Structure and evolution of the Zinkwazi and Umdloti barrier spit and inlet systems along the KwaZulu-Natal coastline, South Africa

By

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Abstract

This thesis proposes a model for the barrier development, breaching and subsequent closure of river-dominated, temporarily open/closed estuaries (TOCE'S), such as the Zinkwazi and Umdloti systems. The Zinkwazi and Umdloti Barrier systems are located along the KwaZulu-Natal coastline, South Africa. The Umdloti estuary is a perched, closed system with an ~ 600 m long barrier that is orientated in a southeasterly direction. An inlet typically forms in the centre of the barrier. The Zinkwazi estuary is a river-dominated system, with the estuary being located in a headland embayment. The sandy barrier has a swash-aligned morphology and the amount of fluvial discharge controls the amount of time the estuary remains open to the Indian Ocean.

The aim of this project is to assess the morphodynamics, structure, and evolutionary history of the sandy barriers that front the Zinkwazi and Umdloti estuaries. Ground-Penetrating Radar (GPR) profiles, Google Earth Imagery and measured sections from the breach/inlet scarps were examined.

The Zinkwazi Barrier and Umdloti River Barrier radar stratigraphy comprise 10 different radar packages (A-I), 9 radar bounding surfaces, and 6 facies associations combined. Unit A1 correlates with the southern margin of the Zinkwazi River incised river valley. Unit A2 comprises moderately well sorted, coarse sand that forms planar, horizontal, subparallel and moderately continuous reflectors of the lowermost washover unit resolved. Unit B comprises moderately well sorted medium sand that forms sinuous/wavy and sub-parallel reflectors. Units E, H and I comprise coarse well sorted sands of planar, horizontal subparallel and moderately continuous reflectors. The uppermost Unit I comprises the up-dip extension of the contemporary washover fans that occur in the back barrier environments of both systems. Both barriers consist almost in their entirety of washover sheets.

Inlet fill facies are restricted to the Zinkwazi system (moderately well sorted, very coarse sands of units D and G). In radar profile, these comprise planar to wavy, sinuous, subparallel to oblique, chaotic, moderately continuous to discontinuous reflectors. Unit D is related to limited lateral accretion of the inlet and Unit G is an aggradational fill in the inlet throat, formed by washover.

A number of washover channels occur in the stratigraphy (Surfaces 4 and 7). These are associated with hyperbolic-forming pebble and small cobble lags. These are filled in by chaotic, concave upward and curved convex reflectors (Unit F) that represent the internal stratification found within the channelized washover. Interspersed amongst these are occasional transitional aeolian facies (Unit C) that mark the intervals between washover periods.

As the barriers are dominated by overwash this is the most important factor in the barrier development. The barriers breach as a result of flooding during storm periods. These inlets are then rapidly filled by washover (not necessarily linked to extreme events). This is a result of the limited inlet accommodation space. The inlets do not migrate, this could be as a result of antecedent conditions (e.g., bedrock control in the Zinkwazi Estuary), or due to the rapid time interval between opening and closing. Inlets usually close before they can begin to migrate with longshore sediment loading. Barrier-building processes are thus typically slower than the interval between breaching processes.

Barriers preferentially breach at the previous inlet position, unless anthropogenic factors force the barrier to breach along a specific section. The constant inundation by washover predisposes these systems to rollover.

Preface

The work described in this dissertation was carried out in the Discipline of Geological Sciences, School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Westville campus, from January 2015 to December 2016, under the supervision of Professor Andrew Green.

These studies represent original work by the author and have not otherwise been submitted in any form for any degree or diploma to any tertiary institution. Where use has been made of the work of others it is duly acknowledged in the text.

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1 Introduction

The microtidal estuaries of KwaZulu-Natal are fronted by long, linear sandy barrier systems that are perched above mean sea-level (Cooper, 2001a). These hold the key to extending our local knowledge and understanding of inlet dynamics, and system behaviour from the historical to geological temporal scales.

The main types of estuaries associated with these barrier/inlet systems along the eastern coast of South Africa are tide-dominated, river-dominated, non-barred, perched, and non-perched estuaries (Cooper, 2001a). These estuaries play a significant role in barrier development as they form the interface between marine and fluvial processes (Cooper, 2001a).

These estuaries are discriminated on the basis of their morphological state with particular reference to the inlet, salinity structures and biological assemblages. Of these estuary "types", South African temporarily open/closed estuaries (TOCE's) are particularly important, not just because they comprise the majority of South African estuarine bodies, but because they are amongst the most studied of these "types" worldwide. A better understanding of their form and geomorphic function is required in order to better manage these systems and their biological resources.

Comparatively little is known concerning the morphodynamics, stratigraphy, and evolution of these local sandy barriers. Despite a wealth of literature on barrier spit systems globally (e.g., FitzGerald, 1996; Jol et al., 2002; Castelle et al., 2007; Vila-Concejo et al., 2006), these small features are an overlooked facet of coastal facies models (e.g., Walker and James, 1992), with their preservation in the stratigraphic record being dependent on whether or not these deposits are reworked (Buynevich and Donnelly, 2006).

As the first line of defence between storms and rising sea levels, these systems protect the low lying lagoonal and fringing reclaimed areas of many of KwaZulu-Natal's river mouths (Begg, 1978). They therefore need to be better understood from a morphodynamic perspective.

The KwaZulu-Natal coastline is an ideal setting for the study of microtidal barrier inlet systems, due to its steep hinterland, wave-dominated, bedrock bound, and embayed coastlines, with steeper, narrower beaches and high beach berms Cooper (2001a), a stark contrast to the western coastline of South Africa (Day, 1981; Reddering and Esterhuysen, 1987).

1.1 Aim

The aim of the project is to assess the morphodynamics, structure, and evolutionary history of the sandy barriers that front the Zinkwazi and Umdloti estuaries in KwaZulu-Natal, South Africa.

1.2 Objectives

The main objectives of the project are:

- To establish a high-resolution morphodynamic model for how these barriers are breached, the inlet dynamics and how these inlets are infilled.
- To establish the internal structure and architectural expression of these sandy barriers using (GPR) ground-penetrating radar.
- To groundtruth the radargrams in order to establish the sedimentological nature of the key stratigraphic units in these barriers.
- To establish linkages between external forcing agents such as storm activity and barrier sedimentology.
- To link the morphodynamics to the overall facies that are preserved in the barrier sequence and to thus assess their preservation potential in the coastal sedimentary record.

This thesis investigates the main controlling agents of inlet opening or breaching along these small barriers, as well as how these systems fill in from a sedimentary perspective. The key architectural components of these barriers are identified, and compared to the larger barrier systems found internationally. This aids in understanding how these systems differ from each other. The period during which these key features formed is further elaborated.

The style of preservation of inlet facies in microtidal estuaries is also explored, in conjunction with how this relates to the structure and facies models of similar sandy systems that have been preserved in the ancient record.

2 Literature Review

2.1 Inlet and barrier morphology

Barriers and associated tidal inlets are found all over the world from a number of different geologic and oceanographic settings. Barriers are defined by Otvos (2012) as emergent coastal-nearshore landforms. These can be represented by shore-parallel elongated islands, barrier spits, strandplains, or chenier ridges. In the most basic of terms, barriers are regarded as divisions between the offshore and onshore environments (Otvos, 2012).

Barrier-spit systems are described as evolving, elongated, narrow, supratidal sand or gravel bodies. Barrier spits are attached to, or prograded from an onshore setting or an island, and usually comprise a number of beach ridges (Oertel, 1985).

Barrier systems are important features as they represent the physiographic, hydrographic, sedimentary, and ecological boundary between onshore and offshore environments. These features have a number of attributes, which include reducing wave energy onshore, and thus providing a means of protection against storm activity (Otvos, 2011). These systems also maintain a continuous path of shore-parallel littoral drift, which is important for sediment transport along coastlines (Otvos, 2011; 2012).

The characteristic stratigraphic succession of barrier-spits in the proximity of inlets was initially represented by three main depositional facies; the inlet floor, channel, and inlet margin or spit platform (Moslow and Heron, 1978) (Fig. 1). These deposits were considered representative of a transgressive sequence that was reworked as a result of inlet formation and migration (Moslow and Heron, 1978). This concept was based on surficial sediment sampling in inlets and surrounding environments and relied on the correlation of facies using Walther's Law to propose a stratigraphic model. It however ignored other stratigraphic facets like washover fans, beaches and dune facies in the proposed stratigraphy, and though plausible, lacked the detailed three dimensional controls on facies distribution and architecture required to confirm its representability.

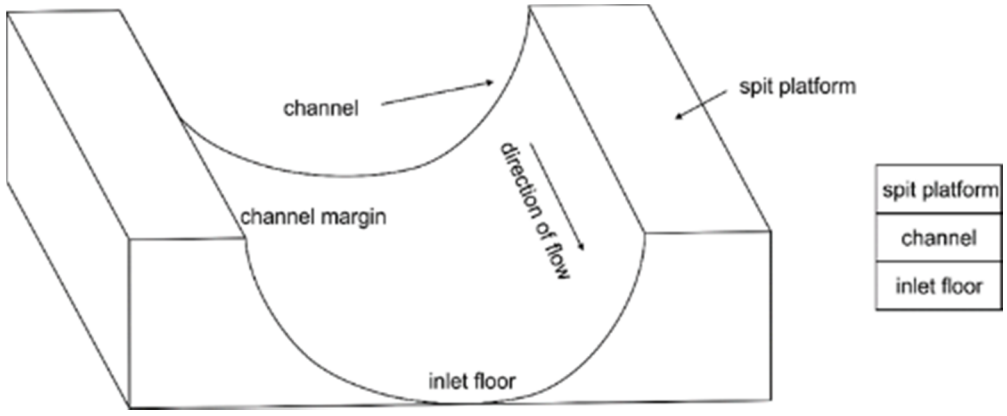


Figure 1. A schematic diagram and simplistic stratigraphic column illustrating the position of the inlet floor, channel, and inlet margin or spit platform as described by Moslow and Heron (1978).

Later studies, based on a number of deep drilling campaigns, cores and offshore seismic profiling, provided a true three dimensional representation of barrier-spit systems and allowed for a more detailed facies model to be proposed (see Kraft, 1971; Kraft and John, 1979; Kraft et al., 1979; Belknap and Kraft, 1981; 1985). Based on the barrier-spit stratigraphy of the Delaware coastline, the facies model comprises a transgressive stratigraphic succession of sand dunes, lagoonal silt, marsh sediment, shallow marine-estuarine sediment, beaches and spits. The tides move sediment across the lagoon, with the lagoonal marsh being eroded to produce sediment for the nearshore area. Sand is also blown from the berms and deposited as dunes parallel to the coastline, and beach-berm sediment is washed back into the shallow marine area of the system (Kraft, 1971) (Fig. 2).

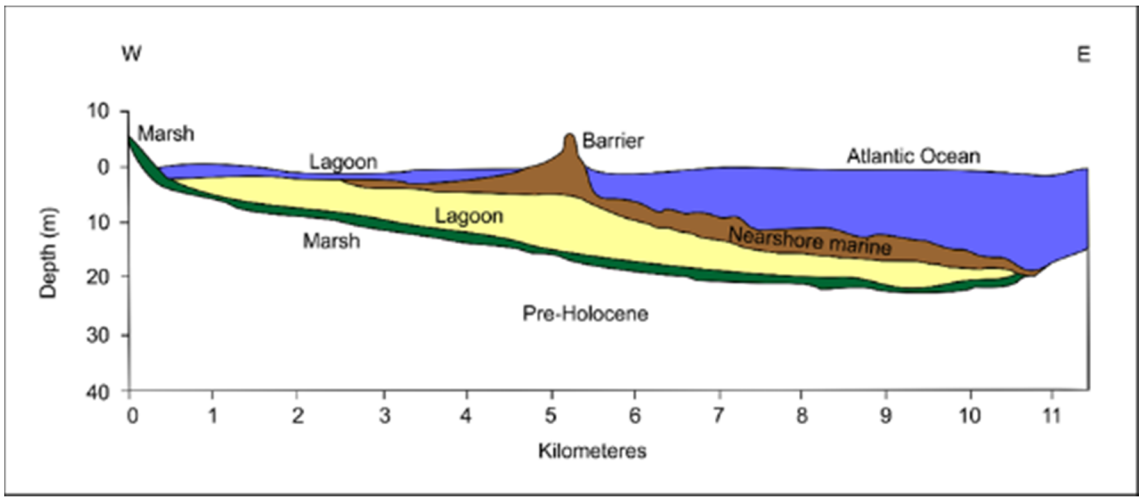


Figure 2. Rehoboth Bay of the Delaware Bay area, showing the main features of the transgressive system as described above. Adapted from Belknap and Kraft (1981).

According to Belknap and Kraft (1985), there are three main driving factors in barrier evolution. Firstly, continuing local relative sea-level rise outstrips sediment supply and results in transgression. Secondly, wave and littoral transport dominates tidal processes and leads to the creation of a straight coast with fewer inlets. Thirdly, antecedent conditions in the form of pre-existing topography and sediment erodibility control accommodation space and preservation respectively.

The barrier thickness is directly dependant on sediment supply and accommodation space, which vary along all coastlines. High sediment supply rates cause the barrier to build and prograde in a seaward direction and aids in dune construction. Accommodation space influences barrier thickness, the greater the accommodation space, the greater the volume of sediment required to fill it, thus given an equal sediment influx rate, lateral progradation would be slower on a steep shoreface and more rapid on a flat-lying coastline (Davis and FitzGerald, 2004).

There are many types of barriers based on coastline morphology. For example, in headland-embayed settings, the barrier morphology and stratigraphy are controlled by factors such as storm waves (Bulhões et al., 2013), underlying topography (Cooper and Jackson, 2011), littoral drift and offshore shelf morphologies (Roy and Stephens, 1980). On near straight coastlines, such as the North Sea in Germany, barriers like the East Friesian Islands are controlled by wind activity, littoral drift, rising sea-level and co-dominated by tidal current activity (Hayes, 1979; Davis and FitzGerald, 2004).

Along irregular coastlines that experience a coast-oblique wave approach, in conjunction with abundant sediment supply and high rates of longshore sediment transport, barrier spit systems are most likely to form (Davis and FitzGerald, 2004). These separate estuaries and lagoons from open ocean conditions and generally span the entire lagoon body. They may develop inlets within them, though these are often isolated and discontinuously open (Cooper, 2001a; FitzGerald et al., 2002). Barrier islands are larger-scale features, which likewise are narrow accumulations of sediment that tend to form parallel to the coastline, but are separated by several tidal inlets. These features can continue for kilometres and usually form chains (Davis and FitzGerald, 2004).

The inlets of barrier-estuary and lagoon systems are considered the most dynamic parts of shore-attached barrier and barrier island systems, with the average barrier length being controlled by the size and number of tidal inlets occurring along the system (FitzGerald, 1996; Vila-Concejo et al., 2006). Tidal inlets are openings found along barrier shorelines, which let water flow through an established opening and allow the exchange of water through reversing tidal currents between lagoons or estuaries and the open ocean (FitzGerald, 1996; FitzGerald et

al., 2002). This interaction among lagoons, estuaries and the ocean is dependent on the relative strength of the currents within the inlet, as well as the wave and tidal currents in the nearshore zone, and creates a connection between the ocean and estuaries, bays, tidal flats, marshes, and tidal creeks, with their main channels being maintained by tidal currents (Cooper, 2001b; FitzGerald et al., 2002; FitzGerald, 1996).

Tidal inlets usually occur in meso-tidal environments and are associated with moderate wave energies, the sedimentary processes and tidal inlet morphology related to the combined action of both tidal currents and wave-induced currents (Castelle et al., 2007). These inlets are in equilibrium with, and maintain a balance between, sand moving toward the entrance of the inlet via wave and tidal action, and the scouring effect of flood-tide and ebb-tide currents flowing through the inlet throat (O' Brien, 1976). The dimensions of modern inlets are related to the volume of water discharged from the rivers and the amount of water that enters and exits the estuaries on a daily basis as a result of astronomical and wind tides (Mallinson et al., 2008). According to O'Brien (1976), inlet size is mainly controlled by the tidal prism, a dominant factor in determining flow through the inlet. The shape of the inlet and associated deltas are also influenced by the wave-induced sand transport alongshore, towards and away from the inlet, as well as by the scouring action of tidal currents in the area (O'Brien, 1976). Seasonally open tidal inlets and non-migrating inlets are considered as ephemeral features, which tend to be opened or closed to the ocean for several months during the year (Ranasinghe et al., 1999; Mallinson et al., 2010). These inlets are usually small (inlet width $\leq$ 100 m) and occur in microtidal, wave-dominated coastal environments where there are strong seasonal variations in streamflow, wave and climate conditions (Ranasinghe et al., 1999).

Estuaries that are situated on microtidal coasts tend to be mostly influenced by the weak tidal current component as opposed to wave action. The end result is smaller inlets due to the smaller tidal prisms (Cooper, 2002). Tidal currents are also responsible for the continual removal of sediment transported into the inlet from the adjacent shorelines (FitzGerald, 1996). Tidal energy can also affect the morphology of inlets, for example, if tidal range is minimal, inlets act primarily as outlets to the ocean for fresh water that flows into the estuaries from rivers, i.e., river-dominated estuaries (Cooper, 2002), this results in fewer inlets and longer barrier islands (Mallinson et al., 2008).

2.2 Energy classification of barrier/inlet systems

Inlet systems can be classified into three basic types on the basis of energy regime. These comprise mixed-energy, tide-dominated and wave-dominated inlets (Nummedahl and Fischer, 1978; Hayes, 1979; Davis, 2013).

Mixed-energy barriers are generally short and drumstick shaped, with one end prograding in the form of beach/dune ridges and the other transgressing landward (Davis, 2013). Tidal inlets are large and unstable and comprise well-developed ebb- and flood-tidal deltas with a single, moderately deep inlet channel which shoals in both a seaward and landward direction. This type of inlet is best developed along mesotidal barrier coasts at medium to large-sized inlets (FitzGerald et al., 2002, Davis, 2013).

Mixed-energy tidal inlets can subsequently be divided into mixed-energy straight inlets and mixed-energy offset inlets (Davis and Barnard, 2003; FitzGerald et al., 2002). Mixed-energy straight inlets (Fig. 4) are ephemeral as a result of the ebb-tide delta having a tendency to modify the down-drift side of the inlet into a drumstick barrier, therefore creating a mixed-energy offset inlet. Mixed-energy offset inlets (Fig. 4) are characterised by smaller ebb tide deltas and a distinct down-drift offset in the shoreline, which occurs as a result of the reversal of the local littoral drift due to wave refraction around the ebb delta, this is the most important factor of drumstick barriers (Davis and Barnard, 2003; FitzGerald et al., 2002).

Tide-dominated inlets (Fig. 4) are characterised by an absence of barriers, with sand bodies that are orientated in an onshore-offshore direction the result of strong tidal currents (Davis, 2013). The sand bodies in tide-dominated estuaries consist of elongate sand bars and broad sand flats that pass headward into a low-sinuosity single channel (Dalrymple et al., 1992). Tidal processes outcompete wave energy; the results are straight and stable inlet channels, along with well-developed ebb-tide deltas and large linear bars that have a nearly perpendicular orientation to the shoreline along the channel margins. Most tide-dominated inlets have large tidal prisms that control their shape, and affect the size of the throat section (Davis and Barnard, 2003; FitzGerald et al., 2002).

According to Dalrymple et al. (1992), wave-dominated estuaries (Fig. 3) have well-defined tripartite zonations. These include a marine sand body comprising barrier, washover, tidal inlet and tidal delta deposits, a fine grained muddy, central basin, and a bay-head delta that experiences tidal or salt water influence. These estuary types tend to occur along microtidal coasts, have narrow barriers with low elevations and abundant washover features (Davis, 2013). The inlets are widely spaced, small, and unstable (Davis, 2013) and lack ebb-tidal deltas due to the sediment being reworked easily by the incoming wave energy (e.g., Hayes, 1979).

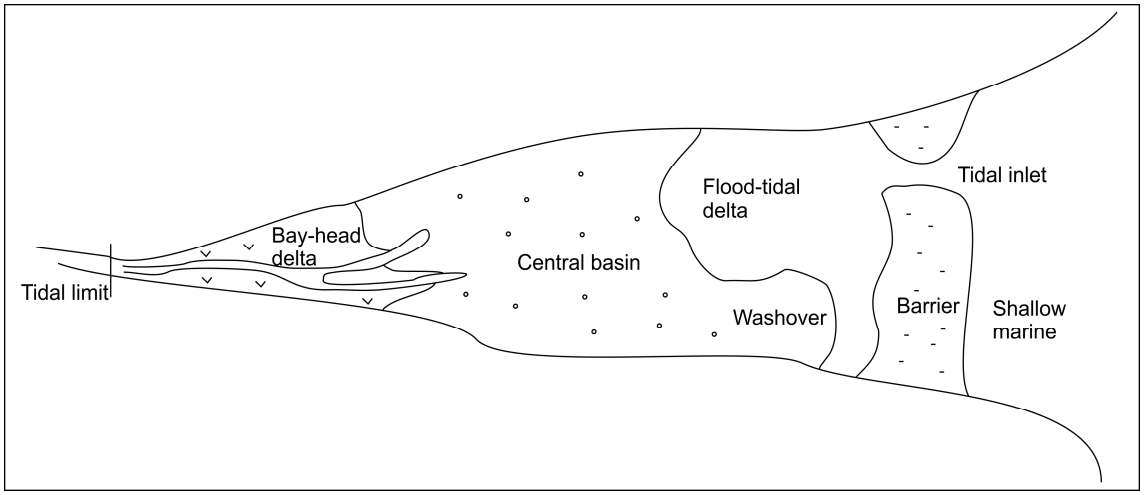


Figure 3. A schematic representation of wave-dominated estuaries including the tripartite zonation, modified after Dalrymple et al. 1992.

Wave-dominated systems have inlets that migrate more than tide-dominated systems. Sediment-bypassing processes dominate over inlet migration processes in mixed-energy systems, whereas in wave-dominated systems, migration is more likely to occur causing downdrift shoreline erosion and updrift accretion as a result of sand delivery and barrier elongation (Fenster and Dolan, 1996). In wave-dominated settings, inlet migration is a significant factor in coastal evolution, the result of seasonal variations in wave climates and longshore drift (Tung et al., 2009). Due to the small tidal range (< 2 m) of these coasts, small tidal prisms tend to be produced with relatively small inlet cross-sections (Davis and Barnard, 2003; FitzGerald et al., 2002).

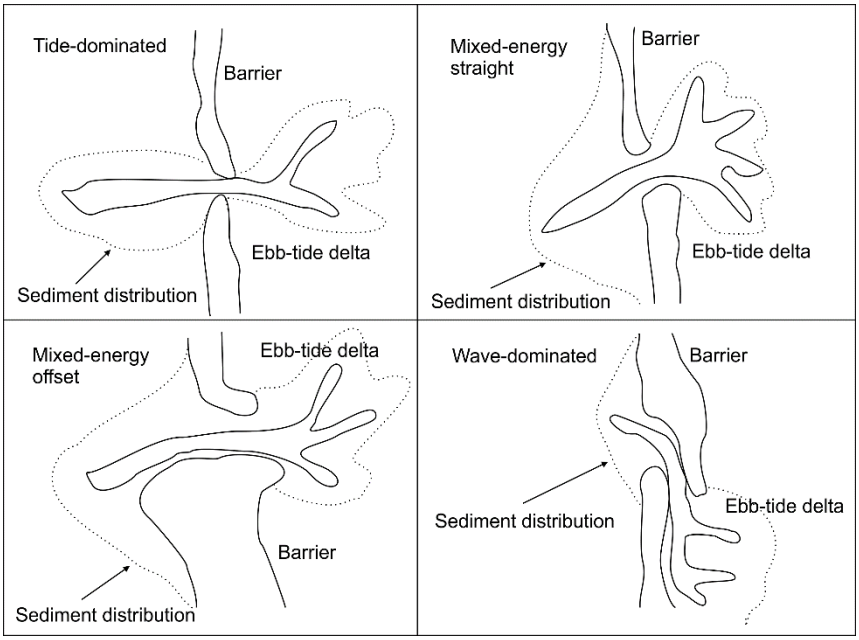


Figure 4. A schematic representation of tidal inlet classification, based on energy, modified from Gibeaut and Davis (1991).

2.3 Inlet evolution

Tidal inlets generally evolve according to four main stages, however each stage may not be present in every example. The first stage in the evolutionary process of ephemeral tidal inlets, regardless of the dominant environment, is opening or breaching. Once opened, the second stage is characterised by these inlets reaching dynamic equilibrium and remaining open. Natural inlets will be able to remain open based on the tidal currents. These are related to the tidal prism and can sometimes be enhanced by river flow, whilst artificial inlets can be stabilised using jetties or groynes (Vila-Concejo et al., 2004; Bezerra et al., 2011).

The third stage is characterised by migration. This is usually down-drift of the dominant longshore transport regime (e.g., Schwab et al., 2000) as the fringing barrier-spit system progrades alongshore with successive increments of longshore sediment input (Cayocca, 2001; Morris et al., 2001; Anthony et al., 2002). Inlets may also show migration patterns characteristic of either high or low energy (e.g., Vila-Concejo et al., 2004). The Ancão, Fuzeta and Lacém Inlets in Portugal undergo two types of migration patterns during either high or low-energy conditions. The high energy conditions have a duration of between 30 and 40 years and, are characterised by readjustment during the initial stages which is then followed by migration in an eastward direction until filling of the inlet begins as the limiting positon is reached. It is also associated with constant inlet widths. According to Vila-Concejo et al. (2004), “a complete cycle takes at least 50 years and the inlet migrates over 3500 m (pg. 972).” This occurrs in

response to major storms and is characterised by an eastward migration that is supplemented by sediment accumulation updrift of the barrier leading to a reduction in the inlet width (and thus cross sectional area) (Vila-Concejo et al., 2002; 2004).

The fourth and last stage is characterised by inlet closure. This may occur over the short-term (days) to mid-term (years) or the long-term (decades). The mechanisms of closure may similarly be due to both natural and anthropogenic activities.

This four-stage evolutionary model is highlighted in the short-to medium-term evolution of the Ancão Inlet of the Ria Formosa barrier island system, Southern Portugal (Vila-Concejo et al., 2004). The Ancão Inlet has characteristics of both tidal and wave-dominated inlets, as it has a well-defined deep main channel as well as a relatively small ebb delta, however, it is tide-dominated most of the time (Vila-Concejo et al., 2004) (Fig. 5).

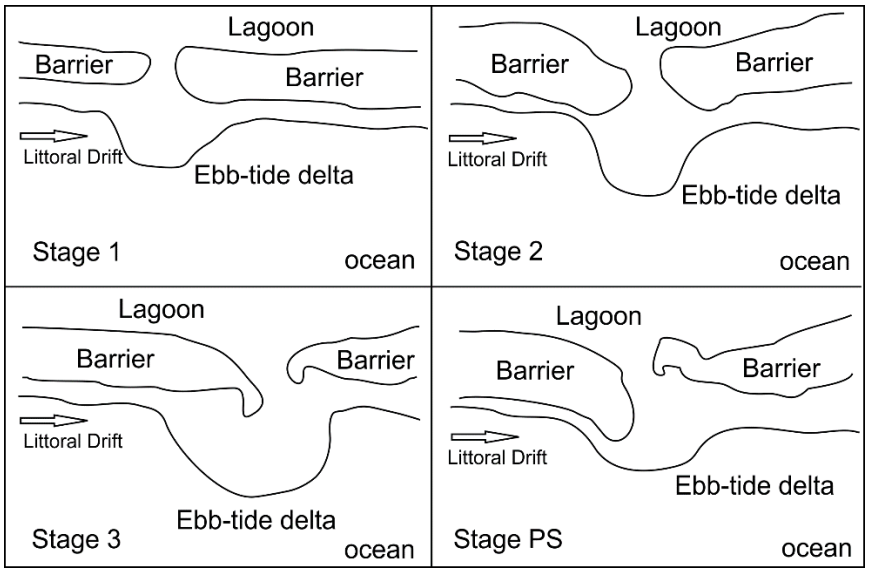


Figure 5. The four main stages of barrier inlet evolution. Stage 1 shows the system immediately after opening, with a narrow newly formed inlet and ebb-tide delta. Stage 2 is the inlet after reaching dynamic equilibrium and until the deltas are fully developed. Stage 3 represents the system after dynamic equilibrium is established, and the inlet is in the mature-migrating stage. Sediment bypassing occurs at the relocated inlet, and there is a well-defined ebb-tide delta. Stage PS is indicative of the inlet after a storm (modified after Vila-Concejo et al., 2004).

2.4 South African Estuaries, Barriers and Inlets

The South African coast is marked by an abundance of estuaries and lagoons, landforms that by definition, mark the transition from fluvial to marine processes and environments. From a geological standpoint, an estuary is considered a “transgressive coastal environment at the mouth of a river that occupies the seaward portion of a drowned valley system which receives

sediment from both fluvial and marine sources and which contains facies influenced by tide, wave and fluvial processes. The estuary is considered to extend from the landward limit of tidal facies at its head to the seaward limit of coastal facies at its mouth" (Dalrymple et al., 1992; 2006).The behaviour of the inlet itself is particularly important in that it marks the point where marine sediment, water and biota exchange with those of terrestrial systems.

Typically, South African estuaries and inlet systems are notoriously difficult to classify. Many types of estuaries exist and can be categorised through a variety of schemes based on biological (e.g., Heymans and Baird, 1995; Perissinotto et al., 2000; Froneman, 2004a; Anandraj et al., 2007), geomorphological (e.g., Garland and Moleko, 2000; Harrison et al., 2000; Cooper 2001a; 2001b) and hydrodynamic (e.g., Largier et al., 1992; van Niekerk et al., 2005) criteria. There are five main types of estuaries in South Africa according to local classification schemes; estuarine bays (1 %), estuarine lakes (3 %), river mouths (5 %), permanently open estuaries (19 %) (POEs), and temporarily open closed estuaries (TOCEs) comprising the majority (74 % of all estuaries (Froneman, 2004a; van Niekerk et al., 2005; Whitfield, 2005; Anandraj et al., 2007; James et al., 2007; Snow and Taljaard, 2007; Taljaard et al., 2009; Riddin and Adams, 2010; Scharler, 2012). These are discriminated on the basis of their morphological state with particular reference to the inlet, salinity structures and biological assemblages. Of these estuary types, South African TOCE's are particularly important, not just because they comprise the majority of South African estuarine bodies, but because they are amongst the most studied of these "types" worldwide. A better understanding of their form and geomorphic function is required in order to better manage these systems and their biological resources.

Cooper (2001a; 2002), and Harrison et al. (2000) provide a comprehensive geomorphological framework within which estuarine inlet and barrier states could be further examined. However, there has been no further attempt to review the geomorphological functioning and morphodynamic character of South African barriers and their associated estuaries, inlets and lagoons since then. A number of excellent reviews of South African estuaries can be found which examine the trophic functioning and biological structures of estuaries (e.g., Day, 1981; Reddering and Esterhuysen, 1987; Swart et al., 1988; Whitfield, 1992).

2.5 Geomorphological setting

The South African coast is a wave-dominated coastline, with small tidal range (< 2m). The estuaries thus fit into Davies (1964) and Roy's (1984) microtidal classification scheme (Cooper, 2001a). Microtidal estuaries are widely regarded as sinks (net accumulation zones) of sediment (Davies, 1964; Roy, 1984) that receive sediment from a variety of sources including marine and fluvial inputs as well as detritus from fringing vegetation, organic material generated within the

estuary itself, aeolian sediment input and human-induced inputs (Cooper, 1995). These systems are considered as ephemeral in the context of geological time scales, and should exhibit progressive shallowing and reduction in area (Davies, 1964; Roy, 1984). This is in fact not always the case, some estuaries, depending on the inlet state, can function mainly as 'conveyor belts' by which excess sediment is transferred through them and deposited in the ocean (Cooper, 2001a).

Almost all South African estuaries are hosted within bedrock-incised valleys, apart from the Kosi System (Cooper et al., 2012) and the Wilderness lakes (Whitfield, 1992). These valleys provide a spatial constraint on the evolution of the estuary and in many cases help to control the positioning and behaviour of both the inlet and barrier (e.g., Cooper, 1994).

For the majority of South African estuarine systems, sediment tends to move up river due to tidal asymmetry in typically constricted inlets. This is as a result of the deposition of marine sediment by wave currents in the nearshore zone which predisposes the system inlets to closure (Cooper, 2001a, b). This mechanism of sediment transport is, however, only effective during storm periods. During fair-weather conditions the transport of sediment into the lagoon mouth depends more on sediment availability at the ocean entrance, as well as available accommodation space at the lagoon entrance (c.f., Morris and Turner, 2010 for Australian counterparts). This acts to build the barrier after large inlet-forming events have occurred.

In flood-dominated estuaries, open inlet conditions occur over shorter timescales and have faster current regimes than ebb tides. This results in sediment accumulating preferentially in the estuary as a series of flood-tidal deltas. In many cases, the flood-tidal deltas may gradually extend upstream (Cooper, 2001a). The St. Lucia and Sundays River Estuaries for example, experience an accumulation of sand on the incoming flood-tide delta, with a subsequent progressive growth of these features landwards indicative of flood dominance. Flood-dominated microtidal estuaries therefore act as sinks for marine sediment (Cooper, 2001a).

Wave height and period are all relatively constant along the coast of South Africa. Subtle variations occur northward along both the east and west coasts (Table 1). The entire coast is a high energy, swell-dominated environment and despite the small variability in wave characteristics coast-wide, there is a regional scale fining of littoral sediment southward (Cooper, 2001a), a result more so of selective sediment source materials as opposed to a variation in wave energy (Cooper, 2001a). The high wave energy and fine sand at the southern Cape generally produces wide, gently sloping dissipative beaches with multiple offshore bars, while the coarser sediment of KwaZulu-Natal and Namaqualand produces characteristically steeper and narrower (reflective) beaches with high beach berms (Cooper, 2001a). The beach

state typically controls the morphodynamic behaviour of the inlets that breach the backshore and foreshore. Similarly, steeper beaches make for narrower and taller barriers that front many of the estuarine systems of the east coast.

Table 1. Wave height and wave period data trending from north to south for major cities along the South African coastline (Westhuysen, 2002).

Location	Wave Height (m)	Wave Period (s)
Richards Bay	1.5	13
Durban	1.8	11
East London	1.8	12
Port Elizabeth	2.3	12
Cape Town	2.2	12

Cooper (2001a) considered the major variability in South African inlet behaviour to be a function of catchment size and gradient, fluvial sediment supply, marine sediment availability, climate and fluvial discharge. Added to this are the controls of antecedent topography (e.g., Cooper 1991; Bond et al., 2013), littoral sediment supply (e.g., Cooper, 2001a; Bond et al., 2013; Green et al., 2013a) and responses to storminess (e.g., Cooper, 2001a; Smith et al., 2014) that have been recognised world-wide as regulatory factors of inlets. However the most important factor in inlet behaviour as stated by O'Brien (1976), is the influence of the tidal prism on inlet size, which, is a dominant factor in determining flow through the inlet.

2.6 Description of the main types of estuaries

At the broadest level of geomorphological discrimination, South African estuarine systems can be classified as either having a permanently open inlet, or a temporarily open inlet.

Permanently Open Estuaries (POEs) are estuaries that maintain permanent tidal inlets in connection with the sea. In these cases sediment transport is in dynamic equilibrium with the estuary in terms of modern sedimentary environments. They receive regular seawater and freshwater inflows, along with a steady supply of nutrients and include a well-defined barrier inlet system (Whitfield, 1992; 2005; Cooper 2001a; Anandraj et al., 2007; Whitfield et al., 2012).

Temporarily Open Closed Estuaries (TOCEs) are described as estuaries that are closed off from the sea by a sandbar that forms at the mouth, during the dry season or under low or no river flow conditions. During storm conditions or periods of high rainfall, the water level within the estuary will rise until it equals or exceeds the height of the sandbar, resulting in breaching of the sandbar at the mouth (Papadopoulos et al., 2002; Pillay et al., 2003; Froneman, 2004a; van Niekerk et al., 2005; Anandraj et al., 2007; Whitfield, 2008; Scharler, 2012; Carrasco and Perissinotto, 2014).

In Cooper's (2001a) morphodynamic classification scheme, these TOCE's are classed as being either normally open or normally closed. It is worth noting that a spectrum of barrier-inlet states and morphodynamic functions exists between the two canonical end members of permanently open and permanently closed. POEs and TOCEs thus fall within a range of these two extremes. As discussed further, these two ideal states rarely exist over the meso-scale of coastal evolution; strong seasonal forcing (e.g., Tyson cycles; Tyson, 1987) and storm imprinting (e.g., Bond et al., 2013) are likely to affect these significantly.

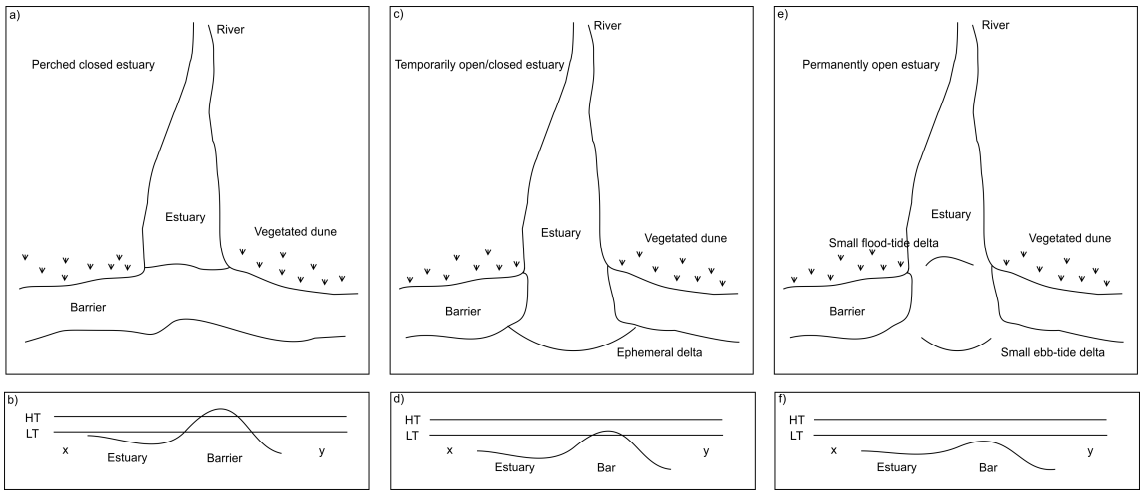


Figure 6a) Plan view sketch of a perched closed estuary. b) Cross-section showing the high barrier that causes the system to close during high tide. c) Plan view sketch of a temporarily open/closed estuary, and ephemeral delta formed during opening. d) Cross-section showing the bar that is overtopped during high tide, inducing breaching and inlet formation. e) Plan view sketch of a permanently open estuary, the flood- and ebb-tide deltas form once the barrier breaches and inlet shoaling begins. f) Cross-section showing a shallow bar that is overtopped during high and low tide, resulting in the estuary remaining open. Adapted from Cooper (2001a).

2.7 Geomorphology of POEs and TOCEs

According to Whitfield (1992; 2005), less than 50 South African estuaries maintain permanent tidal inlets with the sea. The prevailing water column mixing process in these POEs is either tidally or riverine driven, they have moderate tidal prisms (1-10 x 10^6 m³), and catchments that are usually > 500 km² and often > 10 000 km² in size. Some POEs are linked to coastal lakes, with the tides and tidal currents within these systems providing the main driving force for most of the turbulence and mixing in stratified and well-mixed estuaries, under low and moderate river-flow conditions (Whitfield, 1992). Floods can, however, alter the situation, with riverine energy being the main driving force of water movements within the system until a tidal regime is re-established at a later stage (Whitfield, 1992).

In South Africa most TOCEs tend to have small catchments (< 500 km²), with river inflow being either minimal or absent for prolonged periods of time. The tidal prisms of these systems are also generally small (< 1 × 10^6 m³) when the mouth is open and absent when the mouth is closed by a barrier or sandbar (James et al., 2007, Whitfield, 1992). These systems act like a typical estuary when open, but tend to take on the characteristics of a river mouth during flood conditions, with large amounts of sediment being moved out to sea from smaller estuaries during these periods (Whitfield, 1992). TOCEs may also be linked to estuarine lakes with their actions being associated with water-level fluctuations within these systems. The hydrodynamic properties of the water column within TOCEs are influenced by both tidal and riverine inputs when the mouth is open, and wind driven when the mouth is closed, with no fluvial interchange (except during periods of fluvial flooding) (Whitfield, 1992).

2.8 Types of permanently open estuaries – Barred open estuaries

The permanently (or normally) open estuaries maintained by fluvial discharge are termed river-dominated estuaries, and estuaries maintained by tidal discharge are termed tide-dominated estuaries (Cooper, 2001a). These have persistent supratidal barriers that impede the entry of the flood tide into the main estuarine basin.

River-dominated estuaries consist of a sandy barrier, narrow tidal inlet, and a fluvial-dominated channel. The tidal inlet acts as a discharge channel for freshwater and these estuaries are typically fed by rivers which have a high discharge rate because of either large catchments or high rainfall events (Cooper, 2001b). These estuaries are preferentially developed on the east coast of South Africa, where the rainfall is high and the steep hinterland gradient acts to decrease tidal intrusion into estuaries. The extension of the river channel to the inlet also reduces the tidal prism to an extent that the inlet itself is maintained by river discharge and not by tidal currents. The tidal inlets in river-dominated estuaries close during periods of low fluvial

discharge and re-open during periods of increased discharge. In these systems extreme fluvial floods act to scour the estuary channel, and remove fluvial and barrier sediment (Cooper, 2001b).

Tide-dominated estuaries are composed of a sandy barrier with a narrow tidal inlet, and a shallow sandy flood tidal delta deposit that forms landward of the inlet. At the inlet mouth strong tidal currents are the result of large tidal prisms, which form in estuaries that have a large surface area and/or are found in coastal settings that have low gradient. These flood-tide deltas can extend upstream for distances of up to 5 km, and are flanked or divided by an ebb channel that commonly overlies a coarse lag deposit or bedrock outcrop (Cooper, 2001b). These tidal currents are also able to maintain tidal inlets from aeolian, wave and nearshore current-induced littoral sedimentation. Episodic river floods in these systems act to erode flood tide-delta and backbarrier sediments, and are essential to the maintenance of the estuary mouth (Cooper, 2001b).

2.9 Processes, Controls and Examples

2.9.1 Permanently open estuaries

Reduced flood events, as a result of limited discharge due to dam constriction within POEs, occur mainly along the Eastern Cape coastline. This limitation could result in an increase in the size of the sand shoals that are found at the lower reaches of the estuary as well as, a greater degree of mud compaction in the middle and upper reaches of the estuary (Whitfield, 2005). Disproportionately large flood deltas may also constrict the lower estuary channel, causing a reduction in tidal exchange between the sea and the estuary. This in turn results in the tidal prism not being able to maintain an open inlet as it previously could, and when a flood does occur, the amount of sediment that accumulates in the delta would be greater than normal, requiring a larger flood of a greater magnitude to remove this increased amount of sediment (Whitfield, 2005).

The Mlalazi estuary is a good example of a POE (Fig. 7). It is a small, 11 km long, permanently open estuary on the north-eastern coast of South Africa. It is 1 to 3 m deep and is 200 m wide at its mouth. The upper reaches of the estuary are characterised by mud and silt, with the middle and lower reaches of the estuary comprising medium sand (Day, 1981; Papadopoulos et al., 2002). Sediment is supplied from the Thukela River to the south and strong unidirectional waves result in the estuary waters being impounded behind a 3.5 km long, coast-parallel barrier. At the inlet there is also a change in the angle of the shoreline which allows the estuary to receive protection from northeasterly directed storms (Whitfield, 1992; 2005; Bate et al., 2002).

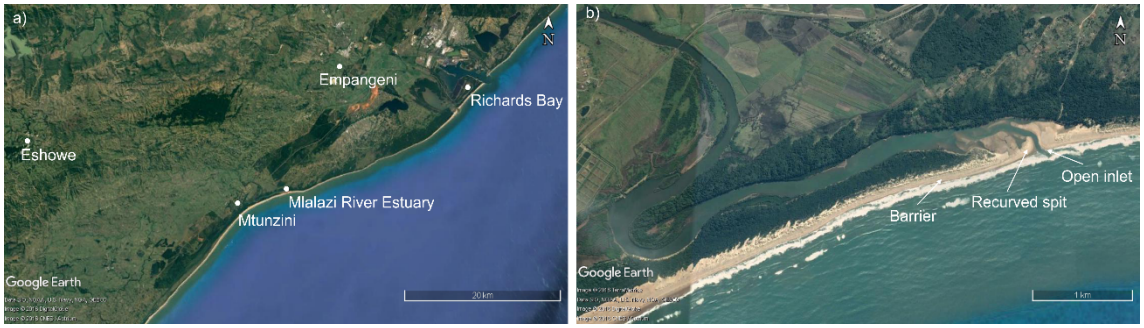


Figure 7. a) Position of the Mlalazi Estuary along the KwaZulu-Natal coastline, in relation to Richards Bay. b) Enlarged image showing the estuary morphology.

The Amatikulu Estuary is described by Cooper (1993) and Green et al. (2013a) (Fig. 8), as a shallow, river-dominated coast-parallel estuary behind a coastal barrier, with an inlet that is maintained via fluvial discharge, and a small tidal exchange (Fig. 8). The Amatikulu Barrier also undergoes rapid reformation once the ephemeral flood inlet has formed, without significant alongshore migration (Green et al., 2013a).

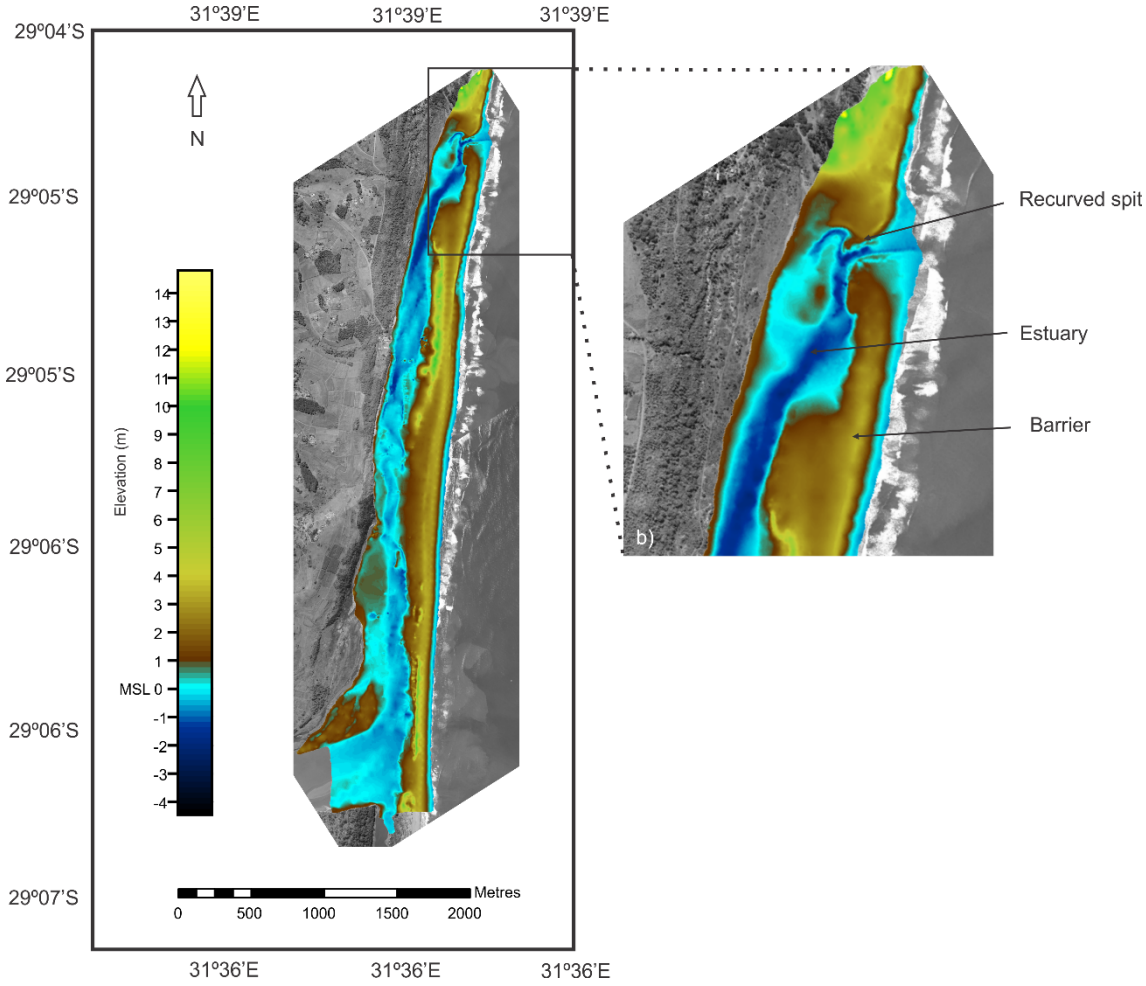


Figure 8. The position of the Amatikulu TOCE inlet and its associated barrier morphology. Note the length of the barrier (~ 4 km) and the northerly located inlet. b) Note the initial development of a recurved spit on the northern and southern sides of the inlet. Image modified from Green et al. (2013a).

2.9.2 Temporarily open/closed estuaries and inlet state

There are three main hydrodynamic states in which TOCEs exist; mouth open, mouth semi-closed, and mouth closed (Snow and Taljaard, 2007). The open mouth end member situation occurs when river inflow to the estuary is high enough to keep the mouth open to the sea. This allows seawater to intrude into the estuary during high tides, and river inflow to introduce freshwater into the upper section of the estuary. The semi-closed end member is characterised by reduced river inflow, along with an increase in the barrier height. Seawater intrusion is limited to spring tides only (Snow and Taljaard, 2007). The barrier high point is, however, not elevated enough to prevent water from draining from the estuary into the sea (Cooper et al., 1999; Perissinotto et al., 2000; Scharler, 2012). The last end member situation, mouth closed, is characterised by extremely low or no river inflow and an increase in the barrier height to

prevent seawater from entering the estuary or draining from the estuary and entering the sea. Overwash may enter the estuary and depends on barrier height and conditions at sea (Snow and Taljaard, 2007). This is a common occurrence in TOCEs worldwide, as estuaries that have low and narrow barriers are subjected to the highest degree of overwash incursion (e.g., FitzGerald et al., 2006; Vila-Concejo et al., 2006).

James et al. (2007) propose a further subdivision into two subcategories namely; intermittently open estuaries and intermittently closed estuaries. These subdivisions were based on the duration of the open mouth phase. Intermittently open estuaries (IOEs) are described as systems that are closed for > 50% of the year, and are only opened intermittently. Intermittently closed estuaries (ICEs) share a link with the sea for more than 50% of the year (James et al., 2007).

2.9.3 Intermittently open estuaries

Intermittently open estuaries (IOEs) are systems that have small river catchments of < 500 km² and that are closed for extended periods of time when there is either low or no river flow. During the lagoon phase, large amounts of sediment tend to accumulate within these estuaries, which are removed during flooding of the river. Inlet opening and closing are directly connected to the amount of runoff that feeds the rivers, with reduced river flow resulting in prolonged mouth/inlet closure and therefore a shorter open phase (Whitfield, 2005). Barrier development via aeolian and washover processes is common.

2.9.4 Intermittently closed estuaries

These estuaries fall under the “normally closed” estuaries of Cooper (2001a). In South Africa intermittently closed estuaries (ICEs) vary in size from -0.2 ha in surface area (Bot Estuary) to > 1 200 ha in surface area (Klein River Estuary) (Cooper, 2001a) (Fig. 9). With regards to morphodynamics, these systems exhibit two main forms based on factors such as back barrier water levels, and whether these are higher than the open sea tidal levels, which in turn is related to barrier crest elevation. These systems are divided into perched and non-perched systems (Cooper, 2001a).

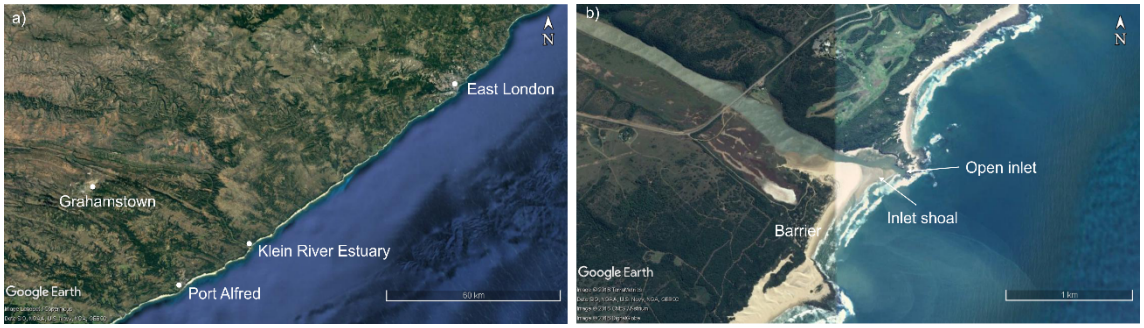


Figure 9. a) Position of the Klein Estuary along the Eastern Cape coastline, in relation to East London. b) Enlarged image showing the open estuary mouth morphology.

The Bot River Estuary (Fig. 10) is a relatively shallow, temporarily open/closed estuarine lake that is breached artificially nearly every two years, and has breached naturally only three times since 1940. It thus falls into the category of an ICE. The estuary is artificially breached, creating an inlet between 80 and 110 m wide and with a depth of -2.0 m to -2.5 m MSL. The Bot River Estuary could naturally breach more frequently, but the loss of water within the estuary has led to longer intervals between when water levels are sufficiently impounded to allow natural breaching to occur (van Niekerk et al., 2005). It thus behaves as a non-perched system.

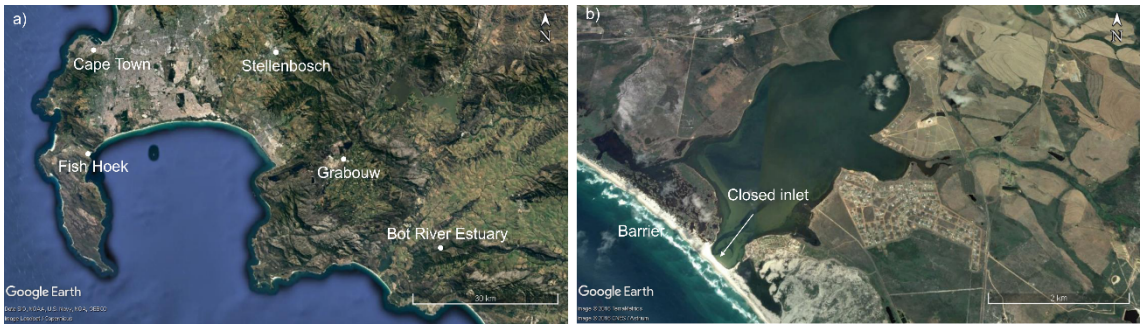


Figure 10. a) Position of the Bot Estuary along the Western Cape coastline, in relation to Cape Town. b) Enlarged image showing the closed inlet morphology.

2.9.5 Perched and Non-perched estuaries

In South Africa perched closed estuaries are described as having high barriers that were produced by the combination of coarse grained sediment, low wave energy (preferentially in South Africa) and impounded water levels that have greater elevations than most high tides (Cooper, 2001a). Sedimentation in these estuaries is graded to the perched water level, enabling the bed of the estuary to be elevated above the tide. Back-barrier water conditions are gentle, promoting suspension settling and mud deposition with organic matter accumulating on the estuary bed during the closed phase and being eroded during open phases (Cooper, 2001a). Breaching in these perched systems occurs when overwash or freshwater discharge inputs

exceed outputs, resulting in a surface channel being cut to allow discharge. These estuaries are found mainly on the east coast of South Africa, where there is coarser grained marine sediment and high fluvial sediment yields that fill the estuarine channel (Cooper, 2001a).

The Mhlanga Lagoon is a typical perched system (Fig. 11). Back-barrier waters are impounded behind a normally continuous supratidal sandy barrier that has a width of 700 m and a crest elevation of between 1 and 2 m above high tide (Cooper, 1989; 2001a). During periods of barrier breaching the elevated beds within these lagoons led to near complete draining, subaerially exposing formerly submerged areas of the estuary bed. These barrier openings normally close within approximately 10 days of breaching. The base of the inlet may scour to MSL, leaving a relief from inlet channel to the top of the supratidal barrier of up to 4 m (Fig. 11). During closed phases, the base level of the river is above sea level, controlled by the substantial build-up of the barrier via washover and accretion (Cooper, 1989; 2001a).

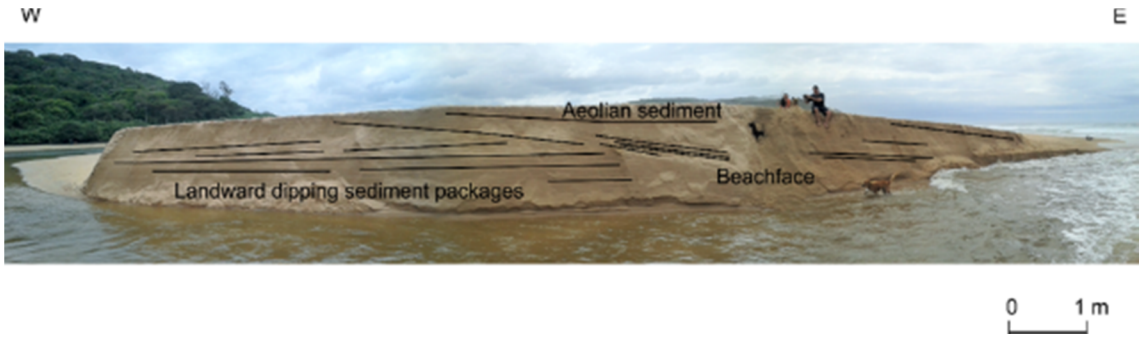


Figure 11. Internal architecture of the Mhlanga Barrier. Note the landward extension of the beachface and gravels capped by flat-lying aeolian sands. These truncate a series of landward dipping planar beds.

Non-perched closed estuaries lack both a sufficient barrier height for impoundment and a surface channel. Consequently, the back barrier waters are impounded close to the high tide level. The beaches that form in front of these estuaries have low gradients, a dissipative profile and also have wide surf zones. The lack of an appreciable barrier and high wave energy promotes a greater frequency of barrier overwash in non-perched estuaries (Cooper, 2001a). This results in the back barrier environment being dominantly built via washover processes (for a good international example, see Hein et al., 2012). These estuaries are commonly found along the southern and eastern Cape and share many common features such as a continuous, low-elevation supratidal barrier. Observations suggest that, during periods of increased fluvial discharge, perched systems may form a connection with the sea and when a surface channel forms, it is usually shallow and broad. Large standing waves may form during the flood tide

when the incoming water shoals over the lower gradient profile. The tendency for flood tidal deltas to develop is lowered due to the focus of deposition in the inlet throat; this is later sealed by aeolian/barrier development.

As a result of the strong fluvial discharges, scouring of the barrier may occur and the ephemeral inlet may form and last for periods of up to 2 months (Cooper, 2001a). When this begins to close after the initial breach, stranded backbarrier material is exposed along the margins of the inlet. This is often marked by sand-lined *Ophiomorpha* burrows that mark the extent of the normally impounded waters.

2.10 Inlet opening of TOCEs/ICEs

The opening mechanisms for the inlets along the South African coastline are diverse, and include overwashing and storm breaching (e.g., Froneman, 2004b; Gama et al., 2005; Bond et al., 2013); hinterland flooding (e.g., Cooper, 1989; Green et al., 2013a); artificial breaching (e.g., James and Harrison, 2008) and overtopping (Froneman, 2004b).

As the wave energy is fairly uniform throughout South Africa (Cooper, 2001a; 2001b), these systems all share wave-dominated attributes to some degree. In areas where the adjacent beaches are reflective, these inlet openings are usually river-dominated, with shallow backbarrier systems, narrow barriers and subdued barrier elevations. The linear planform design of the associated barriers is attributed to the deposition and reworking of older washover fan sediments that act to construct the barrier form (e.g., Bond et al., 2013).

The Zinkwazi River barrier is an approximately 80 m wide, 300 m long linear sandy feature, that tends to narrow during fairweather periods, despite the relatively high-up-drift littoral sediment supply. The narrow width promotes the breaching of the system by overwash (Bond et al., 2013).

In most river-dominated systems, breaching forms ephemeral tidal inlets. These inlets have small tidal prisms with limited landward penetration of the flood tide due to elevated bed-gradients. The small tidal prisms result in inlet closure rather than migration (Cooper, 2001a; Green et al., 2013a). The Amatikulu system has a wide, prograding barrier (Fig. 8) that forms inlets in various places due to either catastrophic flooding (fluvial breaching/overtopping) or through overwash processes where the fringing beach profiles are strongly dissipative (Green et al., 2013a).

This differs from the wave-dominated systems that are recognised globally. In many of these cases, the inlet channel migrates over time (FitzGerald et al., 2002; Davis and Barnard, 2003). In South Africa, the river-dominated estuaries are also unable to maintain an appreciable inlet

size when competing against the strong nearshore wave and tidal action. These are rapidly filled in with a mixture of marine material and capped by aeolian sands (Fig. 11).

Tide-dominated systems on the other hand, tend to have very low back-barrier gradients and consequently the impinging tidal wave is extended farther landwards and tidal prisms are relatively increased. These form best along eroded or embayed shorelines, unlike the wave-dominated (river-dominated) systems which typically form along straight shorelines (Cooper, 2001a; FitzGerald et al., 2002; Davis and Barnard, 2003).

In the past, the tide-dominated East Kleinemonde TOCE used to breach in response to freshwater discharge resulting from rainfall events > 100 mm that stretched over a period of a few months (Cowley and Whitfield, 2001). However, in recent years breaching occurs as a result of marine overwash and storm-surge events (Riddin and Adams, 2010). Open inlet events last for only a few days once river flooding has subsided and the majority of newly formed inlets close after a few tidal cycles (Whitfield et al., 2008). When the mouth has remained closed for an extended period of time, the fronting barrier can build via accretion and marine overwash to levels > 2.3 m MSL, producing an exacerbated impoundment of back-barrier waters (Whitfield et al., 2008). Breaching of the mouth should therefore usually be driven by the perched high water levels and associated seepage along the water table (Anandraj et al., 2007).

The smaller inlet systems of most South African estuaries may also be re-opened by new freshwater discharges that re-establish the tidal inlet (non-migrating inlet) (e.g., Halsey, 1979) and allow tidal currents to be restored with a sufficient prism to keep the inlet open for some time (Harrison et al., 2000; Cooper, 2001a). The tide-dominated Keurbooms River's inlet is cut through approximately 100 m of low-lying barrier sands, whilst the Gamtoos inlet involves erosion across a 1000 m wide barrier-dune field. The sheer width of the barrier precludes significant overwash erosion (e.g., Vila-Concejo, 2004; 2006). In both these systems, the inlets that formed were maintained for a long period of time and migrated in the direction of longshore sediment supply.

The natural opening and closing pattern of the river-dominated Umdloti Estuary has changed as a result of river water abstraction by water treatment works. These alterations have led to an increase in inlet closure in the Umdloti Estuary from <5% to 69%, with the estuary only being open for 13% of the year (Stretch and Zietsman, 2004; Zietsman, 2004). In the Umdloti Estuary the average breaching interval was calculated at approximately 15-20 days, and the estuary closes for extended periods of time during the dry season. The change in freshwater inflow from natural conditions was estimated at 8% (Scharler, 2012), seemingly enough to alter the system's geomorphic functioning substantially.

2.11 Inlet closure

On the KwaZulu-Natal coast TOCEs tend to be predominantly closed during the dry winter season, but open regularly during the wet summer season. The closure of TOCE's is thought to be facilitated by longshore drift sand transport in a south to north direction, and limited scouring through tidal action during the open phase (Whitfield, 1992; Scharler, 2012).

The Palmiet Estuary (Fig. 12) is a small, bar-built estuary that is 1.67 km in length, located 75 km southeast of Cape Town. It conforms to the non-perched morphology of Cooper (2001a). The mouth of the estuary tends to close in response to the westward longshore transport of sand, while the river and ebb tidal flows scour the channel (Largier and Slinger, 1991). The mouth of the Palmiet Estuary is usually open; it is however more constricted during the dry summer months, and only closes for approximately six weeks at the end of every alternate summer (Largier and Slinger, 1991).

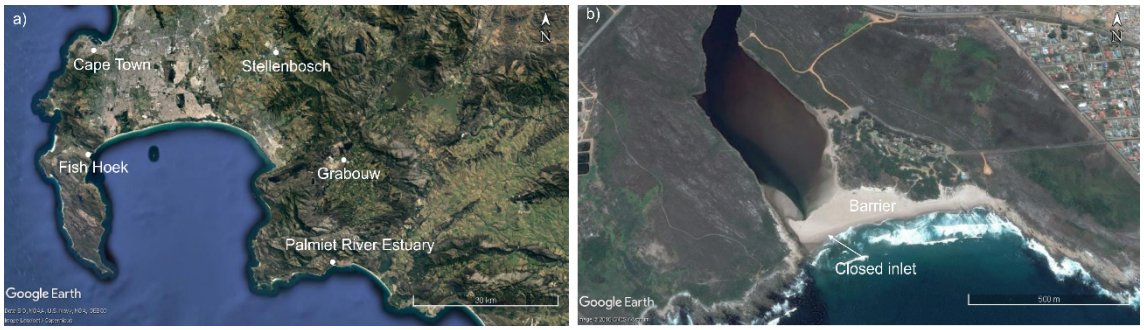


Figure 12. a) Position of the Palmiet Estuary along the Western Cape coastline, in relation to Cape Town. b) Enlarged image showing the inlet morphology.

Likewise, the Amanzimtoti Lagoon, a river-dominated and perched system from the KwaZulu-Natal coast, changes systematically in response to the 18 year long Dyer-Tyson summer rainfall cycles (DTC) (Smith et al., 2014). During the dry part of the DTC, the lagoon tends to generally be closed, and opens mainly during rainstorms. During flood seasons the lagoon outlet generally opens when the barrier and fronting beach is flattened and narrow (Smith et al., 2014) thus making it more vulnerable to overwash breaching during these periods.

There are several examples where inlets have been sealed and never re-opened, their old form being permanently abandoned. Lakes St Lucia, Sibaya, a few of the Kosi lake systems and the Wilderness Lakes have all been subject to rapid closure of their inlets (Wright et al., 2000). Unlike the long-term persistence of barrier-inlet systems documented from the US Atlantic, these sequences show a net shallowing that ended in the complete constriction of the inlet and closure of the system (Wright et al., 2000; Benallack et al., 2016). Throughout South Africa, this appeared to have happened at roughly the same time. Closure of the inlets associated with

the coastal waterbodies in KwaZulu-Natal, the Southern Cape (Wilderness lakes) (Bateman et al., 2011) and the Western Cape (Swartvlei Estuary) system (Whitfield et al., 1983), all occurred ~ 6000-7000 years ago during the Holocene transgression and have maintained a permanent barrier to the ocean since then. This suggests a country-wide climatic shift to dune building that separated these features from the oceanic waters. There appears to be a tipping point that operates on a cycle beyond the morphodynamic time frame where inlets cease to exist and lagoonal and estuarine water bodies transform to lacustrine systems.

2.12 Migrating vs non-migrating inlets

According to Green et al. (2013a) inlet migration is regarded as a common response of estuaries to changing sediment, wave and back-barrier dynamics and generally occurs in the direction of longshore transport. Past studies show that the majority of inlets migrate in the direction of net littoral drift on sandy shores. The migration of inlets may cause inlet-induced changes in the estuary to accelerate, and may result in the inlet being filled with littoral sediment derived from updrift sources (Aubrey and Speer, 1984).

Tide-dominated estuaries tend to migrate if they have formed extensive shore-parallel barriers at the coast (Cooper 2001a). In tide-dominated estuaries, if the barrier is elongated, alongshore flooding can cause barrier breaching forming new inlets, and once flooding has dissipated the inlet can migrate as sediment is being transferred landward from the ephemeral delta (Cooper, 2002). These estuaries are maintained by strong tidal currents, large tidal prisms and may only close as result of extreme marine events, or if the tidal prism becomes unsustainable (Cooper, 2001a; 2001b). The tidal currents within tide-dominated estuaries maintain the tidal inlet against aeolian, wave and nearshore current-induced littoral sedimentation, with episodic river floods preferentially eroding accumulating flood-tidal deltas and barrier associated sands, essential in maintaining an open estuary mouth (Cooper 2001b). For example, in the Gamtoos and Keurbooms estuaries, flood-induced barrier breaching caused the alongshore migration of the inlet (Cooper, 2002). These estuaries are therefore open for longer periods of time and are more prone to migrate.

If an estuary exhibits coast-parallel extension, modifications due to flooding may form new tidal inlets and initiate inlet migration. The tidal inlet in the river-dominated Amatikulu Estuary migrated 400 m north in 1973. These estuaries do not migrate under normal circumstances as these inlets are dominated by fluvial discharge and have small tidal prisms that are not able to overcome wave-induced sediment transport, which causes inlet closure (Cooper 2001a).

The Zinkwazi Estuary is an uncharacteristic example of a river-dominated system. In 2007, following a period of barrier widening, sustained ebb flow was able to scour a channel down to

a sloped bedrock surface. This resulted in the inlet flow being obstructed, forcing the inlet to migrate north. As a result, a deeper inlet was formed mid-way along the barrier in a position that was previously unoccupied (Bond et al., 2013). In this example inlet migration only occurred as the system was shifted from its usual narrow barrier morphology to a wider barrier morphology as the barrier begun to rollover.

In the case of perched estuaries, their inlets do not migrate, as once they are breached the barrier outlets normally close rapidly. The small tidal prism associated with these types of estuaries is not sufficient to sustain the inlet, causing it to rapidly close once breached. For example, the Mhlanga estuary closes within approximately 10 days of opening (Cooper, 2001a).

3 Regional Setting

3.1 Locality

The study area is located along the KwaZulu-Natal coast of South Africa and includes two localities, the Zinkwazi Estuary (29° 16′ 48.09″ S; 31° 26′ 34″ E), and the Umdloti Estuary (29° 39′ 00″ S; 31° 07′ 43″ E) (Figure 13a and 13b).

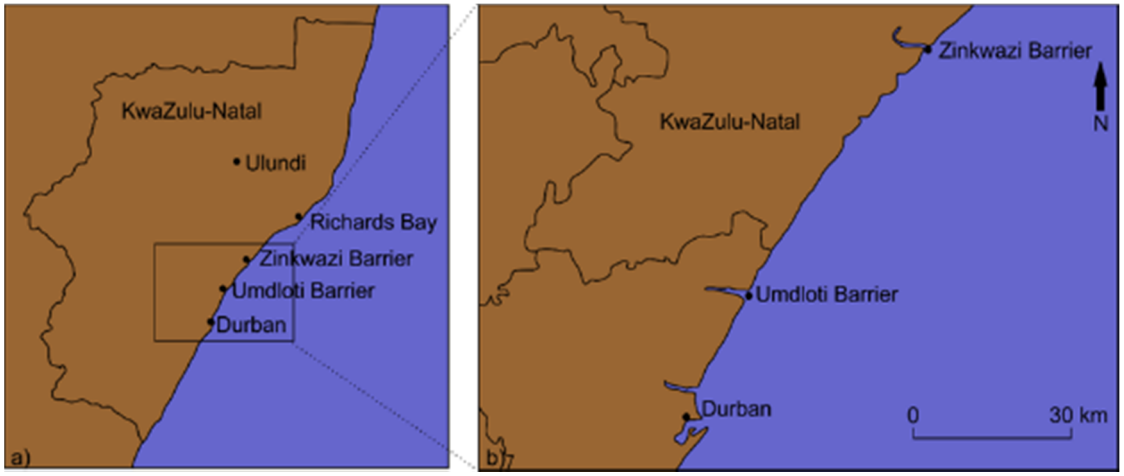


Figure 13. a) Positions of the study areas along the KwaZulu-Natal coastline, in relation to Durban, along with positions of the Richards Bay and Ulundi stations used for correcting the GPS data. b) Enlarged study area showing the barrier inlet systems in relation to each other.

The Zinkwazi River has a small river catchment (approximately 75 km²) and is incised into deeply weathered Pleistocene soils McCormick et al. (1992), and Bond et al. (2013). The river has a mean annual runoff of 14.3 x 10^6 m³ (Chew and Bowen, 1971), with an estimated sediment yield of 29 200 tonnes per year (Rooseboom, 1975).

The Zinkwazi Estuary inlet forms in the wave shadow of a rocky headland, with the estuary being located in a headland-bound embayment. The sandy barrier has a swash-aligned morphology and the amount of fluvial discharge controls the amount of time the estuary remains open to the Indian Ocean. The Zinkwazi Estuary also has a small tidal prism. However, this has little effect on the estuary's ability of maintaining an inlet for long periods of time (Bond et al., 2013).

The Umdloti Estuary is described as a perched closed system by Cooper (2001a), and is between 2 and 150 ha in size (Heydorn and Pistorius, 1978). The Umdloti River catchment covers an area of 558 km² and has a river length of 74 to 88 km, with a mean annual run off of 112 x 10^6 m³ (Heydorn and Pistorius, 1978). The Umdloti River flows perennially, with the mean annual average flow from 2 m³/sec to 2.5 m³/sec (Heydorn and Pistorius, 1978). The

estuary is marked by a 600 m long barrier that breaches toward the extreme southern end of the system, although this can change. According to Garden and Garland (2005), the Umdloti Barrier inlet is orientated in a southeasterly direction, with the inlet position in the centre of the barrier. Artificial breaching historically occurred toward the southern end of the barrier, however in modern times the barrier breaches naturally in a more northern to central position (Garden and Garland, 2005).

3.2 Geological setting

3.2.1 Hinterland topography

According to Cooper (2001b), the hinterland topography along the South African east coast is steep with an average gradient of greater than 1:100 (Cooper, 1990). This results in steep, entrenched rivers that enter the ocean as single estuaries with little amalgamation of the systems in their upper reaches. The associated estuaries are small features that are found within bedrock valleys along the coast.

As a consequence of having short and steep drainage systems, the rivers tend to be shorter with high flow velocities along the eastern sector of the country (Cooper, 1991). River courses along the KwaZulu-Natal coast drain small laterally restricted catchments that are separated from each other by marked divides. As a result, river courses are narrow and have poorly developed flood plains with little storage capacity for riverine sediment (Le Roux, 1990; Cooper, 1991).

3.2.2 Hinterland geology

The hinterland geology of KwaZulu-Natal has implications for the type of sediment comprising the barrier systems studied in this thesis. The Archaean and Proterozoic basement in KwaZulu-Natal comprises granites and greenstones. These are overlain in the study area catchments by the Natal Group, a set of Paleozoic age sedimentary rocks comprising conglomerates, sandstones, siltstones and mudrocks (Marshall, 2006).

The Natal Group is overlain by the Late Carboniferous to the Middle Jurassic age Karoo Supergroup. This comprises the Late Carboniferous to Early Permian Dwyka Group (diamictites, conglomerates, sandstones, and mudrocks) (Johnson et al., 2006). Overlying this is the Permian age Ecca Group, comprising silty mudrocks, sandstones, siltstones and mudstones (Johnson et al., 2006). These are all intruded to various degrees by the Karoo Dolerite Suite, a shallow feeder dyke-sill system that extends to the Drankensburg volcanics, which form the cap to the KwaZulu-Natal escarpment.

Coastal Cenozoic deposits in the study area consist of the loosely consolidated to unconsolidated sediments of the Maputaland Group and comprise Pleistocene to Holocene-age aeolianites and beachrocks overlain by unconsolidated Holocene beach and aeolian sands, which comprise the barrier spits that form the crux of this study.

Table 2. Summary of the stratigraphy of the study area hinterland (detailing important stratigraphic units that comprise the catchment).

Age	Formation	Group	Supergroup	Other
Tertiary-Holocene		Maputaland Group		Berea-type Red Sand
Jurassic				Karoo Dolerite Suite
Permian	Pietermaritzburg and Vryheid Formations	Ecca Group	Karoo Supergroup	
Carboniferous		Dwyka Group	Karoo Supergroup	
Ordovician	Durban Formations	Natal Group		
Archean and Proterozoic basement				

3.3 Climate

According to Tyson (1987), the climate of the KwaZulu-Natal hinterland is dominated by a subtropical high pressure belt, with a mean annual rainfall of 900 — 1000 mm that is largely restricted to the summer months of the year. During these summer months, a central high pressure system is found in the southeast, with moist air moving into the interior of the country from the Indian Ocean. The winter rainfall is associated with coastal low pressure systems that move up from the Antarctic (Begg, 1978; Tyson, 1987; Cooper, 1991; 1993; Tyson et al., 2002).

The eastern coastline of South Africa is a humid subtropical zone that is dominated by South Atlantic and South Indian anticyclonic high pressure cells (Tinley, 1985; Cooper, 2001a). According to Tinley (1985), the coastline is influenced by a bidirectional northerly and southerly wind regime. A dominant northerly to north-easterly wind pattern occurs during

summer, whilst during winter there tends to a strengthening of southwesterly winds in the region (Mallory, 1977).

3.4 Oceanography

3.4.1 Coastal morphology

According to Cooper (1991), the KwaZulu-Natal coastline is described as a high-energy coastline with a relatively straight northeast trending coast orientated at 042°-222°. The coast comprises crenulate bays bound to the south by rocky headlands around which the southeasterly swell refracts. The beaches along the coastline are generally coarse grained, and are reflective to intermediate in nature (Cooper 1991; Smith et al., 2010).

3.4.2 Coastal hydrodynamics

The wave-dominated KwaZulu-Natal coastline is dynamic in nature and experiences wave heights that range from 0.3 to 7.6 m, with a median wave height of 1.49, a median wave period of 10.7 s from the ESE, and a deep water wave height of 2.07 m (Table 3) (HRU, 1968; Cooper, 1993). Beach profiles tend to become steeper as wave energy diminishes and grain size increases (Cooper, 2001a).

Swells are usually higher during the winter months (May to July), as wave approach is most likely to come from the south to the southeast, which is linked to the passage of cold fronts, as well as cut off low systems (Smith et al., 2014). The swell pattern changes during the summer months (December to March) to a largely easterly direction (Wright and Short, 1984; Guastella and Smith, 2014), as a result of the prevailing northeasterly winds, which are related to the South Indian Ocean Anticyclone (Smith et al., 2014). High swells during other times of the year are most likely associated with tropical depressions, storms or cyclones (Smith et al., 2014).

The southern African coastline is dominated by semi-diurnal tides and the tidal range tends to vary comparatively little (Cooper, 2001a). The tidal range along the KwaZulu-Natal coastline varies between a maximum astronomical tide range of 2.3 m and mean neap tide range 1.36 m. The coast is therefore classified as a microtidal to low mesotidal system (Hayes, 1979; Day, 1981). This coastline is influenced by a general north to south net littoral drift direction, which is produced as the primarily south to southeasterly swell intersects the coastline at a slight angle (Wright and Short, 1984; Cooper 1991; 1994; Guastella and Smith, 2014).

Table 3. Annual swell characteristics of the KwaZulu-Natal coastline from 1999 to 2009. Data from Corbella and Stretch (2012), extracted from the Durban and Richards Bay offshore swell buoys.

Year	**Maximum Wave Height (m)**	**Maximum Significant Wave Height (m)**	**Maximum Peak Wave Period (s)**
1999	9	4	18
2000	8	5.8	18
2001	10	6	18
2002	9.8	5.8	18
2003	6.2	3.9	20
2004	7.4	4	20
2005	7.6	4.2	20
2006	7.8	4.2	20
2007	12.4	8.6	20
2008	8	4.2	23
2009	8.2	4	18

4 Methods

4.1 Hardware

The hardware used for the data collection of this project included ground-penetrating radar (GPR) and global-positioning systems (GPS).

4.1.1 Ground-penetrating radar (GPR)

Ground-penetrating radar or GPR, is a non-invasive geophysical tool that detects electrical discontinuities in the shallow subsurface region. This is done by the generation, transmission, propagation, reflection and reception of discrete pulses of high frequency (MHz) electromagnetic energy (Neal, 2004).

A pulseEKKO PRO™ Sensors and Software GPR system was used in this study. It has an operating bandwidth that ranges from 12.5 MHz to 1000 MHz in order to optimise the spatial resolution of the data in light of varying target sizes and exploration depths. It comprises a fully bistatic design that enables variable antenna offsets and orientations for advanced surveys.

The pulseEKKO PRO™ system consists of interchangeable antennas with bandwidths of 12.5, 25, 50, 100, and 200 MHz. The transducer units comprise antennae and electronics in a single package to optimise performance, with bandwidths of 250, 500, and 1000 MHz in shielded transducer sets.

Two GPR surveys were carried out using the Sensors and Software pulseEKKO PRO™ 100 GPR system. The first was a reconnaissance study of the two field areas. The second comprised a series of detailed survey lines which were acquired in January 2016 at both the Umdloti and Zinkwazi Barriers. The profiles were generally oriented either parallel to the beach ridge or perpendicular to the trend of the barrier across the beach ridge. A total of ~ 3.5 km's of line coverage from the two areas was achieved (Fig. 14a, b, c and d).

Intervals of 50 m were marked parallel to the barrier along the ridge line, and 20 m intervals were marked along shore-normal lines. The GPR was then carried along these pre-marked lines recording information and relaying it to the Digital Video Logger (DVL) screen (Fig. 15). The 100 MHz and 200 MHz antennae were used for replicate lines so as to provide adequate depth of penetration as well as, high-resolution profiles of the subsurface geology. The 100 MHz antennae reached a vertical penetration of 12 m in depth, whereas the 200 MHz antenna reached a vertical penetration of 9 m in depth.

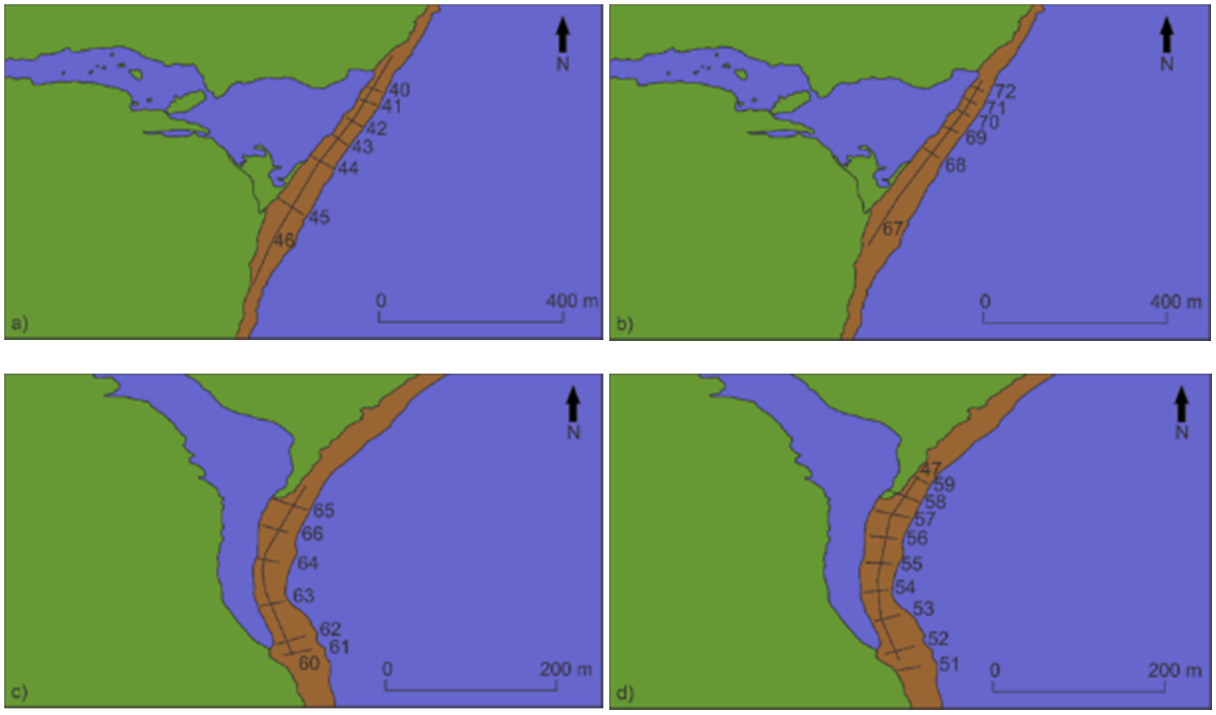


Figure 14. a) and b) show the positions of the low and high frequency GPR lines from the Umdloti Barrier respectively. c) and d) show the positions of the low and high frequency GPR lines from the Zinkwazi Barrier respectively.

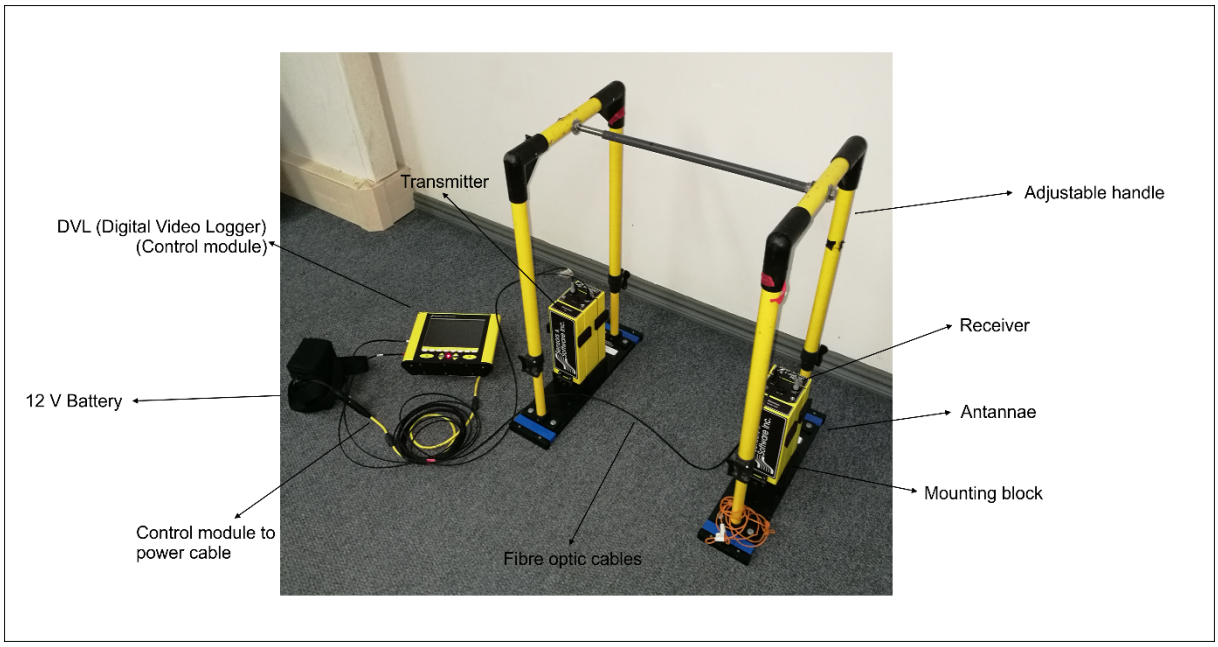


Figure 15. PulseEKKO PRO hand-held high frequency (200 MHz) setup including all the components (PulseEKKO PRO User's Manual). GPR data were collected in specific areas of each barrier complex to characterise any variations in barrier geomorphology (see section 4.3.3) and to link these with the subsurface stratigraphy.

4.1.2 Global Positioning System (GPS)

A Trimble ProXRT receiver with GLONASS capability was coupled to the GPR. This system allows for a 1 Hz re-positioning rate with uncorrected sub-meter accuracy and with a higher positional accuracy obtainable with post processing. It combines OmniSTAR support (for instantaneous 20 cm accuracy), optional GLONASS support (increases the number of GNSS satellites that can be used when working in the field), H-Star™ technology (connects to a real-time correction source for positions in the field) and dual frequency GPS (Lebens, 2010).

Once the data were collected along each GPR profile, the files were downloaded and the data differentially corrected from the PROXRT using a multiple base station approach (Ulundi (trignet) and Richards Bay (sopac)) (Fig. 13a and 13b). The data have a horizontal accuracy of 0 to 15 cm, with the remainder falling between 15 and 30 cm, and a vertical accuracy of 10 cm. ArcGIS version 9 was used to extract the line elevation and the latitude and longitude.

Elevations were corrected according to the geoidal separation at the specific study sites, which were then imported into EKKO Project. The latitude and longitude values were also converted from decimal degrees to decimal minutes before being imported into the program for topographic correction of the GPR profiles.



Figure 16. Trimble ProXRT receiver and GPR components in use during the reconnaissance survey of the Umdloti Barrier.

4.2 Field and lab work

4.2.1 Measured sections from the Zinkwazi and Umdloti Barriers

The various radar facies identified from the GPR profiles were correlated with lithostratigraphic units of the barrier that were exposed where the barrier had been breached. A series of measured

sections were undertaken to inspect the internal architecture and lithostratigraphy of the barriers. The barriers were examined according to standard sedimentological procedures and sampled for grain size, organic debris and macrofossil content.

4.2.2 Grain size analysis

Sediment samples were analysed for their particle-size distribution with a sieve stack. Eight representative samples from each definable layer in the barrier were analysed. The samples were dried for a period of 24 hours at 60° C. Once dried, each sample was weighed and sieved through a stack comprising 2 mm, 1 mm, 0.500 mm, 0.250 mm, 0.125 mm, and 0.063 mm sieves. The samples were mechanically shaken for 10 mins each and the various size classes weighed and calculated as size class percentages. The data were then plotted in GRIDSTAT in order to determine the mean grain size and sorting values, according to the Folk and Ward method (Folk and Ward, 1957).

4.3 Software

GPR data were processed with the following Sensors and Software packages.

4.3.1 EKKO View and EKKO Mapper

EKKO View was used to display files containing raw traces and gained data traces simultaneously. The display position, depth, signal amplitude and, GPS positioning of each trace are able to be viewed. Lines were then checked to see if they were suitable for further processing (pre-processing stage). GPS elevations and line coordinates were imported into EKKO Mapper so as to correct for topography. This aided the initial interpretation process as features such as the water table could be identified.

4.3.2 EKKO Project V2 R3

EKKO Project was used to process and display the GPR data. The GPR lines were imported into the EKKO Project Program, along with the GPS co-ordinates for each line. These lines were then processed in the LineView program by filtering and the addition of gains. For both the 100 and 200 MHz antennae at both the Zinkwazi and Umdloti Barriers, the Dewow and SEC2 filters were used. A signal attenuation value of either 2.00 or 5.00 was used for the 100 MHz antennae, and either 1.00 or 2.00 for the 200 MHz antennae at the Umdloti Barrier. A start gain of 2.00 and a maximum gain of 500 were used for both the 100 and 200 MHz antennae were also used. A signal attenuation of 1.00 was used for the 100 MHz antennae, and 2.00 for the 200 MHz antennae at the Zinkwazi Barrier. A start gain of 1.00 and a maximum gain of 500 were used for the 100 MHz antennae, with a start gain of 2.50, and a maximum gain of 500

being used for the 200 MHz antennae. Colour palettes were also adjusted for better viewing of the reflectors.

4.4 Satellite imagery

Satellite imagery (Google Earth) of the Zinkwazi and Umdloti Barriers was studied to help identify mesoscale geomorphic changes to each system. These span a fourteen-year period from 2002 to 2016 for the Umdloti system, and a six year period from 2010 to 2016 for the Zinkwazi system. All images were geo-referenced and imported into ArcGIS where both mesoscale changes in barrier morphology, and seasonal variability in inlet behaviour were examined.

5 Results

Radar stratigraphy can be treated in a manner similar to seismic stratigraphy. The basic building blocks of radar packages, radar surfaces and radar facies, can be described in the same way (Neal, 2004) and as such, all GPR descriptions in this thesis are based on the terminology created to define these. The descriptive terminology has been modified to a certain extent from the seismic stratigraphic nomenclature of Mitchum and Vail (1977), Campbell (1967) and Allen (1982); radar reflection configurations are described in terms of their shape, dip, the relationship between reflections, and the reflection continuity, as outlined by Neal (2004).

5.1 Zinkwazi and Umdloti River Barrier radar stratigraphy

The Zinkwazi and Umdloti Barrier radar stratigraphy comprises 10 different radar packages and 9 radar bounding surfaces combined (Figs. 17-26). Units have been grouped according to similarity in radar facies across all the barrier systems. Due to salt attenuation, the limit of penetration of the data are ~4.5 m.

Unit A

Unit A is subdivided into Unit A1 and Unit A2. Unit A1 comprises gentle seaward dipping, subparallel, moderately continuous reflectors along the Zinkwazi Barrier system. In the shore-parallel section, Unit A1 appears as steeply inclined, northerly dipping reflectors (Fig. 17). These extend into the adjoining bedrock that anchors the headland at Zinkwazi Beach. The upper boundary of Unit A1 is characterised by reflectors that are concordant with the overlying surface 1 (Fig. 17).

Unit A2 is the lowermost unit of the Umdloti and Zinkwazi Barriers, and consists of horizontal planar or even reflectors (Fig. 18). These reflectors are subparallel and moderately continuous to each other, with the upper boundary characterised by reflectors that are concordant with the overlying surface 2. The reflectors dip gently landwards (Fig. 21)

The depth limits of both Unit A1 and Unit A2 are unresolvable due to salt attenuation, but the upper limits occur at a depth of approximately 4.5 m. In many areas of the barriers, the seaward portions of the lines at this depth may be reflector free. There are multiple hyperbolic reflections associated with bedrock outcrops, boulders and channel lags along surfaces 1 and 2 that cross cut Unit A1 and Unit A2 (Fig. 17 and Fig. 18).

Unit B

Unit B consists of sinuous or wavy reflectors. The reflectors are subparallel and continuous, downlapping surfaces 1, and 2, as well as toplapping with the upper surface 3 (Fig. 19). In the

southern part of the Zinkwazi Barrier, the reflectors dip steeply to the north at up to 60°. Unit B ranges in thickness from 0.5 m to 4.5 m. The Umdloti locality has the thinnest occurrences of Unit B. It is however most common in this barrier (Fig. 19), whereas it is thicker, but restricted to the southern extremities of the Zinkwazi Barrier. In the south of the Umdloti barrier, this unit is only apparent from the higher resolution GPR profiles.

Unit C

Unit C is a 3.5 m thick package of reflectors, characterised by varying degrees of preservation across the two barrier systems. It comprises parallel planar or even reflectors, which are continuous and generally concordant with both the upper (surface 4), and lower boundaries (surface 3) (Fig. 20). The thickest occurrence of Unit C (3 m) is along the southern-most and landward section of the Zinkwazi Barrier. It is not apparent in the low frequency records from the Umdloti Barrier system, and if evident along the high frequency lines, is poorly developed.

Unit D

This unit comprises a dominantly seaward dipping package (Fig. 21). It is characterised by a combination of either planar (or even) and wavy or sinuous reflectors that may be oblique, chaotic and discontinuous. The internal reflectors toplap with the upper boundary surface 5 which is an erosional truncation, and onlap as well as downlap along the lower boundary surface 4. These are irregular and erosionally truncate the units beneath (Fig. 21). The entire unit forms a seaward-thickening package, best developed in the Umdloti Barrier system, along the northernmost portions of the barrier. This unit has a variable thickness due to its channel-like form and it has a maximum thickness of ~ 4.5 m.

Unit E

Unit E is characterised by sinuous or wavy reflectors that are subhorizontal, subparallel and moderately continuous. The upper boundary of the unit comprises surface 6 an erosional surface that underlies the overwash pulse, against which the internal reflectors toplap. This surface has hyperbolic reflectors associated with it, as evident in Figure 20. Reflectors downlap the lower surface 5 in a seaward dipping arrangement; the wavy character of the reflectors is most evident in coast-parallel sections. Unit E thins landward along the Umdloti and Zinkwazi Barriers. This unit reaches a maximum thickness of 2.5 m along the seaward section of the barrier (Fig. 22), closer to the northern-most sector of the barrier.

Unit F

Unit F consists of concave down reflectors that are oblique chaotic and discontinuous. This unit occurs in both barrier systems, but is most common in the southern portions of the Zinkwazi

Barrier. These reflectors prograde landwards, onlapping the seaward inclined lower boundary (Fig. 23). The upper boundary of this unit comprises an erosional truncation (surface 7).

Unit F directly overlies Unit A1 (Fig. 23) and underlies Unit H. It appears to be related to the position of Unit A1 in the Zinkwazi Barrier system, as Unit F only occurs where surface A1 can be seen along the Zinkwazi Barrier. In the Umdloti Barrier system a similar morphological feature is found underlying Unit G. The reflectors in this unit tend to orientate and prograde landward in relation to the position of the contemporary berm of the beach system.

Unit G

Unit G contains planar/ even to wavy reflectors. These reflectors are subparallel to oblique and moderately continuous, with some lines being reflector free (Fig. 24). This unit is found in both the Zinkwazi and Umdloti Barrier systems. The upper boundary of Unit G is erosionally truncated (surface 8). Reflectors of the unit onlap and downlap the lower boundary surface (7), which is an irregular erosional truncation that truncates the units beneath Unit G (Fig. 24). Unit G infills depressions from the underlying surfaces mentioned above, and has a thickness that varies from the Zinkwazi to Umdloti Barrier systems. This unit tends to be thicker along the Zinkwazi Barrier system reaching a maximum thickness of ~ 1 m.

Unit H

Unit H is characterised by moderately continuous, planar/even reflectors that are horizontal parallel to subparallel (Fig. 25). The upper and lower boundaries of this unit are both defined by concordant reflectors (surface 9 above and surface 8 below). This unit is only found in the Zinkwazi Barrier system where it is pervasive. Its thickness varies between 2 m along the southern and central sectors of the Zinkwazi Barrier (Fig. 25) and 0.5 m along the southern section of the Zinkwazi Barrier.

Unit I

Unit I comprises the uppermost unit of both the Zinkwazi and Umdloti Barrier systems. It consists of moderately continuous, sinuous to wavy reflectors that are subhorizontal and subparallel (Fig. 26). The upper boundary is formed by the contemporary barrier surface, against which the underlying reflectors toplap concordantly. The lower boundary is onlapped (Surface 9). Unit I displays wavy reflectors in coast parallel section, with a reflector free (Zinkwazi) to wavy (Umdloti) appearance in the coast perpendicular lines (Figs. 17-26).

Hyperbolic reflectors were observed along the parallel and perpendicular lines from both the barriers. These reflectors are either subparallel, strong and continuous (Figs. 19 and 21), or parabolic, convex down and continuous in nature (Figs. 17, 18, 21, 25 and 26).

Table 4. Stratigraphic framework of Zinkwazi and Umdloti barrier systems, describing the different radar units and surfaces.

Radar Unit	**Underlying Surface**	**Radar Expression**
Unit A1	Not recognised	Steeply inclined seaward dipping, subparallel and moderately continuous reflectors
	Surface 1	Undulating, steeply inclined reflector
Unit A2		Planar, horizontal, subparallel and moderately continuous landward dipping reflectors
	Surface 2	Undulating, laterally continuous reflector
Unit B		Sinuous, northward dipping, subparallel and continuous reflectors
	Surface 3	Erosional truncation, undulating reflector
Unit C		Planar, northward dipping, parallel and continuous reflectors
	Surface 4	Erosional truncation, undulating reflector
Unit D		Planar to wavy, seaward dipping, sinuous, oblique, chaotic and discontinuous reflectors
	Surface 5	Undulating, laterally continuous reflector
Unit E		Sinuous, southward dipping, subparallel and moderately continuous reflectors
	Surface 6	Erosional truncation, undulating reflector
Unit F		Curved concave down, oblique chaotic, landward dipping , discontinuous reflectors
	Surface 7	Erosional truncation, undulating reflector
Unit G		Planar to wavy, subparallel to oblique and moderately continuous reflectors
	Surface 8	Erosional truncation, undulating reflector
Unit H		Planar, horizontal subparallel and moderately continuous reflectors
	Surface 9	Erosional truncation, undulating reflector
Unit I		Sinuous, subhorizontal, subparallel and moderately continuous reflectors

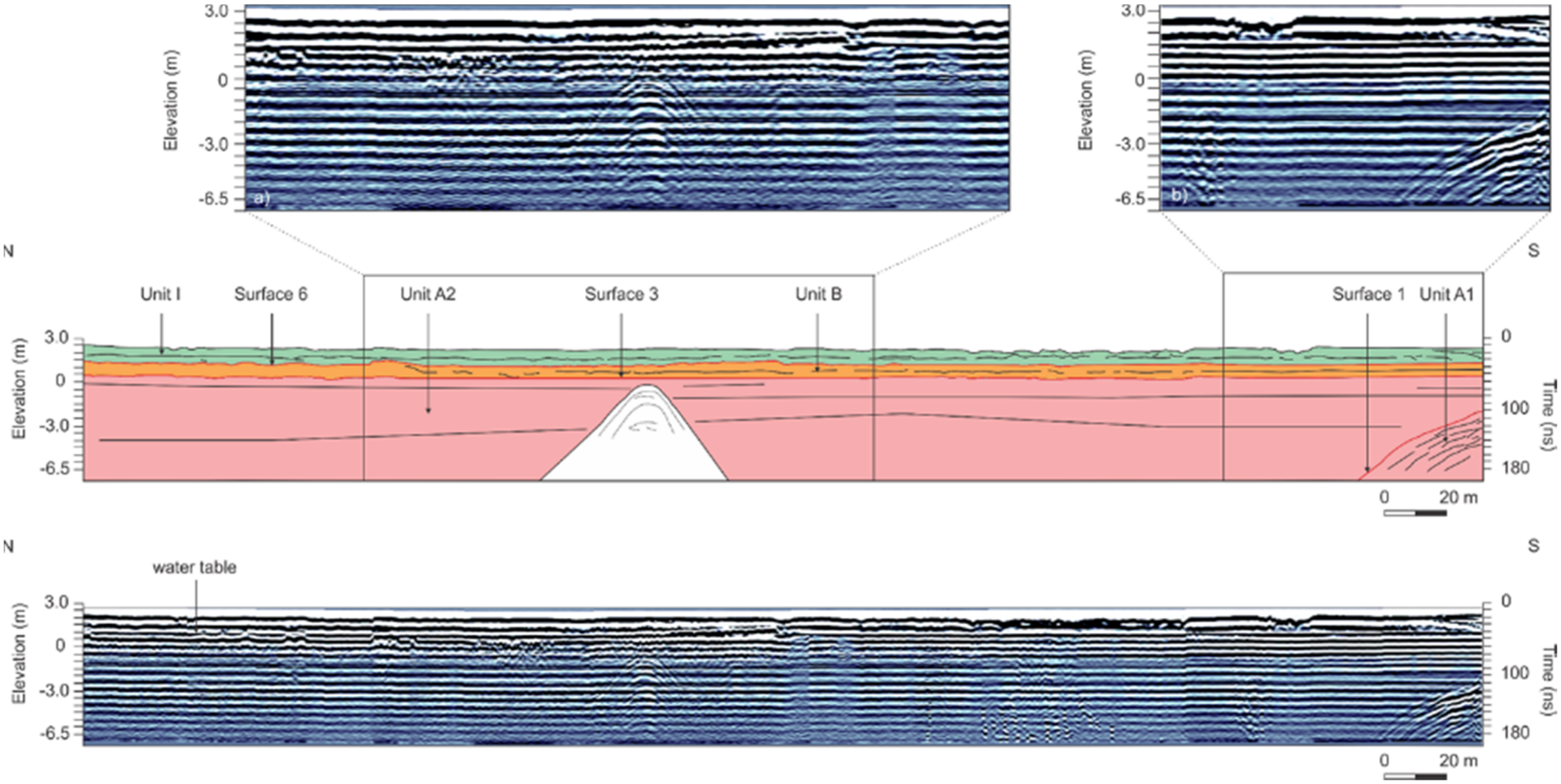


Figure 17. Shore-parallel high frequency 200 MHz GPR section from the Zinkwazi Barrier, line 47 (Fig. 14). Note the position of Unit A1 along the southern sector of the line, and the steeply inclined reflectors (not visible from the shore-normal lines). Figures 17a) and 17b) show enlarged sections of the raw data, emphasising the detail of Unit A1 and surface 1, as well as a prominent hyperbolic reflector toward the centre of the line marking surface 3.

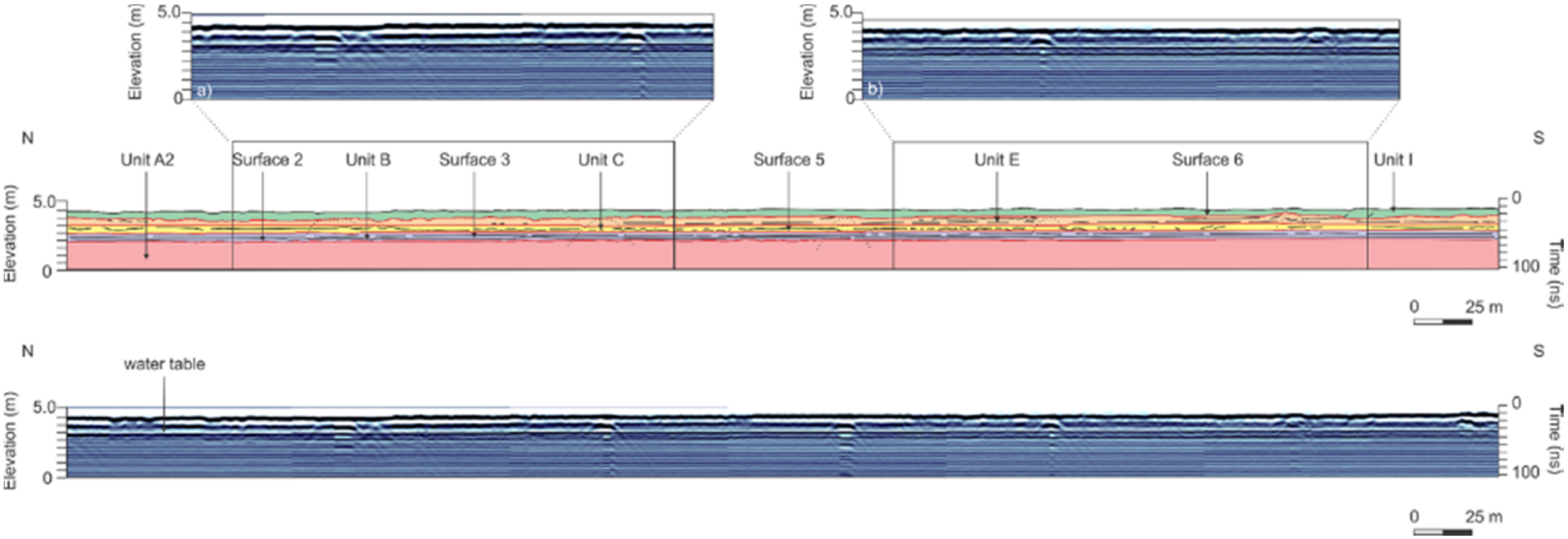


Figure 18. Shore-parallel high frequency 200 MHz GPR cross section from the Umdloti Barrier, line 67 (Fig. 14). The position and extent of Unit A2 can also be seen in this figure, along with its inherent reflector free property. Figures 18a) and 18b) show enlarged sections of the raw image, highlighting the small hyperbolic reflectors associated with surface 6.

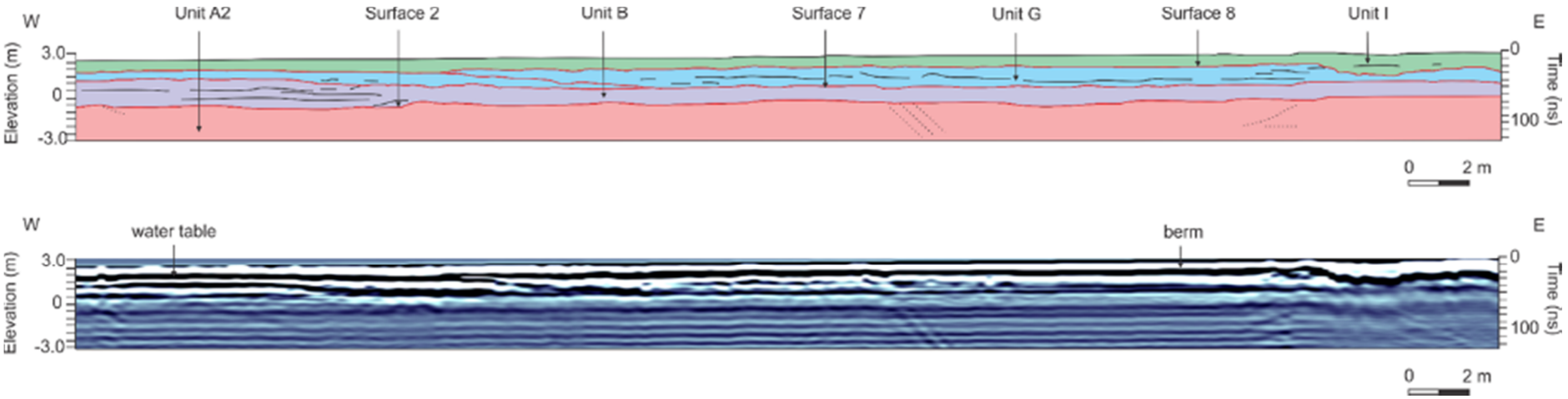


Figure 19. Shore-normal low frequency 100 MHz GPR cross section from southern most section of the Umdloti Barrier, line 45 (Fig. 14). The erosive nature of surface 8 is visible, along with the infilling of depressions associated with the underlying Unit G (Surface 7).

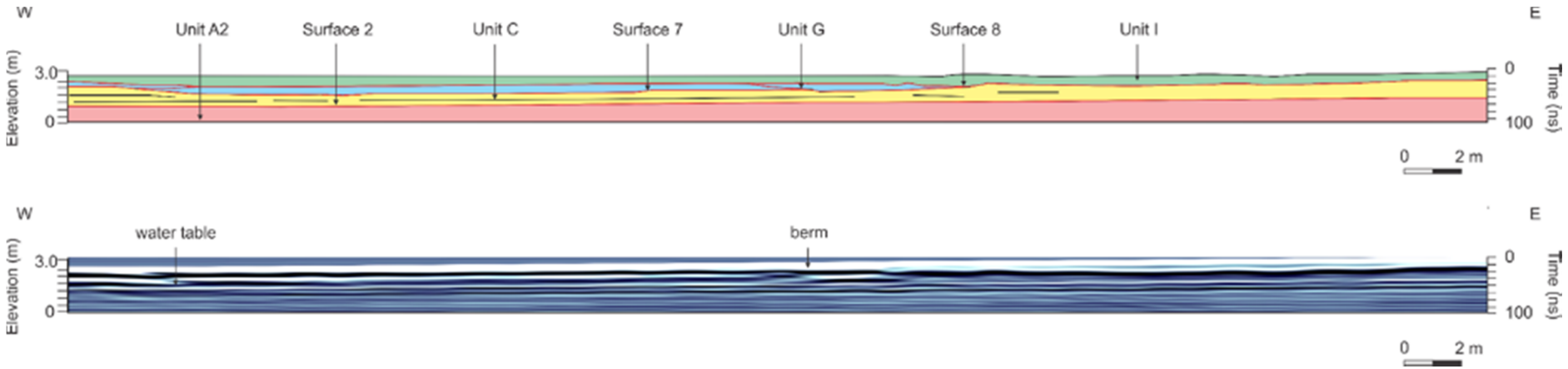


Figure 20. Shore-normal high frequency 200 MHz line, GPR cross section from the southern end of the Umdloti Barrier, line 69 (Fig. 14). Note the extent and position of Unit I, and the variability in thickness of Unit G.

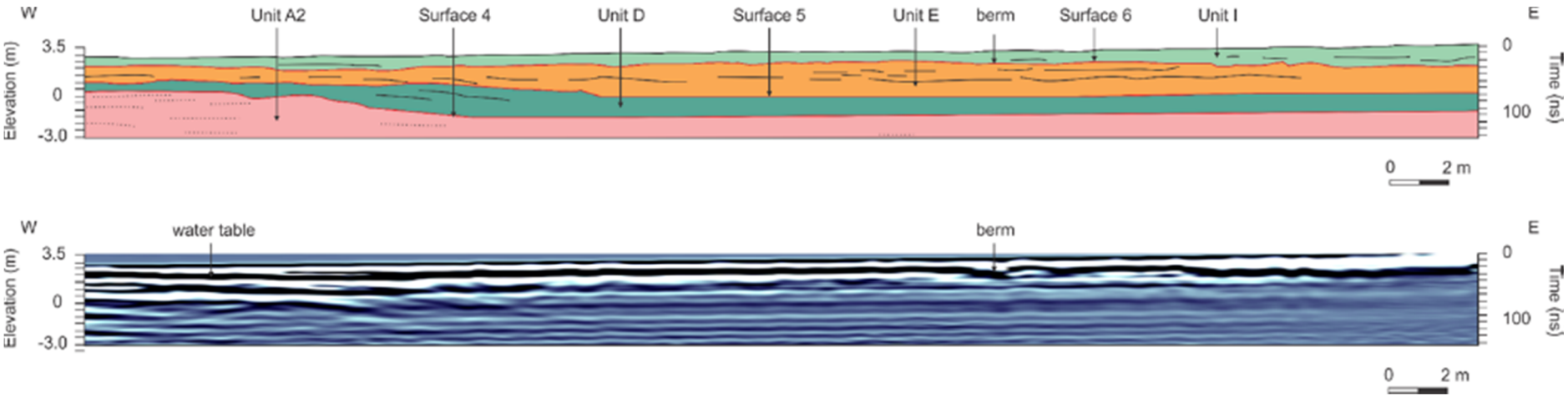


Figure 21. Shore-normal low frequency 100 MHz GPR cross section from the northern part of the Umdloti Barrier, line 41 (Fig. 14). Note the initial seaward thickening and eventual evening out of Units D and E respectively.

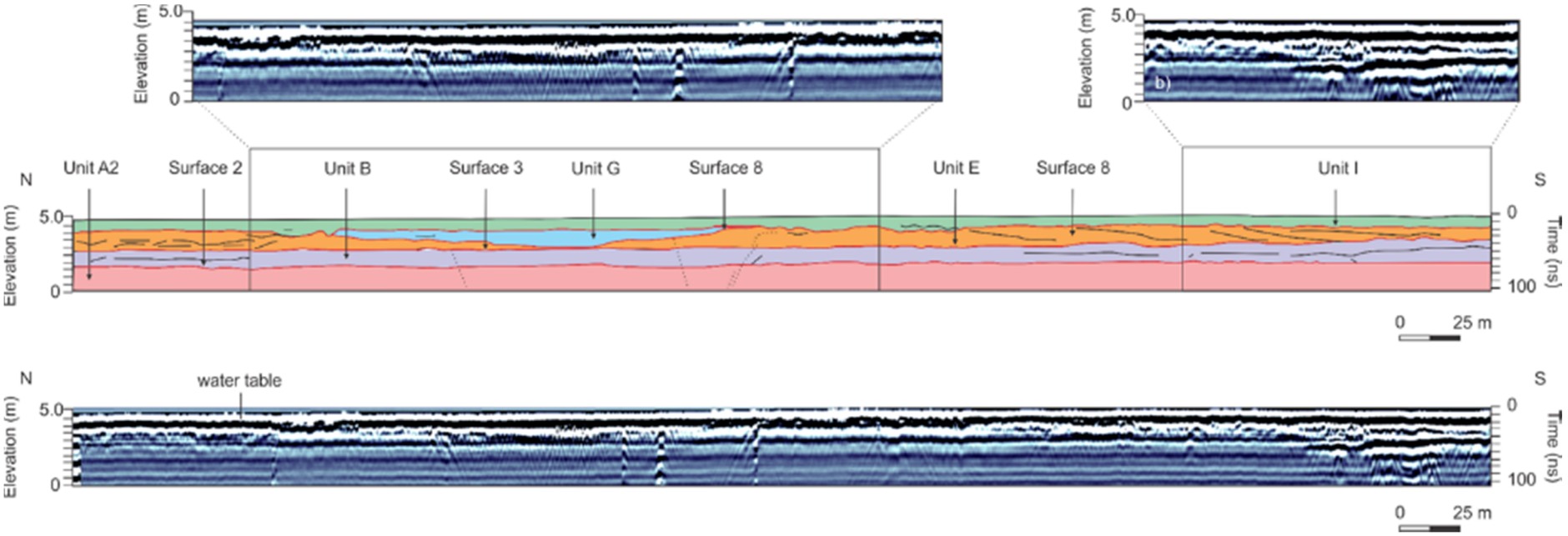


Figure 22. Shore-parallel low frequency 100 MHz GPR cross section from the Umdloti Barrier, line 46 (Fig. 14). Note the southerly dipping reflectors toward the southern section of the line (Unit E), and the extensive along strike continuity of Unit B. Figures 22a) and 22b) detail, such as the spikes in signal attenuation below surface 3, related to hard surfaces such as boulders or channel lag. Inset b highlights a shallow channel fill package (Unit G).

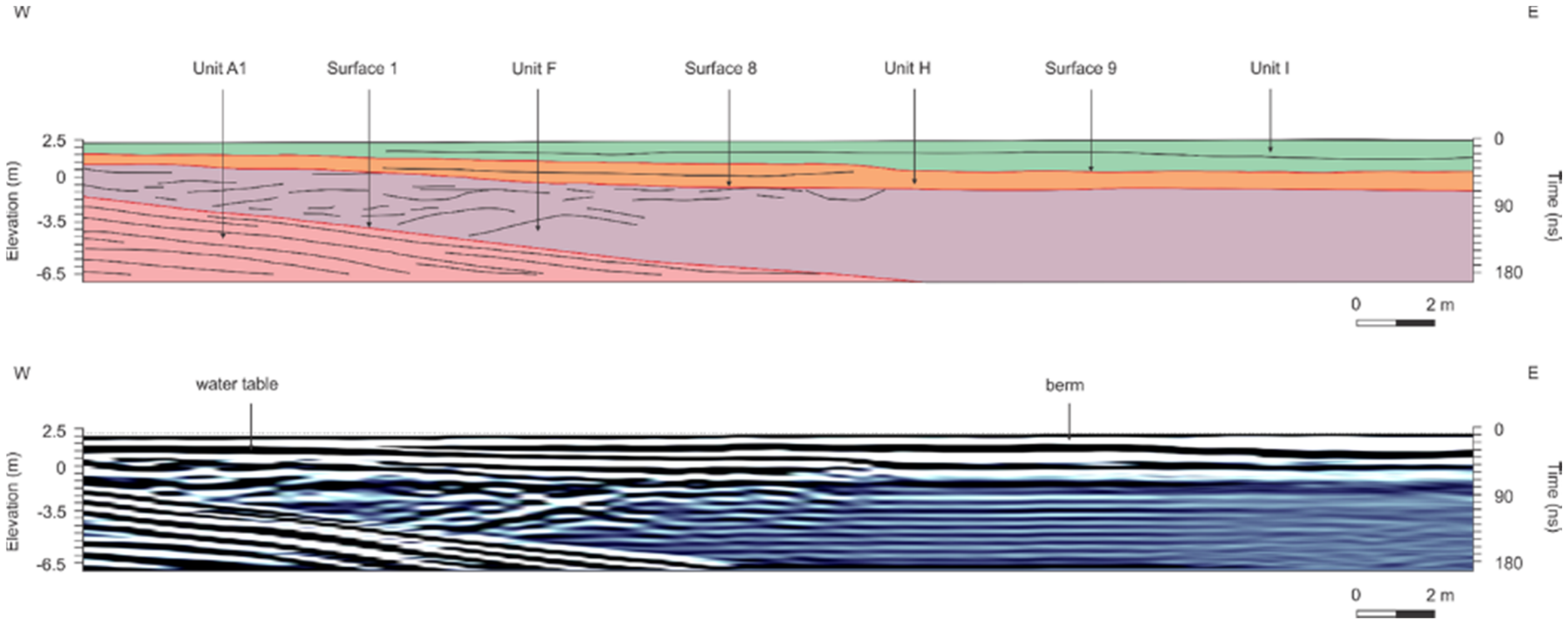


Figure 23. Shore-normal low frequency 100 MHz GPR cross section near the southern limit of the Zinkwazi Barrier, line 62 (Fig. 14). The chaotic nature of Unit F is highlighted here together with its landward dipping architecture.

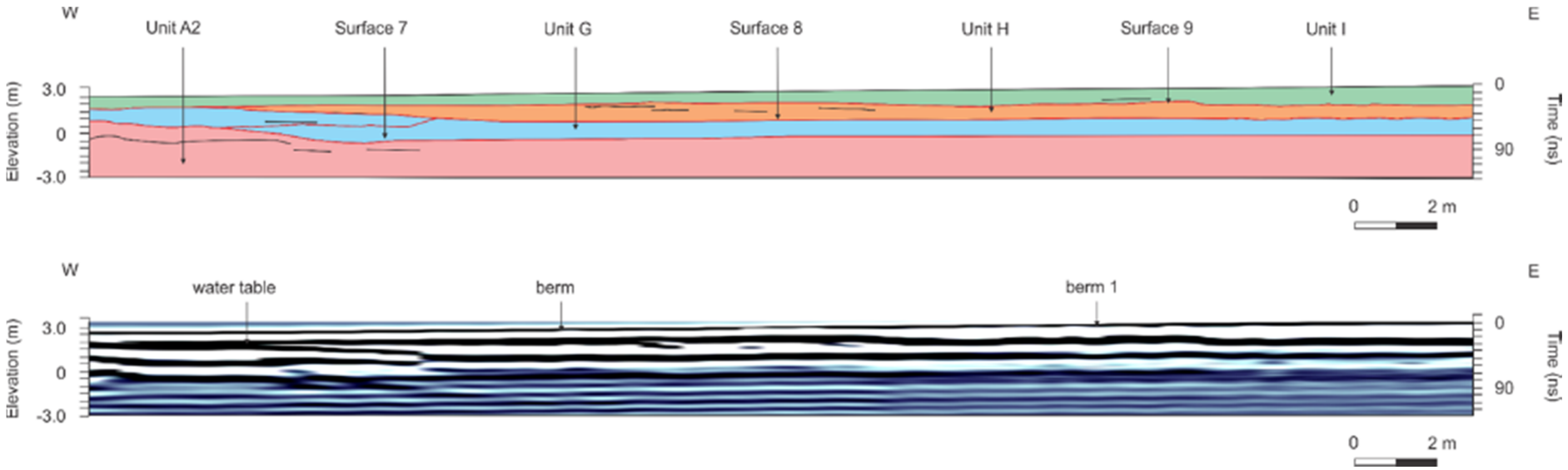


Figure 24. Shore-normal low frequency 100 MHz GPR cross section from the central parts of the Zinkwazi Barrier, line 64 (Fig. 14). Note, the extent of Unit H and its seaward thickening nature.

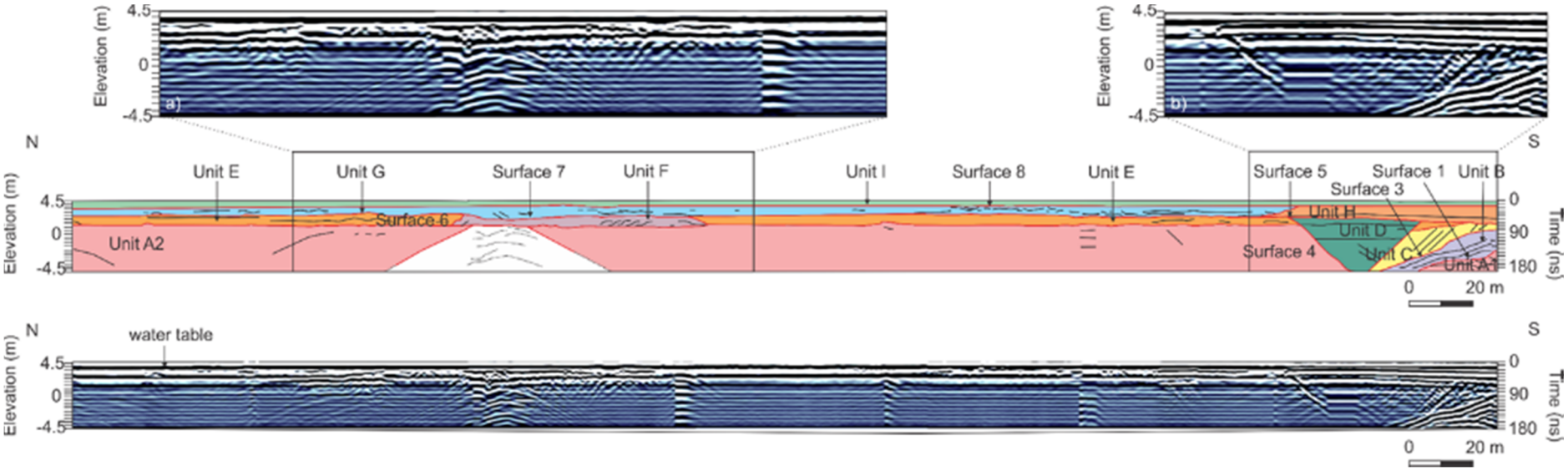


Figure 25. Shore-parallel low frequency 100 MHz GPR cross section from the Zinkwazi Barrier, line 60 (Fig. 14). Note the prominent channel-fill sequence toward the southern end of the barrier (not resolvable in the high frequency line, Fig. 18). Also note the northerly dipping, parallel reflectors of Unit C. Figures 25a) and 25b) show enlarged sections of the raw image, highlighting the detailed channel fill succession, and the prominent hyperbolic reflectors associated with Unit A1.

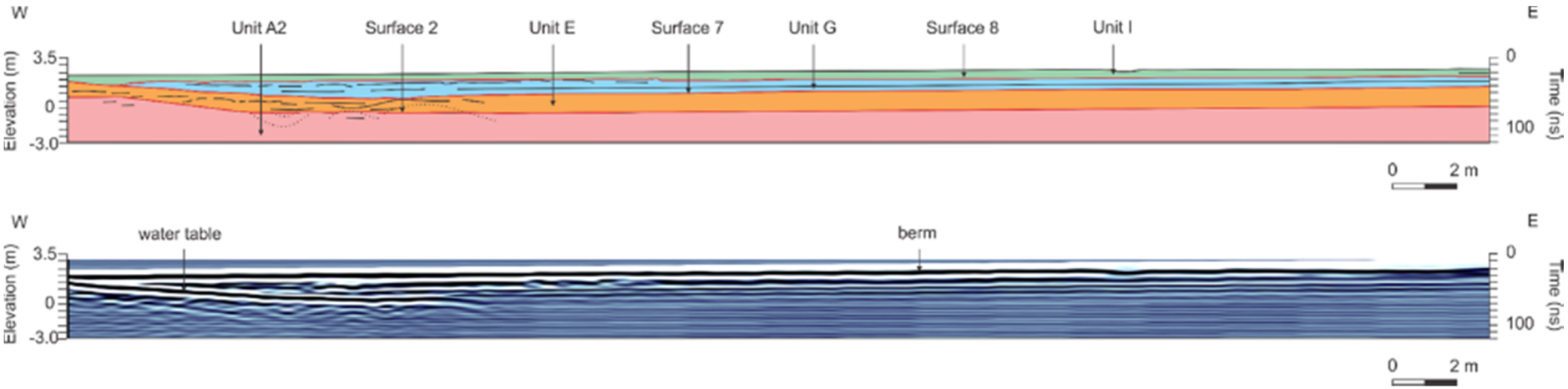


Figure 26. Shore-normal high frequency 200 MHz GPR cross section from the northern sector of the Zinkwazi Barrier, line 58 (Fig. 14). Note the multiple hyperbolic reflections associated with Unit A2 as well as the seaward thickening nature of Unit E.

5.2 Sedimentology and sedimentary architecture

The sections described below intersect the upper ~ 2 m of the GPR record from both the Zinkwazi and Umdloti Barriers. Six sections were examined in total and provide a record of all the uppermost radar units described in the previous section. These lithostratigraphic units are subdivided into six discrete sedimentary facies as outlined below (Fig. 28 and 29).

Facies 1

Facies 1 is composed of a moderately well-sorted, dark yellow, coarse to medium sand (mean: coarse sand) (Fig. 28). This forms the basal unit of all the sections from both study sites. Quartz and feldspar grains are dominant. Thin heavy mineral laminations are common (Fig. 27). Bioclastic (shelly) material in the form of shell fragments, as well as other biogenic fragments such as wood fragments, is very common (~ 20%) This facies is separated from the overlying facies by a sharp contact.



Figure 27. Heavy mineral layers from the seaward (east) to landward (west) side of the Zinkwazi Barrier. These layers are mainly associated with Facies 1.

Facies 2

Facies 2 consists of dark yellow, moderate to moderately well sorted coarse sand (mean: coarse sand) (Table 5). It is most common along the exposed sections of the Zinkwazi Barrier. It comprises quartzose and feldspathic sand, with a significant (~ 50%) heavy mineral component. Shell and wood fragments are common (~ 10%) (Fig. 29). Thickness varies (~ 65 cm to ~ 2 cm) due to an overlying erosional truncation.

Facies 3

Facies 3 comprises dark yellow, moderately well sorted very coarse sand (mean: very coarse) (Table 5) that is found overlying Facies 2 within the inlet scarps from both the Zinkwazi and Umdloti Barriers. Facies 3 is composed of quartz and feldspar grains ranging up to small pebble in size. There are abundant heavy minerals (~ 30%), interspersed with shell and wood fragments. It varies in thickness between study sites (~ 20 cm along the Umdloti; ~ 4 cm along the Zinkwazi), and is likewise erosionally truncated (Fig. 29).

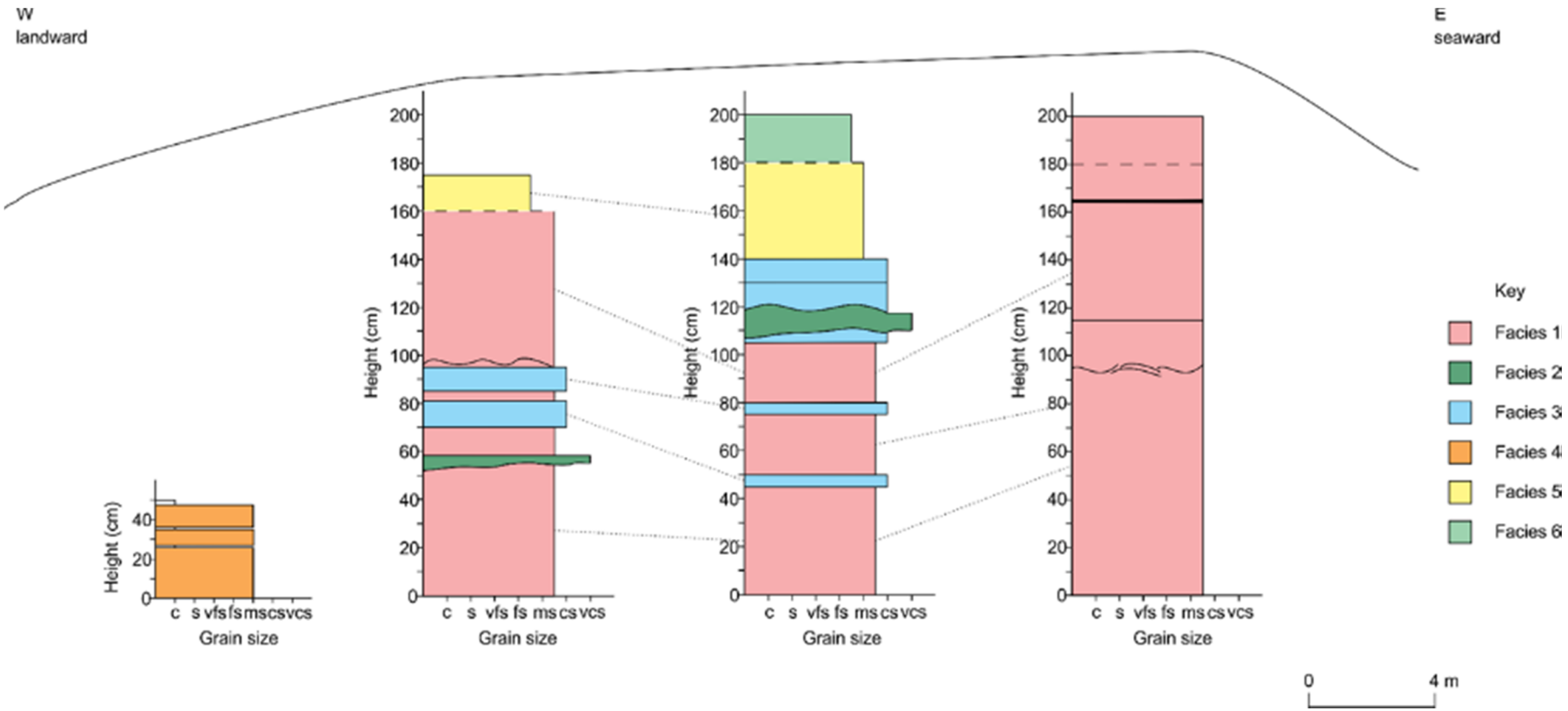


Figure 28. The internal sedimentary characteristics of the Zinkwazi Barrier derived from a series of measured sections. c (clay), s (silt), vfs (very fine sand), fs (fine sand), ms (medium sand), cs (coarse sand), vcs (very coarse sand). Facies 1 is volumetrically dominant and occurs mostly toward the seaward side of the barrier, whereas Facies 2 and 3 erosionally truncate the lower layers, and are more prevalent in the core of the barrier. Facies 4 is restricted to the landward most side of the barrier, with Facies 5 and 6 restricted mostly to the core of the barrier.

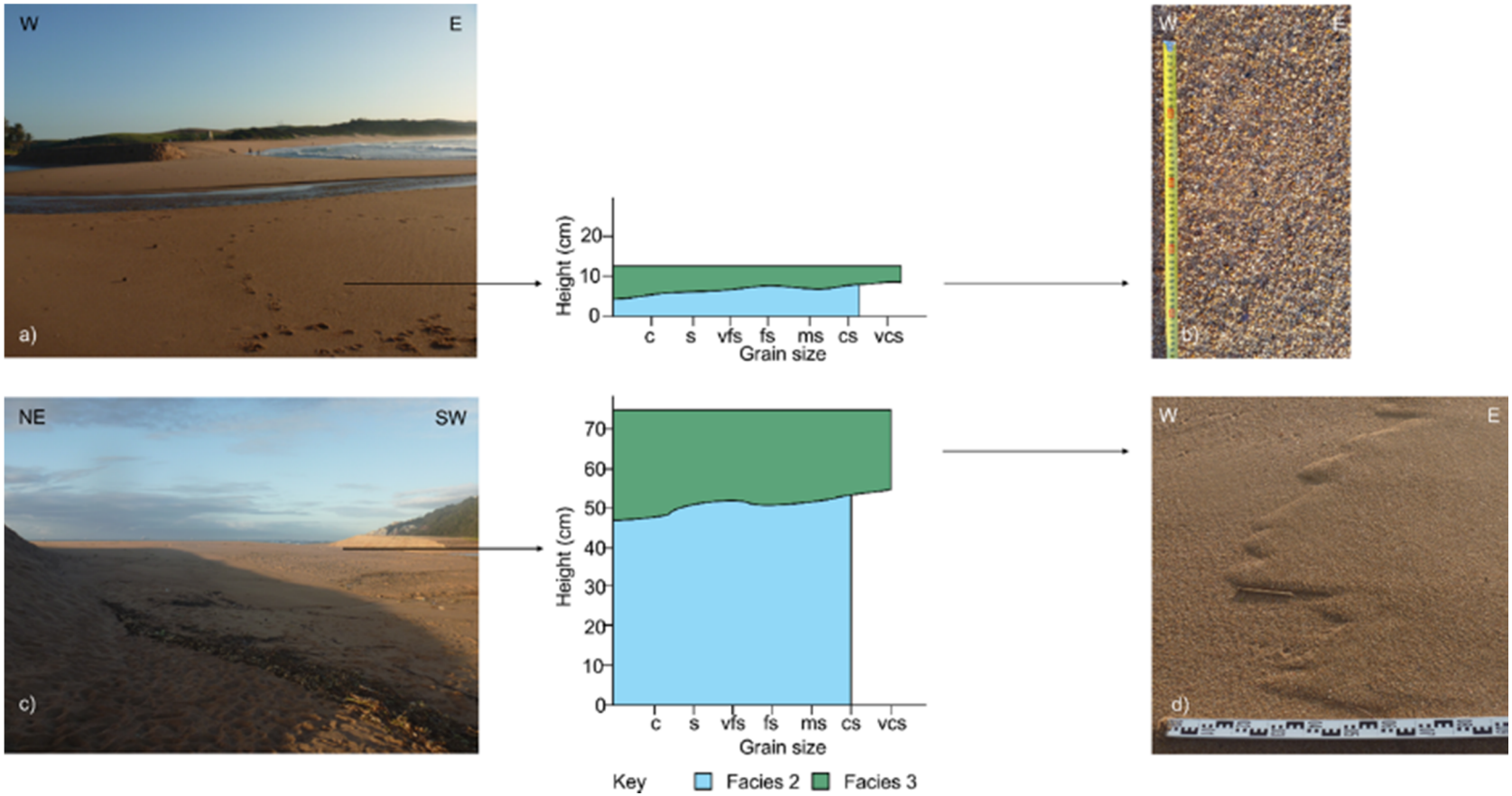


Figure 29. a) The Zinkwazi Barrier and location of measured section. Only ~ 20 cm of stratigraphy was visible. b) Enlarged image of Facies 3, which comprises very coarse sediment, shell and wood fragments, c (clay), s (silt), vfs (very fine sand), fs (fine sand), ms (medium sand), cs (coarse sand), vcs (very coarse sand). c) Umdloti Barrier with the location of the inlet where a measured section was taken. d) Enlarged image of Facies 3 showing the direction of washover from east to west of the Umdloti breach.

Facies 4

Facies 4 contains dark brown moderately well sorted, medium sand with small amounts of mud. It occurs in the most landward portions of the Zinkwazi and Umdloti Barriers near the lagoon (Fig. 30). Like the other facies, it is dominantly siliclastic, with a high percentage of bioclastic (shelly) material (~ 20%). It can be discriminated from the other facies due to its increased organic (plant debris), muddy content. This facies reaches a maximum thickness of ~ 2.5 cm in this area, and is separated from the underlying and overlying facies by a sharp contact (Fig. 28).

Facies 5

Facies 5 comprises dark yellow, moderately well sorted medium grained shelly sand (mean: medium) (Table 5). It is best preserved in the middle and landward edges of the Zinkwazi Barrier, and in the landward section of the Umdloti Barrier. Heavy minerals are not as common as the other facies (~ 10%).



Figure 30. a) Northern and southern washover lobes from the Umdloti barrier, which correlate to Facies 4. View to the southwest b) Enlarged image of the northernmost washover fan on the lagoonal side of the barrier. View to southwest c) Enlarged image of the washover fan from the southernmost side of the Umdloti barrier, highlighting the surface ripples. View to the northwest d) Enlarged image of the mud drapes found on the southernmost washover fan of the Umdloti barrier. View to the northwest.

Facies 6

Facies 6 is composed of a very dark yellow, medium to fine grained (mean: medium), moderately well sorted, shelly sand (Table 5). This facies has a moderately higher heavy mineral content than the other facies (~ 20%) (Fig. 28) and overlies the below facies gradationally.

5.3 Sedimentary architecture

The internal architecture of the Umdloti Barrier consists mainly of planar beds that dip either landwards or seawards. Facies 4, 5 and 6 are volumetrically dominant and comprise a series of low-angle (10°) landward-dipping beds. Each of these erosionally truncate the underlying units (as evidenced by the erosional surfaces found in each measured section) (Fig. 31a). These are erosionally truncated by Facies 1, which dip seawards at a much steeper angle (45°). Facies 2 and 3 are also associated with landward dipping planar beds.

The internal architecture of the Zinkwazi Barrier is mainly composed of homogenous layers, with gradational boundaries between the beds. Facies 1, 2, and 3 are the most dominant covering the largest portion of the barrier, with Facies 4, 5, and 6 found toward the central and most landward sectors of the barrier (Fig. 31b), dipping landward, with a shallow angle of approximately 10°. Facies 1, in the seaward section of the barrier dips at a steeper angle of approximately 40°.

Table 5. Sedimentological characteristics of the Zinkwazi and Umdloti Barrier systems. The mean, sorting, and facies relations for sediment samples are provided.

Sample	**Facies**	**Mean**	**Sorting**
Zinkwazi coarse to medium sand	Facies 1	Coarse sand	Moderately well sorted
Zinkwazi coarse sand	Facies 2	Coarse sand	Moderately well sorted
Umdloti washover lobe (south)	Facies 4	Coarse sand	Well sorted
Umdloti washover lobe (north)	Facies 4	Coarse sand	Moderately well sorted
Zinkwazi inlet	Facies 2	Coarse sand	Moderately sorted
Umdloti inlet	Facies 3	Very coarse sand	Moderately well sorted
Zinkwazi medium sand	Facies 5	Medium Sand	Moderately well sorted
Zinkwazi medium to fine sand	Facies 6	Medium Sand	Moderately well sorted

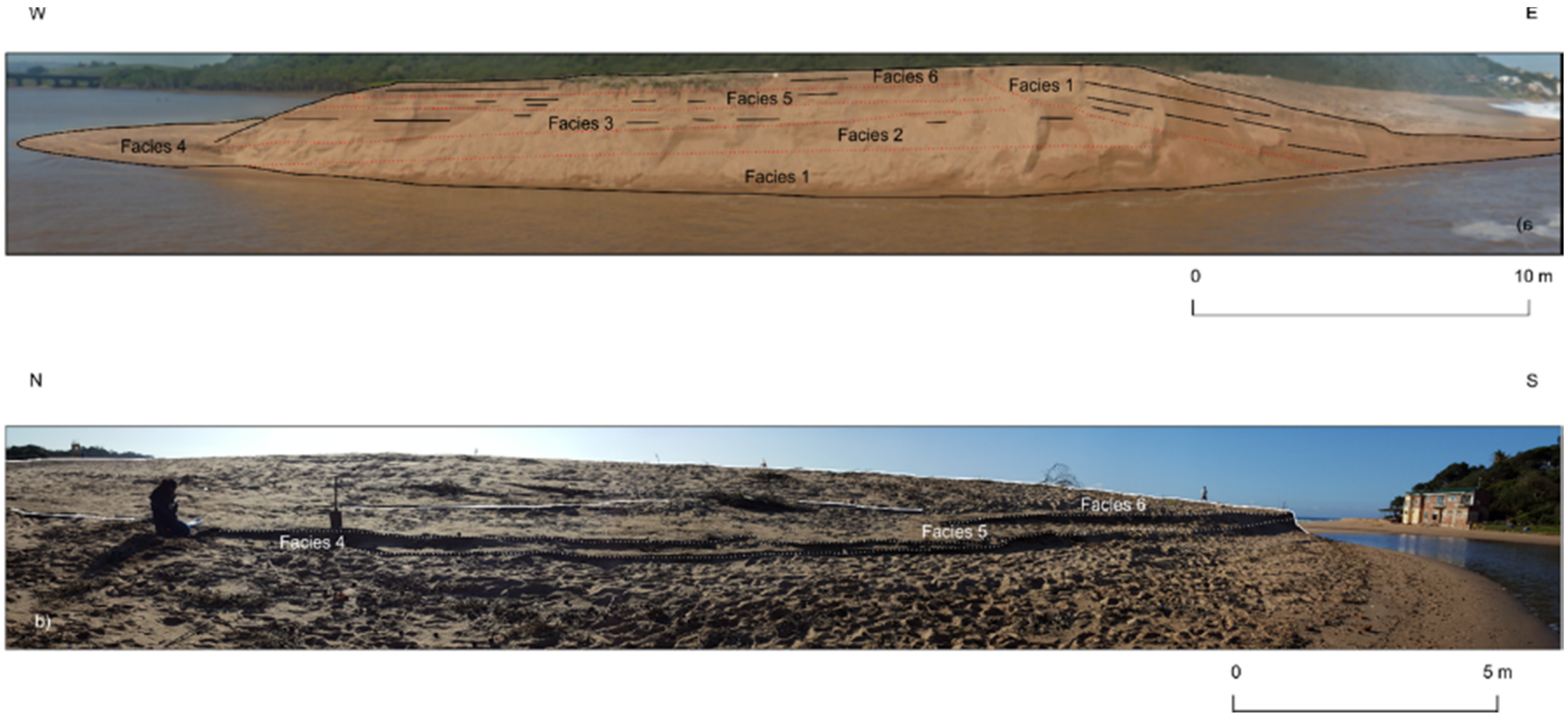


Figure 31. a) Internal architecture of the Umdloti Barrier along with the facies positions and boundaries between them. View to the south. Facies 1 dips steeply seaward, with Facies 4, 5 and 6 dipping shallowly landward. Facies 2 and 3 erosionally truncate the lower facies. b) Internal architecture of the Zinkwazi Barrier detailing the boundaries of Facies 4, 5, and 6, which all dip gently landward. View to the east.

Based on the above descriptions the facies associations can be correlated to the GPR units that were described previously. Facies 1, composed of moderately well-sorted, coarse sand, correlates to the planar, horizontal, subparallel and moderately continuous reflectors of Unit A2. Facies 2 and 3 which comprise moderately well-sorted very coarse sand, can be associated with units D and G, which are described as planar to wavy, sinuous, subparallel to oblique, chaotic, moderately continuous to discontinuous reflector units.

Facies 4, comprising coarse well-sorted sand, is the up-dip extension of Units E, H and I, and can be found along the lagoon-ward side of the Zinkwazi and Umdloti Barriers. Unit E comprises sinuous, subparallel, moderately continuous reflectors. Units H and I comprise a series of planar, horizontal subparallel and moderately continuous reflectors.

Facies 5 consists of moderately well sorted medium sand, and is linked to the sinuous/wavy and sub-parallel reflectors of Unit B and C. Facies 6 is a planar stratified medium sand layer that is linked to Unit E in both the Umdloti and Zinkwazi Barriers, Unit H in the Zinkwazi, and Unit I, in the Umdloti Barriers.

5.4 Mesoscale barrier morphodynamics

The short-term sub-mesoscale evolution of both barrier systems is depicted in Figures 32, 33, 34, and 35. Changes span a fourteen-year period from 2002 to 2016 for the Umdloti system, and a six-year period from 2010 to 2016 for the Zinkwazi system. Both these estuaries are single channel dominated systems that are separated from the ocean by the sandy barrier examined in the preceding section.

The Umdloti Barrier is characterised by an elongate, relatively narrow barrier (~ 70 m wide), with a well-defined inlet position to the north when breached. Major episodes of inlet breaching are evident from 2002, 2009, 2012 and 2015 (Fig. 32a, c, and e) (Fig. 33j). The breaches are focussed toward the northern portions of the barrier, with overwash deposits located on the landward side of the barrier (Fig. 32). The inlet sites are always located where the barrier is narrowest during times when the barrier is sealed (Fig. 32b and d) (Fig. 33k, m, n, o, and p). These breaching events occur biannually, mainly during the summer months of the year, as indicated by the Google Earth images.

In the intervening periods where the system is closed (2009, 2013 and 2014, Fig. 32a, b, d) the barrier retains its elongate, narrow morphology. However, in several years, the barrier bifurcates, with a thin landward section separated from the main barrier by a small subtidal depression (Fig. 32f, g, and h) (Fig. 32l). Notably, the bifurcation point is not related to the

areas where the system breaches. In the southernmost portions of the system, the barrier has been stabilised by vegetated embryonic dunes since at least 2002 (Fig. 32a).

The Umdloti Barrier has undergone several changes in width over time. It was narrowest in June 2007 (40 m, with a net change in width of ~ 80 m since April 2002). In March 2011, the barrier reached its widest point of approximately 100 m. Clear episodes of washover occurred in 2002, 2009, 2011, and 2012 (Fig. 32a, and d) (Fig. 33l, and m), resulting in the barrier prograding on average ~ 35 m into the lagoon.

During the 2002 barrier breach (Fig. 32a) an inlet toward the northern section of the barrier was formed as usual. This was associated with large washover deposits found to the south of the inlet, these washover deposits were still visible 3 weeks after the breach began to form, and they are restricted to the area south of the breach. In 2007, washover deposits can be identified along the barrier, related to inlet closure and major sediment influx into the lagoon during the March 2007 swell event (Table 3), with the barrier shifting approximately 45 m into the estuary during this event (Fig. 32b). In 2011, when the barrier was closed, smaller washover fans were identified on the lagoon ward side of the barrier. In 2015, following the inlet breaching event in August the inlet was closed as a result of washover deposits entering the lagoon and closing the inlet.

The Zinkwazi Barrier is a similarly narrow feature with a width of approximately 60 m. The barrier is constrained to the north by vegetated dunes and to the south by bedrock outcrops (Figs. 34 and 35). The barrier has an arcuate shape, and is typically closed, with breaching periods common.

Based on the available records, the barrier has breached twice over the recorded six-year period (2010 to 2016) once, in August 2011 and again in February 2013. The biggest breach recorded occurred in February 2013, where the inlet attained a width of ~ 52 m. The second breach (August 2011), was smaller by comparison, with a width of approximately 15 m.

From the satellite imagery, the preferential breaching of the Zinkwazi Estuary occurs toward the southern end of the estuary, inferred from the aerial imagery (Figs. 34 and 35). Since the 2013 breach, the barrier system has migrated further landward. The Zinkwazi Barrier was its narrowest (~ 40 m) in February 2015, with much of the bedrock outcrop situated further south of the estuary exposed (Fig. 35).

The images also show changes in the morphology of the barrier over time as a result of sedimentation along the barrier. This has resulted in a wider and longer barrier from the vegetated dunes in the northern sector to the bedrock outcrop toward the southern section (Fig.

34). The barrier was its widest in January 2010 (Fig. 34) with a recorded width of ~ 90 m. The bedrock outcrop is usually exposed and not covered by sediment during the summer months of the year, when breaching is also most likely to occur, as the barrier is at its narrowest.

Major episodes of washover evident from the 2010, 2011, 2012, and 2014 images in 2010 and 2011 a separate ~ 25 m wide sand body was found in the estuary, as a result of overwash. The washover fans during these years extended approximately 25 m into the back barrier environment (Fig. 34). In 2012 washover fans were found further south, closer to the typical inlet position, with the fan extending ~ 20 m into the back barrier environment. In 2014 washover fans were also found in a similar position to the fans identified in 2012, these were however much smaller and extended ~ 10 m into the back barrier area. The Zinkwazi Barrier is stabilised further north by the vegetated dune complex, with breaching and washover in this unlikely area (Fig. 35).



Figure 32. Satellite imagery spanning 2002 to 2014 (a - g) outlining morphological changes to the Umdloti Barrier system. a) (WO) washover and (OI) open inlet in 2002. b) (CB) closed barrier and WO in 2007 c) (SD) subtidal depression in 2009. d) (CB) and WO in 2011 e) OI in 2012 f) SD in July 2013 g) SD in August 2013 h) SD in 2014. The red and blue lines show the landward barrier shoreline position at its widest in March 2011, and narrowest in June 2007 respectively.

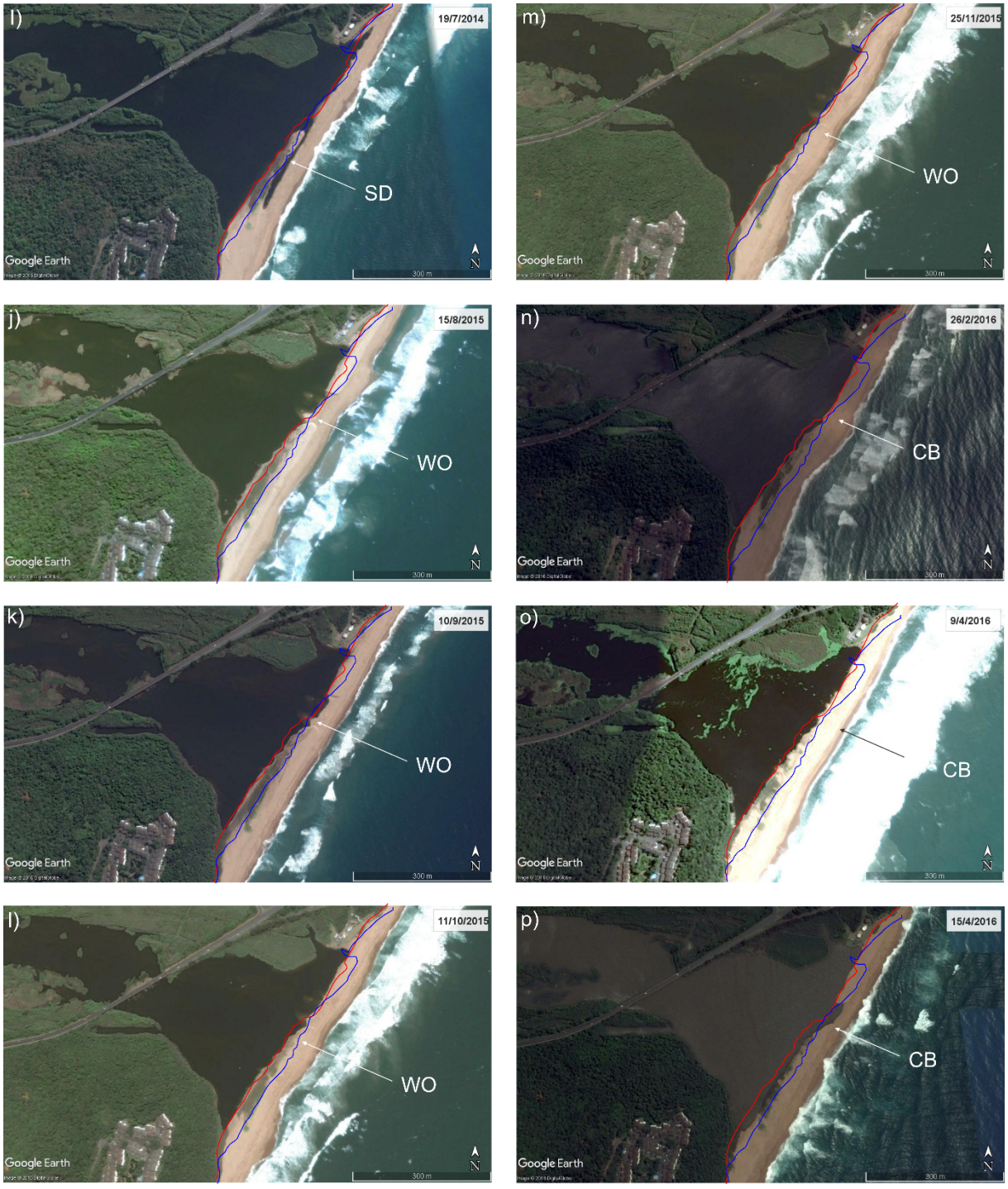


Figure 33. Satellite imagery spanning 2014 to 2016 (i - p) outlining morphological changes to the Umdloti Barrier system. i) SD in 2014 j) WO in August 2015 k) WO in September 2015 l) WO in October 2015 m) WO in November 2015 n) CB in February 2016 o) CB in April 2016 p) CB in April 2016. The red and blue lines show the landward barrier shoreline position at its widest in March 2011, and narrowest in June 2007 respectively.

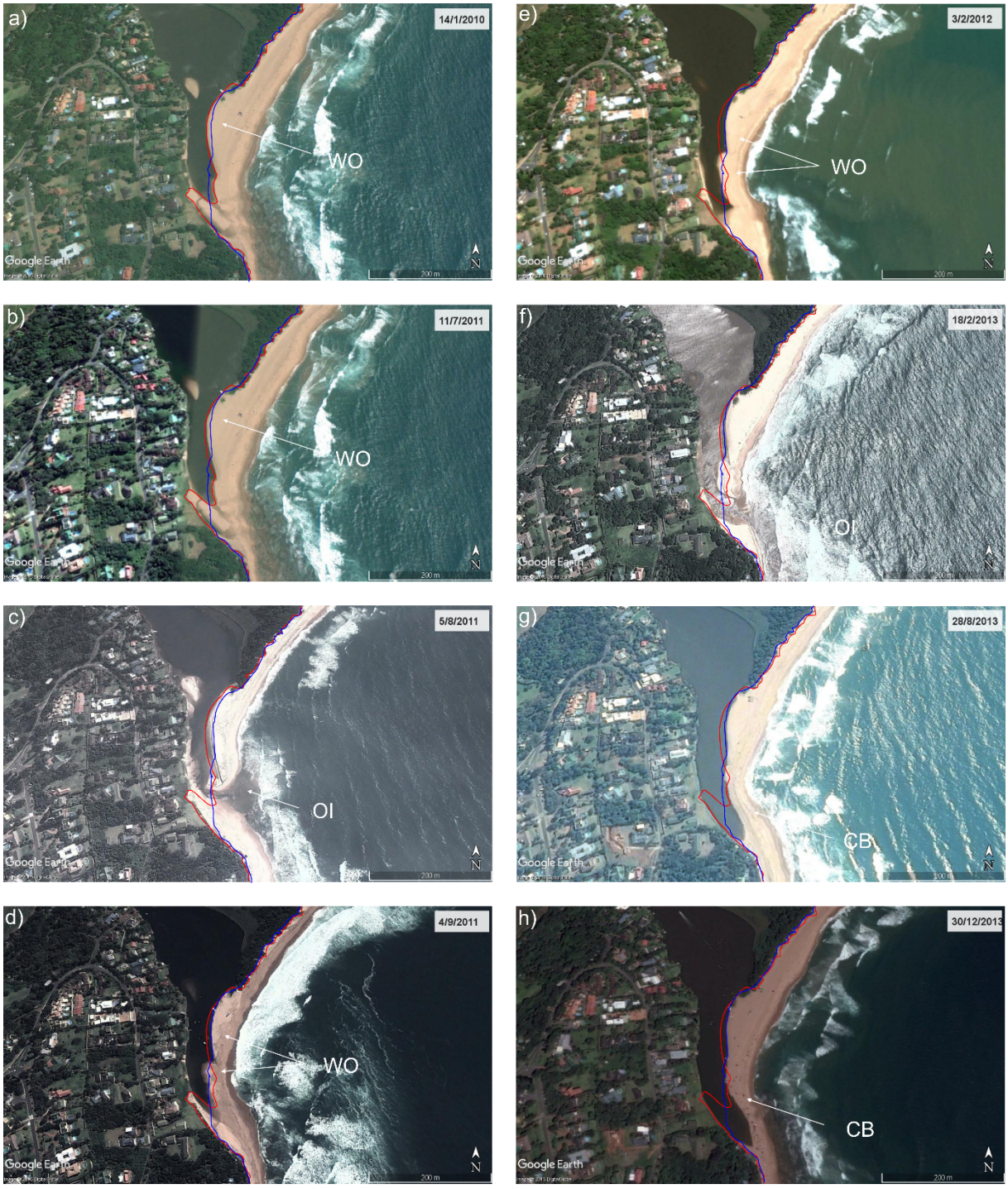


Figure 34. Satellite imagery spanning 2010 to 2013 (a - h) detailing morphological changes to the Zinkwazi Barrier system. a) WO in 2010 b) WO in July 2011 c) WO August in 2011 d) WO in September 2011 e) WO in 2012 f) OI in 2013 g) CB in August 2013 h) CB in December 2013. The red and blue lines show the landward barrier shoreline position at its widest in January 2010, and narrowest in February 2015 respectively.



Figure 35. Google Earth images spanning 2013 to 2016 (i - p) from the Zinkwazi Barrier system. i) CB in February 2014 j) WO in March 2014 k) WO in July 2014 l) CB in January 2015 m) CB in February 2015 n) CB in April 2015 o) CB in May 2015 p) CB in 2016. The red and blue lines show the landward barrier shoreline position at its widest in January 2010, and narrowest in February 2015 respectively.

6 Discussion

6.1 Interpretation of GPR units

Unit A is divided into subunits A1 and A2. Unit A1 is the lowermost and therefore oldest unit identified along the Zinkwazi Barrier. The surface links to the cropping out of bedrock to the south of the Zinkwazi Barrier, in which an incision is apparent in surface 1. This coincides with the position of the contemporary forming inlet where the Zinkwazi Barrier most commonly breaches (Bond et al., 2013). The unit and truncating surface 1 are interpreted as the southern margin of the Zinkwazi River's incised valley in which the Holocene estuarine infill and associated barrier form the transgressive infilling package (e.g., Cooper, 1991). Hein et al. (2012) describe the barriers along the New England coast as bedrock-dominated systems, with tidal inlets situated in drowned river valleys.

Unit A2 is the lowermost unit of the barrier systems studied. This unit formed as the barrier was built, its gently landward dipping, continuous reflectors are comparable to Facies 1. This facies is volumetrically dominant in both barriers, it dips steeply seaward toward the eastern section of both barriers, and gently landward toward the central sections of both barriers (Figs. 27 and 31). This facies is marked by sharp/erosional boundaries that separate the medium to coarse sand from the coarse to very coarse marine sand packages (Fig. 27). On the basis of the architecture and grain size, we consider these to be formed as a thick plug of washover sheets (e.g., Shan et al., 2015).

In coast-parallel orientation, Unit B consists of high amplitude, discontinuous, sinuous wavy reflectors with a convex or concave geometry. In coast perpendicular section, they dip landward. This unit corresponds to Facies 5, medium sand packages with gradational contacts orientated landward. These are interpreted as washover packages (e.g., Shan et al., 2015; Costas et al., 2006b), similar to the underlying units, but not as energetic as evidenced by the finer grain size and gradational contacts.

Unit C appears to be an accretionary deposit that shows vertical or lateral accretion of a barrier (Shukla et al., 2008; Seminack and Buynevich, 2013). According to Shan et al. (2015), and Costas et al. (2006b), both vertical and lateral accretion could be associated with washover. This appears to be case from the southern portion of the Zinkwazi Barrier. In the Umdloti system, this unit is considerably more planar. According to Bennett et al. (2009) and Pascucci et al. (2009), such reflector geometries can also be associated with washover events where there is a barrier-wide inundation. This is not in keeping with the contemporary morphodynamics, where washovers are restricted to localised depocentres (e.g., Fig. 33k; 34e). These reflectors could

also be formed by the aggradation of sand spits parallel to the direction of longshore transport in the region (Daly et al., 2002) or mark a change from washover aggradation to aeolian spit development (Daly et al., 2002; Seminack and Buynevich, 2013). Based on the grain sizes of the correlative Facies 5, it may appear that this is a transitional aeolian facies, marking an interval between washover periods (see section 5.4 Mesoscale Barrier Morphodynamics).

Based on its onlapping nature to surface 4, together with the incision-like morphology of the housing depression, Unit D can be considered a palaeo-inlet fill, and is comparable to Facies 2 and 3, which are interpreted as inlet fill sequences. The heavy minerals of Facies 2 and 3 are likely associated with deposition during the waning stages of intense storms (Buynevich et al., 2004). According to Hein et al. (2012), the presence of an inlet-fill sequence along the Zinkwazi Barrier implies that the tidal prism in this system was once larger than at present. The depth and width of the surface 4 incision is in keeping with contemporary inlet dimensions of the microtidal estuaries of KwaZulu-Natal (c.f., Cooper, 2001a). Similar examples are documented by FitzGerald et al. (2001) from Duxbury Beach, Massachusetts.

In the Zinkwazi Barrier system surface 4 is found near the southern sector of the barrier in the usual location where inlets form (Bond et al., 2013) (Figs. 32-35). In the Umdloti system, Unit D is only visualised in coast perpendicular sections (e.g., Fig. 21). These are located where the inlet formed traditionally (Fig. 32e) (Garden and Garland, 2005) and marks the fill of these inlets. No associated incision is evident from the coast parallel lines. FitzGerald et al. (2001) consider similar radar facies as complex channel fills that formed after breaching when the barrier began to recover through lateral accretion as a result of the interaction between cross-shore and longshore currents (e.g., Costas et al., 2006a). This appears to be limited to only one case in the Zinkwazi Barrier.

Hein et al., (2012) discuss the evolution of Plum Island via spit progradation and migration. In their study, the inlets are characterised by spit accretion and migration of the inlet, along with onshore migration of bars and their eventual welding to the beach system of the spit. In contrast, the palaeo-inlets of the Zinkwazi and Umdloti Barriers are not as well-defined. There is clearly little to no evidence from either satellite imagery, nor from the GPR (laterally accreting reflectors) of numerous migrating inlet-fill sequences. The inlets along the Zinkwazi and Umdloti Barriers are merely ephemeral features that are controlled primarily by washover events and opening during storm periods. Stratigraphically, there is little overlap between the migrating and non-migrating inlet systems.

Unit E comprises reflectors that toplap the overlying surface. Such a geometry is considered to be indicative of washover deposits (Daly et al., 2002). Unit E occurs in association with Units H

and I, both units have similar internal geometries to E. These are all reconciled with Facies 6, a series of landward dipping medium sands with shell debris. These merge up-dip with the contemporary washover fans in the back-barrier (Facies 4), marked by mixed organic-rich sand and shell debris/quartz clasts. This implies that sediment progrades inland via washover, and results in the aggradation of the barrier (Buynevich et al., 2004). This is confirmed in the morphodynamic behaviour of the system (Figs. 32-35) which shows contemporary deposition of washover fans in both the Zinkwazi and Umdloti Barrier systems. These units extend throughout the down-dip extent of the barriers.

Unit F is chaotic in nature and comprises concave upward and curved convex reflectors. These may represent the internal stratification found within washover channels that truncate against the erosional base of the channel (Shan et al., 2015). According to Daly et al. (2002), Bristow and Pucillo, (2006), and Bennett et al. (2009), both the tangential oblique and sigmoidal oblique reflectors are associated with progradational landforms, with the tangential oblique reflectors being interpreted as accretionary bedding of beachface sediments that consist of bars, beach sand and berms or dune sands (van Heteren, 1998). The sigmoidal oblique reflectors are interpreted as spit-platform sands and gravels. The more complex these reflectors become, the more they are associated with the migration of offshore bars (da Rocha et al., 2013). These chaotic reflectors are also indicative of deposition of coarser sediment in a high-energy environment (Barboza et al., 2009, van Heteren et al., 1998). The interpretation of the beachface welding to the incised valley during transgression is favoured here, probably during a sea-level highstand (c.f., Ramsay and Cooper, 2002). The unique preservation of this unit is favoured by the antecedent conditions imparted by the headland and rocky palaeo-valley. This unit is located only in the lee of the rocky headland (onlapping the bedrock basement of the incised valley) where preferential shelter from subsequent wave erosion and scarping of the barrier was afforded.

Unit G fills in depressions found along the underlying surface 7, and has a thickness that varies from an average of 0.5 m in the Zinkwazi Barrier system to an average of 1 m in the Umdloti Barrier system. The incisions in surface 7 are of comparable scale to the channels cut by washover events (Hine, 1979; FitzGerald et al., 2001). FitzGerald et al. (2001) suggest that reflectors, like those of Unit G, conform to horizontal channel fill when sediment is transported into the channel from a seaward source, and form an aggradational channel fill facies (Seminack and Buynevich, 2013). This material marks the channelisation of washover into the back-barrier, and correlates to Facies 2 and 3.

The variation in unit thickness between systems is important; where it is thicker, the preservation potential of the deposit is likely higher (e.g., in the Umdloti system). The sheltering at Zinkwazi precludes the system from developing larger washover lobes and channels under fairweather conditions. In comparison, in Umdloti, despite the initial erosion by washover, there is sufficient volume of infilling material to create thicker (and thus preferable preservation) of these deposits.

The hyperbolic reflectors represent surfaces lined by occasional coarser debris associated with washover events, and could also mark sand and gravel alternations in tidal inlet facies (van Heteren et al., 1998; Yin et al., 2004). These can be linked to previous washover events in which debris was added to the barrier during storm periods. This is confirmed by the coarser material observed in the measured sections, which includes shell debris most likely derived from a marine source (e.g., Buynevich and FitzGerald, 2003). The surfaces from both barriers that are associated with hyperbolic reflectors, are all erosional (Surfaces 3, 4, 6, 7, 8 and 9). These are consequently interpreted as debris lined washover scours where coarser pebble and cobble material has been left as lag deposits.

6.2 Mesoscale dynamics

The Zinkwazi and Umdloti estuaries are both microtidal systems, with the Umdloti being described as a perched closed system by Cooper (2001), and the Zinkwazi a river-dominated system (Bond et al., 2013).

The marine sand body or barrier appears to accumulate in the high-wave-energy section of the estuary (i.e., mouth), which is built via washover processes (Figs. 33 and 35) and is then later cut by inlets (e.g., Figs. 34c, f). From the mesoscale perspective, the most dominant depositional process is washover, coupled with inlet formation during storm and increased discharge periods. These breaches are evident throughout the span of aerial imagery, as are the washover events. These are often interspersed with periods where there is neither washover, nor inlet opening. These time periods can be linked to aeolian dominance, and the deposition of Unit C, and to a lesser extent, Units E, H and I, which may involve mixed aeolian and washover material. Once deposited, washover fans appear to remain as persistent features (e.g., Figs. 34a, b, d, e and 35j, k). In Umdloti this is clearly linked to the widening of the barrier by up to 45 m (Fig. 33l and m). After their introduction to the system, they are then subject to back-barrier modifications by the mixing of the organic-rich material of the sealed lagoon with the marine detritus of the fan (e.g., Facies 4, Fig. 27). In comparison to other examples such as the Amatikulu estuary (Green et al., 2013a), there is very limited back-barrier modification, implying long-lived persistence and increased preservation potential in the stratigraphic record. Conversely, the inlets appear to

be short-lived and seal without extensive alongshore barrier modification. One isolated example consisted of an inlet, which caused the barrier to bifurcate (Fig. 32f, g and h). Interestingly, no record remains of this in the GPR dataset. Back-barrier changes can have a profound influence on tidal inlet processes and barrier morphology (FitzGerald, 1996). Reworking of these back-barrier sediments may have led to this feature (bifurcation) not being preserved in the barrier record.

The Zinkwazi Estuary is characterised as a rock-bound or bedrock dominated estuary according to the classification scheme of FitzGerald et al. (2000) (Figs. 34 and 35). It has a structurally controlled morphology (e.g., Surface 1 and associated macro-scale fill) and abundant sediment supply from the ocean by means of washover. The shallow elevation of the narrow barrier predisposes it to washover (Bond et al., 2013), and appears to be the most dominant process observed at the mesoscale in the Zinkwazi estuary. Like the Umdloti system, the inlets are also major morphological facets, and similarly follow a non-migrational pattern of opening and closing. The presence of both contemporary and older washover fans (Figs. 34a and 35k respectively) is evident, and likewise, these show no back-barrier modification. These have extended the barrier ~ 100 m landward (Bond et al., 2013). Since that time (2007), the width has oscillated, yet never fully returned to its pre-2007 width.

6.3 Inlet closure and the significance of non-migrating inlets

The inlet fill facies observed in this study are characteristically “non-migrating inlet facies.” They comprise symmetrical channel geometries and are composed of reflectors that dip toward the channel centre. Horizontal and parallel stacked reflections are an indication of shoaling and lateral infilling, which may occur during the closing of the inlets. Small scale cut and fill channels are not present in both study areas, showing that these inlets may be formed by single channel blowouts that occur during separate storm events (e.g., Mallinson et al., 2010).

The non-migrating inlets of the Zinkwazi and Umdloti systems are ephemeral features that may open and close in relatively short spaces of time. These stable inlets are characterised by non-migrating inlet throats (e.g., FitzGerald, 1982). The preservation of the inlet throat and original incision is only clear from the Zinkwazi system, where it is probably preserved due to wave sheltering and antecedent inheritance of the incised valley form (Surface 1). The Ocracoke Inlet in the Outer Banks Barrier Islands, North Carolina is a similar example and illustrates the importance of inheritance of antecedent conditions. The inlet is located within a former river valley that drained the Pamlico Sound basin during the Last Glacial Maximum approximately 20 000 years ago (Mallinson et al., 2008) the inheritance of which is considered to account for both the inlet’s stability and longevity (Mallinson et al., 2008).

Inlet fill successions are absent from the Umdloti example. Here it is likely that whatever inlets that did form were completely overprinted by the contemporary morphodynamic functioning (e.g., washover). As these inlets are categorised as non-migrating inlets they are considered to be dominated by overwash processes (FitzGerald et al., 2001). Both barriers breach during storm periods and are subsequently plugged by washover, with no migration of the inlets occurring during the closure (Figs. 32-35). The Umdloti and Zinkwazi Barriers are thus ephemeral in comparison to the systems from the US Atlantic coast. Inlets seal quickly, from a matter of days to weeks, whereas most of the US examples take months to years to close (Mallinson et al., 2008).

According to Cooper (1990), ephemeral stream-mouth bars are generated by flooding events and act as temporary sinks of sediment offshore of the newly opened inlet. Most of this bar sediment is re-incorporated back into the barrier via the landward migration of the deposit through wave attack (Cooper, 1990), which quickly fills the inlet as washover. This is a possible reason as to why the typical channel fill facies as observed by others from coastal barrier systems, is not evident in the GPR records of this study. In contrast, overwash sheets of relatively uniform material are the most dominant stratigraphic signature.

Smaller inlets, such as those that comprise the Zinkwazi and Umdloti barrier systems may close as a result of smaller, less intense storms that occur throughout the year. This may be the result of the smaller tidal prims that need to be overcome for the barrier to seal (Cooper, 2001a; Bond et al., 2013). At the mesoscale, washovers and inlet closure are common (e.g., Figs. 32a, b, d; 33j, k, l, m; 34a, b, d, e; 35j, k). These are not associated with unusual wave events (Table 3) and are most likely related to average, or above-average swell conditions. This is also because river-dominated estuaries (such as our examples presented here) have limited inlet accommodation due to their steep inlet throats and reflective barrier-beach profile (Cooper, 2001). Inlets can be plugged with sediment quickly, especially with high-rates of longshore sediment supply, and inlet modification or adjustment via migration does not occur.

6.4 Barrier behaviour

Kraft (1971) describes the Holocene coastal lagoon-barrier along the Delaware coast as comprising a transgressive sequence. Baymouth barriers along the Delaware coast comprise steep beach faces and are impacted by a strong northerly littoral drift direction which prompts the barriers to accrete in a northward and westward direction. Sediment loss is promoted by winnowing due to ebb tides and trapping in tidal deltas. Washover features are common; during storm period large amounts of sand from the beach and berm may be washed across the barrier into the coastal lagoons (Kraft, 1971). The preservation potential of these barriers during

transgression is dependent on many complex factors, including but not limited to; pre-existing topography, wave energy, sediment supply, resistance to erosion, tidal range, and rate of relative sea-level change (Belknap and Kraft, 1981).

These barriers may be either regressive or transgressive. According to Kraft and John (1979), transgressive and regressive barriers can be differentiated from each other as, regressive barriers form "funnel-shaped" log patterns, whereas transgressive barriers form "bell-shaped" patterns. Regressive barrier sands are also interbedded with nearshore marine sands, silts, and clays near the base, whereas transgressive sands are characterised by a sharp boundary of sand against the basal sediment. Based on the above characteristics transgressive barriers can be easily differentiated from regressive barriers, however studies from the Texas coastline make their differentiation more complex and difficult (Kraft and John, 1979).

Controlling factors of both transgressive and regressive barrier sequences include wave and tidal regime, source and amount of sediment available for transport, surface topography of transgression and regression, as well as tectonic and eustatic changes in relative sea level (Kraft and John, 1979). As sea level rises, tidal inlet and washover deposition play and important role in the development of narrow barriers (Buynevich and FitzGerald, 2003).

Other important factors to consider in either transgressive or regressive barrier evolution is stratigraphy, and the combination of tidal range and wave energy effect on barrier shape (Belknap and Kraft, 1985). For example the Delaware coastal system interacts with the antecedent geology, controlling evolution of the barriers in the area, along with their preservation in the stratigraphic record (Belknap and Kraft, 1985). The behaviour of barriers to sea-level rise may ultimately take the form of three main end members. These include erosion, where the barrier sediment is redistributed into the shoreface (e.g., Belknap and Kraft, 1985), rollover, where the barrier translates landward with rising sea level (Carter, 1986), or overstepping, where the barrier is drowned insitu on the newly formed shoreface (e.g., Storms et al., 2003). These are usually defined by the ambient energy of the system. High-wave and tidal energy predisposes barriers to erosion, rapid rates of sea-level rise in less energetic environments may promote rollover (Tillmann and Wunderlich, 2013).

During the major marine incursions associated with the March 2007 swell events, the Zinkwazi barrier widened landward (Bond et al., 2013). Tillmann and Wunderlich (2013) show that barrier rollover is associated with the erosion of the seaward side of the barrier, temporarily decreasing the barrier width. This is clear from the Zinkwazi Barrier (Figs. 34g, h and 35j, l, m, o). Since the 2013 opening, the barrier system has migrated farther landward, associated with the sediment from the washover fans being reworked and added to the barrier morphology. This

is confirmed by the GPR data, which shows the almost complete construction of the barrier by washover. Based on the sedimentary architecture and radar facies data, the migration of the Zinkwazi barrier in a landward direction (characterised by Unit B, Fig. 25) is considered to have formed as a result of barrier overwashing or barrier aggradation due to barrier overtopping (Costas et al., 2006b). The lack of back-barrier reworking of the washover lobes implies a longevity of these features. As such, each large incursion remains a persistent facet in the stratigraphy, thus predisposing the system to continued rollover.

During the same period (March 2007), the Umdloti Barrier experienced net erosion of the shoreline with little washover. This barrier system experienced erosion of the berm forming a continuous scarp along the barrier. Interestingly this scarp is not evident from any of the GPR data for the area. Despite not appearing to have rolled over in March 2007, the barrier is still dominated by landward dipping stratigraphy which appears to have completely overprinted this marine scarping phase. This is a common feature of retrograding barriers that have high rates of sediment supply (Davis and FitzGerald, 2004).

Smaller-scale events, post-dating the March 2007 event, may be responsible for the erosion of the Umdloti Barrier system. According to Smith et al. (2014), the periods of erosion that occurred along the Umdloti Barrier in 2007, were a result of natural shoreline fluctuations controlled by the Lunar Nodal Cycle (LNC). Figure 32b corresponds with one of these periods, here the barrier was inundated by washover, producing the upper landward dipping stratigraphy of Unit H.

In the Umdloti Barrier system, inlet openings are focused toward the northern portions of the Umdloti Barrier, together with isolated flood tide deltas (Fig. 30). The flood tide deltas, unlike the washover fans, are reworked by limited tidal interaction when the inlet is open. The recurved spits, as evident in Figure 34c, locally widen the barrier (e.g., Davis and FitzGerald, 2004), further predisposing the system to slow landward migration.

The predisposition of these barrier-spits to rollover is important to their net preservation potential in the long term. Green et al. (2014) show a series of preserved barriers located on the adjoining shelf of the study areas. These are of much larger scale when compared to the barriers that front the river-dominated estuaries of South Africa. Similarly, the barriers found on the shelf were rapidly cemented. Both their large volume and early cementation resulted in these features being overstepped during transgression and thus ultimately preserved in the stratigraphic record. Coupled with transgression, the smaller barrier-spits would rollover until no available accommodation space exists and complete reworking by storm-wave processes would occur. Their net preservation potential as persistent features in the stratigraphy is thus

low. Isolated examples of smaller in situ drowned barrier spits have been imaged in a series of incised valleys offshore the Umdloti River (Green et al., 2013b), though these are uncommon and probably relate to a greater amount of back barrier accommodation that allowed for their survival from transgressive ravinement processes.

7 Conclusions

Radar Units (A1-I) comprise the radar stratigraphy of two barrier spits associated with microtidal, river-dominated estuaries. Unit A1 correlates with the southern margin of the Zinkwazi River incised river valley. Unit A2, comprises moderately well sorted, coarse sand that forms planar, horizontal, subparallel and moderately continuous reflectors of the lowermost washover unit resolved. Both barriers consist almost in their entirety of washover sheets. Unit B comprises moderately well sorted medium sand that forms sinuous/wavy and sub-parallel reflectors. Units E, H and I comprise coarse sand well sorted sands of planar, horizontal subparallel and moderately continuous reflectors. The uppermost Unit I comprises the up-dip extension of the contemporary washover fans occurring in the back barrier environments of both systems.

Inlet infill facies are restricted to the Zinkwazi system (moderately well sorted very coarse sands of units D and G). In radar profile, these comprise planar to wavy, sinuous, subparallel to oblique, chaotic, moderately continuous to discontinuous reflectors. Unit D is related to limited lateral accretion of the inlet and Unit G as an aggradational fill in the inlet throat due to washover.

A number of washover channels occur in the stratigraphy (Surfaces 4 and 7). These are associated with hyperbolic forming pebble and small cobble lags. These are infilled (e.g., Unit F) by chaotic, concave upward and curved convex reflectors that represent the internal stratification found within the channelized washover. Interspersed amongst these are occasional transitional aeolian facies (Unit C) that mark the intervals between washover periods.

The Zinkwazi and Umdloti Barriers are described as non-migrating inlet systems that breach during storm periods and are subsequently plugged by washover, with no modification or migration of the inlets occurring during the closure. These ephemeral features may open and close in relatively short spaces of time as a result of smaller, less intense storms that occur throughout the year, and are dominated by overwash processes as shown by the GPR data. The preservation potential of the inlet incision is only clear from the Zinkwazi system, due to wave sheltering and antecedent inheritance of the incised valley form, whereas in the Umdloti system the inlets are completely overprinted by contemporary morphodynamic functioning (e.g., washover).

The Zinkwazi Barrier system rolled over due to the major marine incursions experienced in 2007 and 2013. The barrier continues to migrate further landward as sediment from the washover fans is reworked and added to the barrier morphology, as confirmed by the GPR data.

The lack of back-barrier reworking of the washover lobes implies a longevity of these features. As such, each large incursion remains a persistent facet in the stratigraphy, thus predisposing the system to continued rollover.

The Umdloti Barrier is dominated by landward building stratigraphy, despite not having rolled over. This is a common feature of retrograding barriers that have high rates of sediment supply. Breaches and isolated flood tide deltas are focused toward the northern portions of the barrier (Fig. 30). These flood tide deltas are reworked by limited tidal interaction when the inlet is open, with the recurved spits locally widen the barrier, further predisposing the system to slow landward migration, and the minimal preservation potential of these features.

This thesis proposes a model for the barrier development, breaching and subsequent closure of river-dominated, TOCE's such as the Zinkwazi and Umdloti systems (Fig. 36a, b, c and d). As the barriers are dominated by overwash this is the most important factor in the barrier development. The barriers breach as a result of flooding during storm periods (Fig. 36b). These inlets are then rapidly filled by washover (not necessarily linked to extreme events) (Fig. 36c). This is a result of their limited accommodation space. The inlets do not migrate. This could be as a result of antecedent conditions (e.g., bedrock control in the Zinkwazi Estuary), or due to the rapid time interval between opening and closing. The Umdloti Estuary inlet closes before it can begin to migrate with longshore sediment loading (Fig. 36d).

Barrier-building processes are typically slower than the interval between breaching processes. Barriers thus preferentially breach at the previous inlet position, unless anthropogenic factors force the barrier to breach along a specific section. The constant inundation by washover predisposes these systems to rollover (Fig. 36e).

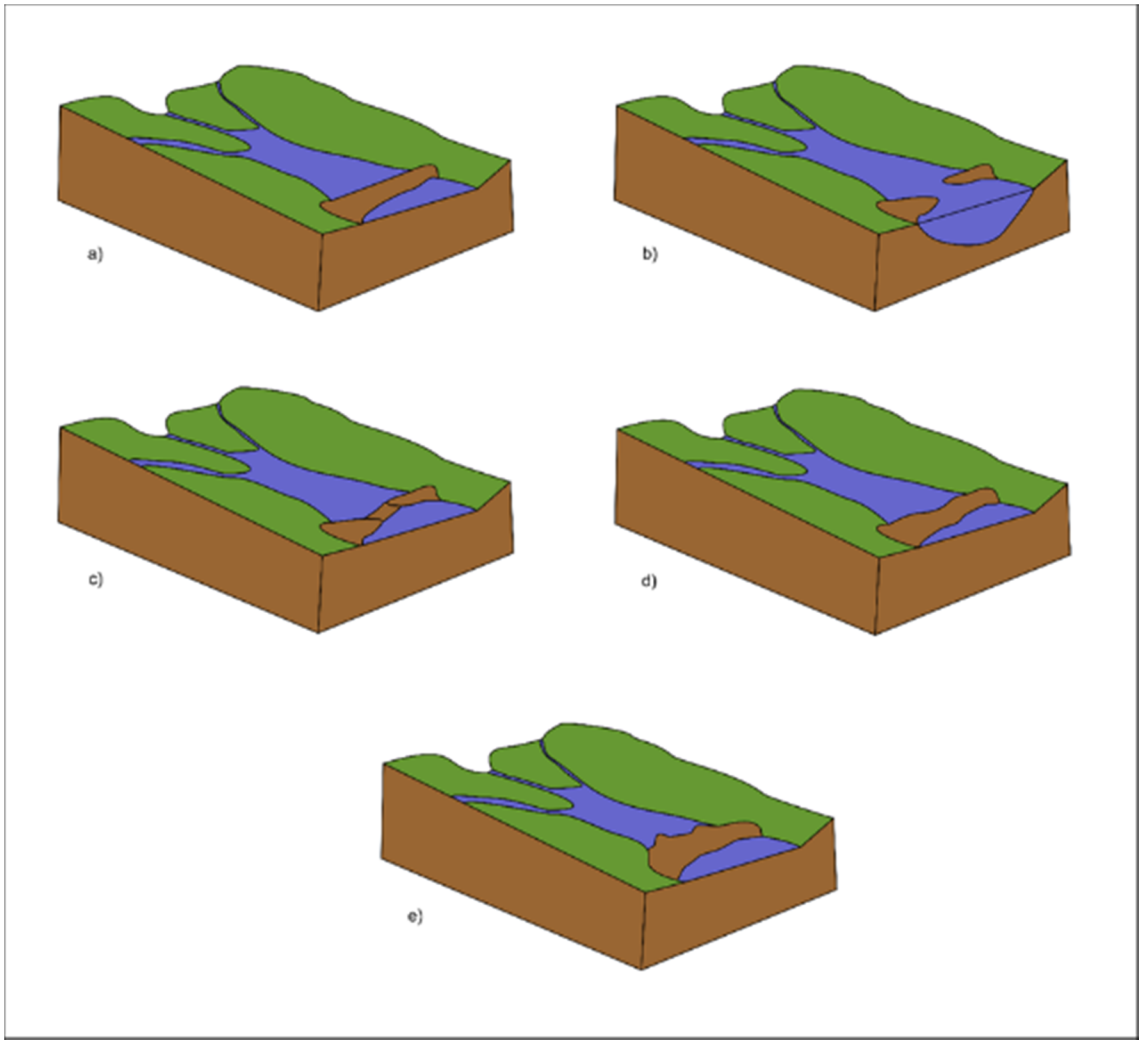


Figure 36. A schematic diagram showing the evolution of the Zinkwazi and Umdloti Barriers. a) The position of river-dominated barriers prior to breaching. b) The system forms an inlet. c) The inlet is subsequently filled by washover that plugs the inlet channel. d) Barrier once that inlet has been almost completely infilled. This may take a few weeks to occur. e) The landward rolling over of the barrier, as a result of up-profile migration, which is not preserved in the GPR record. This barrier rollover occurs due to overwash.

8 Reference List

Allen, J. R. L., 1982. Sedimentary Structures: Their Character and Physical Basis Volume 1. Developments in Sedimentology, Elsevier, Amsterdam, pp. 593.

Anandraj, A., Perissinotto, R., and Nozais, C., 2007. A comparative study of microalgal production in a marine versus a river-dominated temporarily open/closed estuary, South Africa. Estuarine, Coastal and Shelf Science 73, 768-780.

Anthony, E. J., Oyédé, L. M., and Lang, L., 2002. Sedimentation in a fluvially infilling, barrier-bound estuary on a wave-dominated, microtidal coast: the Ouémé River estuary, Benin, West Africa. Sedimentology 49, 1095-1112.

Aubrey, D. G., and Speer, P. E., 1984. Updrift Migration of Tidal Inlets. Journal of Geology 92, 531-545.

Barboza, E. G., Dillenburg, S. R., Rosa, M. L. C. C, Tomazelli, L. J. and Hesp, P. A., 2009. Ground-penetrating radar profiles of two Holocene regressive barriers in southern Brazil. Journal of Coastal Research 56, 579-583.

Bate, G. C., Whitfield, A. K., Adams, J. B., Huizinga, P., and Wooldridge, T.H., 2002. The importance of the river-estuary interface (REI) zone in estuaries. Water South Africa 28, 271-280.

Bateman, M. D., Carr, A. S., Dunajko, A. C., Holmes, P. J., Roberts, D. L., McLaren, S. J., Bryant, R. J., Marker, M. E., and Murray-Wallace, C. V., 2011. The evolution of coastal barrier systems: a case study of the Middle-Late Pleistocene Wilderness barriers, South Africa. Quaternary Science Reviews 30, 63-81.

Begg, G. W., 1978. The Estuaries of Natal. Natal Town and Regional Planning Report, KwaZulu-Natal, South Africa 41, 651 pp.

Belknap, D. F., and Kraft J. C., 1981. Preservation potential of transgressive coastal lithosomes on the U.S. Atlantic shelf. Marine Geology 42, 429-442.

Belknap, D. F., and Kraft J. C., 1985. Influence of antecedent geology on stratigraphic preservation potential and evolution of Delaware's barrier systems. Marine Geology 63, 235-262.

Benallack, K., Green, A. N., Humphries, M. S., Cooper, J. A. G., Dladla, N. N., and Finch, J. M., 2016. The stratigraphic evolution of a large backbarrier lagoon system with a non-migrating barrier. Marine Geology 379, 64-77.

Bennett, M. R., Cassidy, N. J., and Pile, J., 2009. Internal structure of a barrier beach as revealed by ground penetrating radar (GPR): Chesil beach, UK. Geomorphology 104, 218-229.

Bezerra, M., Ferreira, Ó., Pacheco, A., Freitas, M. C., Pires, R., Andrade, C. and Taborda, R., 2011. Evolution stages of an ephemeral inlet immediately after artificial opening. Journal of Coastal Research 64, 1453-1456.

Bond, J., Green, A. N., Cooper, J. A. G., and Humphries, M.S., 2013. Seasonal and episodic variability I the morphodynamics of an ephemeral inlet, Zinkwazi Estuary, South Africa. Journal of Coastal Research 65, 446-451.

Bristow C. S., and Pucillo, K., 2006. Quantifying rates of coastal progradation from sediment volume using GPR and OSL: the Holocene fill of Guichen Bay, south-east South Australia. Sedimentology 53, 769-788.

Bulhões, E., Fernandez, G. B., and Rocha, T. B., 2013. Morphodynamics of Embayed Beaches. Case Study in Cape Buzios, Rio de Janeiro, Brazil. Journal of Coastal Research 65, 1739-1744.Buynevich, I. V., and Donnelly, J. P., 2006. Geological signatures of barrier breaching and overwash, southern Massachusetts, USA. Journal of Coastal Research 39, 112-116.

Buynevich, I. V., and FitzGerald, D. M., 2003. High-resolution subsurface (GPR) imaging and sedimentology of coastal ponds, Maine, U.S.A.: Implications for Holocene back-barrier evolution. Journal of Sedimentary Research, 73, 559-571.

Buynevich, I. V., FitzGerald, D. M., and van Heteren, S., 2004. Sedimentary records of intense storms in Holocene barrier sequences, Maine, USA. Marine Geology, 210 135-148.

Campbell, C.V., 1967. Lamina, laminaset, bed and bedset. Sedimentology 8, 7-26.

Carrasco, N. K., and Perissinotto, R., 2014. Microalgal responses to physico-chemical variability in the small temporarily open/closed Seteni Estuary, South Africa. African Journal of Aquatic Science 39, 327-336.

Carter R. W. G., 1986. The morphodynamics of beach-ridge formation: Magilligan, Northern Ireland. Marine Geology 73, 191-214.

Castelle, B., Bourge, J., Molnar, N., Strauss, D., Deschamps, S., and Tomlinson, R., 2007. Dynamics of a wave-dominated tidal inlet and influence on adjacent beaches, Currumbin Creek, Gold Coast, Australia. Coastal Engineering 54, 77-90.

Cayocca, F., 2001. Long-term morphological modeling of a tidal inlet: the Arcachon Basin, France. Coastal Engineering 42, 115-142.

Chew, J. A. and Bowen, 1971. The water resources of the coastal areas of northern Natal and Zululand. The Natal Town and Regional Planning Commission, Pietermaritzburg, South Africa, pp. 74.Cooper, J. A. G., 1989. Fairweather versus flood sedimentation in Mhlanga Lagoon, Natal; implications for environmental management. South African Journal of Geology 92, 279-294.

Cooper, J. A. G., 1990. Ephemeral stream-mouth bars at flood-breach river mouths on a wave-dominated coast: Comparison with ebb-tidal deltas at barrier inlets. Marine Geology 95, 57-70.

Cooper, J.A.G., 1991. Sedimentary models and geomorphological classification of river mouths on a subtropical, wave-dominated coast, Natal, South Africa. PhD Thesis, University of Natal, Durban, p 401.

Cooper, J. A. G. 1993. Sedimentation in a river-dominated estuary. Sedimentology 40, 979-1017.

Cooper, J. A. G. 1994. Sedimentation in the river-dominated Mvoti estuary, South Africa. Geomorphology 9, 271–300.

Cooper, J. A. G., 1995. Lagoons and microtidal coasts. In: Carter, R.W.G., Woodroffe, C.D. (Eds.), Coastal Evolution. Cambridge University Press, Cambridge, pp. 219–265.

Cooper, J. A. G. 2001a. Geomorphological variability among microtidal estuaries from the wave-dominated South African coast. Geomorphology 40, 99-122.

Cooper, J. A. G. 2001b. Geomorphology of Tide-dominated and River-dominated, Barred, Microtidal Estuaries: a Contrast. Journal of Coastal Research 34, 428-436.

Cooper, J. A. G., 2002. The role of extreme floods in estuary-coastal behaviour: contrasts between river- and tide-dominated microtidal estuaries. Sedimentary Geology 150, 123-137.

Cooper, J. A. G, Green, A. N, and Wright, C. I. 2012. Evolution of an incised valley plain estuary under low sediment supply: a “give-up” estuary. Sedimentology 59, 899-916.

Cooper, J. A. G. and Jackson, D. W. T., 2011. Geomorphology of a high-energy barrier island on the rocky west coast of Ireland Journal of Coastal Research 64, 6-9.

Cooper, J. A. G., Wright, C.I., and Mason, T. R., 1999. Geomorphology and sedimentology. In: Allanson, B.R., Baird, D. (Eds.), Estuaries of South Africa. Cambridge Academic Press, Cambridge, pp. 5-25.

Corbella, S., and Stretch, D. D., 2012. The wave climate on the KwaZulu-Natal coast of South Africa. Journal of the South African Institution of Civil Engineering 54, 45-54.

Costas, S., Alejo, I., and Nombela, M. A., 2006a. Sand barrier behaviour under man-induced inlet relocation. Journal of Coastal Research 39, 428-432.

Costas, S., Alejo, I., Rial, F., Lorenzo, H., and Nombela, M. A., 2006b. Cyclical evolution of a modern transgressive sand barrier in northwestern Spain elucidated by GPR and aerial photos. Journal of Sedimentary Research 76, 1077-1092.

Cowley, P. D., and Whitfield, A. K., 2001. Ichthyofaunal characteristics of a typical temporarily open/closed estuary on the south east coast of South Africa. Ichthyological Bulletin 71, 1-17.

da Rocha, T. B., Fernandez, G. B. and Peixoto, M. N. O., 2013. Applications of ground-penetrating radar to investigate the Quaternary evolution of the south part of the Paraiba do Sul river delta (Rio de Janeiro, Brazil). Journal of Coastal Research 65, 570-575.

Dalrymple, R W., 2006. Incised valleys in time and space: introduction to the volume and an explanation of the controls on valley formation and filling. In: Dalrymple, R. W., Leckie, D. A., Tillman, R. (Eds.), Incised valleys in time and space. Society for Sedimentary Geology. Special Publication., 85. SEPM, pp. 5-12.

Dalrymple, R. W., Zaitlin, and B. A., Boyd, R. 1992. Estuarine facies models: conceptual basis and stratigraphic implications. Journal of Sedimentary Research 62, 1130-1146.

Daly, J., McGeary, S., and Krantz, D. E., 2002. Ground-penetrating radar investigation of a late Holocene spit complex: Cape Henlopen, Delaware. Journal of Coastal Research 18, 274-286.

Davies, J. L., 1964. A morphogenic approach to world shorelines. Zeitschrift für Geomorphologie 8, 127-142.

Davies, J. L., 1980. Geographical variation in coastal development. Oliver and Boyd, Edinburgh.

Davis, Jr. R. A., 2013. A new look at barrier-inlet morphodynamics. Journal of Coastal Research 69, 1-12.

Davis Jr. R. A., and Barnard, P., 2003. Morphodynamics of the barrier-inlet system, west-central Florida. Marine Geology 200, 77-101.

Davis Jr. R. A., and FitzGerald, D. M. 2004. Beaches and Coasts. Blackwell Publishing, Australia, pp. 419.

Day, J. H., 1981. The nature, origin and classification of estuaries. In: Day, J. H. (Ed.), Estuarine Ecology with Particular Reference to Southern Africa. A. A. Balkema, Cape Town, pp. 6.

Fenster, M. and Dolan, R., 1996. Assessing the impact of tidal inlets on adjacent barrier island shorelines. Journal of Coastal Research 12, 294-310.

FitzGerald, D. M., 1982. Sediment bypassing at mixed energy tidal inlets. Coastal Engineering 1094-1118.

FitzGerald, D. M., 1996. Geomorphic variability and morphologic and sedimentologic Controls on Tidal Inlets. Journal of Coastal Research 23, 47-71.

FitzGerald, D. M., Buynevich, I., and Argow, B., 2006. Model of tidal inlet and barrier island dynamics in a regime of accelerated sea level rise. Journal of Coastal Research, 789-95.

FitzGerald, D. M., Buynevich I. V., Davis Jr., R. A., and Fenster, M. S., 2002. New England tidal inlets with special reference to riverine-associated inlet systems. Geomorphology 48, 179-208.

FitzGerald, D. M., Buynevich, I. V., Fenster, M. S., and McKinlay, P. A., 2000. Sand dynamics at the mouth of a rock-bound, tide-dominated estuary. Sedimentary Geology 131, 25-49.

FitzGerald, D. M., Buynevich, I. V. and Rosen, P. S., 2001. Geological evidence of former tidal inlets along a retrograding barrier: Duxbury, Massachusetts, USA. Journal of Coastal Research 34, 436-448.

Folk, R. L., and Ward, W. C., 1957. Brazos River bar: a study in the significance of grain size parameters. Journal of Sedimentary Petrology 27, 3-26.

Froneman, P. W., 2004a. Food web dynamics in a temperate temporarily open/closed estuary (South Africa). Estuarine, Coastal and Shelf Science 59, 87-95.

Froneman, P. W., 2004b. Zooplankton community structure and biomass in a southern African temporarily open/closed estuary. Estuarine, Coastal and Shelf Science 60, 125-132.

Gama, P. T., Adams, J. B., Schael, D. M., and Skinner, T., 2005. Phytoplankton chlorophyll a concentration and community structure of two temporarily open/closed estuaries. Water Research Commission, pp. 91.

Garden, S. E., and Garland, G, G., 2005. Spit development in the Mdloti River estuary, KwaZulu-Natal. South African Journal of Geology 108, 257-270.

Garland, G., and Moleko, L., 2000. Geomorphological impacts of Inanda Dam on the Mgeni estuary, north of Durban, South Africa. Bulletin of Engineering Geology and the Environment 59, 119-126.

Gibeaut, J. C., and Davis, R. A., 1991. Computer simulation modeling of tidal inlets. Coastal Sediments '91. (Seattle, Washington, American Society of Civil Engineers), pp. 1389–1403.

Green, A. N., Cooper, J. A. G., and LeVieux, A., 2013a. Unusual barrier/inlet behaviour associated with active coastal progradation and river-dominated estuaries. Journal of Coastal Research 69, 35-45.

Green, A. N., Cooper, J. A. G., and Salzmann L., 2014. Geomorphic and stratigraphic signals of postglacial meltwater pulses on continental shelves. Geology 42, 151-154.

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

Guastella, L. A. and Smith, A. M., 2014. Coastal dynamics on a soft coastline from serendipitous webcams: KwaZulu-Natal, South Africa. Estuarine, Coastal and Shelf Science 150, 76-85.

Halsey, S., 1979. Nexus: a new model of barrier island development. In: Leatherman, S.P. (Ed.), Barrier Islands: From the Gulf of St. Lawrence to the Gulf of Mexico. Academic Press, New York, pp. 185-210.

Harrison, T. D., Cooper, J. A. G., and Ramm, A. E. L., 2000. Geomorphology, ichthyofauna, water quality and aesthetics of South African estuaries. CSIR Report. Pretoria, pp. 216.

Hayes, M. O., 1979, Barrier island morphology as a function of tidal and wave regime: In Leatherman, S.P., (Ed.), Barrier Islands: From the Gulf of St. Lawrence to the Gulf of Mexico: New York, Academic Press, pp. 1-28.

Hein, C. J., FitzGerald, D. M., Carruthers, E. A., Stone, B. D., Barnhardt, W. A., and Gontz, A. M., 2012. Refining the model of barrier island formation along a paraglacial coast in the Gulf of Maine. Marine Geology 307-310, 40-57.

Heydorn, A. E. F., and Pistorius, R. A., 1978. The Estuaries of Natal. Backhouse, Pietermaritzburg. pp. 657.

Heymans, J. J., and Baird, D., 1995. Energy Flow in the Kromme Estuarine Ecosystem, St Francis Bay, South Africa. Estuarine, Coastal and Shelf Science 41, 39-59.

Hine, A. C., 1979. Mechanisms of berm development and resulting beach growth along a barrier spit complex. Sedimentology 26, 333-351.

HRU (Hydraulics Research Unit). 1968. Wave and wind conditions for the Natal and western cape Coastal areas. CSIR Report. Pretoria, pp. 87.

James, N. C., Cowley, P. D., Whitfield, A. K., and Lamberth, S. J., 2007. Fish communities in temporarily open/closed estuaries from the warm- and cool-temperate regions of South Africa: A review. Reviews in Fish Biology and Fisheries 17, 565-580.

James, N. C., and Harrison, T. D., 2008. A preliminary survey of the estuaries on the south coast of South Africa, Cape St Blaize, Mossel Bay-Robberg Peninsula, Plettenberg Bay, with particular reference to the fish fauna. Transactions of the Royal Society of South Africa 63, 111-127.

Johnson, M. R., van Vuuren, C. J., Visser, J. N. J., Cole, D. I., de V. Wickens, H., Christie, A. D. M., Roberts, D. L. and Brandl, G. 2006. In: Johnson, M. R., Anhaesser, C. R and Thomas, R. J. (Eds.), The Geology of South Africa. The Geological Society of South Africa, Johannesburg/Council for Geoscience, Pretoria, pp. 461-500.

Jol, H. M., Lawton, D. C., and Smith, D. G., 2002. Ground penetrating radar: 2-D and 3-D subsurface imaging of a coastal barrier spit, Long Beach, WA, USA. Geomorphology 53, 165-181.

Kraft, J. C., 1971. Sedimentary facies patterns and geologic history of a Holocene marine transgression. Geological Society of America Bulletin 82, 2131-215.

Kraft, J. C., Allen, E. A., Belknap, D. F., John, C. J., and Maurmeyer, E. M., 1979. Processes and morphologic evolution of an estuarine and coastal barrier system. In: Leatherman, S. P., (Ed.), Barrier Islands, Academic Press, New York, pp. 149-183.

Kraft, J. C., and John, J. C., 1979. Lateral and vertical facies relations of transgressive barrier. The American Association of Petroleum Geologists Bulletin 63, 2145-2163.

Largier, J. L., and Slinger, J. H., 1991. Circulation in Highly Stratified Southern African Estuaries. South African Journal of Aquatic Sciences 17, 103-115.

Largier, J. L., Slinger, J. H., and Taljaard, S., 1992. The stratified hydrodynamics of the Palmiet - a prototypical bar-built estuary. Coastal and Estuarine Studies, Dynamics and Exchanges in Estuaries and the Coastal Zone 40, 135-153.

Lebens, M., 2010. Incorporating GPS and Mapping Capability into Ground Penetrating Radar (GPR) Operations for Pavement Thickness Evaluations. Technical Report. Minnesota Department of Transportation, pp 49.

Le Roux, J. S., 1990. Spatial variations in the rate of fluvial erosion (sediment production) over South Africa. Water South Africa 16, 185-194.

Mallinson, D. J., Culver, S. J., Riggs, S. R., Walsh, J. P., Ames, D., and Smith, C. W., 2008. Past, Present and Future Inlets of the Outer Banks Barrier Islands, North Carolina. Department of Geological Sciences Thomas Harriot College of Arts and Sciences and Institute for Coastal Science and Policy East Carolina University, pp. 23.

Mallinson, D. J., Smith, C. W., Culver, S. J., Riggs, S. R., and Ames, D., 2010. Geological characteristics and spatial distribution of paleo-inlet channels beneath the outer banks barrier islands, North Carolina, USA. Estuarine, Coastal and Shelf Science 88, 175-189.

Mallory, J. K., 1977. Abnormal waves on the south-east coast of South Africa. Institute of Oceanography, University of Cape Town, Occas. Report, pp. 18.

Marshall, C. G. A. 2006. In: Johnson, M. R., Anhaesser, C. R and Thomas, R. J. (Eds.), The Geology of South Africa. The Geological Society of South Africa, Johannesburg/Council for Geoscience, Pretoria, 433-442.

McCormick, S., Cooper, J. A. G., and Mason, T. R., 1992. Fluvial sediment yield to the Natal coast: a review. South African Journal of Aquatic Sciences 18, 74-88.

Mitchum, R. M., and Vail, P. R., 1977. Seismic stratigraphy and global changes of sea level, part 7: Seismic stratigraphy interpretation procedure. In: Payton, C. E (Ed), Seismic Stratigraphy – Applications to Hydrocarbon Exploration. American Association of Petroleum Geologists Memoir 26, pp. 135-143.

Morris, B. D., Davidson M. A., and Huntley, D. A., 2001. Measurements of the response of a coastal inlet using video monitoring techniques. Marine Geology 175, 251-272.

Morris, B. D., and Turner, I. L., 2010. Morphodynamics of intermittently open–closed coastal lagoon entrances: New insights and a conceptual model. Marine Geology 271, 55-66.

Moslow, T. F., and Heron, S. D., 1978. Relict inlets; preservation and occurrence in the Holocene stratigraphy of southern core banks, North Carolina. Journal of Sedimentary Research 48, 1275-1286.

Neal, A., 2004. Ground-penetrating radar and its use in sedimentology: principles, problems and progress. Earth Science Reviews 66, 261-330.

Nummedhal, D., and Fischer, I. A., 1978. Process-response models for depositional shorelines: the German and the Georgia Bights. American Society of Civil Engineering 16, 1215-1231.

O' Brien, M. P., 1976. Notes on Tidal Inlets on Sandy Shores. University of California, Berkeley, pp. 26.

Oertel, G. F., 1985. The barrier island system. Marine Geology 63, 1-18.

Otvos, E., G., 2011. Hurricane signatures and landforms-toward improved interpretations and global storm climate chronology. Sedimentary Geology 239, 10-22.

Otvos, E., G., 2012. Coastal barriers-Nomenclature, processes, and classification issues. Geomorphology 139-140, 39-52.

Papadopoulos, I., Wooldridge, T. H., and Newman, B. K., 2002. Larval life history strategies of sub-tropical southern African estuarine brachyuran crabs and implications for tidal inlet management. Wetlands Ecology and Management 10, 249-256.

Pascucci, V., Martin, I. P., and Endres, A. L., 2009. Facies and ground-penetrating radar characteristics of coarse-grained beach deposits of the uppermost Pleistocene glacial Lake Algonquin, Ontario, Canada. Sedimentology 56, 529-545.

Perissinotto, R., Walker, D. R., Webb, P., Wooldridge, T. H., and Bally, R., 2000. Relationships between Zoo- and Phytoplankton in a Warm-temperate, Semi-permanently Closed Estuary, South Africa. Estuarine. Coastal and Shelf Science 51, 1-11.

Pillay, S., Luichmiah, J., Gengan, R. M., and Lindsay, P., 2003. Morphology and Sediment Dynamics of the Ephemeral Mfolozi Estuary, Kwazulu-Natal, South Africa South African Geographical Journal 85, 158-163.

Ramsay, P. J., and Cooper J. A. G., 2002. Late quaternary sea-Level change in South Africa. Quaternary Research 57, 82-90.

Ranasinghe, R., Pattiaratchi, C., and Masselink, G., 1999. Morphodynamic model to simulate the seasonal closure of tidal inlets. Coastal Engineering 37, 1-36.

Reddering, J. S. V., and Esterhuysen, K., 1987. Sediment dispersal in the Knysna estuary, environmental management considerations. South African Journal of Geology 90, 448-457.

Riddin, T., and Adams, J. B., 2010. The effect of a storm surge event on the macrophytes of a temporarily open/closed estuary, South Africa. Estuarine, Coastal and Shelf Science 89, 119-123.

Rooseboom, A. 1975. Sediment produksiekaart vir Suid- Afrika. Department of Water Affairs and Environmental Conservation Technical report, pp. 61.

Roy, P. S., 1984. New South Wales estuaries: their origin and evolution. In: Thom, B. G. (Ed.), Coastal Geomorphology in Australia. Academic Press, Australia, pp. 99-121.

Roy, P. S and Stephens, A. W., 1980. Geological controls on process-response, SE Australia Coastal Engineering Proceedings 17, 913-933.

Scharler, U. M., 2012. Ecosystem development during open and closed phases of temporarily open/closed estuaries on the subtropical east coast of South Africa. Estuarine, Coastal and Shelf Science 108, 119-131.

Schwab, W. C., Thieler, E. R., Allen, J. R., Foster, D. S., Swift, B. A., and Denny, J. F., 2000. Influence Of inner-continental shelf geologic framework on the evolution and behavior of the barrier-island system between Fire Island Inlet and Shinnecock Inlet, Long Island, New York. Journal of Coastal Research 16, 408-422.

Seminack, C. T., and Buynevich, I. V., 2013. Sedimentological and geophysical signatures of a relict tidal inlet complex along a wave-dominated barrier: Assateague Island, Maryland, U.S.A. Journal of Sedimentary Research 83, 132-144.

Shan, X., Yu, X., Clift, P. D., Tan, C., Jin, L., Li, M., and Li, W., 2015. The Ground Penetrating Radar facies and architecture of a Paleo-spit from Huangqihai Lake, North China: Implications for genesis and evolution. Sedimentary Geology 323, 1-14.

Shukla, S. B., Patidar, A. K., and Bhatt, N., 2008. Application of GPR in the study of shallow subsurface sedimentary architecture of Modwa spit, Gulf of Kachchh. Journal of Earth System Science 117, 33-40.

Smith, A. M., Guastella, L. A., and Goble, B. J., 2014. Forecasting lagoon outlet erosion: KwaZulu-Natal, southeast Africa. Journal of Coastal Research 151-156.

Smith, A. M., Mather, A. A., Guastella, L. A., and Bundy, S.C. 2010. Contrasting styles of swell-driven coastal erosion: examples from KwaZulu-Natal, South Africa. Geological Magazine 147, 940-953.

Snow, G. C., and Taljaard, S., 2007. Water quality in South African temporarily open/closed estuaries: a conceptual model. African Journal of Aquatic Science 32, 99-111.

Storms, J. E. A., and Swift, D. J .P., 2003. Shallow-marine sequences as the building blocks of stratigraphy: insights from numerical modelling. Basin Research 15, 287-303.

Stretch, D. D., and Zietsman, I., 2004. Hydrodynamics: Flows, Residence Times, Water Levels and Mouth Dynamics Contributions to Information Requirements for the Implementation of Resource Directed Measures for Estuaries. In: Response of the Biological Communities to Flow

Variation and Mouth State in Two KwaZulu-Natal Temporarily Open/closed Estuaries, vol. 2. J.B. Adams, (Ed.), Pretoria, South Africa.

Swart, D. H., Morant, P. D., Moller, J. P., Crowley, J. B., and de Wet, A., 1988. A record of events at the Orange River mouth during the March 1988 flood. South African Journal of Science 84, 881-889.

Taljaard, S., van Niekerk, L., and Joubert, W., 2009. Extension of a qualitative model on nutrient cycling and transformation to include microtidal estuaries on wave-dominated coasts: Southern hemisphere perspective. Estuarine, Coastal and Shelf Science 85, 407-421.

Tillmann, T. and Wunderlich, J., 2013. Barrier rollover and spit accretion due to the combined action of storm surge induced washover events and progradation: Insights from ground-penetrating radar surveys and sedimentological data. Journal of Coastal Research 65, 600-605.

Tinley, K. L. 1985. Coastal dunes of South Africa. South African National Scientific Programmes Report 109, pp. 300.

Tung, T. T., Walstra, D. J. R., Graaf, J. van de and Stive, M. J. F., 2009. Morphological modelling of tidal inlet migration and closure. Journal of Coastal Research 56, 1080-1084.

Tyson, P. D. 1987. Climatic Change and Variability in Southern Africa. Oxford University Press, Cape Town. pp. 220.

Tyson, P. D., Cooper, J. A. G., and Mccarthy, T. S. 2002. Millennial To Multi-Decadal Variability in the Climate of Southern Africa. International Journal of Climatology 22, 1105-1117.

van Heteren, S., FitzGerald, D. M., Mckinlay, P. A., and Buynevich, I. V., 1998. Radar facies of paraglacial barrier systems: coastal New England, USA. Sedimentology 45, 181-200.

van Niekerk, L., van der Merwe, J. H., and Huizinga, P., 2005. The hydrodynamics of the Bot River Estuary revisited. Water South Africa 31, 73-86.

Vila-Concejo, A., Ferreira, Ó., Morris, B. D., Matias, A., and Dias, J. M. A., 2004. Lessons from inlet relocation: examples from Southern Portugal. Coastal Engineering 51, 967-990.

Vila-Concejo, A., Matias, A., Ferreira, Ó., Duarte, C., and Dias, J. M. A., 2002. Recent Evolution of the Natural Inlets of a Barrier Island System in Southern Portugal. Journal of Coastal Research 36, 741-752.

Vila-Concejo, A., Matias, A., Pachecoa, A., Ferreira, Ó., and Dias J. A., 2006. Quantification of inlet-related hazards in barrier island systems. An example from the Ria Formosa (Portugal). Continental Shelf Research 26, 1045-1060.

Walker, R. G., and James, N. P., 1992. Facies Models: response to sea level change. Geological Association of Canada, Waterloo. pp. 409.

Westhuysen, A. J. van der., 2002. The application of the numerical wind-wave model SWAN to a selected field case on the South African coast. CSIR Stellenbosch, South Africa.

Whitfield, A. K. 1992. A characterization of southern African estuarine systems. South African Journal of Aquatic Science 18, 89-103.

Whitfield, A. K., 2005. Fishes and freshwater in southern African estuaries – A review. Aquatic Living Resources 18, 275-289.

Whitfield, A. K., Adams, J. B., Bate, G. C., Bezuidenhout, K., Bornman, T. G., Cowley, P. D., Froneman, P. W., Gama, P. T., James, N. C., Mackenzie, B., Riddin, T., Snow, G. C., Strydom, N. A., Taljaard, S., Terörde, A., Theron, A. K., Turpie, J. K., van Niekerk, L., Vorwerk, P. D., and Wooldridge, T. H., 2008. A multidisciplinary study of a small, temporarily open/closed South African estuary, with particular emphasis on the influence of mouth state on the ecology of the system. African Journal of Marine Science 30, 453-473.

Whitfield, A. K., Allanson, B. R., and Heinecken, T. J. E., 1983. Swartvlei. In: Heydorn, A. E. F. and Grindley, J. R., (Eds.), Estuaries of the Cape. Part 11: Synopses of Available Information on Individual Systems. C.S.I.R. Research Report 421, 1-62.

Whitfield, A. K., Bate, G. C., Adams, J. B., Cowley, P. D., Froneman, P. W., Gama, P. T., Strydom, N. A., Taljaard, S., Theron, A. K., Turpie, J. K., van Niekerk, L., and Wooldridge, T. H., 2012. A review of the ecology and management of temporarily open/closed estuaries in South Africa, with particular emphasis on river flow and mouth state as primary drivers of these systems. African Journal of Marine Science 34, 163-180.

Wright, C. I., Miller, W. R., and Cooper, J. A. G., 2000. The late Cenozoic evolution of coastal water bodies in Northern KwaZulu-Natal, South Africa. Marine Geology 167, 207-229.

Wright, L. D., and Short, A. D., 1984. Morphodynamic variability of surf zones and beaches: a synthesis. Marine Geology 56, 93-118.

Yin, Y., Zhu, D.K., Martini, I. P., Tang, W.W., and Xu, Y.H., 2004. Application of ground-penetrating radar for barrier spit stratigraphic interpretation, Hainan Island, China. Journal of Coastal Research 43, 179-201.

Zietsman, I., 2004. Hydrodynamics of temporary open estuaries, with case studies of Mhlanga and Mdloti. Unpublished MSc Thesis, University of Natal, Durban, South Africa, p. 147.

Appendices

Appendix 1 Additional GPR lines from the Zinkwazi and Umdloti Barrier systems

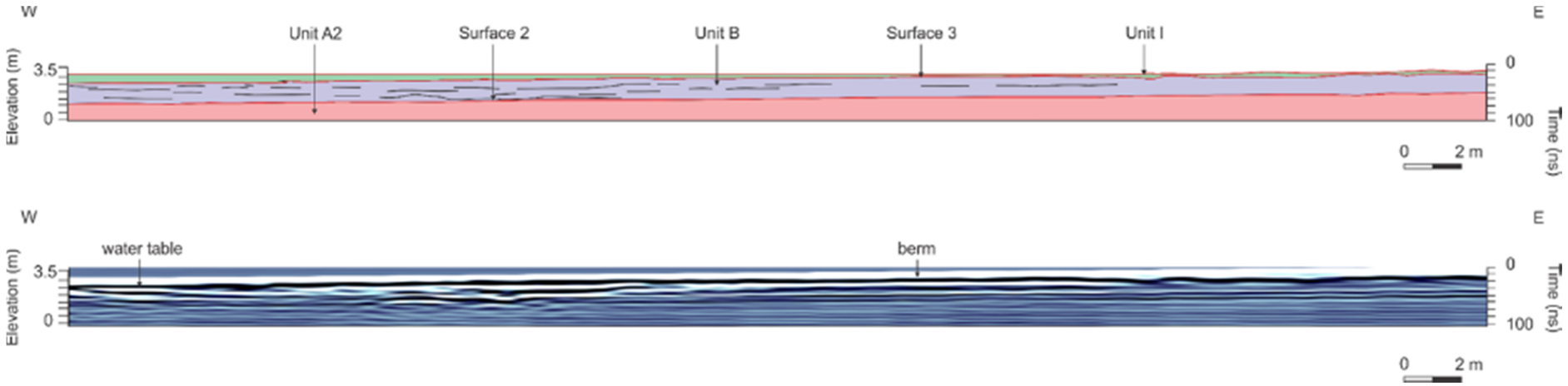


Figure 1. Shore-normal high frequency 200 MHz GPR cross section from the southern most sector line 68 of the Umdloti Barrier.

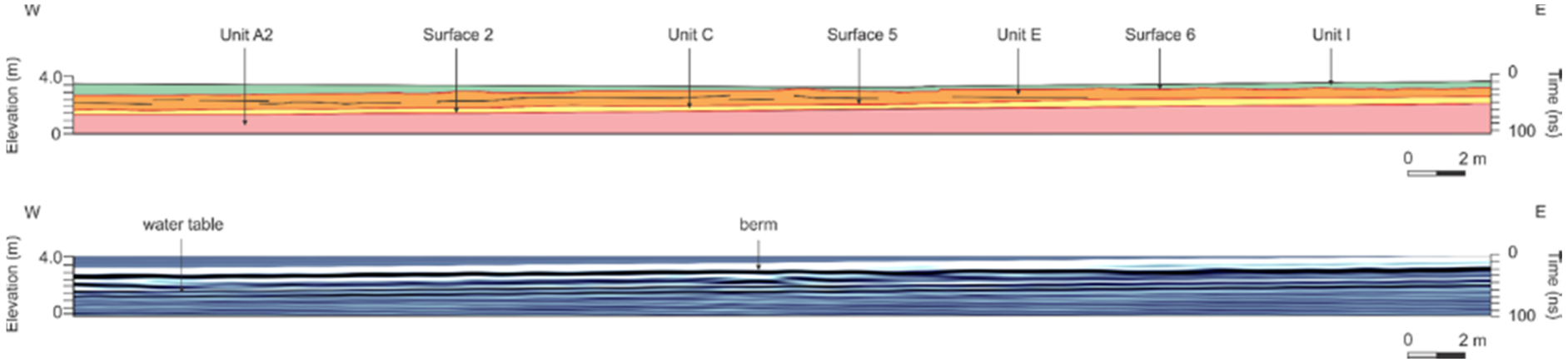


Figure 2. Shore-normal high frequency 200 MHz GPR cross section from the central sector line 70 of the Umdloti Barrier.

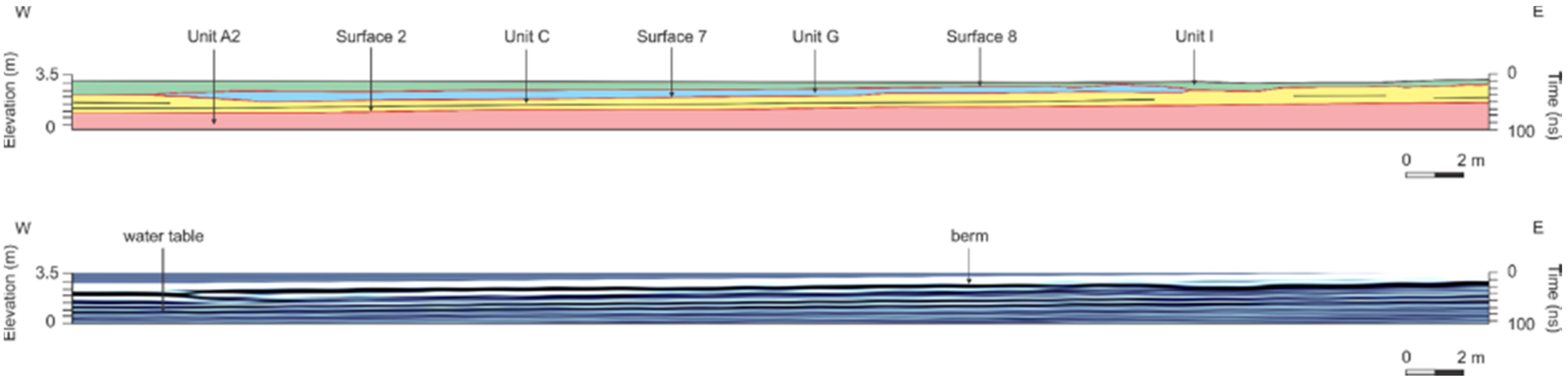


Figure 3. Shore-normal high frequency 200 MHz GPR cross section from the northern sector line 71 of the Umdloti Barrier.

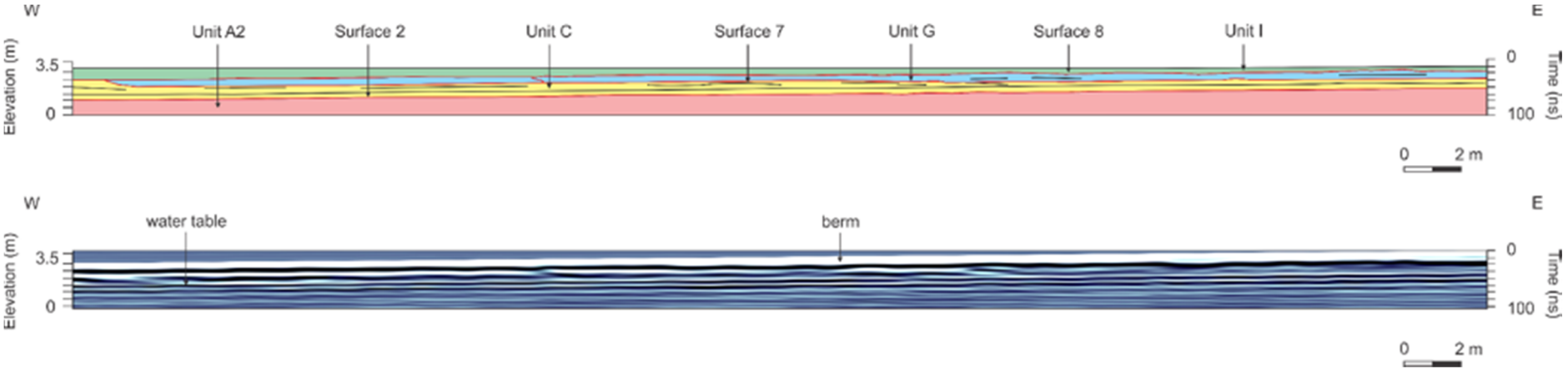


Figure 4. Shore-normal high frequency 200 MHz GPR cross section from the northern most sector line 72 of the Umdloti Barrier.

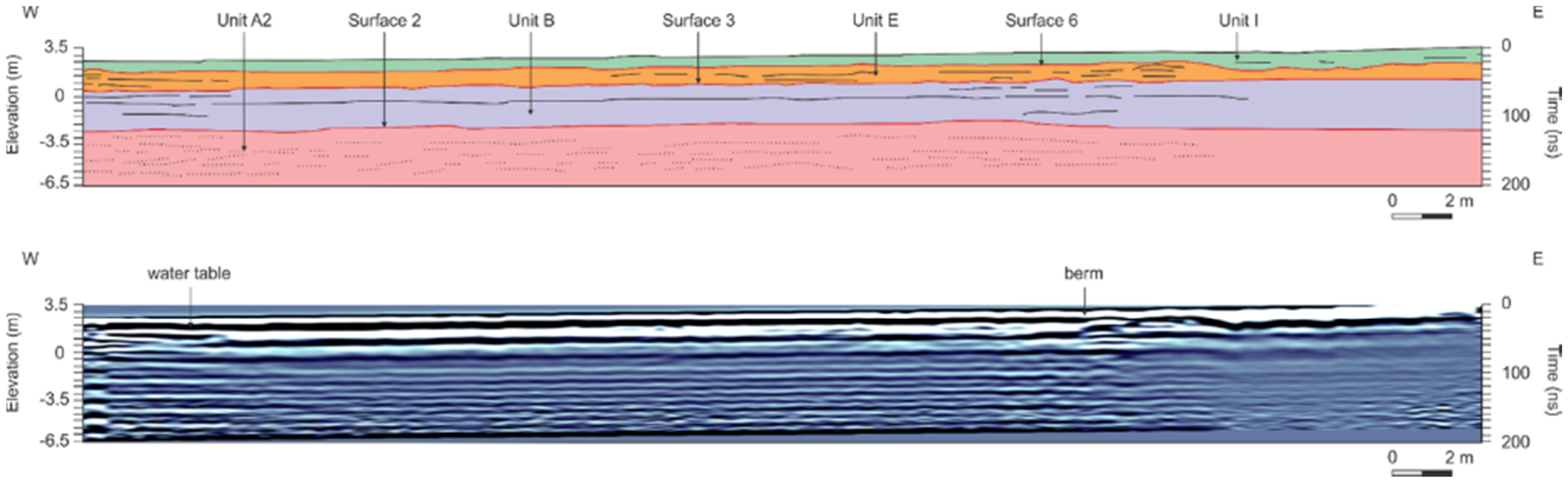


Figure 5. Shore-normal low frequency 100 MHz GPR cross section from the northern most sector line 40 of the Umdloti Barrier.

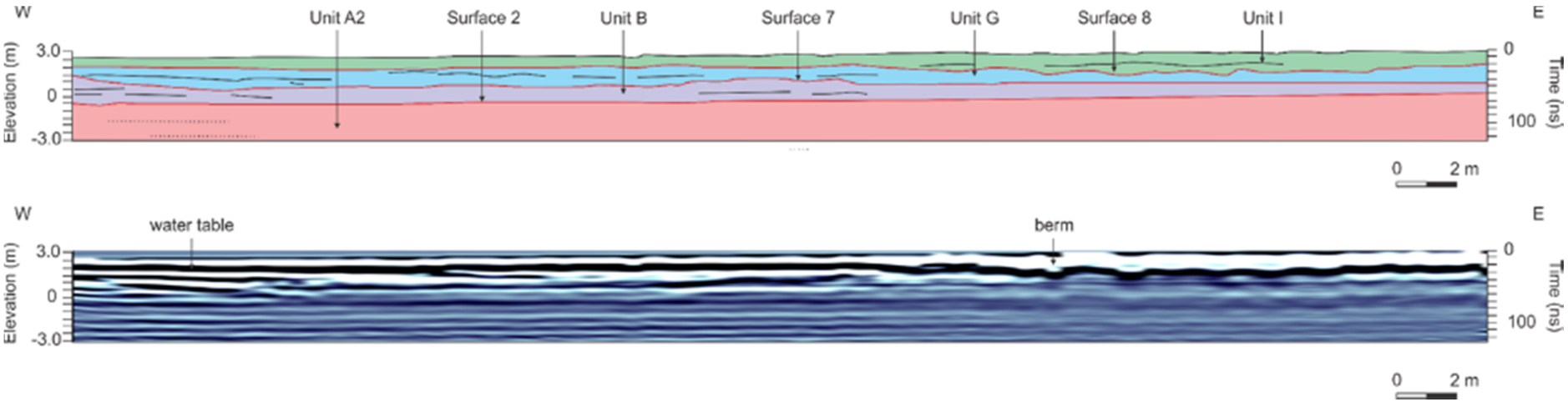


Figure 6. Shore-normal low frequency 100 MHz GPR cross section from the central sector line 42 of the Umdloti Barrier.

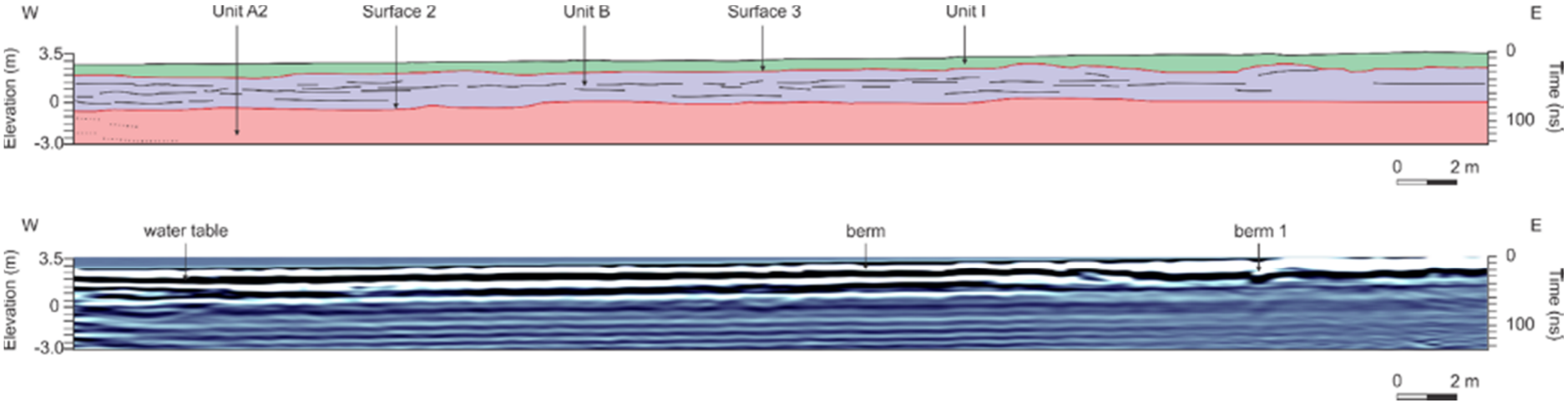


Figure 7. Shore-normal low frequency 100 MHz GPR cross section from the central sector line 43 of the Umdloti Barrier.

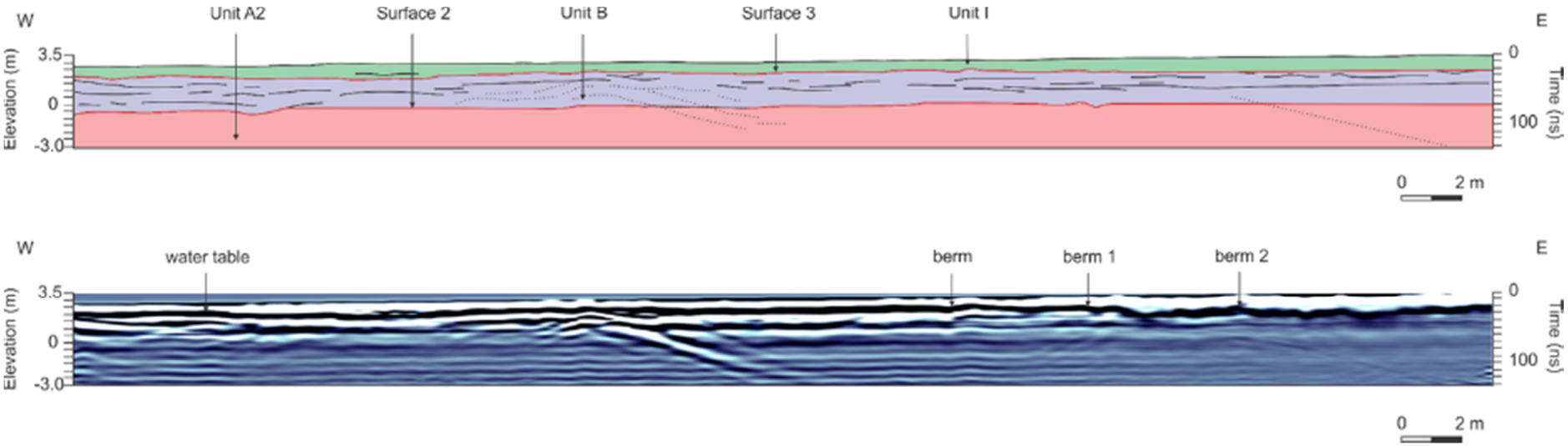


Figure 8. Shore-normal low frequency 100 MHz GPR cross section from the northern sector line 44 of the Umdloti Barrier.

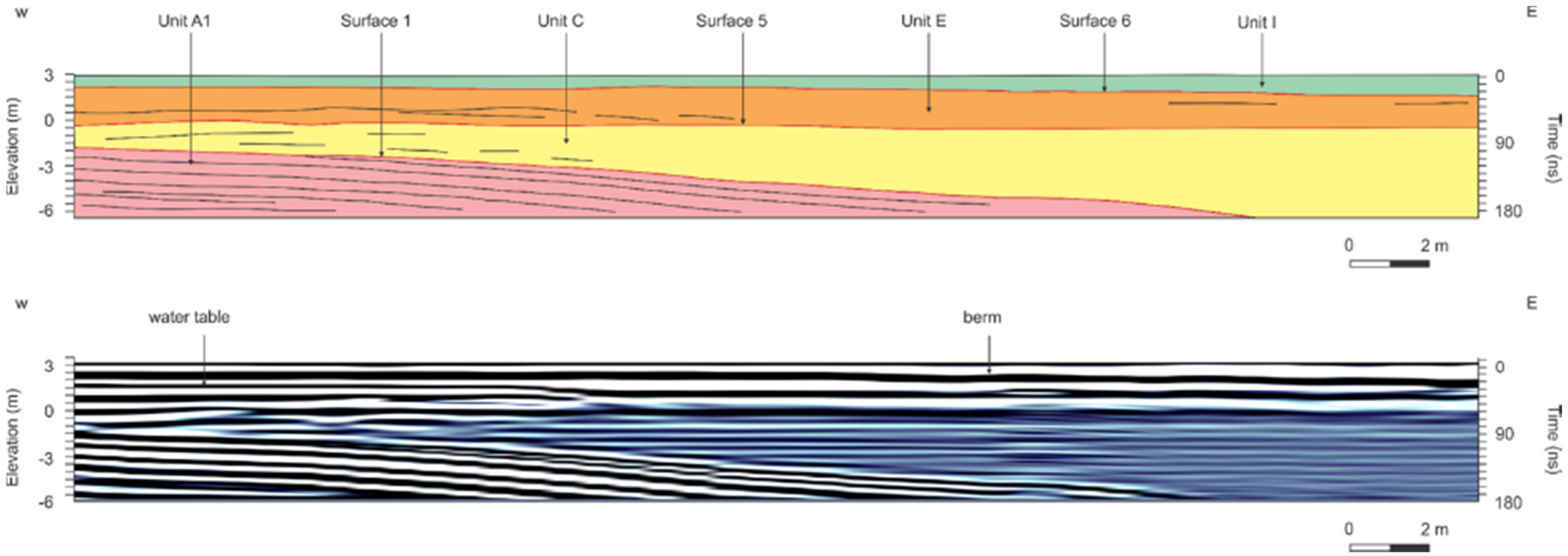


Figure 9. Shore-normal low frequency 100 MHz GPR cross section from the southern most sector line 61 of the Zinkwazi Barrier.

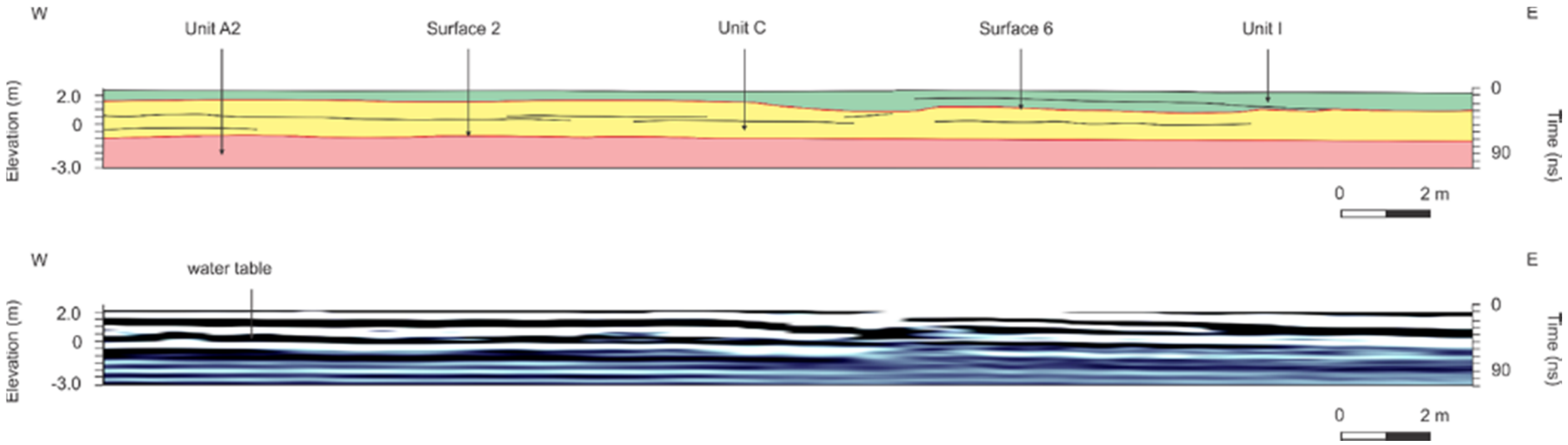


Figure 10. Shore-normal low frequency 100 MHz GPR cross section from the central sector line 63 of the Zinkwazi Barrier.

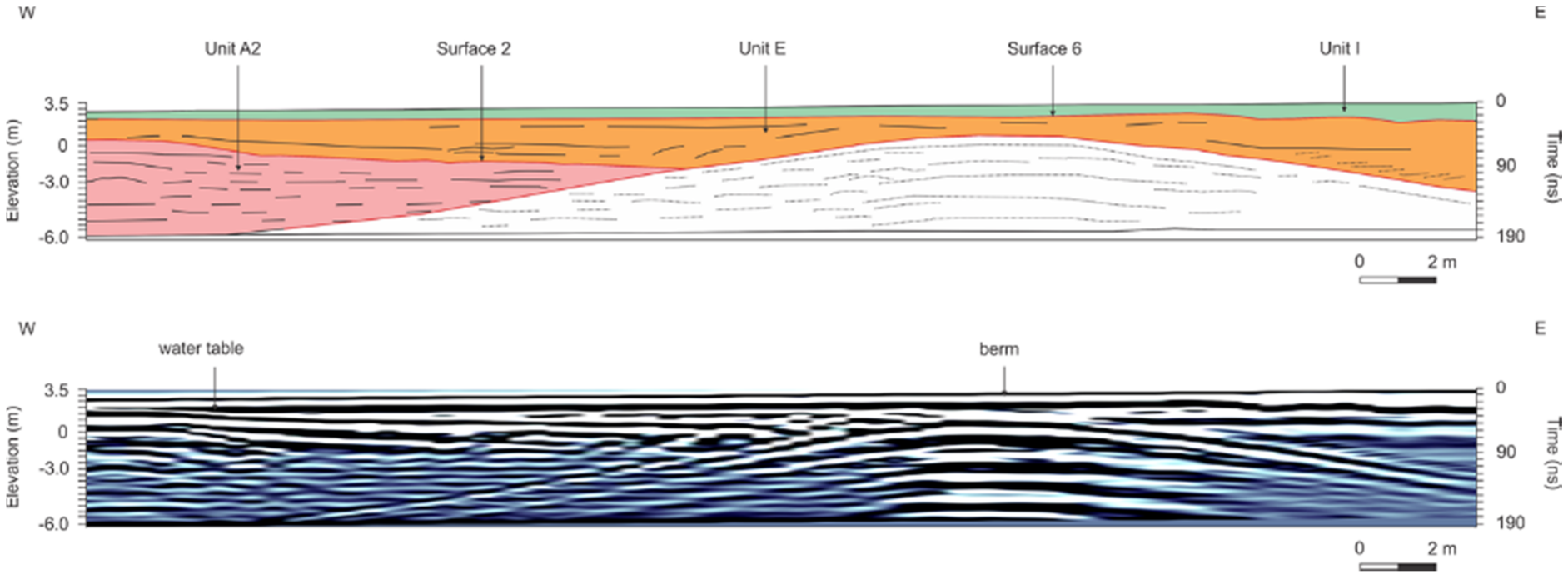


Figure 11. Shore-normal low frequency 100 MHz GPR cross section from the northern sector line 66 of the Zinkwazi Barrier.

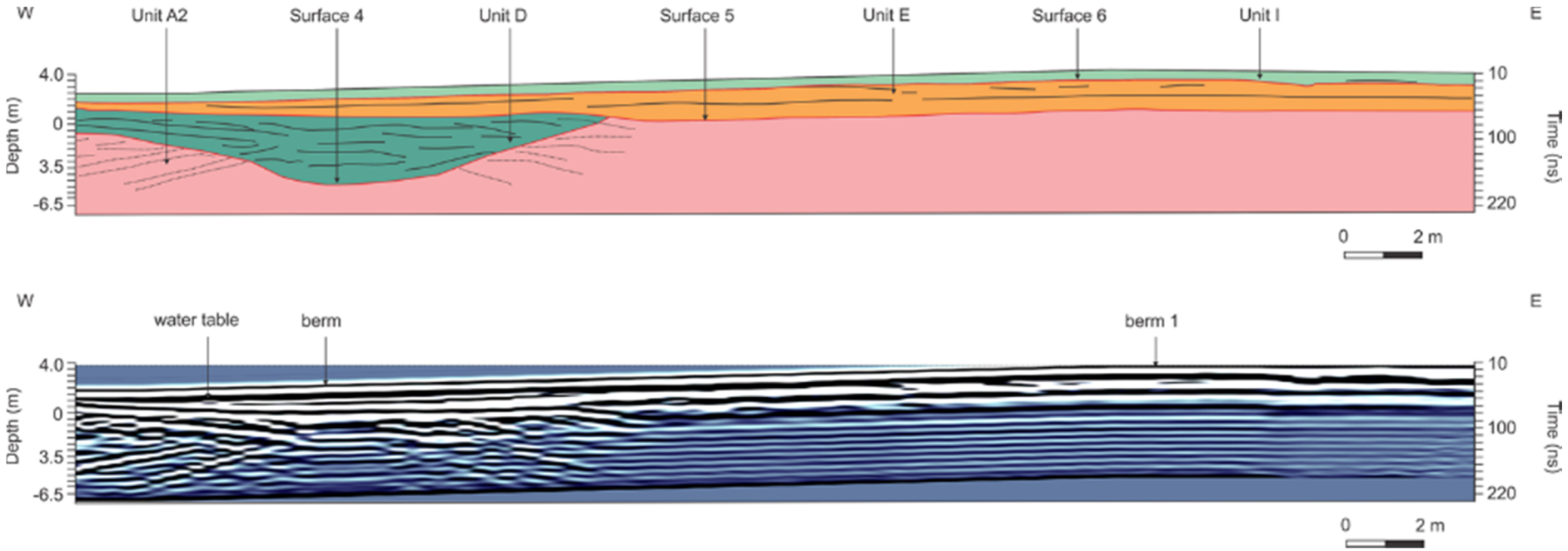


Figure 12. Shore-normal low frequency 100 MHz GPR cross section from the northern most sector line 65 of the Zinkwazi Barrier.

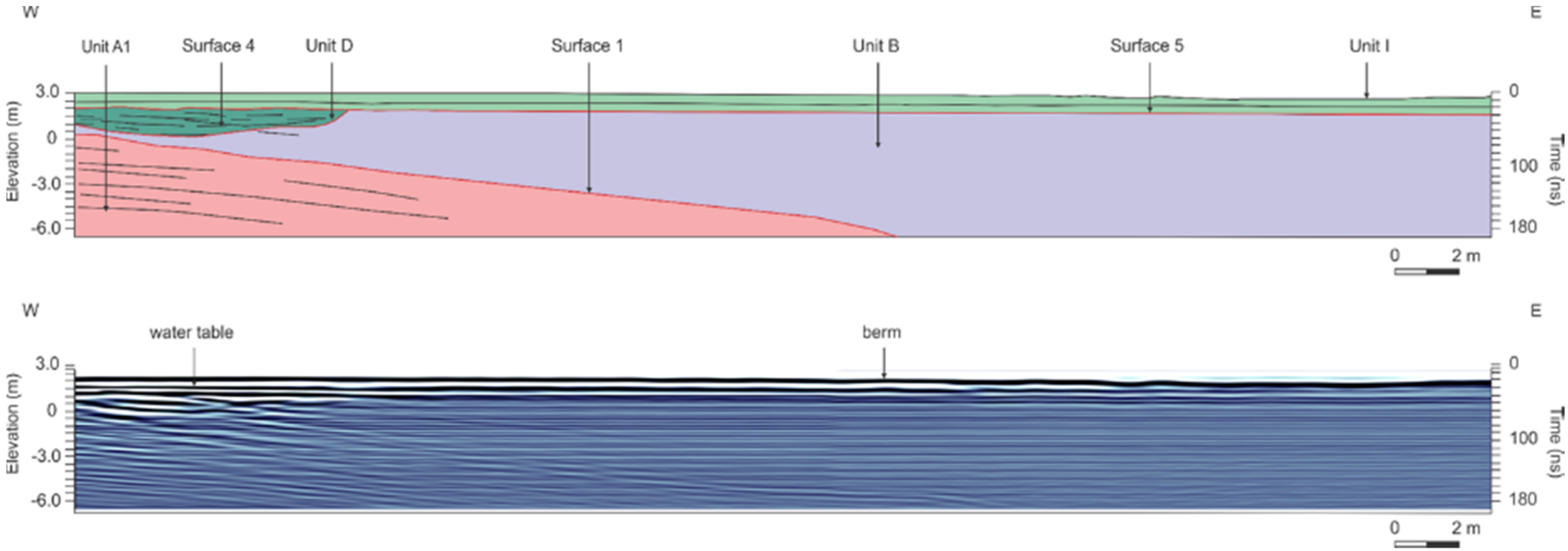


Figure 13. Shore-normal high frequency 200 MHz GPR cross section from the southern most sector line 51 of the Zinkwazi Barrier.

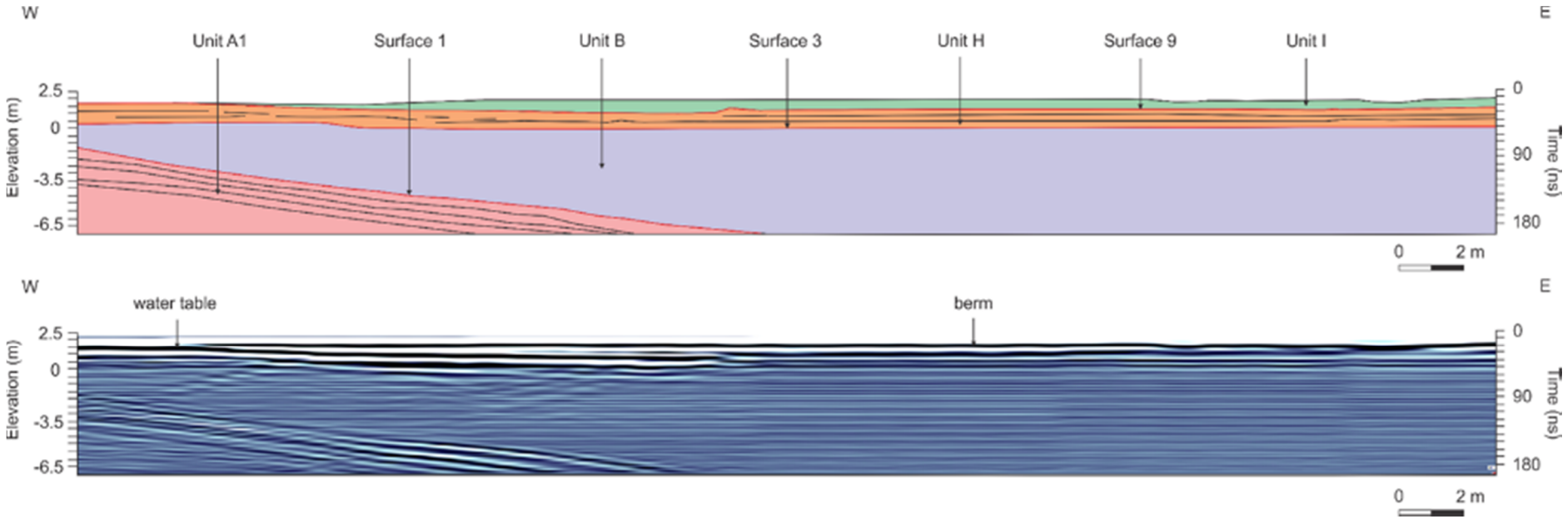


Figure 14. Shore-normal high frequency 200 MHz GPR cross section from the southern sector line 52 of the Zinkwazi Barrier.

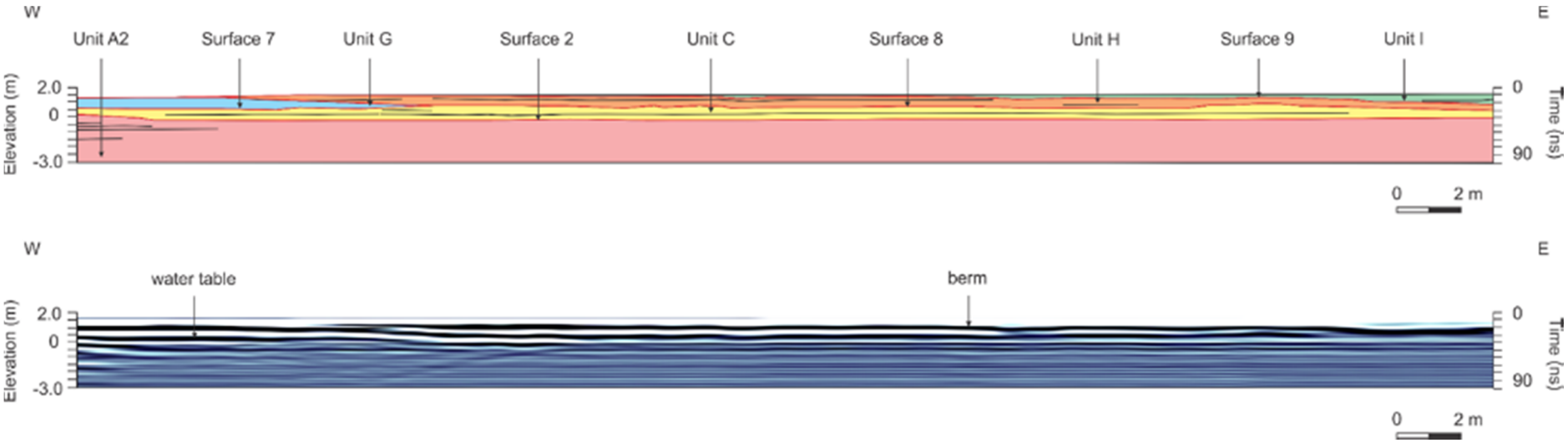


Figure 15. Shore-normal high frequency 200 MHz GPR cross section from the southern central sector line 53 of the Zinkwazi Barrier.

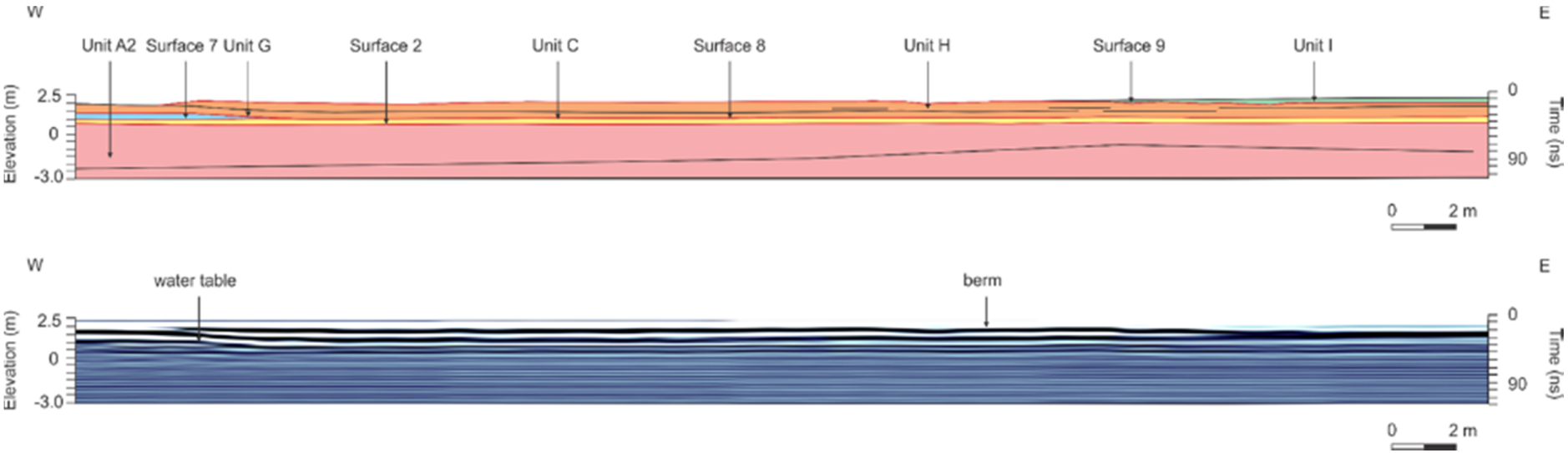


Figure 16. Shore-normal high frequency 200 MHz GPR cross section from the central sector line 54 of the Zinkwazi Barrier.

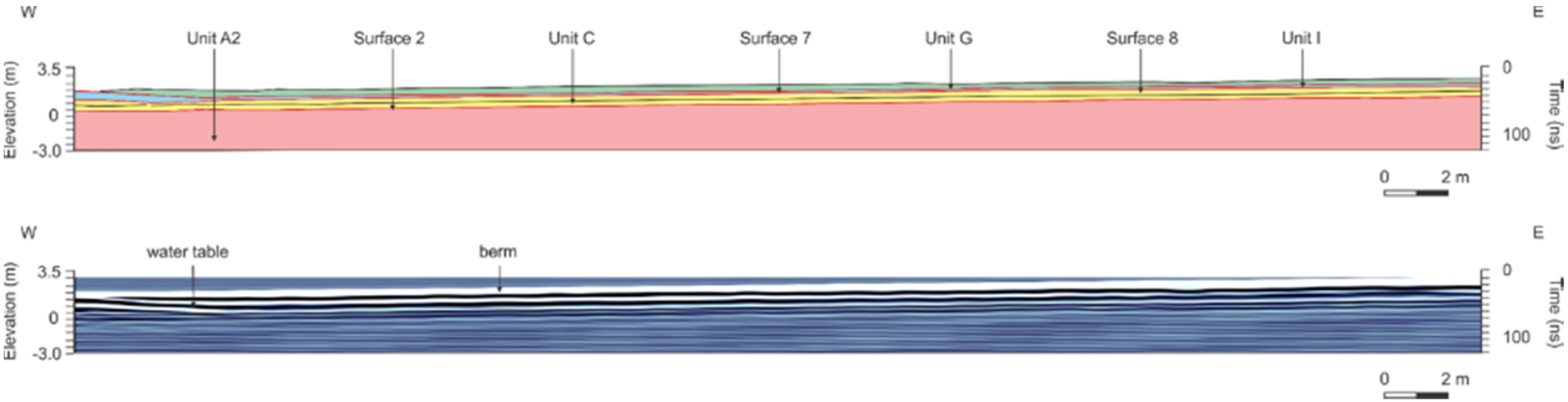


Figure 17. Shore-normal high frequency 200 MHz GPR cross section from the central sector line 55 of the Zinkwazi Barrier.

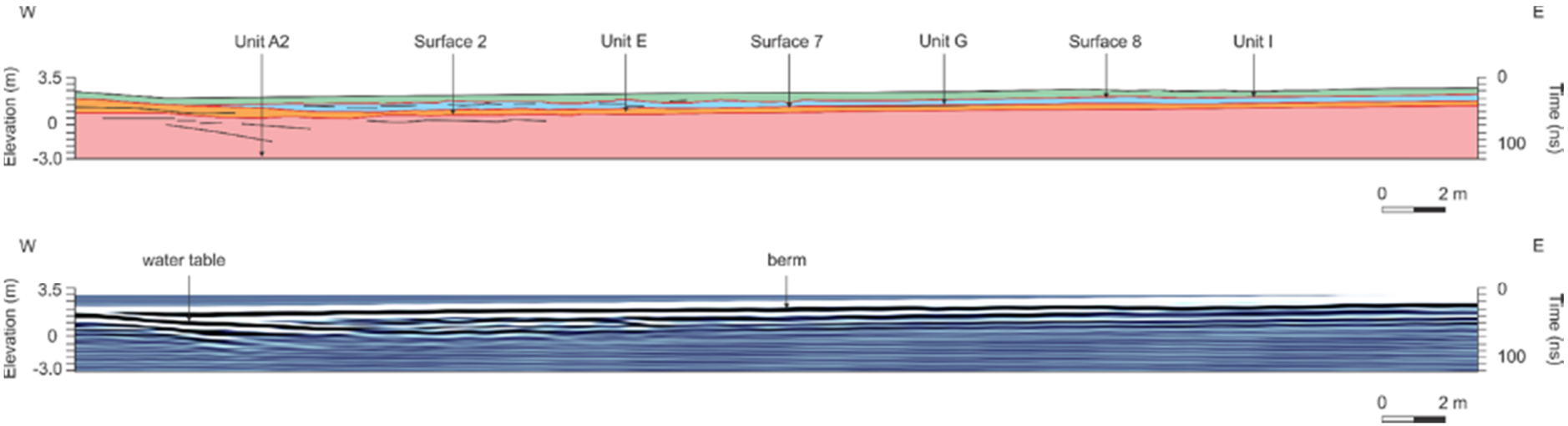


Figure 18. Shore-normal high frequency 200 MHz GPR cross section from the northern central sector line 56 of the Zinkwazi Barrier.

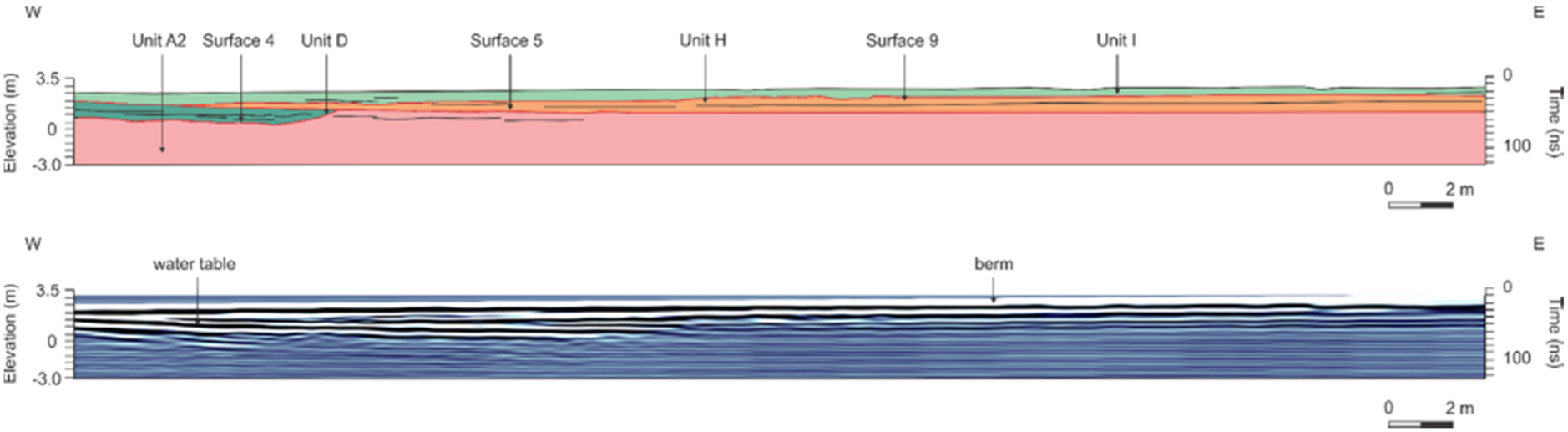


Figure 19. Shore-normal high frequency 200 MHz GPR cross section from the northern sector line 57 of the Zinkwazi Barrier.

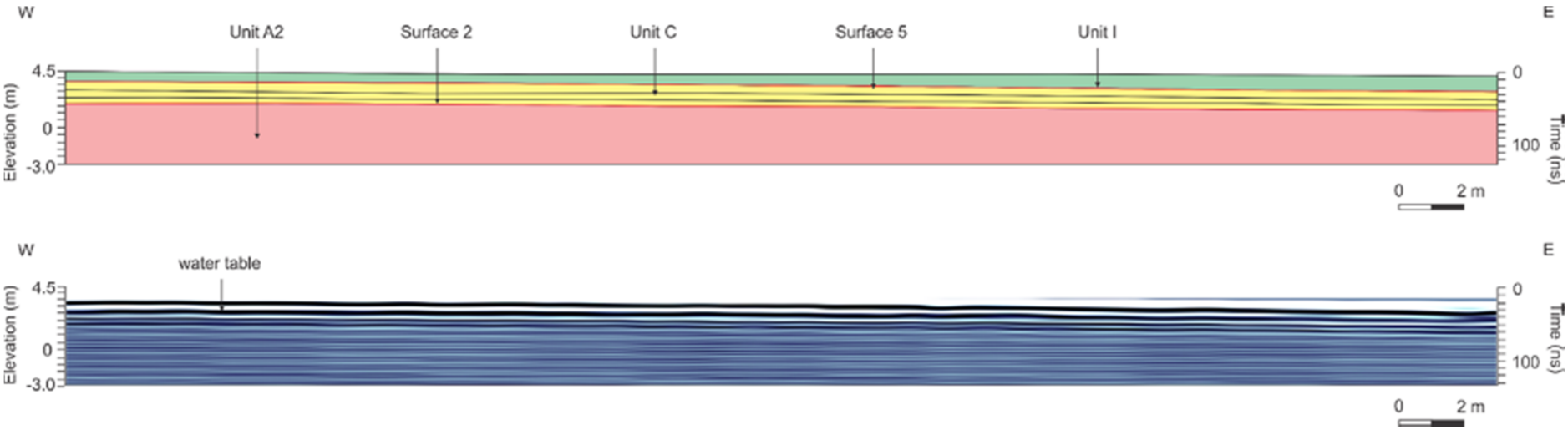


Figure 20. Shore-normal high frequency 200 MHz GPR cross section from the northern most sector line 59 of the Zinkwazi Barrier.