Geomorphic and stratigraphic signals of postglacial meltwater pulses on continental shelves

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ABSTRACT

Selective development and preservation of major shoreline complexes on the continental shelf provide geomorphic evidence in support of alternating periods of Holocene sea-level stillstand and rapid rise during meltwater pulses. On a tectonically stable far-field setting (the southeast African shelf), regionally developed, well-preserved shoreline complexes occur at ~–100 m and ~–60 m within an overall shelf sequence dominated by transgressive ravinement (non-preservation of shorelines). The development of geomorphically mature submerged shorelines with equilibrium forms is attributed to extended periods of sea-level stability, and their preservation is the result of early cementation followed by very rapid sea-level rise (several centimeters per year) that caused overstepping. Meltwater Pulses 1A and 1B are recorded in the shelf stratigraphy and geomorphology. Setting aside local influences of topography and sediment supply, we hypothesize that shelf stratigraphies should preferentially preserve shorelines at water depths associated with the stillstands or slowstands immediately preceding meltwater pulses. A reappraisal of shelf stratigraphy and geomorphology, in particular the preservation potential of former shorelines, is required in the light of contemporary understanding of postglacial sea-level history.

INTRODUCTION

The precise timing, and even the existence, of deglacial meltwater pulses associated with the deglacial–early Holocene transgression is still debated. Meltwater Pulse 1A (MWP1A) began ca. 14.6 ka, when global eustatic levels were ~100 m below present mean sea level during the Bølling-Allerød interstadial (Peltier and Fairbanks, 2006) (Fig. 1). During MWP1A, sea level rose ~16 m (26–53 mm/yr) with a peak ca. 13.8 ka (Stanford et al., 2011). There is still debate regarding the existence of Meltwater Pulse 1B (MWP1B). Following the Younger Dryas cold period, a distinct acceleration in sealevel rise from −58 m to −45 m ca. 11.3 ka at rates of 13–15 mm/yr during MWP1B (Fig. 1)

was described from several sites in Barbados (Liu and Milliman, 2004). This has not been corroborated by evidence from South Pacific coral reefs (Bard et al., 2010).

The preservation of shelf stratigraphic sequences inter alia also reflects the rate of sealevel rise (Locker et al., 1996; Kelley et al., 2010). However, key investigations of the nature of transgressive shelf stratigraphies are not framed in the context of meltwater pulses (e.g., Swift, 1968), despite preservation of the transgressive sequence being promoted by high sediment supply and rapid sea-level rise (Belknap and Kraft, 1981; Davis and Clifton, 1987). In subtropical areas early cementation of shorelines further enhances their preservation potential.

On the basis of more than 1000 km of seismic and ~500 km2 of swath bathymetric data, we examine the regional distribution of submerged shoreline features on the subtropical southeast African continental shelf (Fig. 2). We discuss their genesis and provide an as yet untested hypothesis regarding the implications of their preservation with respect to the late Pleistocene– Holocene sea-level record in general, and MWP1A and MWP1B in particular.

Regional Setting

The tectonically stable east coast of South Africa is characterized by a narrow shelf (with a shelf break at −100 m) that is 20 km wide off Durban and 5–10 km wide off northern Kwa- Zulu-Natal. Several submerged eolianite and beachrock barrier complexes record former shoreline positions (Green, 2009). The limitations of early single-beam echo-sounding sidescan sonar and seismic profiling, however, did not reveal the geomorphic context and interrelationships of these barriers. The shelf is affected by the Agulhas Current (Lutjeharms, 2006), and is exposed to a strong southerly swell. The average significant wave height offshore Durban is 1.8 m, and it is 1.5 m at Richards Bay (Moes and Rossouw, 2008). Durban and Richards Bay have average spring tidal ranges of 1.8 m and 1.84 m, respectively.

OBSERVATIONS AND INTERPRETATION

Durban Shelf

The Durban mid-shelf is characterized by a series of closely spaced drowned eolianite barriers, the bases of which are located at depths between 65 m and 50 m (Fig. 3A). A particularly prominent (5 m vertical relief) coast-parallel, linear barrier fronts the entire complex between −60 m and −65 m. The most landward barriers occur at −50 m and compose a series of linear, coast-parallel ridges of lower relief (0.5–1 m).

Between the most seaward and landward barriers, a series of prograded ridges developed with varying orientations. These become oriented at progressively higher angles to the major barrier shorelines before developing into cuspate features comprising several small prograding ridges. These segment the seafloor between the major shoreline barriers into several semicircular seafloor depressions ~400 m wide. At depths of 100 m, an acoustically reflective ridge either crops out or is partially buried by modern sediment. This ridge is laterally continuous over 30 km off Durban, is oriented parallel to the coast, and has a relief of 10 m (Fig. 3B).

The Durban mid-shelf ridges are interpreted as a series of prograded barrier shorelines that segmented a paleolagoon complex. The lagoon formed behind a prominent barrier complemarked by the most seaward and prominent coast-parallel eolianite ridge and its segmented plan form is similar to features observed along the contemporary coast (Green et al., 2013).

Segmentation evidently proceeded by the formation of barriers produced in the course of reworking of the lagoonal shoreline by wind-generated waves (Ashton et al., 2009). To achieve this, sea level must have remained stable for some time. A prolonged stillstand is also suggested by the cementation of the barrier sands and barrier progradation. Preservation of the system during subsequent transgression on this high-energy shelf suggests a subsequent rapid sea-level rise. A similar shoreline interpretation is made for the eolianite features (cf. Martin and Flemming, 1988) of the ~100-m-deep ridge.

Richards Bay Shelf

The Richards Bay mid-shelf is characterized by a prominent, laterally extensive coastparallel barrier (10–12 m relief) of eolianite and/or beachrock at a depth of 60 m (Fig. 4A). The barrier is continuous over the 10-km-long survey area, forming a crenulate plan shape. At 100 m depth, a high-relief (8 m) coast-parallel ridge is present. The ridge is indented by several depressions ~180 m long and ~90 m wide (Fig. 4B).

The Richards Bay mid-shelf example is interpreted as a shoreline that developed when relative sea level was at −60 m. Its crenulated planform is identical in scale and morphology to the adjacent contemporary shoreline (Fig. 4). It signifies equilibrium between sediment supply and wave regime (Carter, 1988) and suggests that sea level was stable for some time. The cementation points to sea-level stability. Preservation on the shelf during transgression suggests rapid sea-level rise with barrier overstepping.

The linear morphological feature on the outer shelf is also interpreted as a former barrier shoreline. The scales and orientations of the indentations in the ridge are similar to the climbing parabolic dunes observed along the modern barrier shoreline complex of northern KwaZulu- Natal. Such features point to planform equilibrium conditions. The degree of preservation of the dune features in a sandy barrier suggests cementation during a period of stable sea level followed by rapid overstepping of the shoreline. Northern KwaZulu-Natal Shelf

Seismic profiles from the northern KwaZulu- Natal shelf reveal several buried ridge complexes beneath the unconsolidated Holocene highstand sediment wedge (Figs. 5A and 5B). These coast-parallel and acoustically opaque and/or chaotic ridges have substantial relief (2–10 m) and have been mapped along ~80 km of coastline at consistent depths of 100 m (Fig. 5C) and between 55 m and 65 m. The latter ridges mark an abrupt change in relief from the underlying platform. The seaward platform is typically smooth and dips ~0.2° seaward. The outer ridges line the shelf break and commonly penetrate the Holocene sediment cover (Fig. 5C). The modern continental slope commences seaward of these features.

Like the Durban outer shelf examples, the buried ridges of northern KwaZulu-Natal are interpreted as drowned shoreline features composed of eolianite and beachrock (cf. Green and Uken, 2005). The gently sloping platform seaward of the shallower features is interpreted to represent a marine ravinement surface formed during slowly rising sea level (e.g., Trenhaile, 2002). These features are consistent with a sealevel stillstand or slowstand between −60 m and −65 m. Similarly, the outer shelf ridges represent a former shoreline at a depth of ~100 m. In both cases, their preservation during subsequent transgression was aided by cementation, although a rapid rise of sea level must also be invoked. Throughout the study area, the two shorelines are separated by a regionally developed bioclastic gravel pavement (Flemming, 1978). This relic tpavement with its bioclastic lag deposits is considered to be the surface expression of the Holocene ravinement process (Green, 2009).

DISCUSSION

Barriers respond to sea-level rise by erosion, translation, or overstepping (Carter, 1988). Gravel barriers are most commonly preserved as relict seafloor morphologies due to their longer relaxation times and their resistance to dispersal by ravinement processes (Orford and Carter, 1995; Mellett et al., 2012).

The submerged shorelines reported here at −100 m and −60 m occur along at least ~400 km of the KwaZulu-Natal coastline and have also been recorded intermittently on the South African shelf farther south and on the Agulhas Bank (Martin and Flemming, 1986, 1987). These overlie several incised valley complexes associated with the Last Glacial Maximum (Green et al., 2013). Their preservation by in situ drowning is primarily a factor of rapid sea-level rise, enhanced by early cementation of the shoreline complexes (Cooper, 1991). Especially rapid phases in sea-level rise associated with glacial meltwater pulses create ideal conditions for enhanced shoreline preservation on the shelf (Storms et al., 2008). The depths of the drowned shorelines reported here coincide with eustatic sea levels immediately preceding MWP1A and MWP1B. A period of slow sea-level change immediately preceding MWP1A has been linked to submerged shorelines elsewhere (e.g., Zecchin et al., 2011).

The −60 m shoreline has not been linked as clearly, but Liu and Milliman (2004) considered the onset of accelerated sea-level rise to occur from a depth of 58 m. Several records of global sea level indicate a slow rate of sea-level rise prior to this period (e.g., Liu and Milliman, 2004). The formation of equilibrium shoreline complexes is consistent with static or slowly rising sea level. These were then overstepped by rapid sea-level rise associated with the −58 to −40 m rise in sea level of MWP1B. We acknowledge that dates would further bolster this model; however, we consider the following argument as strong support for this hypothesis pending a sampling and dating program. The southeast African shelf stratigraphy reflects the profound influence of meltwater pulses and intervening periods of slow sea-level rise.

The two shoreline complexes are separated by a prominent ravinement surface produced during an intermediate rate of sea-level rise. This feature points to slow rates of shoreface ravinement (e.g., Cattaneo and Steel, 2003). The contemporary barrier in northern KwaZulu-Natal formed over a minimum of ~1.5 k.y. of slowly rising or steady sea level (Botha and Porat, 2007). This is consistent with the 2.5 ka slowstand of Liu and Milliman (2004) that preceded overstepping. Cementation on modern shorelines can occur within ~75 yr (Cawthra and Uken, 2012). An averaged rate of 18 m rise in sea level over 300 yr (6 cm/yr) (cf. Liu and Milliman, 2004) enabled barrier overstepping.

We suggest that preferential submerged shoreline preservation at depths immediately preceding meltwater pulses may be a global phenomenon. A −100 m shoreline has been documented in Florida (USA; Gardner et al., 2007), along the Calabrian coast (Italy; Zecchin et al., 2011), the Rhone Delta

(Germany; Berné et al., 2007), and on the Indian continental shelf (Wagle et al., 1994). A former shoreline at ~−60 m occurs for 500 km along the northeast Gulf of Mexico shelf, ranging from 51 to 65 m water depth (Gardner et al., 2007). Other −60 m shorelines exist on the Calabrian margin (Zecchin et al., 2011), the Great Barrier Reef (Australia; Carter et al., 1986; Carter and Johnson, 1986), South Island, New Zealand (Carter et al., 1986), the Red Sea (Bailey et al., 2007), the Japan Sea (Korotkii, 1985), and the east and west Indian shelves (Bandyopadhyay, 2008; Wagle et al., 1994). Hearty et al. (2010) correlated two periods of ooid formation on Hawaii with the slowing of sea-level rise immediately preceding MWP1A and MWP1B.

The distribution of submerged shoreline indicators at depths commensurate with conditions immediately preceding MWP1A and MWP1B spans both hemispheres and points to global episodes of shoreline stabilization followed by overstepping during subsequent meltwater pulses. This stepped sea-level history is likely to favor preferential shoreline preservation at depths commensurate with the onset of meltwater pulses, setting aside the local variability introduced by sediment supply and topography. Holocene stratigraphy on shelves worldwide is therefore likely to reflect preferential shoreline preservation at specific depths dictated by eustasy and local isostatic factors. Despite the lack of ground-truth data and dating, this hypothesis seems convincing in light of the overall global match in depths of other submerged shorelines.

CONCLUSIONS

Drowned shorelines on the eastern continental shelf of South Africa formed during a period of sea-level stillstand or slowstand. The equilibrium planforms and cementation of these shorelines reflect a period of regional shoreline stability. The depths at which they occur correspond to eustatic sea level immediately prior to MWP1A and MWP1B. The shoreline planforms are remarkably well preserved, a result of both early cementation and shoreline overstepping. Submerged shoreline preservation and shelf stratigraphy worldwide is likely to reflect this stepped sea-level history. Pending the acquisition of valid dates, this is a hypothesis that can be tested on other global examples of submerged shorelines at similar depths.

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REFERENCES CITED

Ashton, A.D., Murray, A.B., Littlewood, R., Lewis, D.A., and Hong, P., 2009, Fetch-limited selforganization of elongate water bodies: Geology, v. 37, p. 187–190, doi:10.1130/G25299A.1.

Bailey, G.N., Flemming, N.C., King, G.C.P., Lambeck, K., Momber, G., Moran, L.J., Al-Sharekh, A., and Vita-Finzi, C., 2007, Coastlines, submerged landscapes, and human evolution: The Red Sea Basin and the Farasan Islands: Journal of Island and Coastal Archaeology, v. 2, p. 127– 160, doi:10.1080/15564890701623449.

Bandyopadhyay, A., 2008, Records of sea level change and realignment of Indian coasts during last glacial rebound in continental shelves during the last glacial cycle: Knowledge and applications: Proceedings, Workshop on IGCP 464, Visakhapatnam, March 2005: Kolkota, Geological Survey of India, p. 146–153.

Bard, E., Hamelin, B., and Delanghe-Sabatier, D., 2010, Deglacial meltwater pulse 1B and Younger Dryas revisited with new boreholes from Tahiti: Science, v. 327, p. 1235–1237, doi: 10.1126/science.1180557.

Belknap, D.F., and Kraft, J.C., 1981, Preservation potential of transgressive coastal lithosomes on the US Atlantic shelf: Marine Geology, v. 42, p. 429–442, doi:10.1016/0025-3227(81)90173-0.

Berné, S., Jouet, G., Bassetti, M.A., Dennielou, B., and Taviani, M., 2007, Late Glacial to Preboreal sealevel rise recorded by the Rhône deltaic system (NW Mediterranean): Marine Geology, v. 245, p. 65–88, doi:10.1016/j.margeo.2007.07.006.

Botha, G.A., and Porat, N., 2007, Soil chronosequence development in dunes on the southeast African coastal plain, Maputaland, South Africa: Quaternary International, v. 162–163, p. 111–132, doi:10.1016/j.quaint.2006.10.028.

Carter, R.M., and Johnson, D.P., 1986, Sea-level controls on the post-glacial development of the Great Barrier Reef, Queensland: Marine Geology, v. 71, p. 137–164, doi:10.1016/0025-3227 (86)90036-8.

Carter, R.M., Carter, L., and Johnson, D.P., 1986, Submergent shorelines in the SW Pacific: Evidence for an episodic post-glacial transgression: Sedimentology, v. 33, p. 629–649, doi:10.1111/j.1365-3091.1986.tb01967.x.

Carter, R.W.G., 1988, Coastal environments: An introduction to the physical, ecological and cultural systems of coastline: London, Elsevier, 617 p.

Cattaneo, A., and Steel, R.J., 2003, Transgressive deposits: A review of their variability: Earth-Science Reviews, v. 62, p. 187–228, doi:10.1016/S0012-8252(02)00134-4.

Cawthra, H.C., and Uken, R., 2012, Modern beachrock formation in Durban, KwaZulu-Natal: South African Journal of Science, v. 108, p. 1–5, doi:10.4102/sajs.v108i7/8.935.

Cooper, J.A.G., 1991, Beachrock formation in low latitudes: Implications for coastal evolutionary models: Marine Geology, v. 98, p. 145–154, doi:10.1016/0025-3227(91)90042-3.

Davis, R.A., and Clifton, H.E., 1987, Sea-level change and the preservation potential of wave-dominated and tide-dominated coastal sequences, in Nummedal, D., et al., eds., Sea-level fluctuation and coastal evolution: Society of Economic Paleontologists and Mineralogists Special Publication 41, p. 167–178, doi:10.2110/pec.87.41.0167.

Fairbanks, R.G., 1989, A 17,000-year glacio-eustatic sea level record: Influence of glacial melting rates on the Younger Dryas event and deepocean circulation: Nature, v. 342, p. 637–642, doi:10.1038/342637a0.

Flemming, B.W., 1978, Underwater sand dunes along the southeast African continental margin—Observations and implications: Marine Geology, v. 26, p. 177–198, doi:10.1016/0025-3227 (78)90059-2.

Gardner, J.V., Calder, B.R., Hughes Clark, J.E., Mayer, L.A., Elston, G., and Rzhanov, Y., 2007, Drowned shelf-edge deltas, barrier islands and related features along the outer continental shelf north of the head of De Soto Canyon, NE Gulf of Mexico: Geomorphology, v. 89, p. 370–390, doi:10.1016/j.geomorph.2007.01.005.

Green, A.N., 2009, Sediment dynamics on the narrow, canyon-incised and current-swept shelf of the northern KwaZulu-Natal continental shelf, South Africa: Geo-Marine Letters, v. 29, p. 201–219, doi:10.1007/s00367-009-0135-9.

Green, A.N., and Uken, R., 2005, First observations of sea level indicators related to glacial maxima at Sodwana Bay, KwaZulu-Natal: South African Journal of Science, v. 101, p. 236–238.

Green, A.N., Cooper, J.A.G., Leuci, R., and Thackeray, Z., 2013, Formation and preservation of an overstepped segmented lagoon complex on a high-energy continental shelf: Sedimentology, doi:10.1111/sed.12054.

Hearty, P.J., Webster, J.M., Clague, D.A., Kaufman, D.S., Bright, J., Southon, J., and Renema, W., 2010, A pulse of ooid formation in Maui Nui (Hawaiian Islands) during Termination 1: Marine Geology, v. 268, p. 152–162, doi:10.1016/j .margeo.2009.11.007.

Kelley, J.T., Belknap, D.F., and Claesson, S., 2010, Drowned coastal deposits with associated archaeological remains from a sea-level “slowstand”: Northwestern Gulf of Maine, USA: Geology, v. 38, p. 695–698, doi:10.1130/G31002.1.

Korotkii, A.M., 1985, Quaternary sea-level fluctuations on the northwestern shelf of the Japan Sea: Journal of Coastal Research, v. 1, p. 293–298.

Liu, J.P., and Milliman, J.D., 2004, Reconsidering melt-water pulses 1A and 1B: Global impacts of rapid sea-level rise: Journal of Ocean University of China, v. 3, p. 183–190, doi:10.1007/s11802-004-0033-8.

Locker, S.D., Hine, A.C., Tedesco, L.P., and Shinn, E.A., 1996, Magnitude and timing of episodic sea-level rise during the last deglaciation: Geology, v. 24, p. 827–830, doi:10.1130/0091-7613 (1996)024<0827:MATOES>2.3.CO;2.

Lutjeharms, J.R.E., 2006, The Agulhas Current: Berlin, Springer-Verlag, 329 p.

Martin, A.K., and Flemming, B.W., 1986, The Holocene shelf sediment wedge off the south and east coasts of South Africa, in Knight, R.J., and McLean, J.R., eds., Shelf sands and sandstones: Canadian Society of Petroleum Geologists Memoir 11, p. 27–44.

Martin, A.K., and Flemming, B.W., 1987, Aeolianites of the South African coastal zone and continental shelf as sea-level indicators: South African Journal of Science, v. 83, p. 597–598.

Martin, A.K., and Flemming, B.W., 1988, Physiography, structure and geological evolution of the Natal Continental Shelf, in Schumann, E.H., ed., Coastal ocean studies off Natal, South Africa: Lecture Notes on Coastal and Estuarine Studies 26: New York, Springer-Verlag, p. 11– 46, doi:10.1029/LN026p0011.

Mellett, C.L., Hodgson, D.M., Lang, A., Mauz, B., Selby, I., and Plater, A.J., 2012, Preservation of a drowned gravel barrier complex: A landscape evolution study from the north-eastern English Channel: Marine Geology, v. 315–318, p. 115– 131, doi:10.1016/j.margeo.2012.04.008.

Moes, H., and Rossouw, M., 2008, Considerations for the utilization of wave power around South Africa: Workshop on Ocean Energy: Stellenbosch, South Africa, University of Stellenbosch, Centre for Renewable and Sustainable Energy Studies, Abstracts, p. 46.

Orford, J.D., and Carter, R.W.G., 1995, Examination of mesoscale forcing of a swash-aligned, gravel barrier from Nova Scotia: Marine Geology, v. 126, p. 201–211, doi:10.1016/0025-3227(95)00078-D.

Peltier, W.R., and Fairbanks, R.G., 2006, Global glacial ice volume and Last Glacial Maximum duration from an extended Barbados sea level record: Quaternary Science Reviews, v. 25, p. 3322– 3337, doi:10.1016/j.quascirev.2006.04.010.

Stanford, J.D., Hemingway, R., Rohling, E.J., Challenor, P.G., Medina-Elizalde, M., and Lester, A.J., 2011, Sea-level probability for the last deglaciation: A statistical analysis of far-fi eld records: Global and Planetary Change, v. 79, p. 193–203, doi:10.1016/j.gloplacha.2010.11.002.

Storms, J.E.A., Weltje, G.J., Terra, G.J., Cattaneo, A., and Trincardi, F., 2008, Coastal dynamics under conditions of rapid sea-level rise: Late Pleistocene to early Holocene evolution of barrierlagoon systems on the northern Adriatic shelf (Italy): Quaternary Science Reviews, v. 27, p. 1107–1123, doi:10.1016/j.quascirev.2008.02.009.

Swift, D.J.P., 1968, Coastal erosion and transgressive stratigraphy: Journal of Geology, v. 76, p. 444–456, doi:10.1086/627342.

Trenhaile, A.S., 2002, Rocky coasts, with particular emphasis on shore platforms: Geomorphology, v. 48, p. 7–22, doi:10.1016/S0169-555X(02)00173-3.

Wagle, B.G., Vora, K.H., Karisiddaiah, S.M., Veerayya, M., and Ahneida, F., 1994, Holocene submarine terraces on the western continental shelf of India; implications for sea-level changes: Marine Geology, v. 117, p. 207–225, doi:10.1016/0025-3227(94)90016-7.

Zecchin, M., Ceramicola, S., Gordini, E., Deponte, M., and Critelli, S., 2011, Cliff overstep model and variability in the geometry of transgressive erosional surfaces in high-gradient shelves: The case of the Ionian Calabrian margin (southern Italy): Marine Geology, v. 281, p. 43–58, doi:10.1016/j.margeo.2011.02.003.

Figures

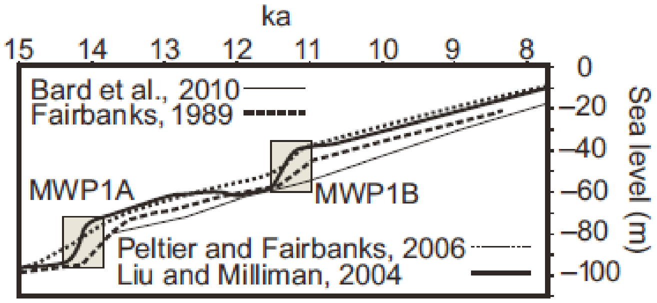

Figure 1. Holocene sea-level curves depicting timing and depth intervals for Melt water Pulses (MWP) 1A and 1B.

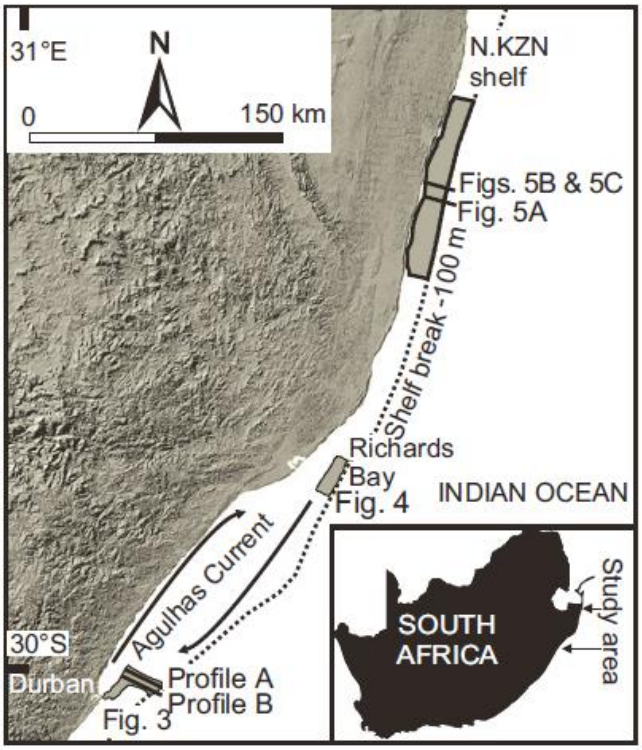

Figure 2. Locality map detailing study sites and extent of shoreline features (gray blocks). N.KZN—northern KwaZulu-Natal (South Africa).

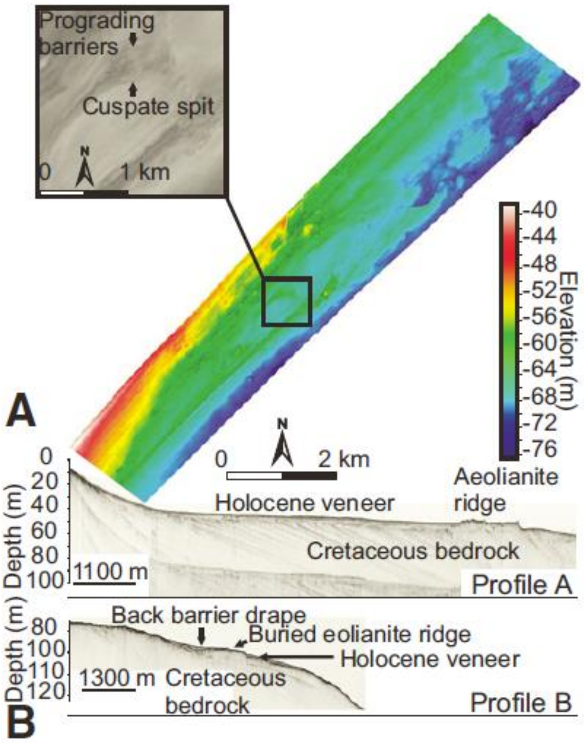

Figure 3. A: Seafloor bathymetry of Durban (South Africa) mid-outer shelf detailing drowned eolianite barriers at depths between 65 m and 50 m (see Fig. 2 for location). Note segmented appearance of seafloor, orientation of major barrier shorelines at progressively higher angles, and prograded ridges on each cuspate feature. B: Singlechannel seismic reflection profiles A and B showing partially buried eolianite ridge in water depths of ~60 m and 100 m (lines ~15 km north of multibeam set).

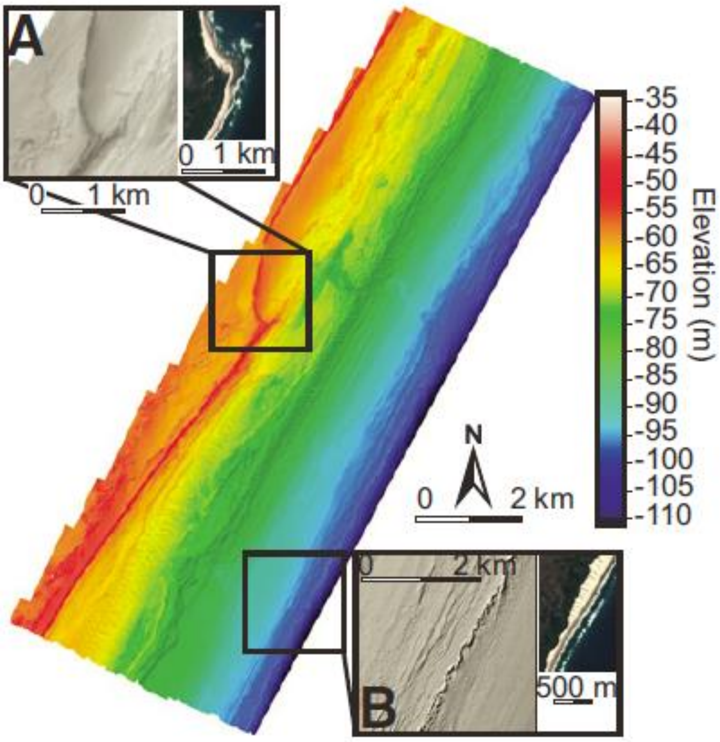

Figure 4. Seafloor bathymetry of Richards Bay (South Africa) mid-outer continental shelf (see Fig. 2 for location). Note two eolianite barriers at 60 m and 100 m depths. A: Inset depicting crenulate nature of the −60 m barrier as compared to contemporary example. B: Indented –100 m ridge compared with modern climbing parabolic dune field (from Google Earth™).

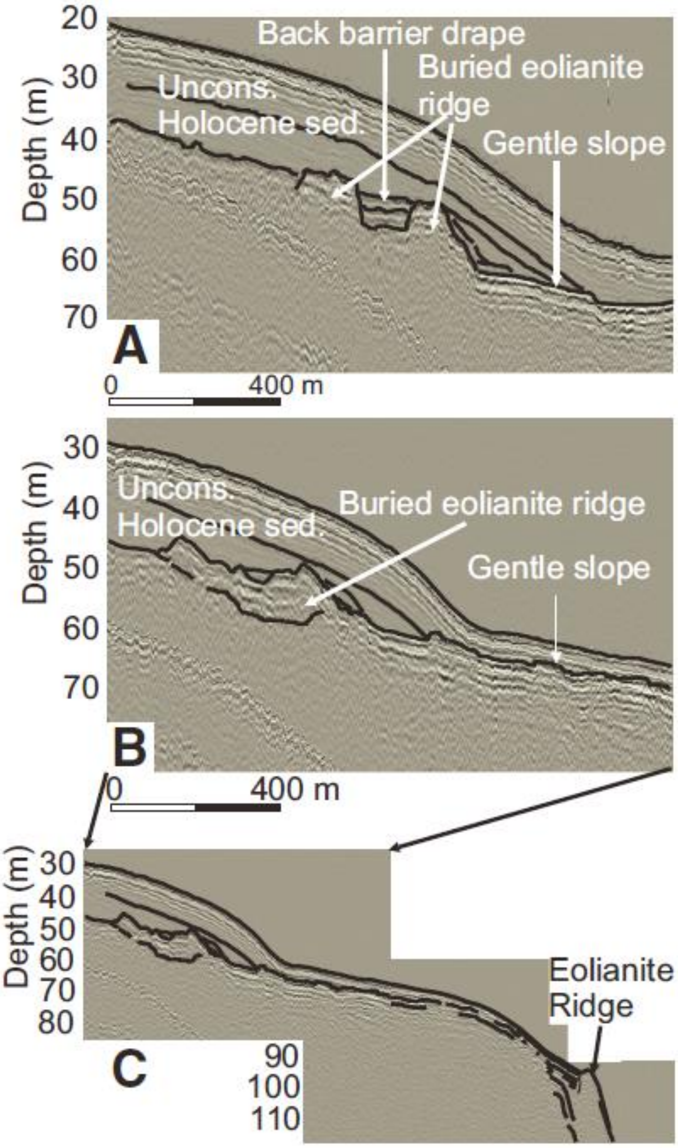

Figure 5. A–C: Single-channel seismic reflection profi les of northern KwaZulu-Natal shelf (South Africa) (see Fig. 2 for location). Note occurrence of eolianite and beachrock barriers at 60 m (A–C) and 100 m depth (C). Uncons.—unconsolidated; sed.—sediment.