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Abstract

Sea-level change around southern Africa (southern Namibia, South Africa, southern Mozambique) since Termination I has been quantified using a variety of indicators. Existing and new data are reviewed to provide a baseline for future studies and identify key research needs and opportunities in the region. While the southern African records broadly agree with other far-field records, detailed Holocene records present as-yet unresolved discrepancies with glacial isostatic adjustment (GIA) model predictions. Two domains, the west coast and east coast are considered. Radiocarbon dated saltmarsh facies and marine shells in life position provide the basis for the west coast sea-level curve back to 9 cal. ka BP. Given the age and elevation uncertainties, a Mid-Holocene highstand of +2 to +4 m is suggested between 7.3 and 6 cal ka BP as are several Late Holocene oscillations of < 1 m amplitude. On the east coast, fewer data are available for the Mid to Late Holocene (post 7 cal. ka BP) compared to the west, but many submerged indicators are available back to 13 cal. ka BP. Reappraisal of existing data suggests a sea-level curve similar to that of the west coast. In both instances, the resolution of existing sea-level index points is neither sufficient to accurately constrain the magnitude and timing of the peak highstand nor the existence of minor inferred subsequent oscillations. Between 13 and 7 cal ka yr BP chronological and geomorphological evidence (submerged shoreline complexes) suggest several alternating periods of slow and rapid sea-level change. Despite abundant data, the indicator resolution to quantify these changes remains elusive.

Keywords	Holocene; sea-level indicators; southern Africa; shelf bathymetry, Termination I; glacial isostatic adjustment; South Africa; Mozambique; Namibia, submerged shoreline

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Submission Files Included in this PDF

File Name [File Type]

revised cover letter.docx [Cover Letter]

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Highlights.docx [Highlights]

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Figure 1.eps [Figure]

Figure 2.tif [Figure]

Figure 3 revised revised.tif [Figure]

Figure 4 revised revised.tif [Figure]

Table 1 revised.docx [Table]

Table 2 revised revised.docx [Table]

Table 3 revised revised.docx [Table]

Submission Files Not Included in this PDF

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Online Table 1 WC final.xlsx [e-Component]

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Research Data Related to this Submission

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Dear Sir

I hereby submit a revised version of our manuscript "**Sea-level change in southern Africa since the last glacial maximum".** It has been fully revised according to the reviewer's instructions (see response to reviewers).

All authors have made substantial contributions to the submission. JC wrote the west coast section. AG wrote the east coast section. JAGC wrote the introduction, discussion and reviewed the entire document. All authors have approved the final version of the manuscript.

Thank you for your patience with us. I hope you now find the manuscript acceptable

Yours faithfully

Andrew Cooper

Response to reviewers:

In the revised document we have accepted all criticisms and responded to each comment by modifying the text. We standardized the dates to 'ka BP', defined MSL and LGM, and clarified all points raised. (unfortunately with 'autosave' turned on in my new version of Word, I didn't save the version with the response to each in-file comment)

Regarding the additional online data contained in the excel files, we have checked the data and uploaded versions that are not corrupted.

Highlights

- Sea-level data from southern Namibia, South Africa, and southern Mozambique since Termination I is reviewed and assessed.
- Holocene records present as-yet unresolved discrepancies with glacial isostatic adjustment (GIA) model predictions for far-field sites
- Offshore data provide age control on seismic stratigraphic units consistent with a stepped eustatic sea-level rise.
- The resolution of existing sea-level index points is neither sufficient to accurately constrain the magnitude and timing of the peak highstand nor the existence of minor inferred subsequent oscillations

Sea-level change in southern Africa since the Last Glacial Maximum

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Abstract

Sea-level change around southern Africa (southern Namibia, South Africa, southern Mozambique) since Termination I has been quantified using a variety of indicators. Existing and new data are reviewed to provide a baseline for future studies and identify key research needs and opportunities in the region. While the southern African records broadly agree with other far-field records, detailed Holocene records present as-yet unresolved discrepancies with glacial isostatic adjustment (GIA) model predictions. Two domains, the west coast and east coast are considered. Radiocarbon dated saltmarsh facies and marine shells in life position provide the basis for the west coast sea-level curve back to 9 ka BP. Given the age and elevation uncertainties, a Mid-Holocene highstand of +2 to +4 m is suggested between 7.3 and 6 ka BP, as are several Late Holocene oscillations of < 1 m amplitude. On the east coast, fewer data are available for the Mid to Late Holocene (post 7 ka BP) compared to the west, but many submerged indicators are available back to 13 ka BP. Reappraisal of existing data suggests a sea-level curve similar to that of the west coast. In both instances, the resolution of existing sea-level index points is neither sufficient to accurately constrain the magnitude and timing of the peak highstand nor the existence of minor inferred subsequent oscillations. Between 13 and 7 cal. ka BP chronological and geomorphological evidence (submerged shoreline complexes) suggest several alternating periods of slow and rapid sea-level change. Despite abundant data, the indicator resolution to quantify these changes remains elusive.

Keywords

Holocene; sea-level indicators; southern Africa; shelf bathymetry, Termination I; glacial isostatic adjustment

1. Introduction

Southern Africa's geology is dominated by ancient cratonic crust, uplifted and eroded since the breakup of Gondwana primarily during the Cretaceous and to a lesser extent during the Cenozoic (Wildman et al., 2016). Significant regional uplift and erosion has been proposed during the Miocene and Pliocene, but southern Africa appears to have been tectonically stable throughout the Quaternary (2.6 Ma) (Partridge and Maud, 1987; 2000). As a far-field location with stable crust, the sea-level record from southern Africa has the potential to contribute to current debates on the magnitude and timing of meltwater pulses (e.g. Abdul et al., 2016) and the influence of glacial isostatic adjustments (GIA) on sea-level records from far-field sites (Fleming et al., 1998; Bassett et al., 2005; Milne and Mitrovica, 2008; Khan et al., 2016). Comparison of sea-level (SL) records from the east and west coasts of southern Africa allows for investigation of potential variations in relative sea level (RSL) that may relate to differences in glacial isostatic adjustment, changes in ice volume and regional tectonic movement, for example.

The region also offers the potential to elucidate the nature of high-frequency, small-amplitude (±1-2 m) oscillations around the present RSL in the mid-late Holocene. Equatorial siphoning (Mitrovica and Peltier, 1991) and continental levering (Khan et al., 2015) have been linked to high Late Holocene sea levels in equatorial and southern Hemisphere mid-latitudes. The RSL oscillations around a mid-Holocene highstand in various localities in the southern Hemisphere (Isla, 1989; Sloss et al., 2007; Angulo et al., 2006), however, remain controversial. These small amplitude oscillations are at the limit of what can be resolved with dating of available sea-level indicators.

In this paper we collate and review evidence of Holocene RSL position around southern Africa (see supplementary data). Various sea-level indicators (Table 1) have been investigated and dated using mostly radiocarbon techniques for the west coast (WC), and a mixture of radiocarbon, uranium series and optically stimulated luminescence (OSL) techniques for the east coast (EC). Derived RSL records vary in both spatial and temporal resolution from shelf, coastal and onshore deposits. Sea-level investigations in salt marshes using foraminiferal transfer functions, that have been used to good effect elsewhere (e.g. Gehrels, 2000), are still being developed in South Africa (Franceschini et al., 2003; Strachan et al., 2014; 2015; 2016; 2017) and only the results of a pilot study spanning less than 2000 years (Strachan et al., 2014) have yet been reported.

At a time of global sea-level rise, reconstruction of past sea level in the region is important for understanding possible impacts on low-lying coastal areas that include several major coastal cities threatened by rising RSL (Hughes and Brundrit, 1992; Mather and Stretch, 2012).

2. Study Area

The study area spans the southern African coast from southern Namibia to southern Mozambique (25° to 35°S) (Fig. 1). Tidal range around the Namibian and South African coast varies little, with most areas experiencing microtidal spring tidal range (1.8 to 2.0 m) and neap tides between 0.6 and 0.8 m. A double-standing wave in the Mozambique Channel (Schwiderski, 1980), however, causes tidal range to increase in southern Mozambique: spring tidal range reaches 3 m at Maputo and 4 m at Bazaruto. Neap tidal range at these locations are 1.2 m and 1.5 m, respectively (Coughanowr et al., 1995, Lutjeharms, 2004).

[Figure 1.]

Wave energy is consistently high around the southern African coast (Roussouw, 1984), although a slight peak in wave heights (modal wave height: 2.1 m, period: 11 s) is evident in the southern Cape. Wave height and period diminishes slightly northward along the east coast (modal wave height: 2.07, period: 9 s at Richards Bay.) The entire coast is a high-energy, swell-dominated environment. Coastal climate is hyper- to semi-arid on the west, Mediterranean in the SW, and grades from warm temperate to subtropical northwards along the east coast (Schultze, 1965).

With the exception of the northern KwaZulu-Natal-Mozambique coastal plain, most of the coastline is framed by bedrock with (mainly) sandy barriers and beaches developed in coastal re-entrants (Cooper, 2010). The southern Cape and west coast coastal morphology is dominated by rocky headlands and log-spiral sandy beaches. Beach sands on the south and west coasts are an approximate equal mix of quartzose and bioclastic sand grains. Quartzose sand tends to dominate in the vicinity of river mouths and shell fragments in the vicinity of rocky headlands (e,g., Franceschini and Compton, 2006). On the east coast, terrigenous sediment dominates, with only localized carbonate sediment concentrations (Cooper, 2010).

Beachrock occurs mainly in the northern portion of the east coast. Most is of Holocene age but the process is still operative since some beachrock is <100 years old (Cawthra and Uken, 2012). Coastal dunes occur throughout the study area (Tinley, 1985), and some Holocene aeolianite is known from the west coast (Roberts et al., 2014). Back-barrier environments include coastal salt pans (confined to the arid west coast; Compton, 2006, 2007) and salt marshes (Compton, 2001), and tidal and river-dominated barred estuaries and lagoons with variable temporal connections to the open sea (Cooper, 2001). Large tidal lagoons and impounded coastal lakes occur in the southern Cape at Wilderness, and on the northern KwaZulu-Natal and southern Mozambique coastal plain. Large marine embayments are present at Durban (Mkhize, 2013), Maputo (Green et al, 2015; De Lecea et al., 2017) and in the lee of the Bazaruto archipelago (Cooper and Pilkey, 2002; Armitage et al., 2006). Because they are protected from the high-energy surf, deposits in these marginal marine environments hold potential for preserving records of Holocene sea-level change, once due allowance is made for their variable hydrodynamic and sedimentary conditions.

Salt marshes occur in some southern and western back-barrier settings (notably in the Knysna estuary and within Langebaan Lagoon), while mangroves become progressively more common north of East London. Limited accommodation space and a dominance of coarse-grained terrigenous sediment in contemporary back-barriers, coupled with restricted circulation in some settings, however, restrict both the distribution and extent of mangroves and salt marshes. Coral reefs in the northeast of the study area occur on submerged aeolianite and beachrock (Ramsay, 1994), but do not grade to sea level (Perry, 2005) and thus hold little potential for contributing to detailed sea-level records. The sea-level indicators and indicated meaning used in this study are summarized in Table 1.

[Table 1. Table of main types of sea-level indicators used]

The continental shelf shows marked variability in morphology and stratigraphy (Fig. 1). In the west there are two distinct shelf zones: a narrow inner shelf and a broad middle to outer shelf that extends to 300 to 500 m water depth (Rogers, 1977). A predominantly rocky shelf extends to 130 m water depth on the SW coast where the margin is cut by two large canyons: the Cape Canyon and the Cape Point Canyon. The South Coast has an extensive shelf area, the Agulhas Bank, which during the Last Glacial Maximum (LGM) lowstand expanded the southern coastal plain area by a factor of five (Compton, 2011). The east coast shelf is narrow, with an average width of ca. 25 km and a minimum of 3 km in northern KwaZulu-Natal (Green, 2009a). The shelf break occurs at ca. -120 m. The warm water and nutrient-poor Mozambique and Agulhas currents flow along the shelf edge, extending along the southern Cape margin of the Agulhas Bank before retroflecting to the east. The Benguela Current flows northwards, far offshore of the west coast as part of the South Atlantic gyre. The inner to middle shelf of the west coast is dominated by the highly productive Benguela Upwelling System (BUS) that is driven by seasonal winds. Bottom waters flow to the south all along the west coast margin.

The shelf contains a variety of sea-level indicators of varying resolution both temporally and vertically. Submerged shoreline complexes have long been known on the South African shelf (Martin and Fleming, 1987), but only recently has it been possible to assign dates to them (Bosman, 2012; Cawthra et al., 2015; Pretorius et al., 2016) and provide some constraint in their indicative meaning with respect to sea level. Increasing resolution of seismic profiling investigations coupled with underwater observations via SCUBA and underwater vehicles, and ship-based coring have yielded higher resolution Holocene sea-level indicators from the southern African shelf and its large marine embayments. In general, the western and southern shelves lack post-LGM (Last Glacial Maximum) sediment and, like many of the world's shelves, are dominated by mostly relict deposits (e.g. Pleistocene aeolianites: Bateman et al., 2004, 2011; Cawthra et al., 2014; 2018) that were rapidly flooded and then generally sediment starved. Holocene sedimentary records are therefore? confined to incised river deltas and mudbelts, most notably the Namaqualand mudbelt that extends from the Orange River mouth 500 km south to St Helena Bay (Herbert and Compton, 2007; Hahn et al., 2016). On the east coast, Holocene sediment is thinly developed or absent, but several Holocene shoreline complexes have been preserved by early cementation in the subtropical setting, and localized Holocene lagoonal and incised valley sediments on the shelf have been investigated (Green, 2009b; Green et al., 2013a).

The coastal geomorphology, climate and shelf morphology enable a convenient subdivision of the coast into two distinctive geographic regions for the consideration of Holocene sea-level records. These are (a) Namibia and Northern Cape and Western Cape and (b) Eastern Cape, KwaZulu-Natal and Southern Mozambique. Port Elizabeth provides a convenient break, and also marks a broad zone of ~ 250 km coastal length for which no RSL data exist. The two regions are discussed below in sections 4 and 5.

3. Sea-level indicators and indicative meanings

A variety of indicators provide evidence of sea-level change in southern Africa. They can be broadly divided into archaeological, geomorphological, sedimentological/stratigraphic and biological categories. Some indicators involve a combination of these types. Each is discussed below and summarized in Table 1.

3.1. Archaeological indicators

Coastal shell midden sites often with human artefacts, have been widely reported around the Southern African coast (e.g. Davies, 1973; Deacon and Geleijnse, 1988). They indicate the terrestrial limit and have proved useful in reconstructing patterns of beach progradation (Compton and Franceschini, 2005).

3.2. Geomorphological indicators

Beachrock outcrop and erosional features cut in beachrock and aeolianite have proved to be useful indicators of past sea levels in the region. Beachrock has been widely used as a sea-level indicator, particularly on the subtropical east coast and shelf where it forms extensive elongated features that faithfully preserve fine details of former shoreline morphology of barrier-lagoon systems including zeta bays (Cooper, 2013), pocket beaches (Cawthra et al., 2012), as well as linear beaches, spits and beach ridges on open ocean and lagoon margins (Green et al., 2013b). Beachrock formation with characteristic cementation is restricted to the intertidal zone of sandy beaches. When properly dated, it provides a reliable sea-level index point (SLIP). Mauz et al. (2015) show that the precision of beachrock-derived indicators involves the combined uncertainty of age and tidal amplitude. The uncertainty can be reduced to half the tidal amplitude or better when a deposit can be ascribed to the upper or lower intertidal zone on the basis of its sedimentary facies and cements.

The age-dating of beachrock involves radiocarbon dating of whole-rock samples or of individual shells within the beachrock. OSL dating has also been applied to South African beachrock samples (Bosman, 2012). OSL dates are believed to be most accurate as they date the time of burial. Individual large shells included within the beachrock provide potentially accurate dates on the assumption that the large shells have not been much abraded before incorporation into the beachrock. Whole rock beachrock ages amalgamate carbon from both cements (which may be multi-phase (Cooper and Flores, 1991; Bosman, 2012, Kelly et al., 2014)) and carbonate clasts (which may be reworked (Illenberger and Verhagen, 1990)). Illenberger and Verhagen (1990) reported that the age of carbonate grains on modern beaches and dunes in Algoa Bay varied according to grain size, a result confirmed independently for the west coast by Franceschini and Compton (2006). Roberts et al. (2009) and Green et al. (2017) demonstrate the landward recycling of material from older interglacials into younger beach and aeolian units. Illenberger and Verhagen (1990) concluded that the skeletal carbonate fraction of contemporary beach sand in Algoa Bay comprises only ca. 30% of modern carbonate and yields an age of ca. 7000 ^{14}C years. Whole rock radiocarbon beachrock dates are therefore less reliable than dates derived from whole shells. Bosman (2012) found a large discrepancy (up to 5000 yrs) between whole rock radiocarbon and OSL ages of early to mid-Holocene beachrock, suggestive of mixing of relict carbon with the cementing carbonate. Therefore, sea-level indicators based on whole beachrock ages have been discarded. Whole shell dates, however, show good agreement with OSL dates and consequently such dates are included in our SL curves.

According to Mauz et al. (2015), the total uncertainty associated with beachrock SLIPs can be described as the square root of $a^2 + b^2 + c^2$ where a, b and c are the independent error terms of levelling, tidal range and indicative meaning (where the particular beachrock facies formed within the tidal frame), respectively. For samples at or above MLW the levelling uncertainty is here estimated at 0.1 m (following Ramsay, 1996). In submerged samples this increases to ca. 0.2 m (Bosman, 2012).

Aeolianite outcrop itself provides only terrestrial limiting points since it forms at various elevations above sea level. However, elevated erosional features (shore platforms and associated potholes) cut in beachrock and aeolianite can provide evidence of intertidal conditions (Ramsay, 1995; Cooper and Green, 2016). The elevation relative to former sea levels can be established by reference to modern erosional features, often in the same outcrop (e.g. Cooper and Green, 2016) and organisms (e.g. oysters) adhering to the sides of such potholes, which occasionally provide material for age control. The indicative range is the intertidal zone (MLW-MHW) and levelling uncertainties (0.1 m) must also be accounted for.

3.3. Sedimentological and stratigraphic indicators

On the east coast, several dates have been reported on woody debris retrieved from incised valley cores (Grobbler et al., 1988). The woody debris is intercalated in coarse-grained estuarine sediments that accumulate during fluvial floods in these river-dominated estuaries. Since extreme modern floods (>100-year recurrence interval) have been recorded to scour to a maximum of -5 m MSL (Cooper, 1993; Cooper et al., 1989), the woody debris can be used to constrain sea level to between MHW and MLW-5 m. Between the LGM and the Mid-Holocene when sea levels were rising rapidly, such vertical resolution can provide useful indications of sea level.

In the study area, stratigraphic relationships observed in outcrop or in seismic-stratigraphic records, often provide indications of the position of a deposit with respect to sea level. Sandy tidal flat sediments deposited between MLW and MHW have been documented at elevations higher than contemporary MHW in Mozambique (Armitage et al. 2006) and below contemporary MLW offshore of Durban (Pretorius et al., 2016). At Inhaca Island, Mozambique a tidal flat deposit truncates dunes that were OSL dated at 6.0 ± 0.3 ka (Armitage et al. 2006). The tidal flat sediments themselves returned an age of 3.7 ± 0.2 ka and the tidal flat was abandoned during a subsequent regression. An OSL date of 2.1 ± 0.1 ka on overlying dune sands records renewed terrestrial sedimentation. The tidal flat deposits indicate sea level to between MHW and MLW, while the stratigraphic relationships indicate sea level trends and provide both terrestrial (dune deposition) and marine (marine erosion) limiting dates between which the tidal flat existed.

Submerged flood tide deltas identified in seismic profiles and associated core records (e.g. Pretorius et al., 2016; De Lecea et al., 2017) provide indications of the position of barriers and inlets related to former sea levels. Flood tide deltas themselves occur in the intertidal and shallow subtidal zone. Hayes and Kana (1977) report flood tide delta sediments to extend to as much as 2 m below MLW. Closer resolution can be achieved if clear evidence of intertidal conditions is preserved in the sedimentary structures or contained biota (Pretorius et al., 2016).

Seismic stratigraphy also identifies the transgressive unconformity, an erosional surface (ravinement surface) often marked by a distinct acoustic signal and characterized sedimentologically by coarse-grained transgressive deposits that represent littoral (beach and nearshore) facies. These accumulate in the zone of active wave erosion that is most vigorous in the surf zone (0 to -5 m MLW). Erosion is, of course, known to extend to the base of the shoreface (-15 m) and to a few metres above sea level during storms (Smith et al., 2010). Even without precise dating, however, it provides a clear marker for the course of Holocene sea-level change. Stillstands of sea level are marked by development of shoreline units on this unconformity.

On the west coast shelf, a sandy gravel beach facies tracks strandline migration from the LGM lowstand through the Termination I transgression. These beach deposits indicate intertidal deposition between MLW to MHW, although can include storm deposits up to 2 m above MHW. They typically include reworked large mollusc shells (*Donax serra* and *Choromytilus meridionalis*) that can be used to date the deposits. These beach deposits can also contain articulated bivalves (e.g., *Dosinia lupinus*) in life position that lived there after the beach deposits were abandoned by rapidly rising sea levels. The beach deposits are overlain by muddy sediment on the shelf that can be used to indicate when water depths were greater than wave base (approximately 75 m on the west coast). In protected, lagoonal settings, the subtidal channel (<LAT), intertidal sand flats (MLW to MHW) and *Zostera* muddy sands (MSL (Mean Sea Level) to MHW), and saltmarsh facies (MSL to HAT) indicated by the presence of, among others, the foraminifer *Trochammina inflata,* can be dated using *in situ* biological material (see below).

3.4. Biological indicators

Organic carbon that is in-situ and from environments (such as those within salt marshes or estuaries) that have a narrow and well-defined position relative to mean sea level is preferred for dating purposes. It is also critical that the dated sample does not include allochthonous organic matter, such as older organic matter derived from eroded soils. Bulk organic carbon, moderately reworked shell and shells in life position, including those fixed to a solid substrate, have been used as sea-level indicators in South Africa. Bulk organic carbon dates are often unreliable because of the contribution of reworked soil organic matter. However, in-place tree stumps indicate the terrestrial limit in Knysna Lagoon (Marker, 1997), and in settings with mostly autochthonous organic matter, such as freshwater peats in coastal lakes (vleis) at Verlorenvlei (Baxter, 1997), at Groenvlei (Deevey et al, 1959; Martin, 1968) and at Rietvlei (Schalke, 1973). Bulk organic carbon dates are also considered reliable from salt marsh deposits at Langebaan Lagoon, which has no riverine input (Compton, 2001).

Shells fixed in life position on a solid substrate include encrusting serpulid worms, barnacles and oyster shells. Serpulid worm encrustations have been documented on the rocky shores of modern estuaries in South Africa (Cooper et al., 2013) and are characteristic of the upper balanoid zone (high intertidal) on the exposed rocky east coast (Branch and Branch, 1981). They have been recorded in several rock pools above modern MHW where they record higher than present sea levels (Botha et al., 2018). Oysters (*Saccostrea cuccullata*) colonise the high intertidal zone of the east coast, close to MHW (Branch and Branch, 1981) where they often form a conspicuous belt in the upper intertidal zone (Kilburn and Rippey, 1982). Their inferred resolution is therefore within the upper half of the tidal range. Radiocarbon-dated shells adhering to bedrock in the incised valley of the Mkomazi estuary (Grobbler et al., 1988) were not identified but are almost certainly oysters (which tolerate the muddy conditions of South African estuaries (Kilburn and Rippey, 1982, p170)). Bosman (2012) also dated several oysters (*Crassostrea margaritacea*) adhering to submerged aeolianite stacks at depths of -24 m to -30 m. This oyster “forms beds from extreme low water and just below” (Kilburn and Rippey, 1981, p169.) The oyster *Ostrea atherstonei* lives subtidally at water depths <LAT and has been used to date subtidal channel deposits in Langebaan Lagoon (Tankard, 1976; Flemming, 1977; Compton, 2001). The subtidal barnacle *Austromegabalanus cylindricus* found in life position attached to rocky outcrop was dated from Anichab Pan in southern Namibia (Compton, 2006). Like *O. atherstonei*, this barnacle is known to live at subtidal water depths (below LAT) (Branch et al., 1999) and provides a useful lower limit of sea level.

Fossil molluscs in life position but not affixed to a hard substrate can also be used as sea-level indicators and are included here under the 'fixed biological' category. In some instances, these molluscs have an established relationship to contemporary sea level and can act as index points (e.g., Reddering, 1988). On the west coast, the bivalve *Lutraria lutraria* has been found articulated and in a vertical life position in sand deposits now exposed above sea level. *L. lutraria* lives subtidally at water depths below LAT in clean sands typically in the lee of offshore islands. The bivalve *Gastrana matadoa* has also been found articulated and in life position in sand deposits along the coast of Namibia, often in association with *L. lutraria*, living at subtidal depths (< LAT). It is not known to what depth these bivalves burrow into the sand, but it is probably not more than 1 m, making them limiting indicators of LAT. The intertidal bivalves *Donax serra* (white mussel) and *Choromytilus meridionalis* (black mussel) are commonly found together in modern and fossil beach deposits on the west coast. Although rarely found in life position, these two bivalves are useful indicators of intertidal sand and rocky shore beach deposits (MLW to HAT or higher if associated with storm deposits, though likely to be abraded and disarticulated). The estuarine burrowing bivalve *Loripes clausus*, in some cases found in life position, has been used to date middle intertidal to subtidal (MTL to LAT) mudbank deposits in the Knysna (Marker and Miller, 1993) and Keurbooms (Reddering, 1988) estuaries.

In deeper shelf waters, the bivalve *Tellina analogica* and *Dosinia lupinus* can be found in life position in sediments along with the gastropods *Nassarius vinctus*. These shells have been useful in dating offshore deposits and are preferred over bulk organic carbon ages because of the contribution of older, reworked terrestrial organic matter.

4. West Coast (WC) sea-level records: Southern Namibia to Port Elizabeth, South Africa

4.1. Offshore records of the LGM to Holocene sea level

On the west coast shelf, the LGM lowstand shoreline is interpreted to correspond, in general, to the landward extent of predominantly rocky substrate (Fig. 2). The rocky substrate variably consists of Precambrian Malmesbury Group metasediment, intruded bodies of Cambrian Cape Granite and overlying Ordovician Table Mountain Group sandstone and Cretaceous sedimentary rocks. The transition from predominantly rocky seabed to seabed draped by Quaternary sediment is clearly delineated on the bathymetric map of the continental shelf (de Wet, 2013), particularly between Cape Columbine (St Helena Bay) and Cape Agulhas (Fig. 1). Shoreface deposits associated with this transition at --120 m to -130 m mean sea level (MSL) have not yet been dated but they are interpreted to correspond to the LGM (marine isotope stage 2 (MIS2), 26-18 ka) before they were drowned and abandoned by rapidly rising sea levels during Termination I (18 to 8 ka).

Previous glacial periods had lowstand shorelines similarly situated near -120 m to -130 m prior to MIS2. The oldest glacial period with a lowstand near -120 m to -130 m msl was probably MIS22, the first high-amplitude glacial period associated with the Mid-Pleistocene Transition (870 ka) (Elderfield et al., 2012). Other glacial periods that appear to have had lowstands around this depth include MIS20 (790 ka), MIS18 (715 ka), MIS16 (650-640 ka), MIS12 (440-430 ka), MIS10 (350-340 ka), MIS6 (160-135 ka) and possibly MIS4 (70 ka) (Compton, 2011). The high-energy shoreline of glacial lowstands re-occupying a similar position on the shelf, followed by marine transgression of the shoreline across the mid to inner shelf, has sustained a predominantly rocky seabed offshore of the Cape Columbine – Cape Agulhas Arch. This arch comprises a major NW-SE trending structure at the southwestern tip of Africa. The Holocene sediment drape is thin to non-existent on the shelf bordering the Cape Columbine – Cape Agulhas Arch because of low sediment supply combined with the removal of fine sediment by dissipation of wave and tidal energy on the shelf (Compton and Wiltshire, 2009).

Holocene sediment accumulation sufficient to completely drape the rocky seabed is restricted to the Namaqualand mudbelt on the West Coast. The Namaqualand mudbelt is a linear deposit that extends from the Orange River prodelta to St Helena Bay between water depths of 75 m to 120 m (Fig. 2; Herbert and Compton, 2007). Otherwise, Holocene deposits on the West Coast shelf (including the outer shelf to 400-500 m water depth) are thin or absent. Much of the extensive Agulhas Bank on the South Coast is similarly draped by only a thin or absent Holocene sediment cover (Rogers, 1971). The few areas of significant Holocene accumulation on the South Coast Agulhas Bank shelf have yet to be cored and dated. In theory, the rise in sea level during Termination I (18 to 8 ka) could be reconstructed by dating abandoned (drowned) shoreface deposits out to water depths of 130 m. However, the shoreface deposits do not appear in general to be well-preserved on the shelf, perhaps as a result of the low shelf gradients, slow sediment accumulation rates and high-energy waves.

One of the few depocentres on the shelf with appreciable sedimentation rates (1-2 mm/yr) is the Holocene Namaqualand mudbelt. The mudbelt has been extensively cored and dated (Herbert and Compton, 2007; and references therein), but unfortunately the bulk organic matter and mollusc shells dated from the mudbelt are not good sea-level indicators. However, the dated sediment facies from the cores, combined with their stratal architecture from seismic profiles (Lodewyks, 2010) do provide some constraints on sea level from the LGM to Holocene (Fig. 2). Shelly gravels and sandy beach (shoreface) deposits are a primary target in diamond mining offshore the Orange River. The shoreface deposits rest unconformably on the eroded surface of seaward-dipping Cretaceous sedimentary bedrock and commonly occur as a wedge of sediment between -130 m and -90 m (Fig. 2). Basal gravels are latest Pleistocene in age and represent a highly condensed lag deposit, as indicated by scattered phosphorite pebbles ranging from early Miocene to Pleistocene in age as dated by strontium isotope stratigraphy (Compton et al., 2002).

[Figure 2.]

The shoreface deposits contain articulated molluscs that are interpreted to be in life position and preserved as the shoreface was flooded and abandoned at the start of the marine transgression associated with Termination I (18 – 14 ka). Unfortunately, none of these articulated shells have been dated, but unspecified bulk shell samples (species composition unknown) were dated from beach and nearshore (shallow water) facies cored offshore between the Orange River mouth and Lüderitz (Vogel and Visser, 1981; John Pether, pers. comm., 2017). The shallow water shells recovered from -105 m and

-118 m have calibrated ages between 16.8 ka BP and 14.3 ka BP, prior to melt water pulse (MWP) 1a (Hanebuth et al., 2000; Stanford et al., 2011, Deschamps et al., 2012; Liu et al., 2013). Stanford et al., (2011) estimate a rise of sea level from -90 m to -70 m between 14.3 and 12.8 ka. Shells from the beach facies are of similar age (16.5 to 14.3 ka BP), but occur at shallower water depths of between -70 m and -80 m. These shells may have been transported upslope as the shoreline transgressed during MWP1a. A shell from a sand unit directly below the mudbelt, in a core taken at -95 m offshore the Olifants River has a radiocarbon age of 12.8 ka BP (Herbert and Compton, 2007).

The oldest mudbelt deposits form a wedge that onlaps the older shoreface deposits (Fig. 2). This mudbelt wedge was recovered to depths of -124 m off the Holgat River and ranges in age from 11 ka BP to 8.8 ka BP (Herbert and Compton, 2007). Dated mollusc shells from the Namibian shelf also indicate sea level was around -50 to -60 m msl by 11 ka (Compton et al., 2001). Together these ages suggest that the basal gravelly sand unit was deposited from the LGM through MWP1a as a transgressive beach to shallow water facies that youngs upslope as sea-level rose. These deposits were then draped by an initial mudbelt deposit consistent with further rapid rise of sea level that coincides with that associated with MWP1b.

Mudbelt deposition continued from 8.8 ka BP as prograding clinoforms that downlap onto the older mudbelt deposits (Fig.2). Therefore, the ages and seismic stratigraphy of the mudbelt provide a scenario that is generally consistent with the eustatic sea-level curve established by previous workers (see references in Stanford et al., 2011) but which lacks precise sea-level index points. Coastal and onshore deposits, however, provide more sensitive sea-level indicators than the offshore mudbelt for construction of the West Coast sea-level curve since ca. 9 ka BP.

4.2. Coastal and onshore record of Holocene sea levels

Estuarine, lagoonal, coastal lake (vlei), salt pan and salt marsh deposits on the west coast and less so on the south coast provide a reasonably complete record of Holocene sea level since around 9 ka BP (Table 2). Dates and elevations from Namibian coastal sites up to 60 km north of Lüderitz (Anichab pan) and numerous intervening sites to the Groenvlei, Knysna and Keurbooms estuaries are generally in good agreement (Fig.3). Although the south coast has fewer data points, its general agreement with the west coast suggests that this long stretch of coast experienced similar local sea levels during the Holocene. Sea-level indicators include marine and estuarine carbonate shells, organic carbon from salt marsh or estuarine facies, in-situ peat deposits, and tree stumps (Table 2) . The preferred carbonate shell sea-level indicators are those in life position (articulated bivalves, attached oysters or barnacles, etc.) and species that occupy a narrow and well-defined position relative to mean sea level. In some cases, the shell is not in life position but occurs in deposits that have a well-defined position relative to mean sea level (salt marsh, beach, intertidal sand flats, subtidal channel, etc).

[Table 2.]

A compilation of the best dated sea-level indicators from the west and south coasts reveals that sea level rose from below -13 m at 9 ka BP to a maximum of at least 3.8 m (given indicator uncertainties) from 7.6 to 5.8 ka BP taking account of maximum age errors (Fig. 3). From around 5.3 to 4.2 ka BP sea level was around +1 m. One index point indicates 0 m at ca. 2 ka BP. Subsequent terrestrial limiting points are at and around 0 m. These sea-level indicators have defined uncertainties in their age and position relative to mean sea level that allow them to be used to construct a relative sea-level curve within the limitations of the data portrayed in Table 2 (Fig. 3a). Other data, which cannot be plotted for lack of an age or position relative to mean sea level, can be used to corroborate the sea-level curve. For example, coastal lakes provide sedimentary evidence of when sea level was generally higher or lower based on indicators of marine or terrestrial deposition (Kirsten, 2014; Wundsch et al., 2016).

[Figure 3]

5. East Coast (EC) sea-level records: Port Elizabeth, South Africa to Bazaruto, Mozambique

5.1. Continental shelf

On the east coast, the LGM shoreline is considered to have occurred around -125 m MSL. A series of -125 m erosional notches within submarine canyons of the northern KwaZulu-Natal region, associated with in-situ beach deposits, were linked to the LGM shoreline by Green and Uken (2005). Though undated, this provides the best evidence for a lowstand sea level from that depth for the east coast, and matches the data from the west coast. Like the west coast, the east coast shelf has been subject to multiple regressive/transgressive cycles throughout the Pleistocene (Ramsay and Cooper, 2002), which have resulted in the continental shelf off KwaZulu-Natal and southern Mozambique containing only a thin Holocene sediment veneer, grading into bedrock from the mid shelf (~ -60 m) seawards (Fig. 2). The shelf nonetheless contains several lines of evidence for former Holocene sea levels. These include submerged cemented shorelines comprising aeolianite and beachrock that have been overstepped and preserved, post LGM-aged incised valley fills, and scattered lagoonal deposits that survived the post LGM transgressive ravinement (Fig. 2a)

Prominent beachrock and aeolianite sequences have long been known from the continental shelf between East London and southern Mozambique (Martin and Flemming, 1987; Ramsay, 1994). Aeolianite sequences on the east coast shelf are of Pleistocene age but Holocene beachrock is often found in association with them (Bosman, 2012; Pretorius et al., 2018). Two major submerged beachrock shorelines have subsequently been documented at -60 m and -100 m MSL (Green et al., 2014), however, neither of these has been directly sampled for dating of the material. Their depths, relative to global eustatic sea level curves, and dating of associated back barrier deposits (discussed below) however, allow approximate ages to be assigned (see Fig 2a).

Ramsay and Cooper (2002) described a series of regressive palaeo-coastlines from Sodwana Bay (Fig. 1), based on a single uranium-series date on a beachrock at -44 m and the apparent down-stepping nature of the sequence. Green (2009b,c) later mapped these palaeo-coastline sequences in conjunction with the LGM drainage of the region and showed that they postdate MIS2, and are regionally developed shorelines that form a series of zeta-bays (see for example the image presented in Cooper, 2013), likely developed in response to disruption of the longshore sediment supply during transgression. These shorelines were preserved by a series of stepped sea-level rises from -100 m to -25 m. Bosman (2012) examined beachrocks from shallower depths from the southern coast of KwaZulu-Natal and dated them using OSL and radiocarbon. He found that beachrocks from -33 m, -29 m and -26 m dated to 10800, 10200 and 9850 BP, respectively (Table 3; Fig.4).

A series of massive beds of the oyster *Crassostrea margaritacea* were reported by Bosman (2012), attached to the seaward edge of an aeolianite outcrop at depths of -24 m to -30 m. These oysters dated to 9.3 ± 201 ka BP at -29 m; 8.7 ± 208 ka BP at -30 m and 7.3 ± 151 ka BP at - 24 m. They are thought to live at extreme low tide or just below (Kilburn and Rippey, 1982), but the dated samples are much lower than equivalent indicators from the west coast and comparable aged indicators on the east coast (Fig. 4). They appear to show age contamination.

Green et al. (2013b) reported the discovery of a drowned segmented-lagoon complex offshore of Durban. This was later elaborated on by Green et al. (2014), who linked this to a regional-scale palaeo-coastline at ca. -60 m MSL. AMS ^{14}C bulk organic matter dates of a stiff lagoonal clay beneath the system revealed an age of 35.3 ± 592 ka BP (Pretorius et al., 2016). Based on the current morphological arrangement of lagoons on the KwaZulu-Natal coast, this yields a vertical uncertainty of ± 2 m in light of the tidal variation and close association of the lagoon bed with spring high tides.

The subsequent truncating LGM-aged incised valleys and their MIS 1-age yielded two potential sea-level indicators. A well-developed flood tide delta at -64 m MSL in the upper incised valley fill package was dated, based on organic material from a tidal rhythmite, at 12.9 ka BP (Pretorius et al., 2016) (Table 3; Fig.4)). An articulated bivalve found at -38 m in life position (*Eumarcia paupercula*) dated to 6.7 ka BP. This species burrows 2-3 cm below the surface in ”muddy low tide sandbanks” (Kilburn and Rippey, 1982, p. 200). It was recovered from the more proximal area of the incised valley and was associated with another, back-stepped flood tide delta. Like the oysters reported above, it is, however, much lower than other indicators of equivalent age, suggesting that it too suffers from age contamination.

[Table 3.]

These associated back-barrier environments constrain the age of the adjoining submerged-shorelines. Green et al (2014) proposed, on the basis of their elaborate planform equilibrium morphologies, that these shorelines were formed during a phase of protracted Holocene sea-level stability or slow rise in sea level, and were then overstepped during a rapid rise in sea level consistent with that inferred by other authors for MWP 1b. The period of overstepping (Fig.4), as defined by the wave ravinement surface in the back barrier, immediately postdates 12.9 ka BP and slightly predates the accelerations in sea level identified by Camoin et al. (2004) in their Indian Ocean records.

Seismic records from Maputo Bay, southern Mozambique, together with detailed micropalaeontological and stable isotope analyses of cores, allowed a broad pattern of stepped Holocene sea-level rises to be reconstructed for the region (De Lecea et al., 2017). These studies linked changes in sedimentation styles to periods of enclosure of the marine embayment. These in turn were linked to changes in sea level, with periods of sea-level stability being accompanied by shallowing and segmentation of the embayment. An initial phase of segmentation occurred prior to 10.8 to 10.6 ka BP, matching closely the period of slowly rising sea level identified by Pretorius et al. (2016) in the Durban area, and the records of Camoin et al. (2004) in the Western Indian Ocean. Tidal ravinement surfaces, as recognised from seismic data, truncate well-developed tidal flat sediments and were interpreted as the manifestation of subsequent rapid rates of sea-level rise. This terminated at 8.8-8.5 ka BP (Fig.4). A slow rise in sea level then continued until 4.1-3.9 ka BP. De Lecea et al. (2017) linked this evidence for a rapid pulse in sea-level rise to MWP 1c and the 8.2 ka event, which saw a short-lived period of cooling and yet a sudden rise in sea levels (Törnqvist et al., 2004). Unfortunately, no precise sea-level indicators were found that could define these dates and rates more precisely.

5.2. Onshore and estuarine records

Organic material derived from commercial coring investigations for bridge foundations in several KwaZulu-Natal estuaries provide indications of early-mid Holocene sea levels (Ramsay and Cooper, 2002). The material comprises woody debris from the Mfolozi, Mgeni and Mkomazi estuaries (Fig. 1) and oysters attached to bedrock in the Mkomazi estuary (Maud, 1968; Grobbler et al., 1988).

A previously published Late Holocene curve for this region (Ramsay, 1995) was based partly on radiocarbon-dated beachrock. These included some whole rock dates that have been discarded in the present review in light of the discrepancies between ^{14}C and OSL dates reported by Bosman (2012). The revised Late Holocene curve is presented in Figure 3.

In addition to studies that place limits on sea level, a number of investigations in the region, provide evidence of trends in sea level. Armitage et al. (2005), in a study of barrier island and dune evolution in southern Mozambique, presented several OSL-dated features that record changes in sea level. OSL-dated intertidal beachrock on the eastern shoreline of Bazaruto indicates sea level to have been approximately at the present level by about 7.2 ± 0.9 ka BP (BA2), and again at 1.0 ± 0.1 ka BP (BA8) (Armitage et al. 2008). Truncation of a dune during initial development of an elevated palaeotidal flat (MSL +1.5 m) on Inhaca island was dated to 6.0 ± 0.3 ka BP (IN15) while an OSL date of 3.7 ± 0.2 ka BP (IN20) represented the final abandonment of the tidal flat. Later parabolic dunes that override the palaeotidal flat provide a minimum age for a lower sea level at 2.1 ± 0.1 ka BP (IN16).

[Figure 4.]

As in the west, several studies provide supporting evidence for changes in sea level during the Late Holocene, but without providing index points. For example, the vegetation history at Lake Eteza, KwaZulu-Natal (Neumann et al. 2010) indicates a higher sea level between 6.8 and 3.6 ka BP, while multi-proxy investigations in Macassar Pan, Southern Mozambique suggest that this period included two distinct peaks in sea level (6630-6300 BP and 4700-1000 BP), with an intervening period of relatively lower sea levels (Norstrom et al., 2012). Sitoe et al. (2017) presented multi-proxy evidence from the Limpopo floodplain of a subsequent higher than present sea level between 1220 and 1050 BP. Strachan et al.'s (2014) results from a pilot study using foraminifera transfer function analysis suggest that sea level oscillated slightly below present from 1.1-0.3 ka BP, which fits well with the west coast sea-level curve and spans a period unrepresented by other east coast data (Fig. 3b).

6. Discussion

Southern Africa contains abundant evidence of sea-level position and relative trends since the LGM. Quantifiable sea-level indicators include several reliable index points with a known relationship to sea level being provided by biological remains (e.g. in-situ molluscs and foraminifera) that may record sea level to decimetre-scale resolution and/or geomorphological/sedimentological features (e.g. beachrock, salt marsh and tidal flat sediments) that constrain sea level to within 2 m in the region. A secondary set of sea-level indicators includes terrestrial (e.g. estuarine channel/palaeosols) and marine (marine lag gravels) limiting points that set upper and lower limits, respectively, for sea level. This level of resolution is useful for periods of rapid sea-level change up to ca. 7 ka BP when sea level reached close to present levels. However, for the subsequent time period, although there is abundant sedimentary and geomorphological evidence of sea-level fluctuations on the scale of 1-3 m, the indicator resolution to quantify these changes remains insufficient.

On the basis of this review, a number of apparent pieces of evidence reported in former studies must be discarded because of a lack of suitable age control. Radiocarbon dates on whole beachrock, for example, have been shown to differ significantly (several thousand years) from OSL dates on the same sample (Bosman, 2012). Further investigation of beachrock with appropriate age dating, however, holds much potential for elucidation of sea-level change because of the potentially tight constraint on vertical levels (Mauz et al., 2015) and its ubiquity on the east coast of southern Africa. Some spurious dates have, however, been obtained from material that appeared to be suitable as sea-level index points (oysters and in-situ molluscs). The ages for these are inconsistent with the rest of the dataset and the discrepancy is tentatively attributed to contamination. They are regarded as unreliable data points and while they remain in the associated online datasets, have been removed from the sea level plots (Fig 3, 4) .

The stratal architecture (Fig. 2) of the west coast mudbelt (Herbert and Compton, 2007) and the preservation of major shoreline complexes on the east coast shelf (Green et al., 2013b; Salzmann et al., 2013; Green et al., 2014) provide compelling evidence of periods of variable rates of sea-level change, consistent with a model of punctuated sea-level rise involving meltwater pulses 1a and 1b (Bard et al. 1990; Camion et al., 2004; Stanford et al., 2006, 2011). The South African data point to widespread development of a shoreline complex during a Younger Dryas stillstand at ca -60 m (Pretorius et al., 2016) and its overstepping and preservation during a subsequent sea-level rise consistent with current estimates of MWP 1b (Green et al., 2014). While the rates and timing of this sea-level rise are still contentious (see Abdul et al., 2016 and subsequent comment and reply by Bard et al., 2016 and Mortlock et al., 2016), the onset of rapid sea-level rise suggested by the southern African geomorphological data, seem to support the rapid sea-level rise recognized by Stanford et al. (2011) and Abdul et al. (2016). Further dating of the submerged shorelines and associated deposits on the southern African shelf holds potential for quantifying the magnitude and timing of the stillstand and MWP.

Later trends involving stepped sea-level rise have been documented on stratigraphic evidence in Maputo Bay, Mozambique (De Lecea et al., 2017). A cluster of sea-level data (Figure 4) around -30 m dates to between 10 and 8.5 ka BP and suggests a slowstand of sea-level at that time, followed by a rapid rise. Similarly, a period of rapidly rising sea level implied from seismic stratigraphic evidence in the coastal waterbodies of northern KwaZulu-Natal (Wright et al., 2000) was followed by deposition of a series of well-developed flood tide delta units at ~ 6.8 ka BP (Benallack et al., 2016; Gomes et al., 2017). These tidal deltas appear to mark a period of stable or slowly rising sea level, before they were drowned ~ 5.5 ka BP (De Lecea et al., 2017; Gomes et al., 2017) by ongoing sea-level rise.

Notwithstanding the relative scarcity of sea-level index points, the available evidence points to generally similar Holocene sea-level records for east and west coasts. The limiting and index point data from the west coast constrain sea level at the vertical resolution limits of the indicators currently available for the last 9 ka. The east coast data for the same period (Fig. 3b) are less abundant, but are dominated by index points with variable vertical resolution. Elimination of whole-rock beachrock data from the east coast record removes some of the discrepancies between the curves presented by Compton (2001; 2006) and Ramsay (1995). The west coast SL curve, including the mid-Holocene highstand is generally consistent with GIA models, except that GIA models predict a gradual decrease in RSL rather than the rapid decrease observed following the mid-Holocene highstand (Compton, 2006). The timing of the mid-Holocene highstand appears somewhat later and lower in the east, but is not well-constrained by the available data. The peak highstand from currently dated evidence on the east coast is ca. +1.5 m at ca. 5.5 ka BP, which on the west coast is identified as a period when sea level was at present-day levels. Both east and west coast curves agree in suggesting a subsequent minor highstand between 1 and 2 ka BP superimposed on an overall drop from a maximum highstand at ca. 5.5 ka BP to the present. In summary, however, the evidence from the east coast is insufficient to enable the necessary level of comparison with the west coast to investigate the magnitude of differences in SL history and any potential reasons for them (e.g. GIA, neotectonics, oceanography, continental levering). Milne and Mitrovica's (2009) GIA model outputs suggest subtle differences between the west and east coasts of southern Africa, and thus make comparison of the east and west coasts a challenging but useful future endeavour.

While a near-ubiquitous southern Hemisphere Mid Holocene highstand is now accepted (Isla, 1989) and attributed to equatorial siphoning (Mitrovica and Peltier, 1991) and/or levering (Mitrovica and Milne, 2002), the presence of metre-scale oscillations in the Mid-Holocene remains controversial (Angulo et al., 2006). The evidence presented here is suggestive of modest Mid-Late Holocene sea-level oscillations on both east and west coasts of southern Africa. These will be difficult to constrain precisely except perhaps through well-dated beachrock and foraminifera or diatom-based work. Although these inferred oscillations are small (<2 m) in the context of the overall sea-level change during Termination I (120 m), they nevertheless are important to understand in light of the low-gradient, low-elevation coastal settings in which several major coastal cities in South Africa are situated (Hughes and Brundrit, 1992).

Coastal flooding and erosion, associated with an increase of no more than 2 m in sea level would have profound implications for the southern African coastal environment and its human population. Much of the Durban coastline, for example, is heavily urbanized, reclaimed from marshes situated at below mean sea level and lacks natural barriers that buffer rising sea level, e.g. dune cordons. It stands to be seriously impacted by near-future sea-level rise (Roberts, 2008). An understanding of the nature and causation of the Mid-Late Holocene fluctuations observed here, will have implications for predicting the future course of sea-level and in steering the human response to such changes.

Conclusions

Southern Africa contains a diverse assemblage of post-LGM sea-level indicators on the continental shelf and along the contemporary shoreline. Geomorphological and seismic stratigraphic studies on the shelf provide clear indications of sea-level change including periods of rapid and slow sea-level rise. While chronological constraints are relatively poorly developed for shelf sediments and only a few units have been dated, there is much potential for further investigations of submerged sea-level indicators (beachrock, lagoonal deposits and incised valley estuarine sediment) to more tightly constrain the sea-level record in this far-field location. Some sea-level indicators have poor vertical resolution and vertical errors but careful analysis of stratigraphy and sedimentology can yield indicators with sub-metre resolution from the shelf.

Coastal indicators of former sea-level in southern Africa are diverse and are based on a variety of coastal environments. Transitional coastal environments (lagoons, estuaries and tidal flats) provide geomorphic and sedimentological indications of former sea-level but have relatively poor vertical resolution with large error bands. On the open coast, high wave energy and consequently variable runup, require careful analysis of sediments to interpret the indicative meaning. Even so, beachrock and erosional features such as potholes and tidal notches provide evidence of sea-level change. In some cases they have yielded sea-level index points and limiting data. In-situ biological indicators have provided some index points and offer potential for further investigation, although in some instances reported above, spurious ages have been yielded from oysters and life-position bivalves. Salt marsh is poorly developed in southern Africa and only preliminary studies have been carried out to assess their potential as sea-level archives.

Evidence of Mid-Late Holocene sea level is based largely on terrestrial and marine limiting points on the west coast, while the more sparse east coast record is dominated by index points based on beachrock and in-situ biological organisms. On both coasts, the current evidence suggests a highstand of ca. +3.8 m between 6.5 and 5.5 ka BP. This is followed by a general fall to the present, although a subsequent positive oscillation ca. 1.5 ka BP is suggested by both index points and sedimentological trends on the east coast. More data, particularly with better vertical control, are needed to tightly constrain the apparent small fluctuations during the Mid-Late Holocene.

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Figure Captions

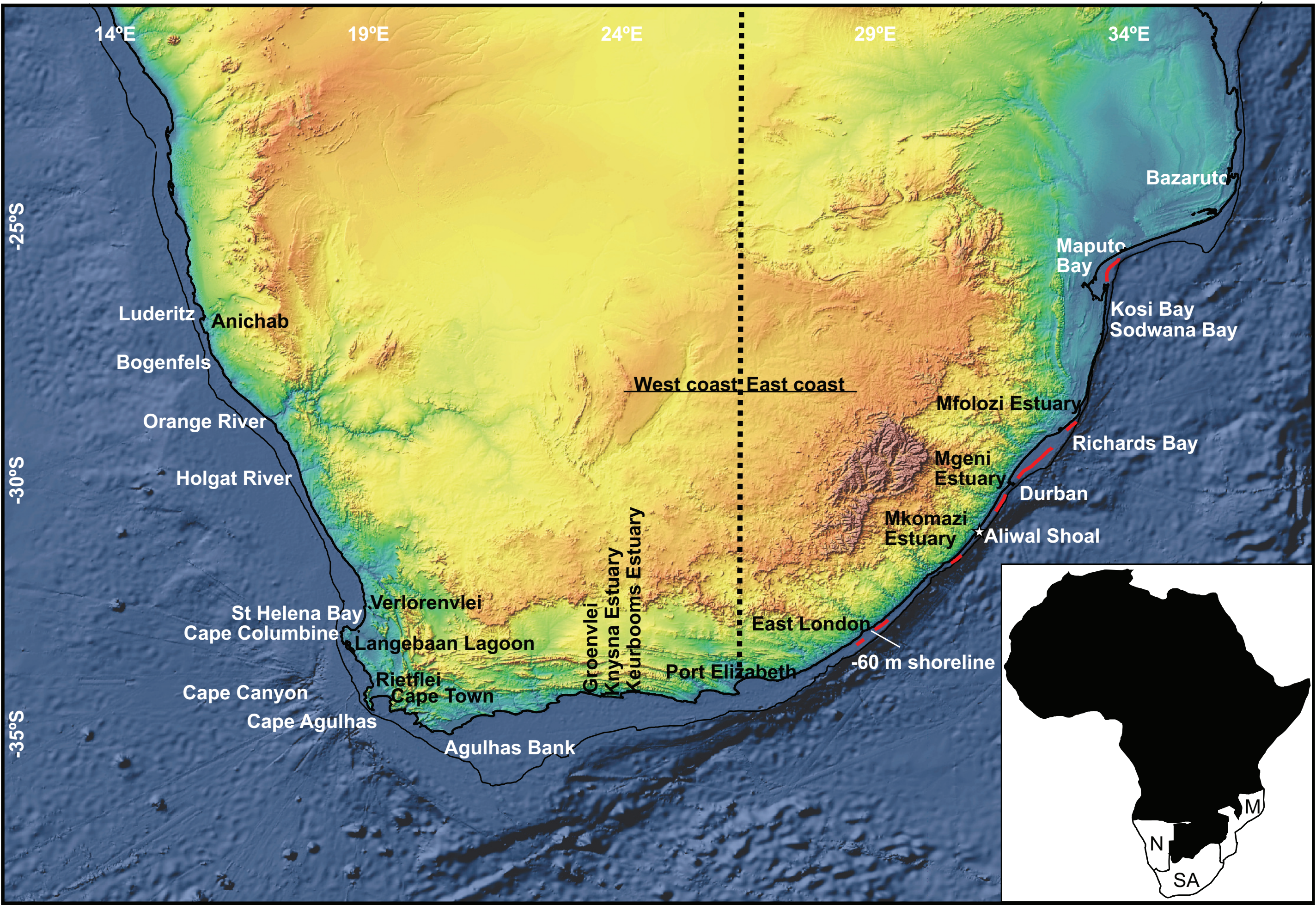
Figure 1. Locality map with specific points of reference from the text. Note the wide west and south coast shelf compared to the narrow eastern shelf. The -130 m isobath marks the approximate position of the LGM shoreline. Red lines indicate the mapped positions of the -60 m shorelines. N= Namibia; SA= South Africa; M= Mozambique. Data derived from the GEBCO and SRTM30 data sets.

Figure 2. Interpreted seismic profiles of contrasting east (upper) and west coast (lower) shelves showing Holocene stratigraphy and sedimentary record. East coast profile

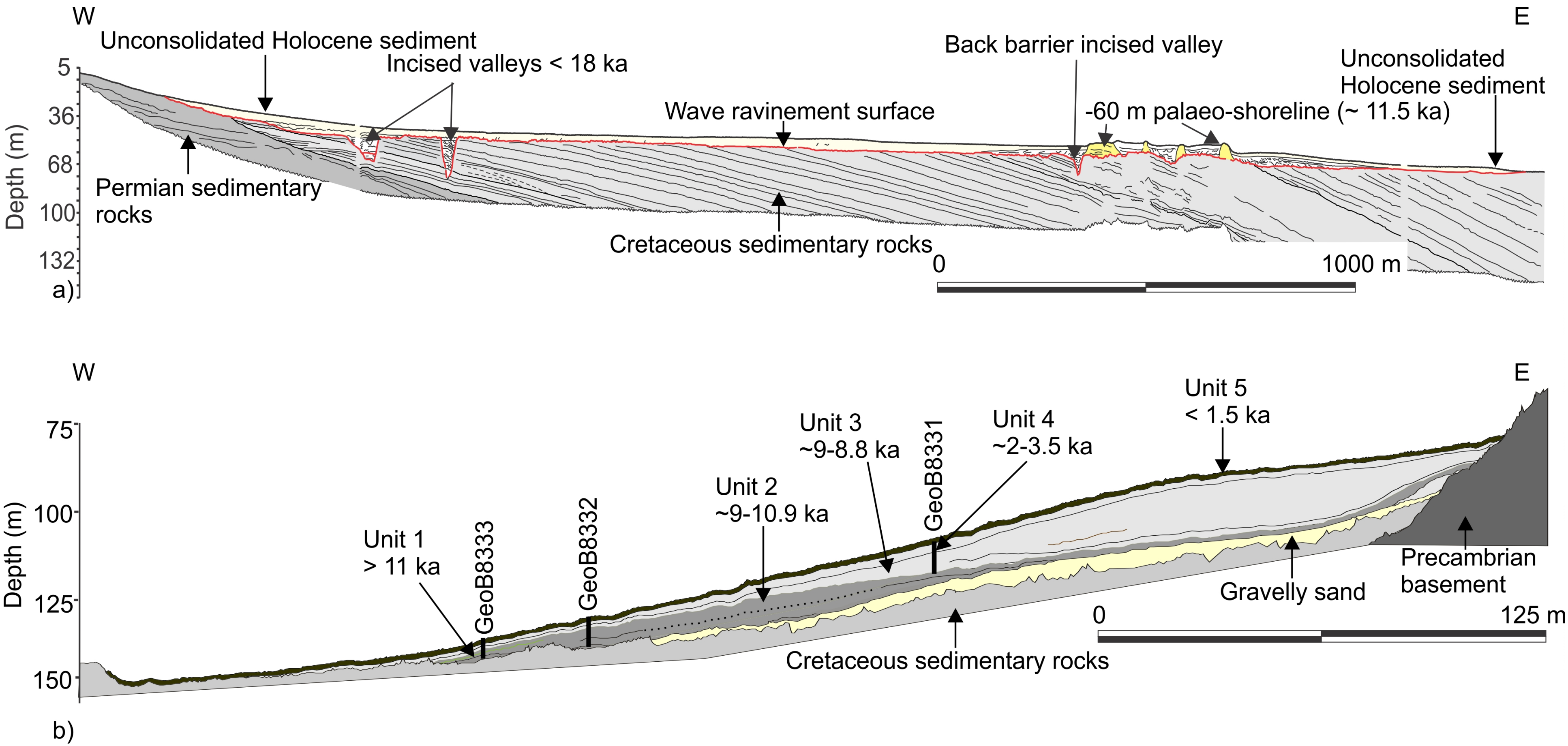
(above) off Durban (from Green et al., 2014b) showing the -60 m shoreline complex, incised fluvial alleys and Holocene unconformity marked by wave ravinement surface. West Coast Profile (below) shows the mudbelt off the Holgat River (from Herbert, 2009), with key core positions and dates for each stratigraphic unit. GeoB8333 to 8331 denote core positions.

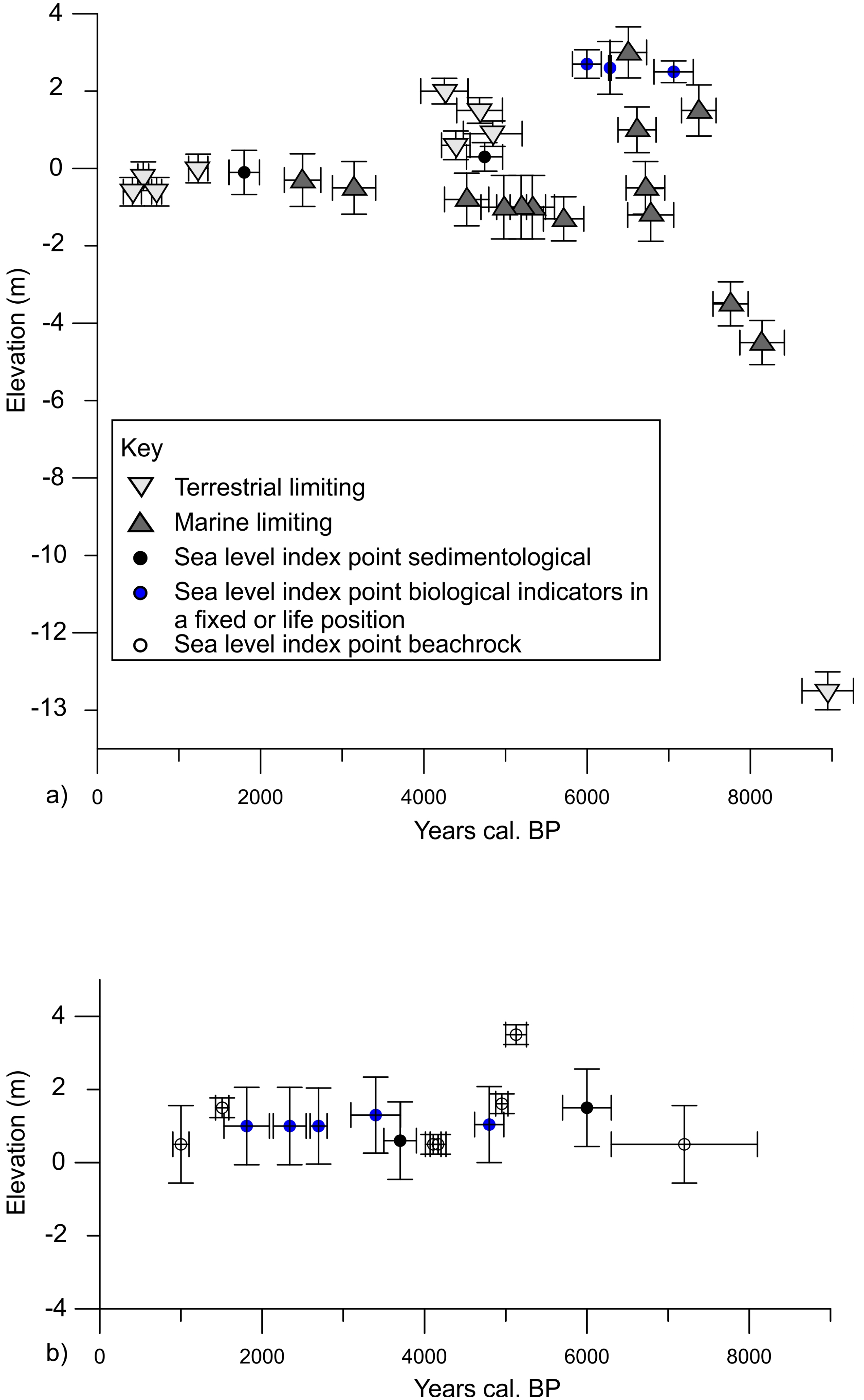
Figure 3. Sea level fluctuations since ~ 10 ka BP. a. West coast sea level indicators and curve (after Compton, 2006) and this study. b. East coast sea level indicators and curve (this study). Data have been corrected and plotted to MSL.

Figure 4. Sea-level curve 13 to 7 cal. ka, showing index points and major stratigraphic/sedimentological supporting evidence from east coast. Grey blocks denote major sea level events recognised from the region. For detailed plots of Mid-Late Holocene sea level see Figure 3.

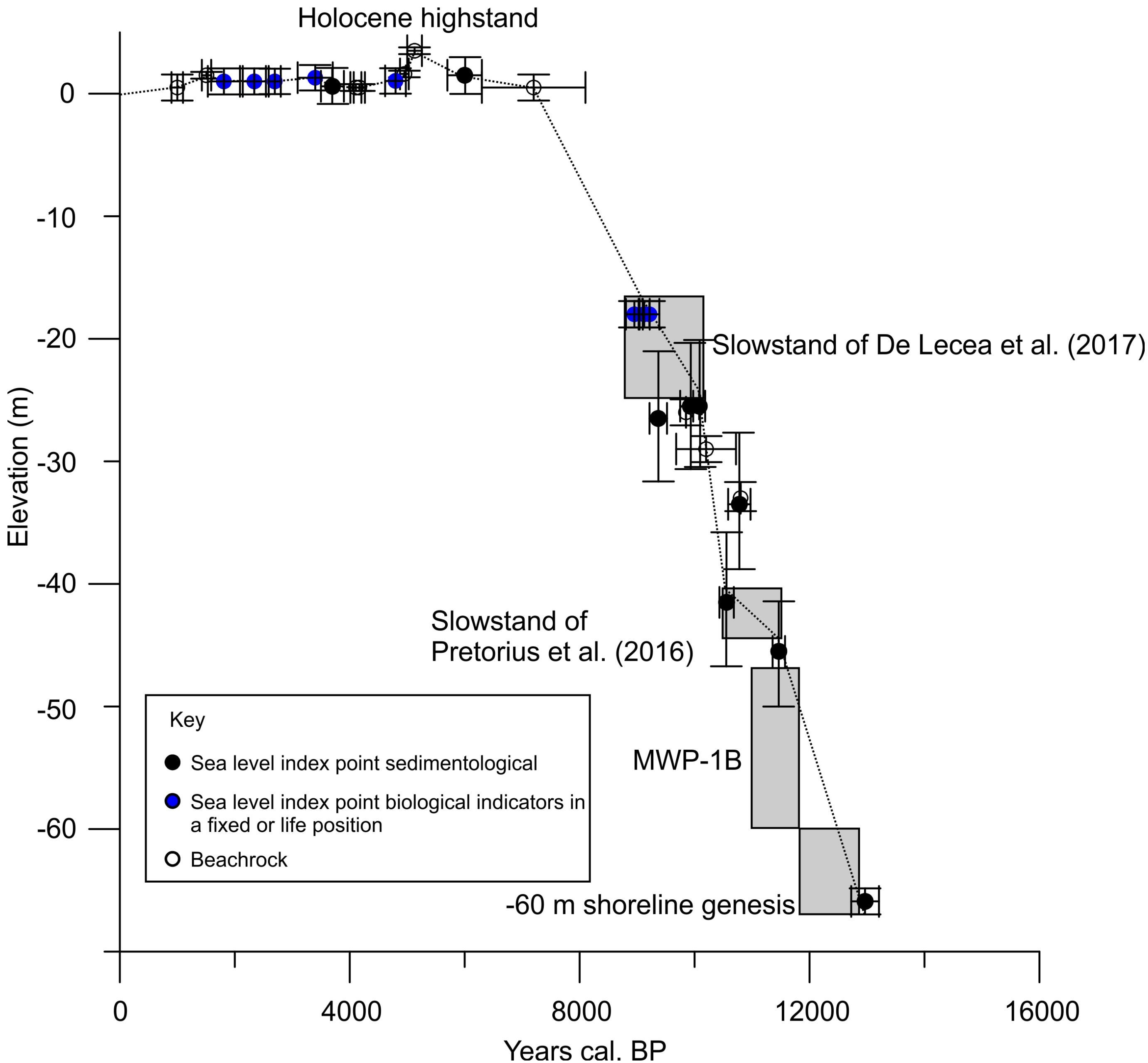


14ºE
19ºE
24ºE
29ºE
34ºE
-25ºS
-30ºS
-35ºS
Bazaruto
Maputo Bay
Kosi Bay
Sodwana Bay
Luderitz
Anichab
Bogenfels
West coast
East coast
Orange River
Mfolozi Estuary
Richards Bay
Holgat River
Mgeni Estuary
Durban
Mkomazi Estuary
Aliwal Shoal
Verlorenvlei
St Helena Bay
Cape Columbine
Langebaan Lagoon
Groenvlei
Knysna Estuary
Keurbooms Estuary
East London
-60 m shoreline
Port Elizabeth
Rietflei
Cape Canyon
Cape Town
Cape Agulhas
Agulhas Bank
M
N
SA


W
E
Unconsolidated Holocene sediment
Incised valleys < 18 ka
Back barrier incised valley
Unconsolidated
Holocene sediment
Wave ravinement surface
-60 m palaeo-shoreline (~ 11.5 ka)
5
36
68
100
132
Depth (m)
Permian sedimentary
rocks
Cretaceous sedimentary rocks
0
1000 m
a)
W
E
75
100
125
150
Depth (m)
Unit 1
> 11 ka
GeoB8333
GeoB8332
Unit 2
~9-10.9 ka
Unit 3
~9-8.8 ka
GeoB8331
Unit 4
~2-3.5 ka
Unit 5
< 1.5 ka
Precambrian
basement
Gravelly sand
Cretaceous sedimentary rocks
0
125 m
b)



Elevation (m)
Years cal. BP
a)
Key
Terrestrial limiting
Marine limiting
Sea level index point sedimentological
Sea level index point biological indicators in a fixed or life position
Sea level index point beachrock
b)



Holocene highstand
Slowstand of De Lecea et al. (2017)
Slowstand of
Pretorius et al. (2016)
MWP-1B
-60 m shoreline genesis
Key
Sea level index point sedimentological
Sea level index point biological indicators in a fixed or life position
Beachrock
Elevation (m)
0
-10
-20
-30
-40
-50
-60
0
4000
8000
12000
16000
Years cal. BP

Table 1. Summary of indicative types and their water level ranges used to calculate relative sea levels.

Sample type	Evidence	Reference water level	Indicative Range	Reference
Beachrock (Index)	Intertidal beachrock	MLW	MLW-MHW	Mauz et al. (2015)
Biological indicators in a fixed or life position (Index)	Organisms (molluscs or serpulid worm encrustations in life position with known relationship to sea level when alive	MLW	Variable (some limited to intertidal, some to specific tidal elevations, refer to text)	Branch and Branch (1981); Kilburn and Rippey (1982)
Geomorphology (Index)	Pothole/pool	MLW	MLW-MHW	Miller and Mason (1994); Cooper and Green (2016)
Sedimentology (Index)	Tidal flat sediments	MHW	MHW to HAT	Edwards (2007)
	Saltmarsh facies with foraminiferal species	MHW	MHW to HAT	Shennan et al. (2015)
	Woody debris in estuarine channel sediments	MHW	MHW to – 5 m	Cooper (1993); Cooper et al. (1989)
	Lagoonal sediments	MHW	MHW to – 5 m	Cooper (2001)
Marine limiting	Marine shells in a littoral or sub-littoral facies	MHW	<MHW	Compton (2001); Branch et al. (1999)
Terrestrial limiting	Terrestrial material (tree stumps/rootlets/ soil) in situ aeolianite, archaeological shell middens	MHW	>MHW	Marker (1997); Ramsay (1995); Compton and Franceschini (2005)

Unique sample ID	Reference	Sub-region	Lat.	Long.	Dating method	Corrected age (14C a BP)	Corrected age uncertainty (14C a)	Age (cal a BP)	Age 2σ Uncertainty + (cal a)	Age 2σ Uncertainty - (cal a)	Sample elevation (m MSL)	Primary indicator type	Sample indicative meaning	RSL (m)	RSL 2σ Uncertainty + (m)	RSL 2σ Uncertainty - (m)
BGP1	Compton (2006)	southern Namibia	-27.46	15.42	Radiocarbon	6710	60	7060	7301	6818	1.50	Fixed biological indicators	MTL	2.50	0.28	0.28
BGP2	Compton (2006)	southern Namibia	-27.46	15.42	Radiocarbon	6220	60	6505	6729	6280	2.00	Fixed biological indicators	<LAT	3.00	0.66	0.66
Bper	Compton (2006)	southern Namibia	-27.48	15.43	Radiocarbon	7013	82	7368	7580	7156	0.50	Fixed biological indicators	<LAT	1.50	0.66	0.66
BP3	Compton (2006)	southern Namibia	-27.46	15.42	Radiocarbon	4740	90	4843	5203	4483	1.40	Raised/storm beach	HAT-MTL	0.90	0.33	0.33
BP5	Compton (2006)	southern Namibia	-27.46	15.42	Radiocarbon	4650	70	4682	4962	4401	2.00	Raised/storm beach	HAT-MTL	1.50	0.33	0.33
BP7	Compton (2006)	southern Namibia	-27.46	15.42	Radiocarbon	4330	60	4251	4540	3961	2.50	Raised/storm beach	HAT-MTL	2.00	0.33	0.33
VC51-30	Compton et al. (2001)	southern Namibia	-25.98	14.84	Radiocarbon	10230	100	11029	11381	10676	-62.50	Sedimentary	<LAT	-61.50	2.59	2.59
26SEPT	Compton (2006)	southern Namibia	-26.25	15.00	Radiocarbon	5180	70	5328	5600	5055	-2.00	Fixed biological indicators	<LAT	-1.00	0.82	0.82
26SEPT1	Compton (2006)	southern Namibia	-26.25	15.00	Radiocarbon	5060	70	5191	5490	4892	-2.00	Fixed biological indicators	<LAT	-1.00	0.82	0.82
26SEPT2	Compton (2006)	southern Namibia	-26.25	15.00	Radiocarbon	4840	50	4978	5257	4699	-2.00	Fixed biological indicators	<LAT	-1.00	0.82	0.82
WB4	Compton (2006)	southern Namibia	-26.28	14.97	Radiocarbon	6310	50	6611	6844	6377	0.00	Fixed biological indicators	<LAT	1.00	0.59	0.59
SP1-87	Compton (2001)	Langebaan Lagoon South Africa	-33.20	18.13	Radiocarbon	4260	80	4744	4965	4523	0.30	Sedimentary	MHWN-MLWN	0.30	0.37	0.37
SP2-48	Compton (2001)	Langebaan Lagoon South Africa	-33.20	18.13	Radiocarbon	560	45	563	629	496	0.80	Sedimentary	>HAT	-0.20	0.37	0.37
SP2-82	Compton (2001)	Langebaan Lagoon South Africa	-33.20	18.13	Radiocarbon	840	45	726	788	664	0.40	Sedimentary	>HAT	-0.60	0.37	0.37
TOP83	Compton (2001)	Langebaan Lagoon South Africa	-33.20	18.11	Radiocarbon	450	70	429	540	317	0.40	Sedimentary	>HAT	-0.60	0.37	0.37
TOP159	Compton (2001)	Langebaan Lagoon South Africa	-33.20	18.11	Radiocarbon	1390	50	1235	1353	1117	0.00	Sedimentary	MHWN-MLWN	0.00	0.37	0.37
SL2-105	Compton (2001)	Langebaan Lagoon South Africa	-33.20	18.11	Radiocarbon	3470	60	3145	3410	2880	-1.50	Sedimentary	<LAT	-0.50	0.68	0.68
SL3-48	Compton (2001)	Langebaan Lagoon South Africa	-33.20	18.11	Radiocarbon	2920	50	2514	2737	2291	-1.30	Sedimentary	<LAT	-0.30	0.68	0.68
BOT126	Compton (2001)	Langebaan Lagoon South Africa	-33.20	18.11	Radiocarbon	4510	50	4524	4796	4252	-1.80	Sedimentary	<LAT	-0.80	0.68	0.68

BOT176	Compton (2001)	Langebaan Lagoon South Africa	-33.20	18.11	Radiocarbon	6460	70	6779	7061	6497	-2.20	Other bioconstructed reefs	<LAT	-1.20	0.68	0.68
OYS	Tankard (1976)	Langebaan Lagoon South Africa	-33.18	18.10	Radiocarbon	6410	45	6714	6951	6477	-1.50	Other bioconstructed reefs	<LAT	-0.50	0.68	0.68
K1	Marker and Miller (1993)	Knysna Lagoon SA	-34.07	23.03	Radiocarbon	5910	30	6280	6297	6263	2.60	Fixed biological indicators	LAT	2.60	0.68	0.68
Ke1	Reddering (1988); Miller (1990); Miller et al. (1993)	Keurbooms estuary SA	-34.01	23.43	Radiocarbon	5580	70	5997	6174	5819	2.70	Fixed biological indicators	HAT	2.70	0.37	0.37
Ke2	Reddering (1988); Miller (1990); Miller et al. (1993)	Keurbooms estuary SA	-34.02	23.40	Radiocarbon	4280	60	4391	4566	4215	1.50	Fixed biological indicators	HAT-MHWS	0.60	0.37	0.37
G2	Deevey et al (1959); Martin (1968)	Groenvlei, South Africa	-34.03	22.85	Radiocarbon	1905	60	1802	1989	1614	-0.10	Fixed biological indicators	>HAT	-1.10	0.45	0.45
KS1	Baxter and Meadows (1999); Baxter (1997)	Verlorenvlei, South Africa	-32.41	18.48	Radiocarbon	3640	60	3903	4085	3720	-0.30	Sedimentary	>HAT	-1.30	0.57	0.57
KS2	Baxter and Meadows (1999); Baxter (1997)	Verlorenvlei, South Africa	-32.41	18.48	Radiocarbon	1900	60	1799	1986	1612	0.90	Sedimentary	>HAT	-0.10	0.57	0.57
CC1	Baxter and Meadows (1999); Baxter (1997)	Verlorenvlei, South Africa	-32.32	18.38	Radiocarbon	7840	110	8144	8417	7871	-5.50	Sedimentary	<LAT	-4.50	0.57	0.57
CC2	Baxter and Meadows (1999); Baxter (1997)	Verlorenvlei, South Africa	-32.32	18.38	Radiocarbon	7430	80	7757	7972	7541	-4.50	Sedimentary	<LAT	-3.50	0.57	0.57
CC3	Baxter and Meadows (1999); Baxter (1997)	Verlorenvlei, South Africa	-32.32	18.38	Radiocarbon	5490	80	5712	5960	5463	-2.30	Sedimentary	<LAT	-1.30	0.57	0.57

Unique sample ID	Source	Sub-region	Lat.	Long.	Dating method	Corrected age (^{14}C a BP)	Age Uncertainty (^{14}C a)	Age (cal a BP)	Age 2σ Uncertainty + (cal a)	Age 2σ Uncertainty - (cal a)	Sample elevation (m MSL)	Primary indicator type	Sample indicative meaning	RSL (m)	RSL 2σ Uncertainty + (m)	RSL 2σ Uncertainty - (m)
PTA-U432	Ramsay and Cooper (2002)	Kwa-Zulu-Natal (Kosi Bay)	-26°53' 34.65	32°52' 42.02	U-series	n/a	n/a	11300	300	300	-16.00	Beach rock	MHW-MLW	-16.00	1.44	1.44
PTA-3597	Grobbler et al. (1988)	Kwa-Zulu-Natal (Mkomazi)	-30°11' 35.91	30°46' 54.40	Radiocarbon	9990	30	11465	108	108	-48.00	Sedimentary	MHW to -5m (depth of maximum scour)	-45.5	5.11	5.11
PTA-4344	Grobbler et al. (1988)	Kwa-Zulu-Natal (Mfolozi)	-28°27' 22.95	32°08' 43.31	Radiocarbon	9440	36	10779	194	194	-36.00	Sedimentary	MHW to -5m (depth of maximum scour)	-33.5	5.11	5.11
PTA-4343	Grobbler et al. (1988)	Kwa-Zulu-Natal (Mfolozi)	-28°27' 22.95	32°08' 43.31	Radiocarbon	9350	90	10557	126	126	-44.00	Sedimentary	MHW to -5m (depth of maximum scour)	-41.5	5.11	5.11
PTA-3570	Grobbler et al. (1988)	Kwa-Zulu-Natal (Mkomazi)	-30°11' 35.91	30°46' 54.40	Radiocarbon	8950	30	10081	104	104	-28.00	Sedimentary	MHW to -5m (depth of maximum scour)	-25.5	5.11	5.11
PTA-4346	Grobbler et al. (1988)	Kwa-Zulu-Natal (Mkomazi)	-30°11' 35.91	30°46' 54.40	Radiocarbon	8840	90	9926	177	177	-28.00	Sedimentary	MHW to -5m (depth of maximum scour)	-25.5	5.11	5.11
GaK1389	Maud et al. (1628)	Kwa-Zulu-Natal (Mgeni)	-29°48' 35.17	31°01' 56.96	Radiocarbon	8420	140	9367	152	152	-29.00	Sedimentary	MHW to -5m (depth of maximum scour)	-26.5	5.11	5.11
PTA-3622	Grobbler et al. (1988)	Kwa-Zulu-Natal (Mkomazi)	-30°11' 35.91	30°46' 54.40	Radiocarbon	8240	140	9214	172	172	-18.00	Fixed biological indicators	MHW-MLW	-18.00	1.07	1.07
PTA-3573	Grobbler et al. (1988)	Kwa-Zulu-Natal (Mkomazi)	-30°11' 35.91	30°46' 54.40	Radiocarbon	8140	70	9122	96	96	-18.00	Fixed biological indicators	MHW-MLW	-18.00	1.07	1.07
PTA-3575	Grobbler et al. (1988)	Kwa-Zulu-Natal (Mkomazi)	-30°11' 35.91	30°46' 54.40	Radiocarbon	8070	80	8952	146	146	-18.00	Fixed biological indicators	MHW-MLW	-18.00	1.07	107
PTA-6252	Ramsay (1995)	Kwa-Zulu-Natal (Black Rock)	-27°08' 05.23	32°49' 49.51	Radiocarbon	4480	70	5128	128	128	3.50	Beach rock	MHW-MLW	3.5	1.00	1.00
PTA-6297	Ramsay (1995)	Kwa-Zulu-Natal (Black Rock)	-27°08' 05.23	32°49' 49.51	Radiocarbon	4350	60	4952	76	76	1.61	Beach rock	MHW-MLW	1,61	1.00	1.00
PTA-5052	Ramsay and Mason (1990)	Kwa-Zulu-Natal (Mabibi)	-27°23' 04.21	32°43' 55.71	Radiocarbon	3780	60	4167	98	98	0.50	Beach rock	MHW-MLW	0.50	1.00	1.00
PTA-6300	Ramsay (1995)	Kwa-Zulu-Natal (Black Rock)	-27°08' 05.23	32°49' 49.51	Radiocarbon	3740	60	4107	96	96	0.50	Beach rock	MHW-MLW	0.50	1.00	1.00
PTA4972	Ramsay (1995)	Kwa-Zulu-Natal (Kosi Bay)	-26°53' 34.65	32°52' 42.02	Radiocarbon	1610	70	1508	82	82	1.50	Beach rock	MHW-MLW	1.50	1.00	1.00
ABER-BA2	Armitage et al., 2006)	Mozambique (Bazaruto)	-21°38' 29.27	33°29' 35.49	OSL	0	0	7200	900	900	0.50	Beach rock	MHW-MLW	0.50	1.44	1.44
ABER-BA8	Armitage et al., 2006)	Mozambique (Bazaruto)	-21°30' 58.75	33°28' 54.85	OSL	0	0	1000	100	100	0.50	Beach rock	MHW-MLW	0.50	1.44	1.44
ABER-IN15	Armitage et al., 2006)	Mozambique (Inhaca)	-26°00' 03.05	32°57' 46.23	OSL	0	0	6000	300	300	1.50	Sedimentary	MHW-MLW	1.50	1.44	1.44

ABER-IN20	Armitage et al., 2006)	Mozambique (Inhaca)	-26°00' 14.62	32°56' 37.77	OSL	0	0	3700	200	200	0.60	Sedimentary	MHW-MLW	0.60	1.44	1.44
GC1/1b	Bosman (2012)	KwaZulu-Natal (Aliwal Shoal)	-30°16' 2.68	30°49' 29.40	OSL	0	0	10800	0	0	-33.00	Beach rock	MHW-MLW	-33.00	1.44	1.44
GC-2/3/9	Bosman (2012)	KwaZulu-Natal (Aliwal Shoal)	-30°16' 2.68	30°49' 29.40	OSL	0	0	9850	0	0	-26.00	Beach rock	MHW-MLW	-26.00	1.44	1.44
Poz-64329	Pretorius et al. (2016)	KwaZulu-Natal (Durban shelf)	-29°48' 50.57	31° 7'59.32	Radiocarbon	11690	90	12966	228	241	-64.00	Sedimentary	MHW-MLW	-64.00	1.44	1.44
Pta-9400	Botha et al. (2018)	KwaZulu-Natal (Aliwal Shoal)	-30°16' 2.68	30°49' 29.40	Radiocarbon	4320	50	4797	180	180	1.04	Fixed biological indicators	MHW to + 0.2 m (Tidal variation)	1.04	1.04	1.04
Pta-9413	Botha et al. (2018)	KwaZulu-Natal (Aliwal Shoal)	-30°16' 2.68	30°49' 29.40	Radiocarbon	2650	40	2695	105	105	1.00	Fixed biological indicators	MHW to + 0.2 m (Tidal variation)	1.00	1.04	1.04
Pta-9402	Botha et al. (2018)	KwaZulu-Natal (Aliwal Shoal)	-30°16' 2.68	30°49' 29.40	Radiocarbon	3370	60	3399	306	306	1.30	Fixed biological indicators	MHW to + 0.2 m (Tidal variation)	1.30	1.04	1.04
Pta-9419	Bosman (2012)	KwaZulu-Natal (Umgababa)	-30°09' 24	30° 49'45	Radiocarbon	2010	60	1810	280	280	1.00	Fixed biological indicators	MHW to + 0.2 m (Tidal variation)	1.00	1.06	1.06
Pta-9460	Botha et al. (2018)	KwaZulu-Natal (Mission Rocks)	-28°18' 25	32° 28'12	Radiocarbon	2440	45	2340	202	202	1.00	Fixed biological indicators	MHW to + 0.2 m (Tidal variation)	1.0	1.06	1.06