sediment supply was comparatively low, central basin deposits are prominent and flood tide-deltas, washovers and barriers are present. In comparison, the inner portions appear to be related to river-dominance, where flood tide deltas are small or absent, with side attached bars (of sandy fluvial sediment) common. Such a change can be explained from the perspective of changing rates of relative sea level rise over time. The initial rapid rise in sea level following the LGM (Fig. 12a) would foster rapid drowning of the outer segments, lower rates of fluvial sediment supply and general dominance of the central basin and mouth plug deposits (Fig. 12b). The gradual slowing of relative sea level rise in the late Holocene (Fig. 12) (Ramsay and Cooper, 2002) would conversely cause the proximal inner segments of the systems to behave in a river-dominated manner; a greater degree of fluvial infilling and lesser degree of marine infilling the result (Fig. 12b). The coastward younging of the valley fills thus means that the outer portions would behave in a tide-dominated manner, whereas the inner sections would possess the characteristics of the contemporary, river-dominated estuaries of the KwaZulu-Natal coastline (e.g. Cooper, 2001).

Lastly, we examine the comparative absence of proximal incised valleys on the shelf (namely the Glenashley Beach to La Mercy Beach stretch). Instead of well-preserved valleys extending directly offshore of the modern day river mouths, incised valleys become progressively better preserved in the mid-shelf (apart from the Mloti River). This could be the product of 1) differential subsidence along a shelf/coastal plain hinge line (sensu Laubane et al., 2010); 2) the shelf morphology (Lericolais et al., 2001; Chaumillon et al., 2008); or 3) removal of the valleys by ravinement processes during the late transgressive systems tract. The KwaZulu-Natal coastline in this case is shown to be rising slightly (Mather, 2011) and as such it appears that the first argument is not applicable. The second situation occurs when the shelf gradient shallows towards the shelf break and as such causes a reduction in the incision depth.

We consider that the wedging out of incision depths is most likely a factor of the latter two scenarios. Nordfjord et al. (2004) show a similar style of erosion; deglaciation in the post LGM period caused the development of a ravinement surface that removed most of the proximal portions of fluvially incised valleys on the New Jersey shelf, yet not to the extent that has occurred in this study. In the examples documented here, there is a disconnect between the inner and outer segments of the incised valley systems. Distal overstepping during transgression in the



**Fig. 12.** a. Late Pleistocene sea level curve for the east coast for South Africa (after Ramsay and Cooper, 2002). Note the rapid transgression during deglaciation in the latest Pleistocene/early Holocene followed by slowing rates of sea level rise in the late Holocene. b. Partitioning of the incised valleys into mid-outer segment tide-dominated and inner segment river-dominated systems. Such partitioning is related to the differential influence of rate of sea level rise along the profile of each valley segment.

early Holocene and proximal erosion by ravinement during the slower transgression in the late Holocene would produce such morphology (Fig. 12b). An extensive, well-preserved barrier and back barrier complex is recognised in the mid-shelf of the study area (Green et al., 2012) and confirms that rising sea level overstepped rather than eroded the shelf in this part of the study area.

**7. Summary and conclusions**

Several networks of incised valleys encompassing early Santonian–late Pliocene and late Pleistocene ages are documented. The oldest incised valleys are associated only with the largest fluvial system (the Mgeni River) in the study area and correspond to the development of compound valleys that (under) filled in a low gradient, low accommodation setting. The younger incised valley networks are associated with smaller fluvial systems and show that these systems only evolved in the late Pliocene, when a cross shelf sediment transport network was established. These valleys appear to have been heavily reworked by wave-ravinement processes in their more proximal portions when compared to examples from a slowly subsiding margin. This highlights in particular the subtle influence that hinterland uplift has on the overall transgressive arrangement of both architecture and fill of these systems; namely poor preservation in the inner-middle segment of the incised valley system.

The incised valley fills documented from the Durban Bight to La Mercy Beach areas appear to conform to fairly standard stratigraphic successions as recognised by many other authors. However, the dominant allocyclic controls on infilling appear to be a combination of glacio-eustasy, available accommodation and degree of exposure to later ravinement (a function of valley depth and rapid deglaciation in the early Holocene). The geometry and architecture of the earliest fills appear to be driven primarily by sediment supply and gradient more-so than tide or wave domination.

Older Cretaceous aged compound incised valley systems appear to be dominated by only monotonous fills of the central basin type, this being a function of the low accommodation of these incised valleys and their role in bypassing sediment at lowstand. The more recent incised valleys associated with the Last Glacial Maximum conversely had greater accommodation space allowing better preservation of the full suite of units associated with a lowstand-highstand sea level cycle. In these cases, we show evidence to a lesser degree of control on the infilling succession by the updrift trapping of longshore drift.

Initial tectonic controls dictated to some extent the positioning of the early subaerial unconformities. The development of both the Cretaceous and late Pliocene age incised valleys as a function of hinterland uplift influenced the evolution of later incised valley networks by the creation of an antecedent topography that would be inherited by successive

incision phases. The influence of antecedent topography on the manner in which such systems behave when sea level falls below the shelf break is shown. The lowstand courses, in particular that of the Mgeni River during the LGM lowstand, were constrained to positions previously held by older incised valleys, an influence which is exerted on the incised valley system throughout the sea level cycle. The examples presented here document the evolution of a network of incised valleys from a tectonically dominated perspective to one influenced primarily by glacio-eustasy and antecedent topography. The models presented here may thus be extended to other shelves that have been exposed to intermittent uplift in their evolutionary history, superimposed by glacio-eustatic fluctuation.

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