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Regional and global context of the Late Cenozoic Langebaanweg (LBW) palaeontological site: West Coast of South Africa

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A B S T R A C T

The palaeontological site of Langebaanweg (LBW) is internationally renowned for its prolific, diverse and exceptionally well preserved Mio-Pliocene vertebrate faunas. The site is located on the southern West Coast of South Africa which represents a passive intraplate, trailing edge setting. The southern African subcontinent is also removed from glacial influence and has experienced no Cenozoic volcanic activity. Rates of vertical crustal motion are consequently low and Late Cenozoic shoreline datums at LBW chiefly reflect glacio-eustatic sea level history. The primary aim of this study is to clarify the chronology as well as the regional and global context of LBW and to review previous work on these aspects. LBW is ideally situated to document the complex interactions of ocean, atmosphere and land and their respective influence on climate evolution, given its location near the coast and mix of marine, estuarine and terrestrial faunas and depositional settings. This paper also provides a background to the study of the vast existing faunal collections and a guide to undiscovered fossil deposits. Towards these ends, the first detailed geological/topographic maps of the site and surrounds, accompanied by a summary stratigraphic column are provided. Virtual geological modelling using a subsurface database has clarified the spatial and temporal relationships of sedimentary facies, as well as their depositional settings.

The geological and palaeontological record at LBW tracks and documents the major regional and global climatic/oceanographic events of the Late Cenozoic. During the Oligocene drawdown in sea levels, the landscape was etched by river incision. Fluctuating sea levels of the Neogene periodically reversed the trend from erosion to deposition, preserving contemporary faunas and floras in the Oligocene palaeovalleys. Earlier Miocene pollen from fluvial facies indicates a humid sub-tropical climate, reflecting a warm southern Atlantic Ocean. The abrupt late Middle Miocene global cooling (Monterey Excursion) coincided with intensified cold upwelling in the Benguela Current and extensive phosphate authigenesis. A globally documented Early Pliocene highstand possibly related to the shoaling of the Isthmus of Panama reached ~90 m above sea level (asl), implying extensive melting of the cryosphere. Palaeomagnetic data in tandem with global sea level reconstructions suggested an age of ~5.15 ± 0.1 Ma for the faunas and a correlation with the earlier part of this transgression. A subtropical C3 vegetation is indicated by the faunas and floras, but with a significant contribution by sclerophytic *fynbos* pointing to a cooler and more seasonal climate than in the Miocene. A mid-Pliocene highstand to ~50 m asl truncated the Early Pliocene succession at LBW and the globally documented Late Pliocene highstand to ~30 m asl saw the Atlantic shoreline approaching LBW for the last time. With the progressive climatic cooling and instability of the terminal Pliocene, culminating in the growth of the Arctic ice cap, strengthening southerly winds driven by a tighter coiled South Atlantic Anticyclone deposited extensive coastal dune fields over the region.

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Contents

1. Introduction

In terms of diversity, the Late Miocene has been termed the 'climax of the Age of Mammals' (Kurten, 1971) and LBW offers a unique African archive of the latter part of this period. This record includes the first bear found in Africa (*Agriotherium africanum*), a wolverine (*Plesiogulo monspessulanus*), the only African peccary (*Pecarichoerus)* and several species of hyaena. Some forms are present in great abundance, such as the short-necked giraffid *Sivatherium hendeyi* (Fig. 2), of which more than 500 individuals have been counted (Hendey, 1981a,b). Isotopic and dental pathological studies on the teeth of this species have shed light on aspects of dietary and population health and confirmed the prevalence of C3 vegetation in the Mio-Pliocene (Franz-Odendaal, 2002; Franz-Odendaal et al., 2002; Franz-Odendaal and Solounias, 2004; Franz-Odendaal, 2006; Ungar et al., 2006). Importantly though, LBW also documents the initiation of the more specialised and less diverse mammalian faunas, evolving to cope with the climatic instability and extremes of the Quaternary (Hendey, 1981a). The seal *Homiphoca capensis*, which shows adaptations to colder waters exemplifies this transformation. The Mio-Pliocene time frame of LBW also overlaps the emergence of the hominin lineage and some of the earliest forms in eastern Africa come from sites with temporally comparable faunal assemblages (Grine et al., 2006; Adams et al., 2007). The Elandsfontyn site where the early Middle Pleistocene 'Saldanha Man' cranium was discovered (Strauss, 1957) is situated only 30 km south of LBW. The coastal deposits which hosted these remains have counterparts at LBW, associated with which are Early and Middle Stone Age artefacts (Kandel et al., 2006).

Avians are also exceptionally well represented at LBW and Rich (1980) suggested that the site ranks amongst the richest pre-Pleistocene fossil bird localities in the world. Although several works on the avifauna have been published (Simpson, 1971; Olson, 1984, 1994; Rich and Haarhoff, 1985; Olson and Eller, 1989; Stidham, 2006; Manegold, 2009) most of the material remains unstudied. Amongst the lower vertebrates, the anurans are especially prolific and diverse with at least four and probably six families documented (Van Dijk, 2006). Less well known are the Plio-Pleistocene faunas found in the aeolianites unconformably overlying the Tertiary strata, as well as phosphatic fluvial sediments at Baard's Quarry ~2 km east of LBW (Tankard, 1974; Hendey, 1981a). These faunas are less diverse and more fragmentary in nature than their Mio-Pliocene counterparts, but nonetheless contribute significantly to the continuum between Tertiary and Quaternary forms. The LBW fauna also provide an important context for dating and interpreting contemporary sites in other parts of Africa, thereby helping to distinguish between extinction/migration events in space and time. Some mammalian groups such as the felids and micromammals display a high degree of endemism (Hendey, 1981a; Matthews, 2004, 2006), shedding light on the origins of Quaternary and present faunas indigenous to the region.

The Mio-Pliocene palaeontological site of Langebaanweg (LBW) is internationally renowned for its prolific, divers and exceptionally well preserved fauna. This National Heritage Site occupies an old phosphate

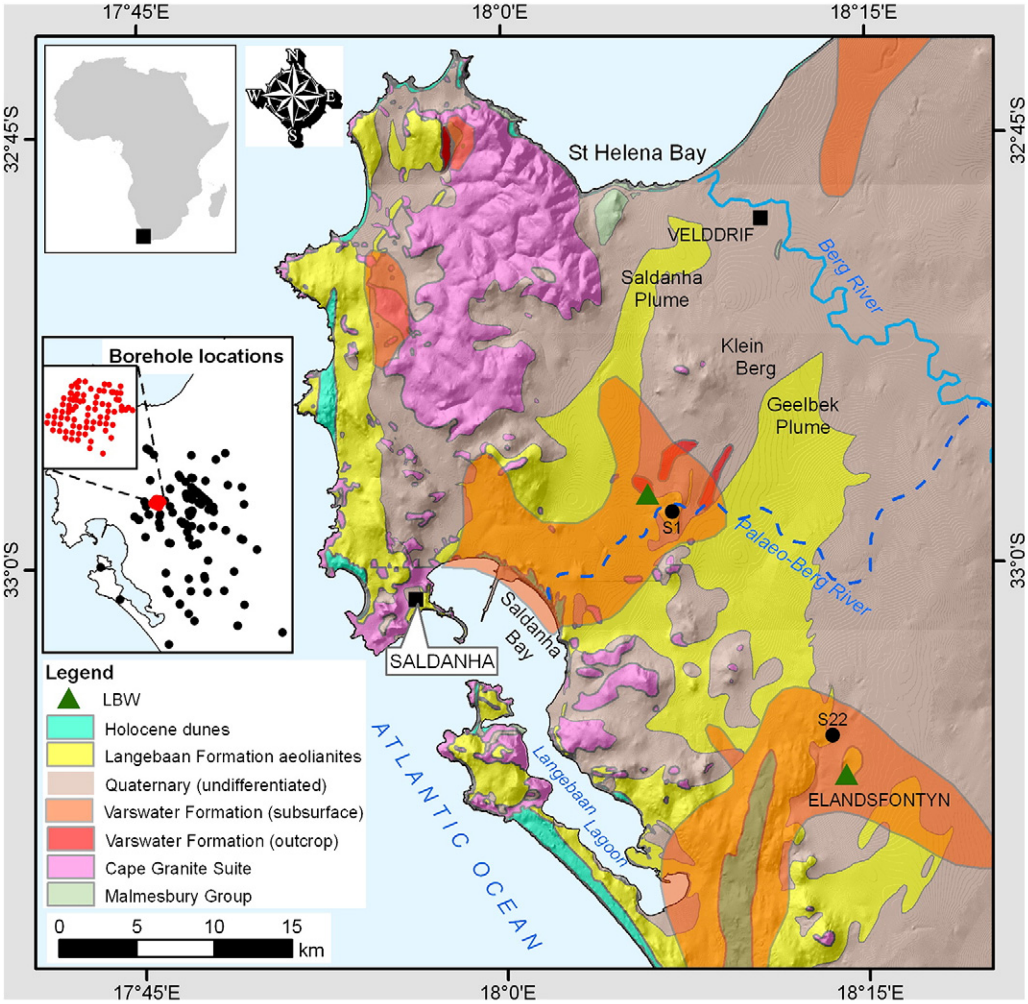

Fig. 1. Locality and geological map of LBW and environs, with distribution of boreholes used in the study (inset shows borehole distribution at LBW). The subsurface extent of the Neogene formations is also indicated.

mine situated on the West Coast of South Africa, approximately 110 km north of Cape Town (Fig. 1). Since 1998 it has formed the seat of the West Coast Fossil Park, becoming a focus for renewed research, education and ecotourism (Haarhoff, 2006). Recently, these activities received a further impetus from the establishment of a multidisciplinary palaeontological/geological research group, including members from the Iziko Museum of Cape Town, the West Coast Fossil Park, the University of Cape Town and the Council for Geoscience. Part of the (ongoing) research results of this group, with particular emphasis on chronology, are presented here. The last review papers on LBW date from the early 1980s (Hendey, 1981a,b;1983a,b,c), and here we offer a comprehensive survey of the literature pertaining to the site. Many of these works are published in relatively inacessible journals and this study makes this information available to a wider audience. Q. Brett Hendey has been the most active and prolific researcher since the discovery of the first fossils in the late 1950s (Boné and Singer, 1965) and published numerous works on the geology and palaeontology of LBW over a period spanning more than two decades (Hendey, 1969, 1972a,b,c,d; 1974a,b; 1975, 1976a,b; 1977, 1978a,b,c; 1980, 1981a,b,c; 1983a,b,c; 1984; Maglio and Hendey, 1970; Hendey and Repenning, 1972; Hendey and Deacon, 1977; Hendey and Dingle, 1990).

With its location near the coast and mix of marine and terrestrial faunas and sedimentary facies (Figs. 1 and 3), LBW is ideally situated to unravel the tightly interwoven fabrics of ocean, atmosphere and land which mediate climate evolution (Miller, 1992; Zachos et al., 2001; Lisiecki and Raymo, 2005). A wide range of depositional environments are represented, including marine, estuarine, fluvial, marsh, back-swamp and aeolian (Tankard, 1974, 1975a,b; Hendey, 1981a,b). Collectively, these sedimentary facies are sensitive barometers of fluctuations in palaeoenvironments, as archived in their lithology, geometry, internal architecture, diagenesis, palaeontology and archaeology (Roberts et al., 2009). In particular, they should record the development and variability of the cold Benguela Upwelling System (BUS), one of the four Eastern Boundary Upwelling Systems distributed around the globe, which profoundly influence patterns of global sea surface temperatures and, consequently, adjacent terrestrial climates and ecosystems (Siesser, and Dingle, 1981; Weldeab et al., 2007). BUS has mediated sea surface temperatures and climates along the African West Coast since the Early Miocene (Siesser, and Dingle, 1981; Pether, 1986; 1994a,b; Cohen and Tyson 1995; Pickford and Senut, 1997; Du Pont et al., 1999 Roberts and Brink, 2002).

Since the last syntheses of the stratigraphy and sedimentology of LBW (Hendey, 1981a,b; 1983a,b,c), the surface and subsurface geology of the region has been mapped in greater detail (Theron et al., 1992; Roberts Siegfried, in press) and the stratigraphy revised and formalised according to the guidelines of the South African Committee for Stratigraphy (Roberts, 2006a,b,c,d,e). These developments have helped clarify the regional context of the site. On the global stage, LBW provides biogeographic links with Eurasia subsequent to the Late Miocene collision of the African and Eurasian plates. This seminal event allowed free migration of faunas endemic to each of these continents. In this regard LBW is one of the strategic sites in time and

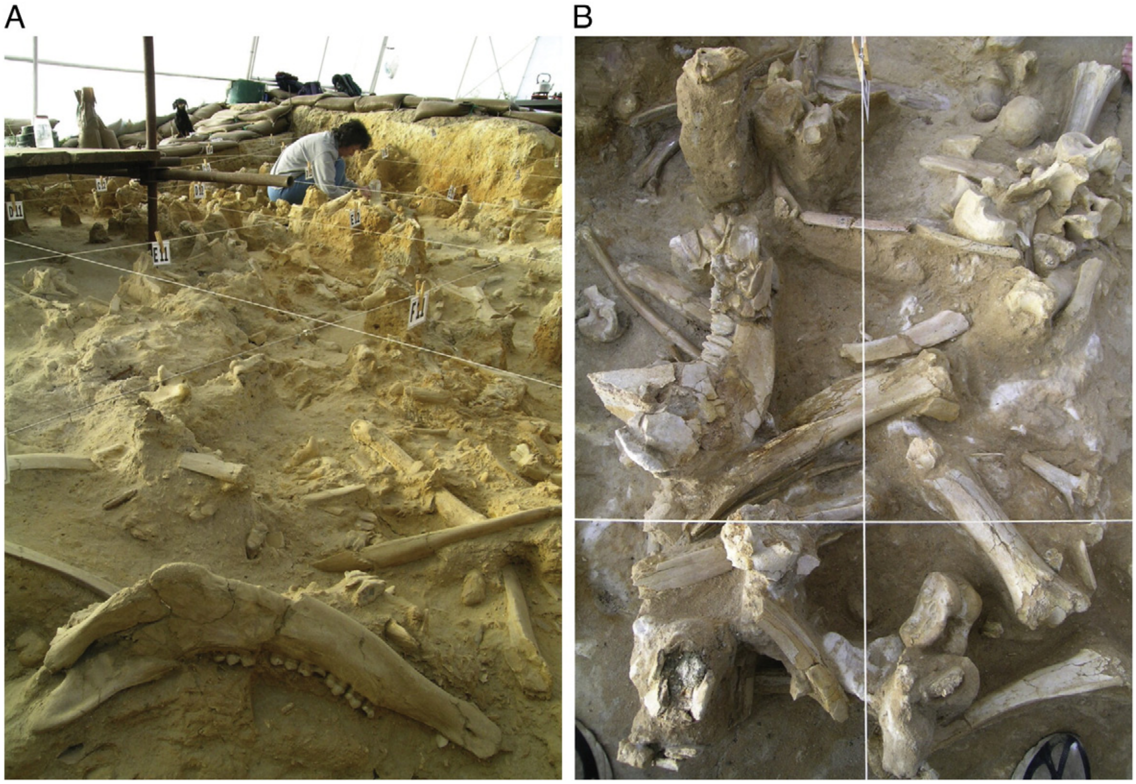

Fig. 2. Bone bed (Channel 3aN) at the dig site, with the large fossils mainly consisting of the short necked giraffid *Sivatherium hendeyi*. Note the lack of orientation of the long bones and steep (southwesterly) dip of the channel base (in (A) towards viewer).

space, illuminating the contrasting developmental pathways of faunas with common ancestry in different environments on Eurasian and African landscapes (Pickford and Senut, 1997; Pickford, 2005, 2006). In the past 3 decades, the understanding of the trends, tempo and chronology of global oceanographic and climate evolution in the Late Cenozoic have been clarified, allowing more precise correlation of LBW and surrounds with these events.

The chief aims of this study are to refine the global, regional and local oceanographic, climatic and geochronological context of LBW. We critically review previous work on these aspects, providing clarifications and new interpretations in some instances, especially with regard to Pliocene sea level history. We have created a high resolution (2 m) digital elevation model (DEM) of the old mine area, providing a topographic framework for the first detailed geological/palaeontological map of the site (Fig. 4A). This map is designed to help locate undiscovered fossil concentrations in the subsurface. Approximately 70% of the fossiliferous strata (Varswater Formation) and overlying Quaternary cover has been removed during mining operations at LBW. A previous study (Erasmus, 2005a,b) created a borehole database embracing the LBW site and environs, the aim of which was to reconstruct the geomorphic expression and spatial distribution of contrasting palaeo-environments of Cenozoic strata using virtual modelling, which is updated here. We also report on the application of numerical dating methodologies (optically stimulated luminescence (OSL) and palaeomagnetics on selected formations to refine the prevailing relatively low resolution biochronology of the site.

2. Geographical and geological setting

LBW is situated on the stable coastal platform of the South African West Coast (Fig. 1), bounded on the landward side by the Great Escarpment. The platform originated in the late Mesozoic dismemberment of Gondwanaland and has since been influenced by repeated Cenozoic marine transgressions (Pether, 1986; 1994a,b; Roberts et al., 2007a, b). The southern West Coast (Fig. 1) is sporadically blanketed by late Cenozoic aeolian and marginal marine deposits (Rogers, 1982; Roberts and Berger, 1997; Roberts and Brink, 2002), with the thicker deposits occupying depressions in the Precambrian basement. The basement in the LBW environs is Neoproterozoic in age and comprises the intensely deformed metapellites of the Malmesbury Group and slightly younger plutons of the Cape Granite Suite. The granites are more resistant to weathering and form topographically elevated terrain (Fig. 1), whereas the metasediments tend to floor the depressions (Roberts Siegfried, in press). The onshore Cenozoic sediments contain a sedimentological, palaeontological and palaeoenvironmental archive ranging in time from the Miocene to the Holocene, whereas Cretaceous strata predominate offshore (Rogers, 1982; Dale and McMillan, 1999; Roberts, 2006a).

The southern West Coast of South Africa currently experiences a semi-arid, Mediterranean climate (~300–400 mm p/a rainfall). The dominant (dry) southerly summer winds are generated by the South Atlantic Anticyclone and the (wet) winter westerlies are associated with polar frontal systems (Tyson, 1999). The study area is situated near the convergence of the cold Benguela and warm Agulhas Currents (Atlantic and Indian Oceans respectively, Fig. 1). Late Cenozoic fluctuations in relative current strength, disposition and upwelling regimes would have profoundly influenced patterns of sea surface temperatures and regional climates (Pether, 1994 a,b; Cohen and Tyson 1995; Schumann et al., 1995). Because of the influence of BUS, aridity increases rapidly northward in concert with the waning influence of the polar frontal systems. Mediterranean climate-adapted *fynbos* therefore also diminishes northward and the vegetation becomes increasingly Karooid. According to Roberts and Brink (2002), these fundamental atmospheric/oceanographic dynamics have dominated at least since the early Late Miocene (~10 Ma), embracing much of the time span of the faunal and floral elements at LBW (Fig. 3).

3. Stratigraphy

The history of stratigraphic subdivision and terminology at LBW dating back to the 1960s, is summarised in Table 1. The lithostratigraphy of the entire southern West Coast Cenozoic succession, including LBW was revised by Roberts (2006a,b,c,d,e) and is now termed the 'Sandveld Group'. A summary stratigraphic column of the Cenozoic succession and detailed geological/satellite image map of the site are shown in Figs. 3 and 4A & B respectively. The stratigraphy at LBW was progressively revealed during phosphate mining and in the logs of exploration drill holes (Tankard, 1974, 1975a, b; Hendey, 1981a,b). The phosphatic part of the upper Varswater Formation (Fig. 3) is extensively exposed in the existing quarries, but the contacts between underlying members (LQSM, KGM and LCSM) can only be seen in detail in a small pit ('excavation HW1') in the floor of E quarry near the Highwall (Figs. 4A & 5).

3.1. Elandsfontyn Formation

The Elandsfontyn Formation is present only in the subsurface on the West Coast (up to 30 m below present sea level) and locally reaches ~60 m in thickness (Rogers, 1980, 1982). It is mainly composed of poorly sorted, angular sands and gravels, alternating with fine sands and silts, grading to carbonaceous clays and peaty material, best developed near the top of the formation. These fluvial facies have an essentially linear form and are arranged in upward-fining sequences (Fig. 3), up to eight of which may be developed (Timmerman, 1985, 1988; Roberts, 2006b). Palynological studies at LBW revealed the presence of subtropical forest species (including palms), but with a notable component of summer drought tolerant *fynbos* taxa. Collectively, the flora and stratigraphy suggests an Early/Middle Miocene age (Coetzee, 1978, 1980, 1983; Coetzee and Rogers, 1982; Scott, 1995). Biogeochemical studies showed that

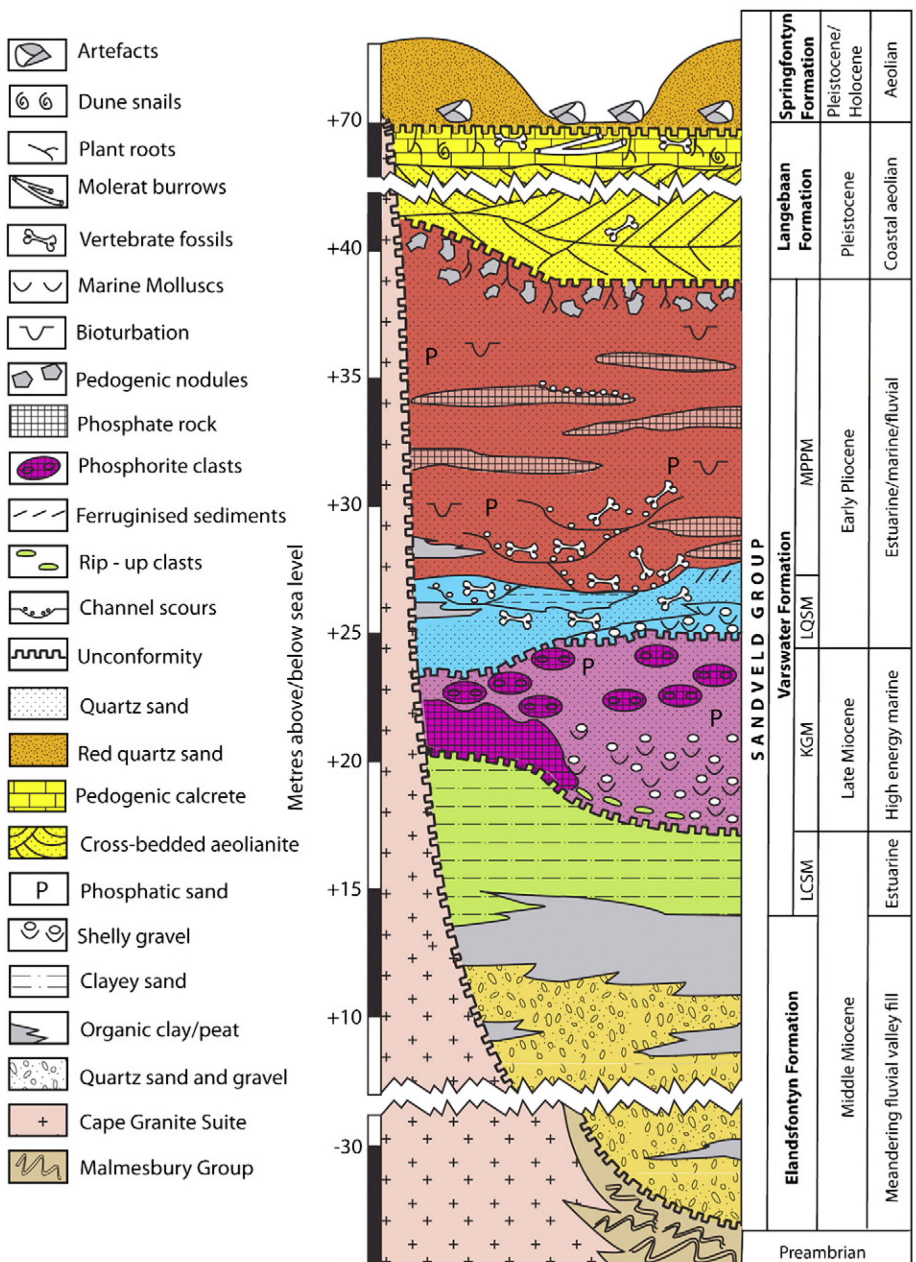

Fig. 3. Summary stratigraphic column for LBW.

palaeotemperatures during deposition of the Elandsfontyn Formation varied from 12–27 °C, with warmer temperatures in the uppermost part of the succession (Sciscio, 2011). This possibly records the transition from the cool Oligocene to the warmer Miocene.

3.2. Varswater Formation

The terrestrial Elandsfontyn Formation is overlain in places by the marine/estuarine Varswater Formation (Figs. 3 and 6), which accumulated in basement depressions during Neogene marine transgressions (Tankard, 1974; Rogers, 1980, 1982; Roberts 2006a,b, c). The Varswater Formation at LBW comprises four members, namely the Langeenheid Clayey Sand (LCSM), Konings Vlei Gravel (KGM), Langeberg Quartz Sand (LQSM) and Muishond Fontein Pelletal Phosphorite Members (MPPM). Their biological age, spatial relationships, approximate thickness, lithology, depositional setting in 'C' Quarry at LBW are shown in Figs. 3 and 4A.

The LCSM forms the basal member of the Varswater Formation (Figs. 3 and 5; Table 1) with a thickness ranging from 1 to 11.5 m. The member consists of clayey, greyish green (10Y 7/4) sand with reddish mottles. The sand is fine-grained, well-rounded and well-sorted (Fig. 5) and rests conformably on carbonaceous silts and clays of the Elandsfontyn Formation. This lithology closely resembles recent estuarine deposits in the nearby modern Berg River (Fig. 1) and is interpreted as its ancient counterpart (Roberts, 2006b).

The gravels comprising the KGM reach a maximum elevation of ~25 m above sea level (asl) and rest with an erosional unconformity on the estuarine LCSM (Figs. 3 and 5). Polished and rounded to subangular clasts are set in a matrix of phosphatic sand and range up to boulder size (Fig. 5). The deposits thicken from ~2 m in the north to ~8 m in the southwest, where sandy sediments with pockets of thermophyllic marine molluscs, scattered shark teeth and rare mammalian bones also occur (Fig. 3). A high energy, shallow marine origin is envisaged for the member.

The LQSM is typically only about 0.5–2 m thick and mainly comprises quartzose sand (Figs. 5 and 7C). Silty and peaty facies are also developed in places. The member mainly reflects a fluvio-estuarine environment, although a molluscan fauna and palynomorphs in the silty facies suggests that salt marsh and tidal flat deposition was also important (Tankard, 1974, 1975a,b; Kensley, 1972, 1977; Hendey, 1981a,b). The contact of the LQSM with the underying KGM is unconformable, marked by intense ferruginisation in the upper part of the KGM as seen exposed in the floor of E Quarry (Fig. 7A). The wide diversity of vertebrate fossils preserved in the member broadly indicates a Mio-Pliocene age for the LQSM (Fig. 3).

The overlying MPPM (Figs. 3 and 5) comprises fine- to medium-grained, light brownish grey sand (10 R/6) which ranges up to 15 m in thickness (Smith, 1971; Tankard, 1974). The contact with the underlying LQSM is sharp and slightly erosional, as seen in pit HW1. Fine laminae a few mm thick defined by variations in peletal phosphorite content (Fig. 7B) are sporadically visible in the exposures of E Quarry, but otherwise the strata are generally structureless; bioturbation is locally evident (Roberts, 2006d). The phosphatic material is of two kinds: (1) amber-coloured shell fragments replaced by authigenic carbonate apatite and (2) pelletal carbonate apatite grains (Smith, 1971; Rogers, 1980; 1982; Middleton, 2000, 2006). The formation is locally hard and well cemented by secondary phosphorite, forming (nodular) lenses (Fig. 3) that extend laterally for up to 300 m (Dingle et al., 1979; Roberts, 2006d).

The phosphate was produced authigenically as a result of periodic cold upwelling systems in the BUS (Tankard and Rogers 1978; Dingle et al. 1983; Middleton, 2000, 2006). The MPPM attains a maximum thickness of 11 m and elevation of up to ~45 m asl at the type site of 'E' Quarry and is considered to record estuarine, marine and localised fluvial sedimentation (Tankard, 1974; Hendey 1981a; Rogers, 1982; Roberts 2006c). In contrast to the LQSM, the fossils occur mainly as lag deposits within southwesterly orientated linear channels (Figs. 2 and 4). In common with the LQSM, a wide diversity of vertebrate fossils broadly indicates a Mio-Pliocene age for the member. (Hendey, 1974a, b; 1975, 1976a,b; 1977, 1978a,b,c; 1980, 1981a,b,c). A general consensus has emerged that the age difference between the LQSM and MPPM is minimal (Hendey, 1970a,b; 1980, 1981a). The

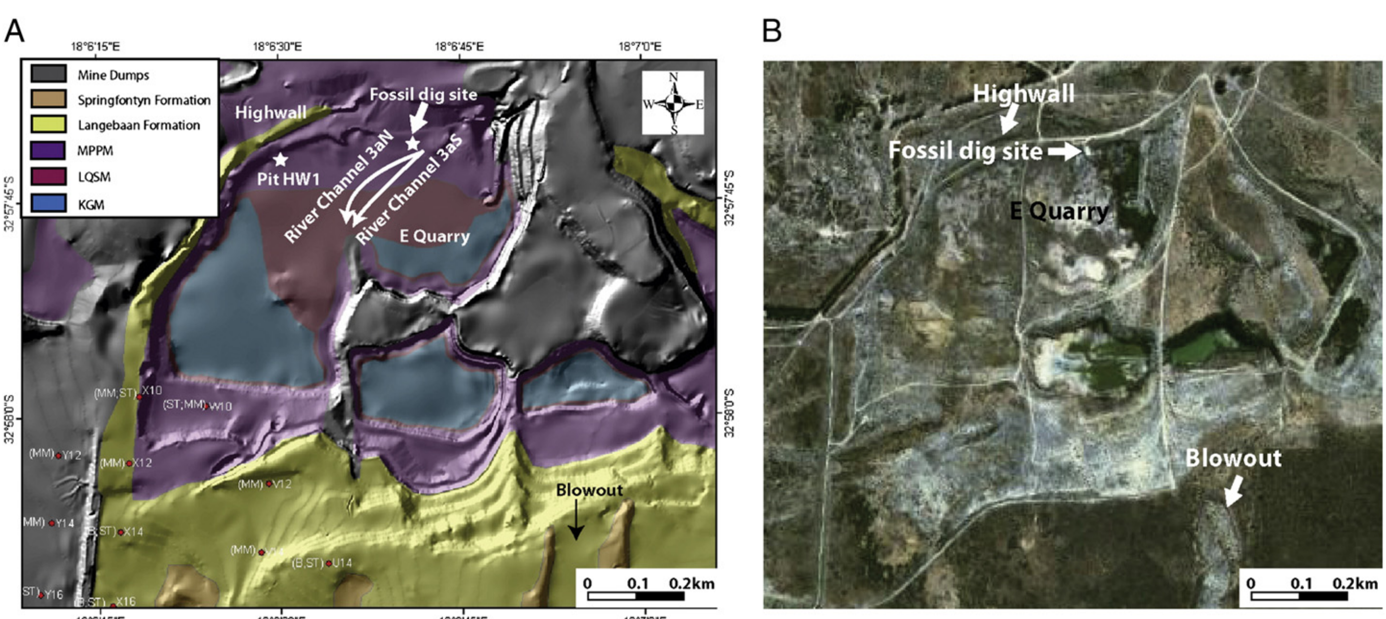

Fig. 4. A) Geological map of the LBW site draped over a high resolution (2 m) DEM showing the present topography of the old phosphate mine. Trends of palaeo-rivers and boreholes drilled ahead of mining which intersected fossiliferous material are also shown (red dots-ST=shark teeth; MM=marine molluscs; B=bone); B) Satellite image of the old LBW phosphate mine corresponding with the DEM shown in (A).

Table 1
Evolution of stratigraphic nomenclature at LBW.

Hendey (1970a, b)	Tankard (1974)	Tankard (1975a, b)	Dingle et al. (1979)	Rogers (1980, 1982)		Roberts (2006c)
Bed 3	Pelletal phosphorite member	Pelletal phosphorite member	Upper Varswater Formation	Pelletal phosphorite member (Duynefontein, Bookram Members)		Muishond Fontein peletal phosphorite member
Bed 2	Fluvial sand member	Quartzose sand member		Quartzose sand member		Langeberg quartzose sand member
Bed 1	Beach gravel member	Gravel member	Lower Varswater Formation	Shelly gravel member (Silverstroom, Strandfontein members)	Saldanha Formation	Konings Vlei gravel member
	Kaolinitic clay/fine quartzose sand	Kaolinitic clay/fine quartzose sand				Langeenheid clayey sand member
	Basal bed	Saldanha Fm				

chronology and taphonomy of the MPPM fossils are considered further in Section 7.

3.3. Langebaan Formation

The Quaternary succession at LBW mainly comprises calcified coastal aeolianites of the Langebaan Formation (Roberts, 2006d; Table 1). The formation is well exposed at Anyskop in the south and the 'Highwall' of E Quarry in the north, where mining operations have produced cut faces (Figs. 8A and B). The aeolianites consist of quartzose sand and marine bioclasts cemented by secondary carbonate. The large scale, steeply inclined dune foresets capped by pedogenic calcretes are typical of coastal aeolianites in the region (Rogers, 1980;1982; Roberts, 2006e). Rhizoliths, molerat burrows, abundant fossil dune snails (*Trigonephrus globulus* and *Phortion occidentalis*) as well as terrestrial vertebrate remains (mainly tortoises) are associated with the pedogenic horizons (Hendey, 1981a; Van Bruggen, 1982; Roberts, 2006e). The unconformable contact with the underlying Mio-Pliocene strata is marked by intense pedogenesis, which is especially well displayed at the Highwall (Fig. 8A) and is suggestive of a lengthy hiatus between the two units (Dingle et al., 1979). For these reasons, the aeolianites at LBW which were previously named the 'Calcareous Sandstone Member' (Table 1) were removed from the Varswater Formation and referred to the Langebaan Formation (Roberts, 2006e).

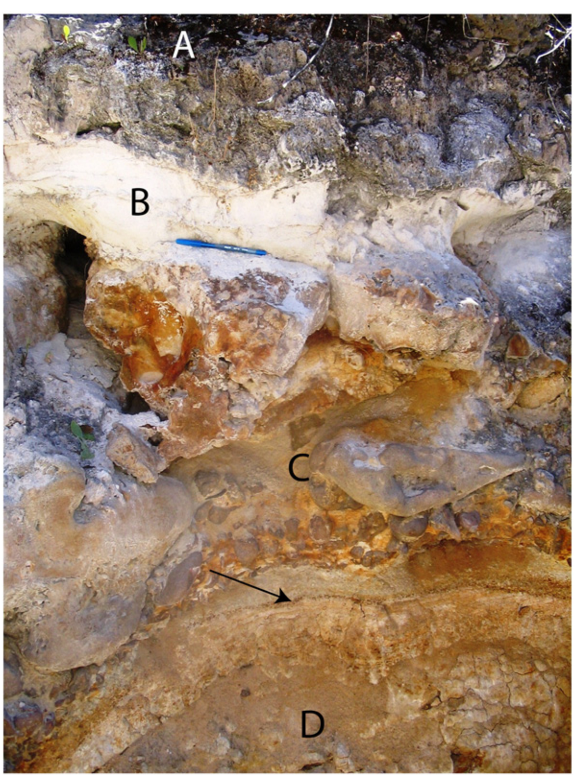

Fig. 5. Pit HW1 near the Highwall showing the lithology and stratigraphic relationships of the various members of the Varswater Formation. (D = LCSM; C = KGM; B = LQSM; A = MPPM). The erosive contact between the LCSM and overlying KGM is marked by a clay pellet conglomerate (arrowed). Pen for scale (upper left).

Hendey (1981a) reported the presence of Plio-Pleistocene mammalian fossils in the Langebaan Formation at Anyskop (Fig. 8B). Acheulian artefacts, indicative of an age range of ~1.5–0.5 Ma, have been found cemented onto the upper surface of pedogenic calcretes exposed in the blowout east of Anyskop, providing a minimum age consistent with the age constraints provided by the mammalian fossils. The context and origin of the Langebaan Formation at LBW is further discussed in Section 7.

3.4. Springfontyn Formation

The concept of the Springfontyn Formation had its origins in the unconsolidated quartz sands with rounded grains exposed in the coastal Springfontyn cliffs 20 km north of Cape Town (Rogers, 1980, 1982). The sands were thought to represent leached aeolian sands of the originally calcareous Langebaan Formation. The formation was subsequently expanded to embrace all unlithified, aeolian quartz sands of the southern West Coast regardless of the origin or age (e.g. Theron et al., 1992). Active sedimentation is occurring in some areas, whereas at other localities dunes are vegetated and relict (Rogers, 1982; Roberts and Brink, 2002). Because of the loose definition and uncertain chronology, the formation has not been formalised as part of the Sandveld Group.

The sands of the Springfontyn Formation are widespread along the West Coast (Roberts and Siegfried, in press) and are sporadically developed in the region of LBW (Fig. 4). They are well exposed in a blowout East of Anyskop, where structureless, reddish (10R 4/6) fine grained, well rounded and sorted quartz sands rest unconformably on the Langebaan Formation (Fig. 8C). We have dated these sands at LBW to the Middle Pleistocene and Holocene (Table 2) using optically stimulated luminescence (OSL), as further reported in Sections 4 and 7.

4. Palaeomagnetic study

4.1. Methods and materials

For the methodology employed in the palaeomagnetics study, see the Supporting Online Material.

4.2. Results and discussion

Two of the three clayey sand samples (LB05/6) from the upper part of the LCSM gave no conclusive result. Although one sample gave a normal polarity (Table 2) no overall polarity can be inferred for the

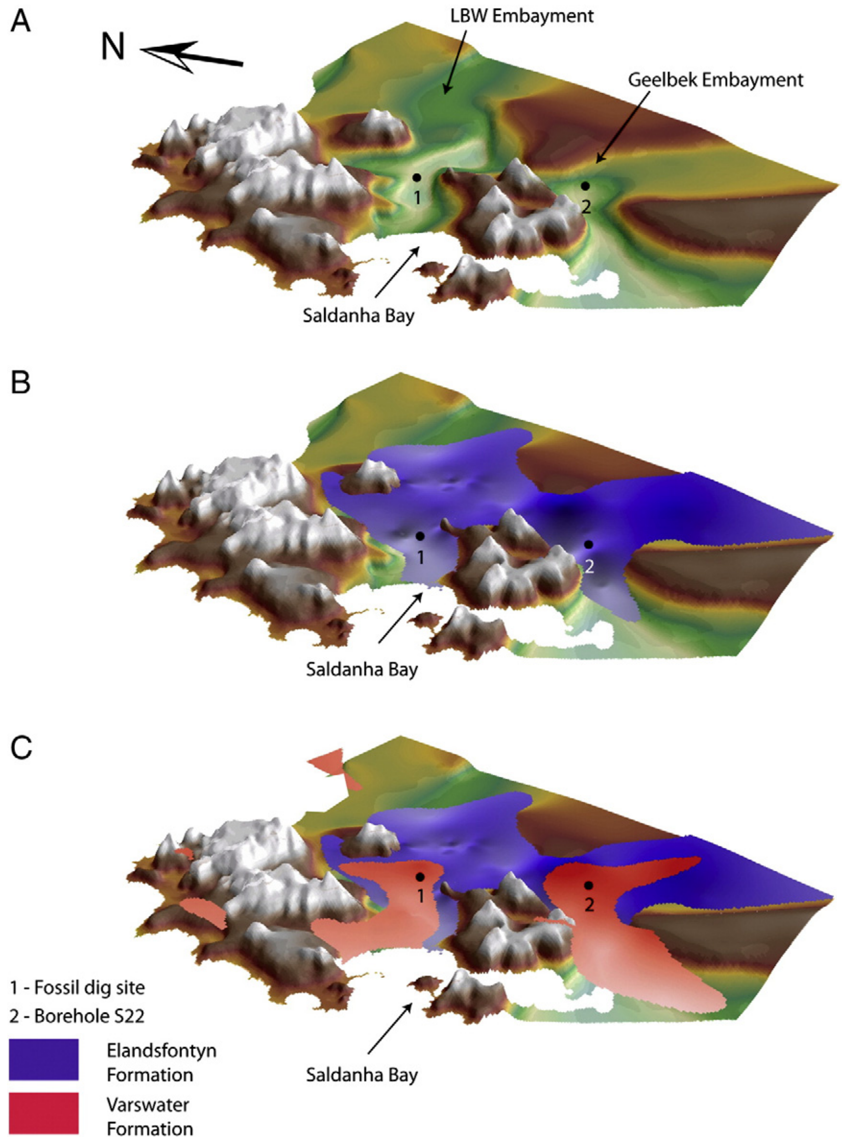

Fig. 6. Sequence of major Neogene erosional and depositional events in the LBW environs: A, Fluvial incision during Oligocene lowstands; B, Early–Middle Miocene sea level (base level) rise and deposition of the fluvial Elandsfontyn Formation; C, Major Early Pliocene transgression and deposition of the Varswater Formation.

LCSM. The mineralogy of the two samples from the KGM (LB11 and LB12) is complex due to the secondary subaerial ferruginisation (see Section 3). LB 11 records a normal polarity using alternating field (Afd), but this remanence is removed at 150 °C during thermal demagnetisation (THd) analysis, probably due to the remanence being held by goethite. This remanence is interpreted as secondary in nature, formed by late stage precipitation of iron-bearing minerals. Sample LB12 also records such an overprinting Normal remanence, but this is removed at 200 °C during thermal demagnetisation, revealing a weak reversed polarity (Table 2), which is possibly syndepositional (Fig. 9: samples 10–12).

Only AFd could be applied to the weakly cemented, fragile samples collected in plastic cubes from the MPPM sands from the middle part of the member (LB08). AFd of all the MPPM samples (heavily and lightly cemented) record normal polarity chemical remanence (ChR), characterised by a gradual decrease in magnetisation and stability up to 60 mT (Table 2). The cemented MPPM sands (LB09-10) were also subjected to THd and similarly recorded a normal polarity ChRM (Fig. 9). Mineral magnetic analysis of the MPPM sands indicates that the remanence is held by low coercivity ferrimagnetic minerals with a Curie point (570 °C), suggestive of magnetite. Although the remanence is probably secondary and geochemical rather than depositional in origin, it is improbable that the hard, dense phosphorite rock acquired the polarity after its cementation. Dingle et al. (1979) present compelling evidence, including water abraded phosphorite rock in the MPPM, that cementation preceded the deposition of Early Pliocene fossils. This concept is supported by our observation that the tops of lenses of phosphorite rock have in places been eroded and reworked into the overlying, weakly consolidated phosphatic sands in the upper MPPM, illustrating multiple phases of phosphorite rock cementation in the course of deposition of this unit. Furthermore, the distinctive patterns of rare earth enrichment in the MPPM is consistent with carbonate fluorapatite precipitation in seawater (Middleton, 2006), supporting an early digenetic origin. Birch (1979) indicated that the intense cementation of phosphorite rock may have resulted from mass mortality of marine organisms during phases when cold upwelling subsided. Several considerations therefore suggest that the cementation was authigenic and penecontemporaneous with deposition of the MPPM.

Overall the results of the palaeomagnetic study indicate that the ChRM of each sample/subsample is a chemical remanence held by a number of minerals and formed by varying processes after their deposition. Tentatively, late stage (subaerial) diagenesis of the KGM could have occurred under Reversed polarity and – with a high degree of confidence – under normal polarity during very early diagenesis of the MPPM (Fig. 9). The interpretation and significance of these results are considered further in Section 7.

5. Optically stimulated luminescence (OSL) dating

5.1. Methods

The methodology for the optically stimulated luminescence (OSL) dating is provided in the Supporting Online Material.

5.2. Results

The results of the OSL analyses are summarised in Table 3, and indicate Middle Pleistocene and Holocene deposition for the aeolian quartz sands of the Springfontyn Formation. The interpretation and significance of these results are considered further in Section 7.

6. Biochronology

The biochronological ages inferred for the upper Varswater Formation (Table 1) by various authors and in some instances, by the same author have varied since the inception of study of the LBW faunas in the late 1950s. The initial age estimate of Early Pleistocene (e.g. Boné and Singer, 1965; Hendey, 1969) gave way from the 1970s onward to a realisation of the essentially Late Tertiary age. Gentry (1970, 1974) proposed a late Miocene age (6 Ma) based on the bovids, or according to Hooijer and Maglio (1974) even exceeding 6 Ma, founded on comparison of elephantids and suids with Lothagam in northern Kenya. Other researchers have compared the LBW suids to Kanapoi south of Lothagam, thought to be ~4 Ma in age (e.g. Harris and White, 1979). Hendey (1980) placed upper and lower palaeontological age limits of 7 and 3.5 Ma respectively on the upper Varswater Formation, reflecting the uncertainties of the biochronology.

This spread of ages is partly a consequence of the difficulties in relating the faunas at LBW to their radiometrically dated counterparts in East Africa. Endemism is also a perennial problem (especially regarding

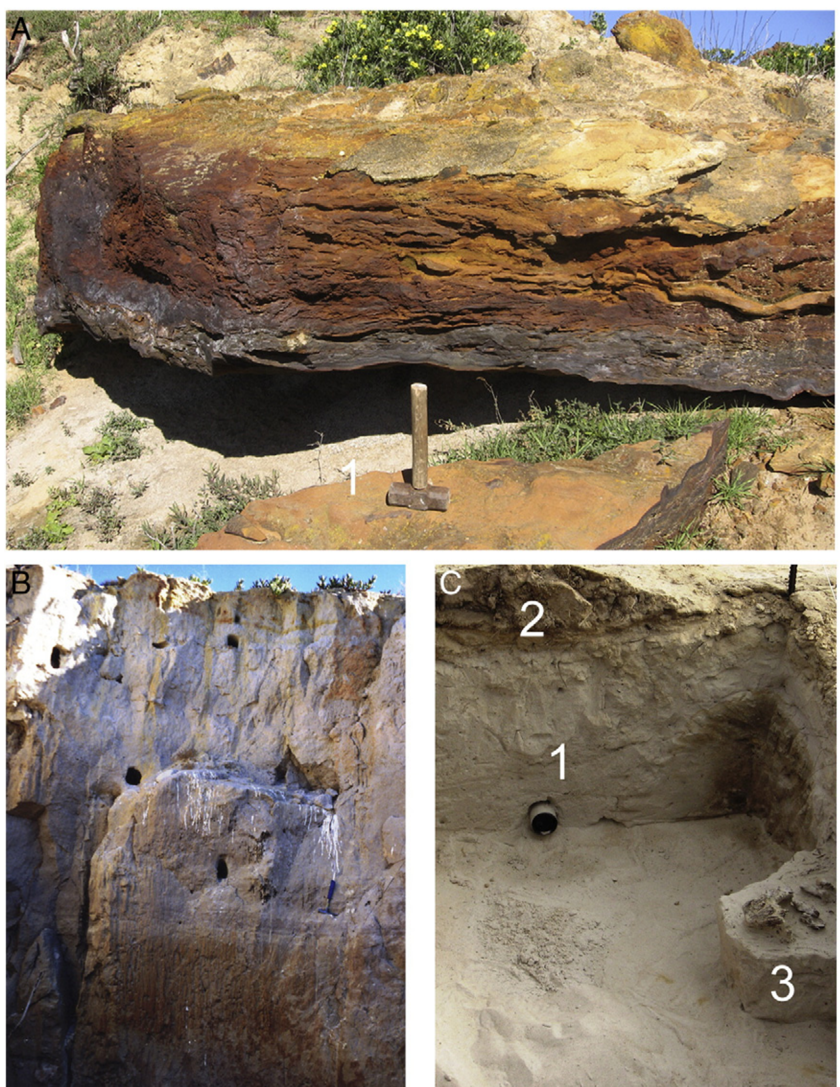

Fig. 7. A) Ferruginised upper part of the KGM, 40 m south of pit HW1. Hammer 36 cm long; B) Exposure of the phosphatic MPPM in E Quarry, showing laminated sediments in the middle part of the unit (indicated by hammer at middle right which is 28 cm long); C) The whitish, fine sands of the LQSM (1) exposed in a trench next to the main dig site and abruptly overlain by the (darker coloured) MPPM (2). Fossilised bones of a rabbit are visible on the pedestal on the middle right (3).

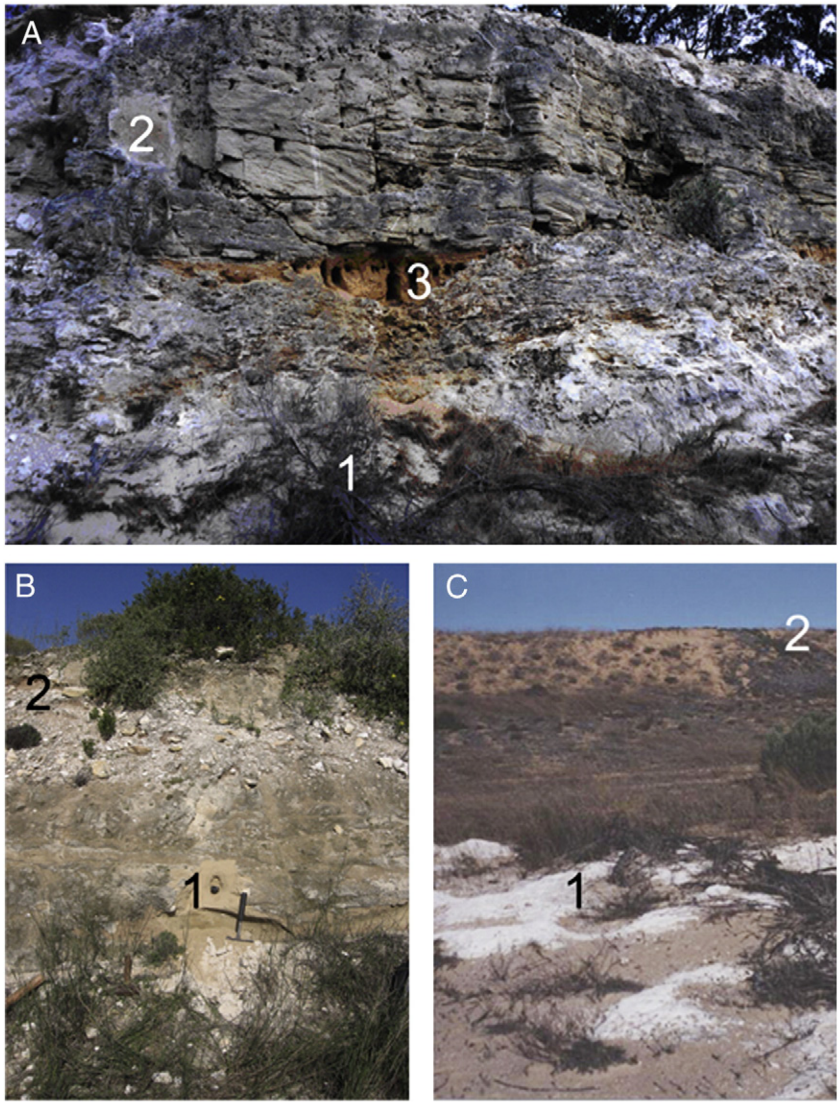

Fig. 8. A) Strongly unconformable contact of the Early Pliocene MPPM (1) with the overlying aeolian (Plio-Pleistocene?) Langebaan Formation (2), marked by intense pedogenesis (3). Note also the characteristic large scale cross-stratification and pedogenic calcrete at the top of the Langebaan Formation; B). Remnant aeolianites (1) that formed the hill Anyskop prior to mining at LBW. Note the calcretised paleasols (2), dune snails (e.g. left of 28 cm-long hammer) and C) Reddish, uncemented aeolian quartz sands (Springfontyn Formation) exposed in the blowout east of Anyskop (2) and resting unconformably on the calcretised top of the underlying Langebaan Formation (1).

the micromammals and most carnivores), as well as uncertainties concerning migration rates of newly evolved taxa (Hendey, 1974a,b; 1978a; Denys, 1996, 1999; Matthews, 2004, 2006; Matthews et al., 2007). Herbivores, such as hippos tend to be environmentally restricted and migration may take place over long time periods. For this reason, Hendey (1974b,1980) favoured the biochronology of the carnivores which are more independent and can migrate rapidly over long distances. Thus certain felids and the bear *Agriotherium* are virtually indistinguishable from material at the Early Pliocene site of Montpellier, southern France.

Only mammalian faunal groups that have been recently studied at LBW (post-dating the last major works of Hendey, 1981a, 1983b) and that have provided further age constraints are considered below:

6.1. Non-carnivora

6.1.1. Equids

The upper Varswater Formation hipparion (3-toed horse) *Eurygnathohippus* cf. *baardi* exhibits morphological features of the skull

Table 2
Palaeomagentic data. (No. = number of sub-samples, Dec. = declination, Inc. = inclination, P.Lat = Palaeo-latitude).

Sample	No.	Formation	Lithology	Dec.	Inclination	α95	Polarity	P.Lat.
LB8	3	MPPM	Phosphatic sand	30.9	−47.2	6.3	N	63
LB9	4	MPPM	Phosphatic rock	353	−39	44.5	N	74.4
LB10	4	MPPM	Phosphatic rock	337	−38	25.6	N	72.6
LB11	4	KGM	Light red (10R6/6) ferruginised sand	80	−49	31	I	25.6
LB12	3	KGM	Dark red (5R3/4) ferruginised sand	223	48	32.8	R	−62.5
LB6	2	LCSM	Sandy clay	287.1	40.9	82.3	I	−4.2
LB5	1	LCSM	Sandy clay	25.2	−41.8	–	N	63.5

Table 3
OSL data summary.

Lab sample	Depth (m)	No. of aliquots	De (Gy)	OD (%)	Total dose rate (μGy/a)	Age (ka)
Shfd08214	1.0	69	0.09 ± 0.02	N/A	358 ± 22	0.3 ± 0.6
Shfd08215	2.8	23	61.3 ± 1	7	337 ± 15	182 ± 9

and postcrania that reveal a relationship to the Old World founder *Cormohipparion* from the later Miocene in Turkey. The observation that its postcrania are larger, but similar in their proportions to *Eurygnathohippus feibeli* from the Upper Nawata Formation at Lothagam in Kenya, dated to ~5.2 Ma may be significant (Bernor et al. 2003; Bernor, 2006; Haile-Selassie, 2006).

6.1.2. Hippopotamids

Since the latest Miocene, the Hippopotaminae have exhibited great diversity and basinal endemism that continued for most of the Pliocene. A preliminary examination clearly indicated that LBW hippopotamids are dentally close to primitive Late Miocene and Early Pliocene forms in East Africa, and cannot be attributed to the genus *Hippopotamus* (Boisserie, 2006).The hippopotamids from LBW are therefore exceptionally important for the biogeographical history of the family. They are the oldest recorded hippopotamids in southern Africa and appear to represent an isolated clade epitomised by a unique C3 diet (Boisserie, 2006).

6.1.3. Suids

The suids are important biochronological indicators because the evolutionary history of these ubiquitous and often abundant mammals is well understood (Haile-Selassie, 2006). *Nyanzachoerus*

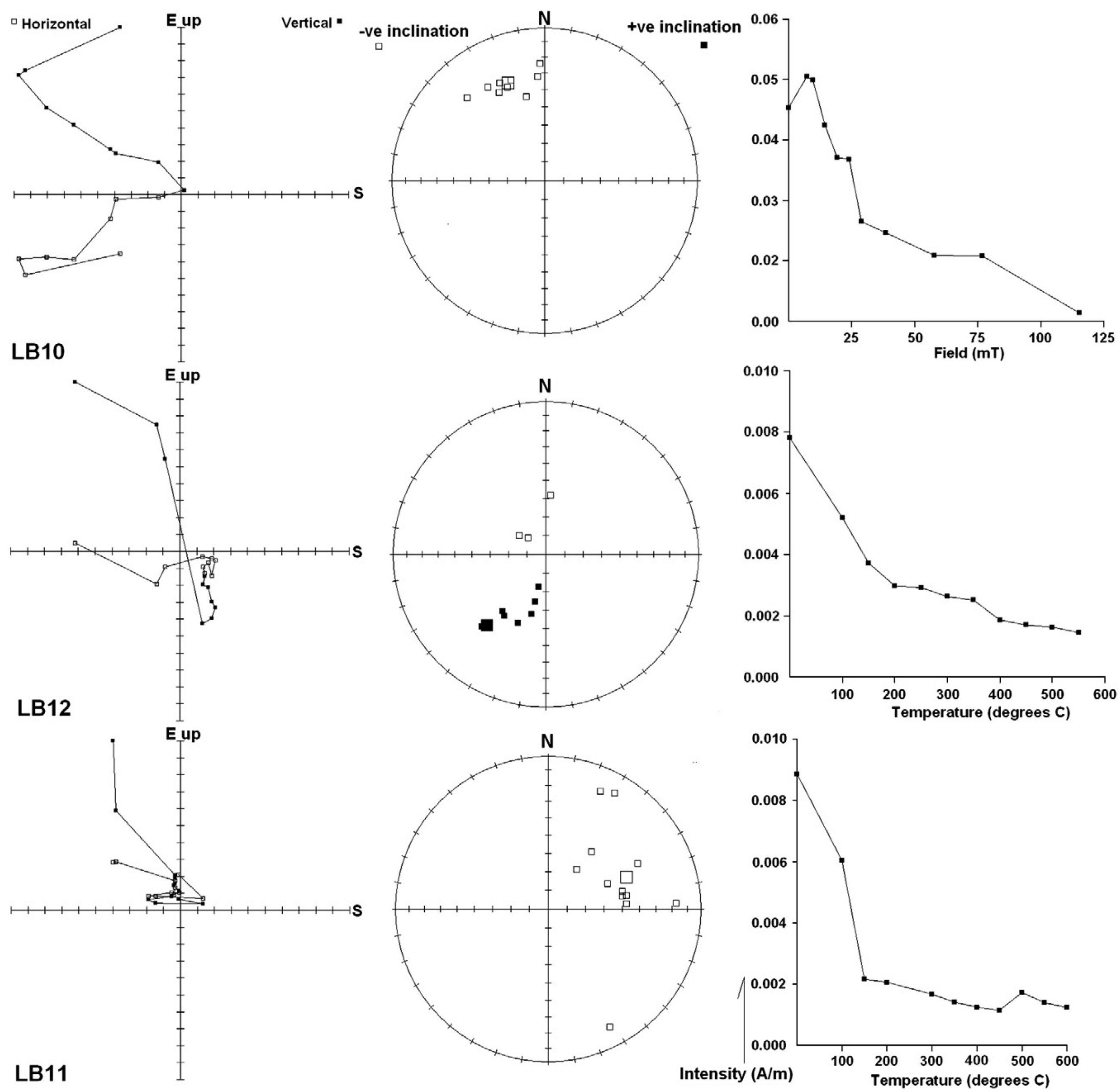

Fig. 9. Demagnetisation behaviour for samples LB10 (cemented phosphatic sand: MPPM), LB12 and LB11 (red iron sand and orange iron sand; KGM).

australis is found at LBW and also at radiometrically dated sites in East Africa, such as the Kuseralee Member of the Middle Awash Formation (Ethiopia) and upper member of the Nawata Formation at Lothagam (Kenya), both of which are dated to ~5.2 Ma (Haile-Selassie, 2006).

6.1.4. Proboscideans

A gomphothere mastodont (*Anancus* sp.) occurs in some abundance in the upper Varswater Formation and being so far south represents a remarkable discovery. Anancines migrated into Africa from Eurasia in the Late Miocene, and persisted on the continent well into the Late Pliocene (Sanders, 2006). The dentition of the LBW anancine gomphothere most closely resembles the derived morph of *A. kenyensis*, from East-Central African sites dated to ca. 5.0–3.5 Ma (Sanders, 2006), a younger estimate than the 5–6 Ma age suggested by comparison with Lothagam (Maglio and Hendey, 1970; Maglio, 1973).

The most common elephant at Langebaanweg is *Mammuthus subplanifrons*, possibly representing the origin of the genus (Hendey, 1983a; Mol, 2006). However, this form is regarded by Sanders (2006, 2007) as a new, primitive species of *Loxodonta.* In overall morphology, it most closely resembles Late Miocene–Early Pliocene loxodonts from the Lukeino Formation of the Tugen Hills in the Kenyan Rift Valley and the Apak Member of the Nachukui Formation at Lothagam in Kenya, and from the Nkondo and Warwire Formations of Uganda.

6.1.5. Micromammals

The biochronological implications of the upper Varswater Formation micromammals have received little attention and much new material has recently been collected from the dig site. The rodent faunas of South Africa and their radiometrically dated East African counterparts show different stages of evolution in contemporaneous faunas and consequently there are few species common to the two regions (Denys 1996, 1999). Genera cited as evidence of this are *Aethomys*, *Dendromus, Steatomys, Thallomys* and *Otomys* (Denys 1987; Denys 1989, 1994a, 1994b, 1996, 1999). These considerations place limits on the biochronological utility of micromammals at LBW. This applies especially to the soricids (shrews) of which only two species (of the four at LBW) have been studied in any depth. These two species are thought to represent an extinct lineage with unique dental and mandibular characteristics (Matthews and Stynder, in press); their phylogeny is uncertain. All murid species (rats and mice) represented in the MPPM and LQSM are extinct, but all the genera are extant except for the relict Miocene genera *Stenodontomys* and *Euryotomys* (Matthews, 2004; Matthews et al., 2006; 2007). The latter two genera are generally supportive of a Mio-Pliocene age for LBW. *Stenodontomys* has been found in 'Late Miocene' contexts from three Namibian sites, namely the breccias in the Otavi mountains and the Harasib 3a site in the north and in fluvial deposits at Berg Aukas along the Orange River in the south (Pickford et al., 1994). *Euryotomys* (*E. bolti*) occurs at only one other fossil site, namely Bolt's farm in central South Africa and is thought to be in the age range of 4–5 Ma (Sénegas and Avery, 1998).

The murid and soricid communities from LBW show stability over the time period encompassed by the MPPM and LQSM, in that there is a great deal of similarity in the composition of micromammal assemblages from different localities within these units (Matthews, 2005). The mole rat *Bathyergus hendeyi,* the rat *Euryotomys pelomyoides* and the (as yet) undescribed lone gerbillid species dominate the majority of assemblages in both members (Matthews, 2004, 2005). In some instances however, there are significant differences in the taxa abundances between the two members, but this probably relates to the complex taphonomic history of LBW and ecological factors, rather than suggesting major temporal differences. Moreover, no compelling evidence from the micromammals suggests any marked climatic or other environmental fluctuations during deposition of the MPPM and LQSM (Matthews, 2005; 2006).

6.2. Carnivora

In terms of diversity, abundance, and quality of preservation, the carnivores at LBW are unique (Hendey, 1980; Werdelin, 2006; Stynder, 2009). They include a mixture of archaic Miocene and progressive Pliocene taxa, in keeping with the Miocene–Pliocene age and location at the southern tip of Africa. There are significant differences between the carnivore faunas of the MPPM and LQSM, with several taxa occurring exclusively in either unit.

6.2.1. Ursidae

Agriotherium africanum was the first pre-Pleistocene bear to be described from Africa (Hendey, 1972a) and the record from Langebaanweg allows for a detailed understanding of the anatomy and ecology of *A. africanum* (Werdelin, 2006), which is indistinguishable from material at the Early Pliocene site of Montpellier, southern France. Mustelidae: Three species of large mustelid are known from Langebaanweg (Werdelin, 2006): Mellivora benfieldi, a primitive honey badger, known from a number of Mio-Pliocene African localities; Plesiogulo monspessulanus, a primitive wolverine, which has subsequently been described from similarly aged localities in eastern Africa; Sivaonyx hendeyi, a Langebaanweg endemic of a genus known from numerous Mio-Pliocene African localities.

6.2.2. Hyaenidae

The Hyaenas of Langebaanweg comprise 4 species in 4 genera and have long time ranges (Werdelin, 2006); they are not generally useful for biochronology. They cannot be older than 7 Ma and therefore are broadly supportive of a Mio-Pliocene age.

6.2.3. Viverridae

There are at least two viverrids from Langebaanweg (Werdelin, 2006). *Viverra leakeyi* is a very large animal that had a pan-African distribution in the Late Miocene to Pliocene.

6.2.4. Tubulidentata

The aardvarks are unusually abundant at LBW. Large aardvarks may have radiated from Kenya into central and southern Africa and replaced Miocene species in the Mio-Pliocene. A derived South African form (perhaps already *Orycteropus afer*) might have subsequently migrated northwards, around the Plio-Pleistocene (Pickford 2005; Lehmann, 2006).

7. Correlation with the regional and global record

7.1. West Coast sea level history

The Neogene witnessed major geological, oceanographic and atmospheric transformations whose history and complex interactions have yet to be fully deciphered, sea level in particular. Strong evidence has emerged over the past few decades that cyclical components of sea level variations are caused by orbitally driven glacio-eustatic effects superimposed on broader trends mediated by rearrangements in the configuration of ocean basins and land masses. Since the Neogene, glacio-eustacy has dominated with amplitudes of fluctuations increasing with time (Miller, 1992; Zachos et al., 2001; Lisiecki and Raymo, 2005).

Flights of raised marine terraces at consistent elevations and of various ages are widely distributed along the entire western coastal belt of South Africa. Following early studies of these features by Rogers (1905), Haughton (1926, 1928, 1931) and Krige (1927), placer diamond deposits were found in the terrace deposits, which provided an impetus for further geomorphological, biostratigraphic and sedimentological studies, e.g. Haughton (1928), de Villiers and Söhnge (1959), Hallam (1964) and Keyser (1972). Detailed molluscan biostratigraphic analyses include those of Carrington and Kensley

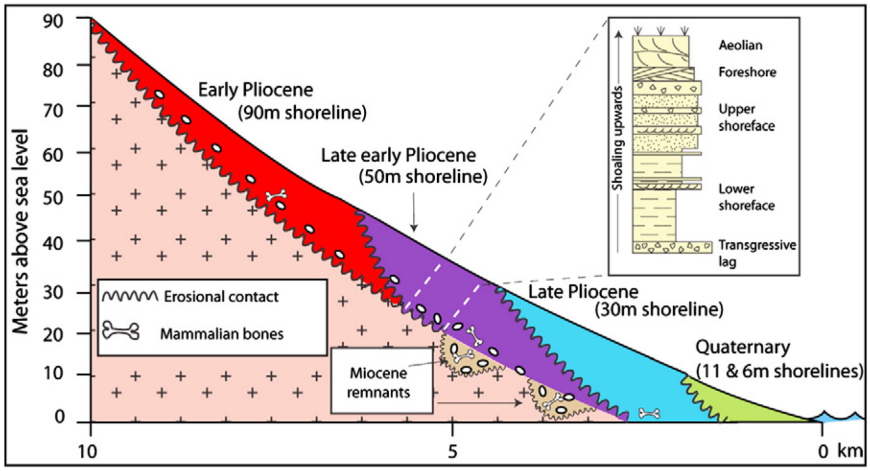

Fig. 10. Idealised sea level history of Namaqualand, illustrated by the characteristic series of marine terraces with transgressive maxima of ~90, 50 and 30 m asl. Offlapping terrace deposits essentially represent progradational shorelines (inset).

(1969), Tankard (1975a,b) and Gresse (1988), whereas the Cenozoic palaeoclimates and sea-level history were considered by Tankard and Rogers (1978), Siesser and Dingle (1981), Hendey (1983a,b,c) and Roberts and Brink 2002. Focussed studies of the sedimentology and biostratigraphy of the marine deposits were conducted by Pether (1986, 1994a,b). Senut and Pickford (1995) and Pickford (1998) recognised the existence of older, Miocene terrace remnants inferred from a fragmentary mammalian fauna. Because of the influence of BUS, the West Coast forms a distinct biogeographical zone as recognised in the stratigraphic subdivision of terrace deposits formalised by Pether et al. (2000) and Roberts et al. (2007a,b).

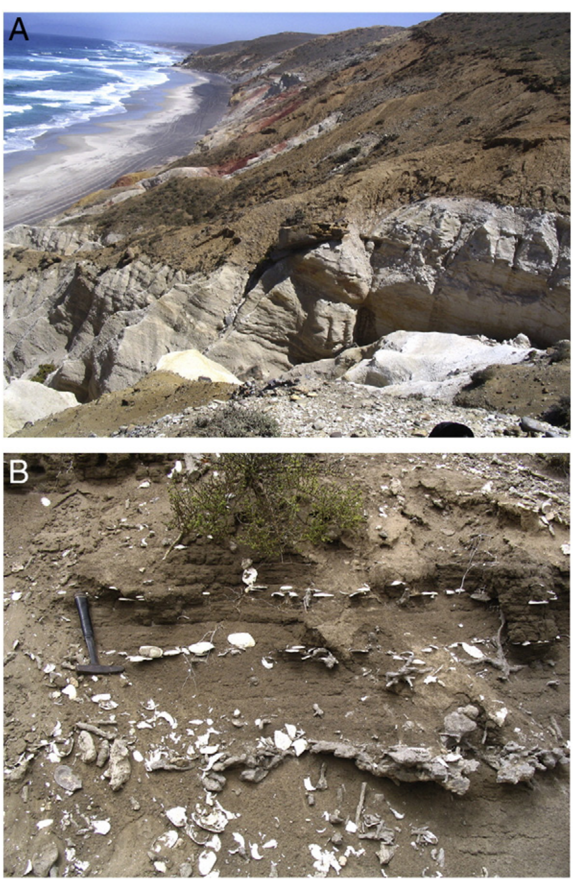

Fig. 11. A) Late Tertiary terraces of the northern West Coast incised into bedrock (light coloured), mantled by marine deposits (darker coloured). B) Marine terraces deposits with the zone fossil of the 50 m highstand *Donax haughtoni*.

Three Pliocene marine units consistently are represented along the length of the West Coast (Pether et al. 2000; Roberts et al., 2007a,b; Roberts and Brink, 2002), reaching elevation maxima of about 30, 50 and 90 m amsl (Figs. 10 and 11A and B). Older Miocene terrace deposits situated below 50 m amsl that survived the later transgressions are locally preserved. Each marine sequence comprises sediments deposited during regression from the transgressive maxima and are arranged *en echelon* down the coastal platform (Fig. 10). In terms of sequence stratigraphy they are highstand tracts, each comprising only one parasequence. Terrace ages are mainly inferred from the sparse mammalian fossils (Hendey, 1981a; Pether et al. 2000; Roberts et al., 2007a,b). The molluscan faunas bear some similarities to those of the present, but with a significant extinct or extralimital thermophyllic component (Fig. 11B). Index molluscan fossils have been identified for each terrace which enables their identification and correlation even where the transgressive maxima are not preserved (Carrington and Kensley, 1969; Pether et al., 2000; Roberts et al., 2007a, b).

The relative contributions of eustacy and tectonism to the currently observed elevations of Late Tertiary terraces of the West Coast have long been contentious. Most authors have gravitated to either one of these mechanisms, but a few have invoked both. Tectonic instability during the Late Cenozoic has been inferred from perceived variations in the disposition of marine terraces, but there is little consensus concerning the spatial aspects, sense, magnitude and timing of deformation.

Krige (1927) conducted groundbreaking studies of ancient sea levels along the South African coast, concluding that marine terraces in the Saldanha environs along the southern West Coast were situated at lower elevations than biostratigraphically equivalent terraces to the north and south. Tankard (1976a,b) amplified Krige's earlier work, positing a Late Tertiary marginal downwarp in this region (Fig. 1). Partridge and Maud (1987; 2000) followed suite, citing Miocene terrestrial deposits near Cape Town at ~50 m below present sea level (Coetzee, 1978; Rogers, 1982; Coetzee and Rogers, 1982) as additional evidence of coastal subsidence. The location of their axis of tectonic downwarp differed from that of Tankard (1976a,b). Dingle et al. (1983) proposed a progressive northward downwarping of up to ~55 m along the northern West Coast, based on apparent declines in terrace elevations. However, Keyser (1972) had presented evidence of terraces exposed by diamond mining at Alexander Bay near the Orange River Mouth, with elevations only 4–6 m lower than those to the south. Gresse (1988) took issue with Keyser (1972), placing these terraces at roughly equivalent height to those further south. North of the Orange River, there is some agreement

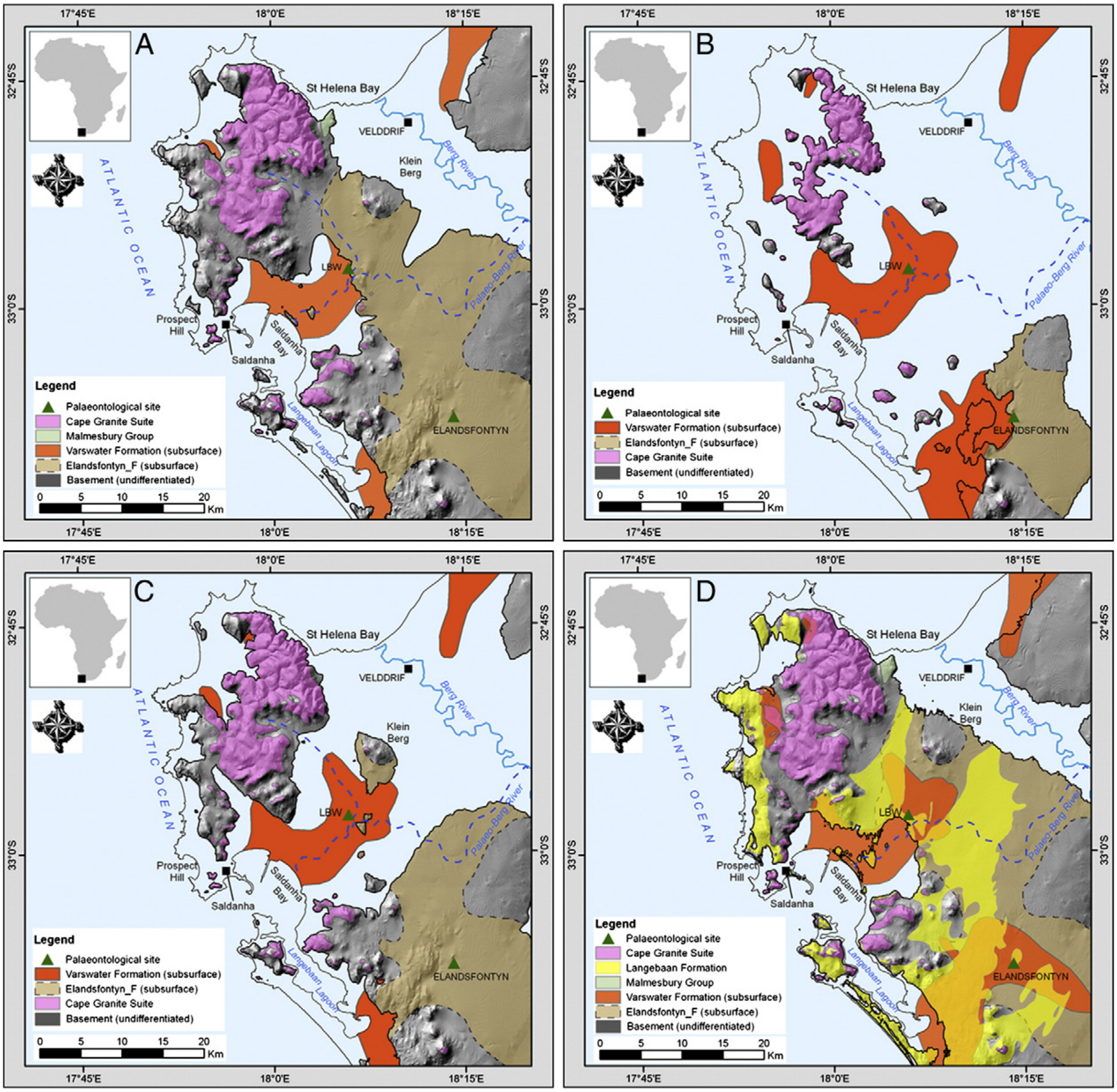

Fig. 12. Palaeogeography and depositional history at LBW in relation to sea level history. A) Earliest Pliocene sea level rise to 30 m coinciding with accumulation of the MPPM fossil beds (subsequently rising to 90 m); B) Early Pliocene 90 m shoreline; C) Late early Pliocene 50 shoreline; D) Early Pleistocene 20 m shoreline and widespread deposition of aeolian sediments.

that 'upper' terraces at ~20–28 m coalesce with the lower terraces (~10 m), pointing to Latest Tertiary/Quaternary downwarping (Krige, 1927; Hallam, 1964; Davies, 1973; Pether, 1994a,b).

In contrast to these suggestions of downwarping, uplift of the northern West Coast in the Early Miocene (100 m) and Pliocene (150 m) was postulated by Partridge and Maud (1987; 2000), partly on the basis of raised terraces along the Orange River (~45 m above msl) dating from the Early Miocene (Pickford, 1998). Compton et al. (2006) also inferred Miocene uplift along the West Coast, citing a perceived lack of onshore sediments of this age. Hendey (1981a) and Pether (1994a,b) cited the equivalence in ages and elevation of the marine terraces along the northern and southern West Coasts with the global sea level curves as evidence of regional tectonic stasis, concluding that glacio-eustacy was the dominant force. Pickford (1998) echoed these sentiments, citing the similarity of terrace elevations and ages with those of Australia, but with the caveat that epeirogenesis may subsequently have altered their altimetry.

The above discussion reveals that there is little consensus concerning neotectonic deformation of marine terraces along the West Coast. We suggest that LBW hosts the best dated Miocene and Pliocene successions along the West Coast and as such sheds light on the discussion of neotectonism offered in Section 7.2. The extensive development of Oligo-Miocene fluvial deposits (Elandsfontyn Formation) extending well below present sea level (Fig. 3) at several localities along the northern and southern West Coast can readily be explained by eustacy, without recourse to major (localised) neotectonism of the type proposed by Partridge and Maud (1987, 2000). Global sea levels rose from their Oligocene lows in the early Miocene and palaeotemperature data (Sciscio, 2011) suggest a rapid warming of climate during Elandsfontyn times-consistent with the Oligocene-Miocene transition and is inconsistent with the notion of broader Miocene uplift, suggested by Compton et al. (2006). It is also noteworthy that all onshore West Coast marine Miocene deposits are presently situated below 30 m asl (Pether et al., 2000). The further contention of Compton et al. 2006 that onshore Miocene deposits are scarce because of subsequent erosion due

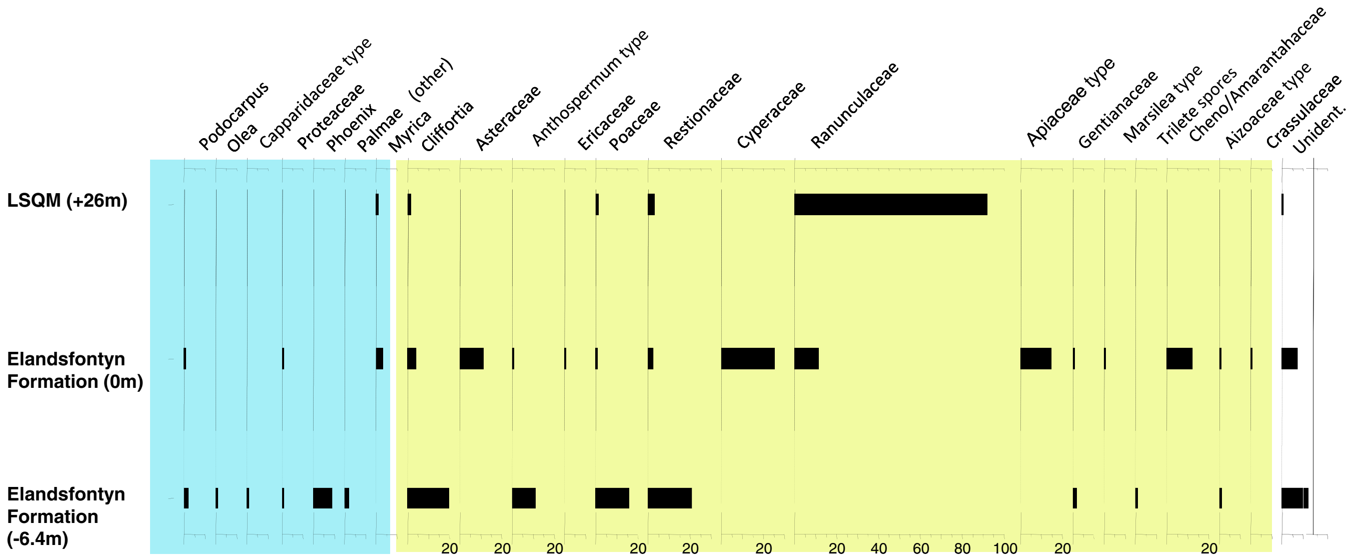

Fig. 13. Pollen diagram comparing the early-Middle Miocene Elandsfontyn Formation with the Eraly Pliocene LQSM.

to uplift is also inconsonant with the wide distribution of the Elandsfontyn Formation indicated in Roberts (2006b), Cole and Roberts (1996, 2000) and Timmerman (1985, 1988) and their notable thickness exceeding 60 m (Rogers, 1980, 1982). The lack of subaerial weathering of the formation is testified by the excellent preservation of palynomorphs at Noordhoek and LBW, even at the top of the successions e.g. Coetzee and Rogers (1982).

Marine terraces/deposits at ~90 m occur sporadically along the northern and southern West Coasts. The existence of a flight of terraces at consistent elevations and similar ages below 90 m strengthens the contention of Hendey (1981a) that it represents a single transgressive episode, whose age at LBW is well constrained to basal Pliocene. On the basis of the data presented here and conclusions drawn from them, we agree with Hendey (1981a) and Pickford (1998) that the present marine terrace disposition along the West Coast was chiefly eustatically controlled, including LBW. The amount of epeirogenic uplift subsequent to terrace incision/marine deposition remains a moot point and hinges on the extent of Early Pliocene melting of the cryosphere. The required detailed examination of this variable is beyond the scope of this paper. However, a passive intraplate, trailing edge tectono-seismic model has been indicated for the mid-latitude southern African coastline (Pickford, 1998; Goedhart, 2007; Jacobs and Roberts, 2009), which is also removed from glacial influence (Tyson, 1999) and has experienced no Cenozoic volcanic activity. Consequently, expectations are that rates of vertical crustal motion should be low and Late Cenozoic shoreline datums chiefly reflect glacio-eustatic sea levels. This implies extensive melting of the cryosphere complemented by thermal expansion of the oceans (Douglas, 1997).

7.2. Fluvial Elandsfontyn Formation

The Neogene history of the West Coast traces its origins to the Oligocene eustatic drawdown in sea levels (Fig. 6), when the landscape was etched by seaward flowing drainages in response to lowered base levels (Rogers, 1982; Cole and Roberts, 1996; Pickford, 1998). The fluctuating sea levels of the Neogene periodically reversed the trend from erosion to deposition, preserving contemporary faunas and floras in palaeovalleys incised into Neoproterozoic/Cambrian bedrock during the Oligocene (Figs. 6 and 12).

The Elandsfontyn Formation is well developed in the vicinity of LBW (Figs. 6 and 12), occupying a network of palaeovalleys and depressions in basement rocks (Rogers, 1980, 1982). In the vicinity of LBW, basement configuration suggests that the Elandsfontyn Formation represents deposits of the palaeo-Berg River. The modern Berg River, which is the largest and only perennial drainage in the region, flows northwest as opposed to southwest in its ancient counterpart (Figs. 1 and 12). According to Coetzee and Rogers (1982) and Cole and Roberts (1996, 2000), sedimentation of the Elandsfontyn Formation was initiated by a sea level rise from well below the present level (−36 m at LBW, Figs. 3, 6 and 12). The low initial sea level and rapidity rising air temperatures (from ~12 °C to 20 °C) as infered from biogeochemical parameters in the upper Elandsfontyn Formation (Sciscio, 2011), suggest an Oligo-Miocene age for these events. The high sinuosity river deposited coarse, immature channel-fill clastics, fining upwards into and interfingering with muddy, carbonaceous overbank and backswamp facies (Timmerman, 1988).

The Elandsfontyn Formation underlies a large area in the region of LBW, which in conjunction with the notable thickness (exceeding 60 m), suggests that the fluvial depositional systems were of considerable proportions. It has been suggested that the palaeo-Berg River deposited the Elandsfontyn Formation in the LBW Embayment and the probable course of the river as suggested by basement configuration is shown in Figs. 6 and 12. The present river is a substantial and perennial drainage, and given the higher rainfall regime of the Early Mio-Pliocene (Hendey, 1980) should have been considerably larger, as inferred for other Late Tertiary West Coast drainages (Pether 1994a,b). The formation extends about 60 km northward from LBW, suggesting that the palaeo-Berg River once exited into the sea some 60 km north of LBW.

Further marine transgression allowed the rivers in the region to aggrade (~13 m asl at LBW) and partially bury the prior topography (Fig. 6 and 12). With the consequent loss of stream power, fine-grained channel-fill, overbank and backswamp facies dominated, reflected by the ubiquitous, thick muddy, carbonaceous sediments of the uppermost Elandsfontyn Formation (Rogers, 1982; Roberts 2006b). Palms and other sub-tropical vegetation thrived in the extensive wetlands in the region of LBW (Coetzee and Rogers, 1982), the considerable extent of which are illustrated by the subsurface map of this unit (Figs. 6 and 12). The depositional facies of the Elandsfontyn Formation thus underpin the palynological and biogeochemical indications of a generally humid and warm climate with extensive wetlands. Nonetheless, representatives of sclerophytic *fynbos* taxa such as Restionaceae and Asteraceae (Fig. 13) heralded the transformation to a drier, more seasonal climate.

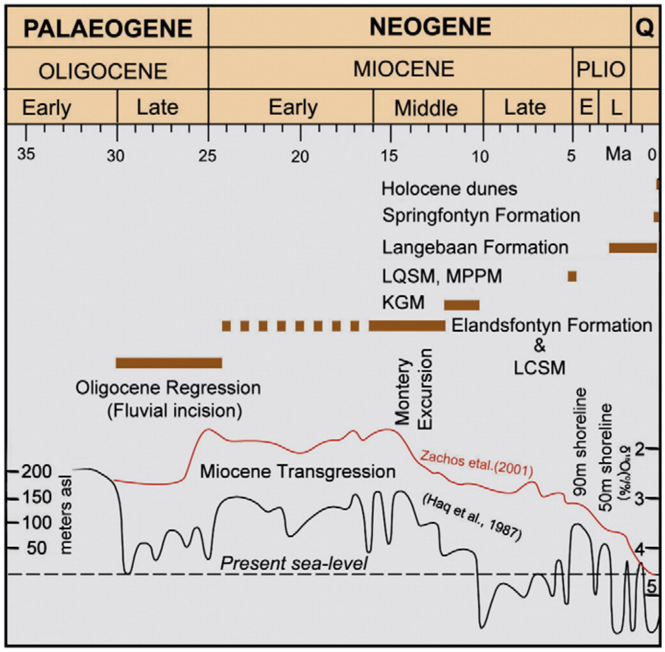

Fig. 14. Late Cenozoic depositional history at LBW compared with the sequence stratigraphic curve of Haq et al., 1987 and glacio-eustacy (Zachos et al., 2001).

7.3. Marine/estuarine/fluvial Varswater Formation

The marine/estuarine Varswater Formation occupies coastal basement embayments and depressions along the southern West Coast (Rogers, 2006a; Roberts, 2006d). The distribution in the LBW environs generally coincides with the underlying fluvial Elandsfontyn Formation, which only partially filled the basement lows (Figs. 6 and 12). LBW is located in the central region of an embayment, here termed the 'LBW Embayment', which extends up to ~14 km inland (Figs. 1, 6 and 12). The LBW Embayment is separated from the Geelbek Embayment (Geelbek Gap of Rogers, 1980; 1982) to the south by a basement high (Figs. 1 and 6).

7.3.1. LCSM and KGM

With rising air temperatures (Sciscio, 2011) and continued marine transgression, the Elandsfontyn Formation wetlands gave way to estuarine conditions and deposition of the LCSM, which is only locally developed in the region and best represented at LBW (Visser and Schoch, 1973; Rogers, 2006a; Roberts, 2006d). The age of the LCSM, which is non-fossiliferous has remained uncertain, but because of its generally conformable contact with the underlying Elandsfontyn Formation (Early Miocene), which shows only slight and local surficial paleoweathering, it is probably only slightly younger (Fig. 3). The reddish mottling of the LCSM points to subaerial paleoweathering (Roberts, 2006d) and the contact with the overlying KGM is erosive and marked by a clay pellet horizon 0,20 m thick (Figs. 3 and 5). These observations point to a notable time break between the two units. Regionally, the muddy, greenish fine sands of the LCSM are comparable to the estuarine sediments of the present Berg River and deposits of the palaeo-Olifants River situated ~250 km to the north. Here Late Tertiary greenish clays overlain by river gravels at ~25 m asl are exposed in diamond mine workings just north of the present day drainage (Keyser, 1972).

The ensuing series of marine transgressions and regressions probably resulted not only in the subaerial weathering the LCSM, but also gave rise to the complex lithology of the overlying KGM (Hendey, 1981a,b,c). These deposits, which rise to a maximum of ~25 m amsl, originated via partial reworking of pre-existing phosphorite rock in a high energy, shallow marine regime (Hendey, 1970b; Tankard, 1974; Roberts, 2006d). The northeastward (landward) attenuation of the KGM in E Quarry is consistent with an offlapping progradational shoreline. The associated marine fauna, comprising shark teeth and molluscans, are generally suggestive of warm water, open coast conditions (Kensley, 1972; Hendey, 1981a). The maximum age of the KGM as gauged by the presence of the three-toed horse *Hipparion primigenium* is ~12.5 Ma (Hendey, 1976a; 1981a,b).

In the wave cut terraces of Namaqualand (northern West Coast) desribed in Section 7.2, the older (Miocene) phosphatic marine deposits occur as remanants below ~50 m asl (Fig. 10) and contain a sparse mammalian fauna, including forms such as the primitive elephantid *Tetralophodon* dated to ~12–9 Ma (Senut and Pickford, 1995), suggesting that biostratigraphic equivalents of the KGM are represented in this region. The marine isotope curve and stratigraphic

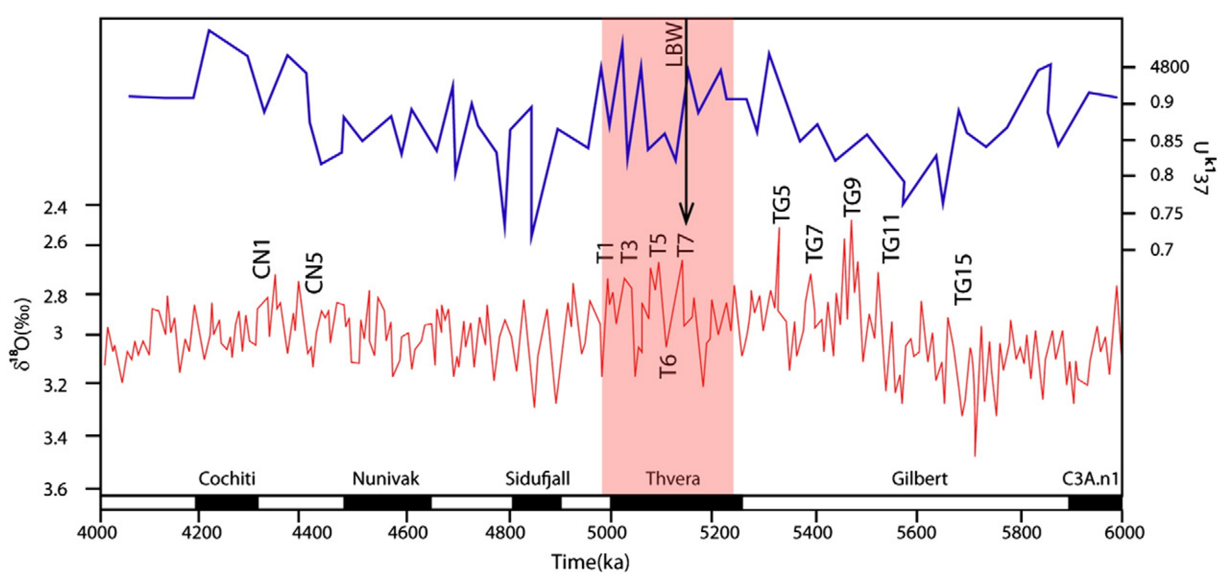

Fig. 15. The relationship of the Thvera Chron to the marine isotope (glacio-eustatic) and alkenone (SST) record, both of which suggest a highstand during this Chron. The marine isotope record up to 5.2 Ma is from Lisiecki and Raymo (2005) and the older part is from Shackleton (1995). The alkenone (SST) record is from east Atlantic Site 9581 (Herbert and Schuffert, 1998). The central age of the fossil accumulation is estimated at 5.15 Ma ± 0.10 Ma (arrow).

data of Haq et al. (1987) indicate moderately high sea levels at ~12–10 Ma (Fig. 14). These observations underpin Hendey's (1981a) view that the marine KGM is of earlier Late Miocene age (Fig. 3). The composite marine isotope curve of Zachos et al. (2001) indicates a highstand in the Late Miocene, attaining a maximum at ~7.5 Ma (Fig. 14), and the possibility that this highstand may correlate with the KGM event cannot be excluded. However, the sea level curve of Haq et al. (1987) indicates only moderately high sea levels at around this time, contrasting with the relatively large light isotope anomaly (Zachos et al., 2001).

The phosphorite rock partially reworked to form KGM at LBW and its correlates of the northern West Coast appear to record the advent of regional phosphate authigenesis, possibly coinciding with a marked increase in cold upwelling in the BUS in the early Late Miocene (~12 Ma). This event is documented in West Coast marine cores, e.g. from the Walvis Ridge (DSDP site 362 and ODP 1087 in the Cape Basin, correlating with the globally recorded decline in bottomwater temperatures commencing at ~13.9 Ma (Monterey Excursion), but reaching maximum intensity at ~12 Ma (Siesser, 1978, 1980; Flower and Kennett, 1993; Holbourn et al., 2004). Regionally, the KGM may be comparable to marine deposits at Prospect Hill 25 km to the west with a similar maximum elevation of ~30 m asl (Roberts and Brink, 2002). Here thin, slightly phosphatic gravels comprised of locally derived granite clasts contain a sparse open coast marine molluscan fauna and are overlain conformably by aeolianites of the Prospect Hill Formation. The aeolianites age were inferred to be early Late Miocene on the basis of eggshells of the extinct ostrich *Diamantornis wardi* (Roberts and Brink, 2002; Stidham, 2008). This species was first recorded in the aeolian Tsondab sandstone in the Namib desert of southern Namibia, where associated micromammals suggested an age of 12–10 Ma (Senut and Pickford, 1995). *D. wardi* has since been found at Lothagam, Kenya where radiometric dating has constrained its age to not less than ~9 Ma (Stidham, 2008).

In addition to *D. wardi,* the calcretised palaeosols within the Prospect Hill Formation contain a giant form of the dune snail *Trigonephrus* cf. *globulus*, typical of the winter rainfall regime of southwestern Africa (Connolly, 1939; Visser and Schoch, 1973; Roberts and Brink, 2002; Roberts, 2006c). The aeolianites constitute a dune plume deposited under a southerly wind regime (which drives upwelling) analogous to the late Pliocene, Pleistocene and Holocene dunefields along this coastal segment, which form in response to the summer-dry conditions and strong South Atlantic Anticyclone-driven southerly winds (Tyson, 1999; Roberts and Brink, 2002; Roberts et al., 2009). This scenario agrees with the timing of advent of the cold upwelling regime suggested by the extensive phosphate authigenesis in the Varswater Formation noted above. However, the upwelling appears to have been episodic, as suggested by the mixed thermophyllic and thermophobic molluscan assemblages of the KGM (Kensley, 1972, 1977; Tankard, 1974) and possibly correlating with cooler (glacial/stadial) conditions.

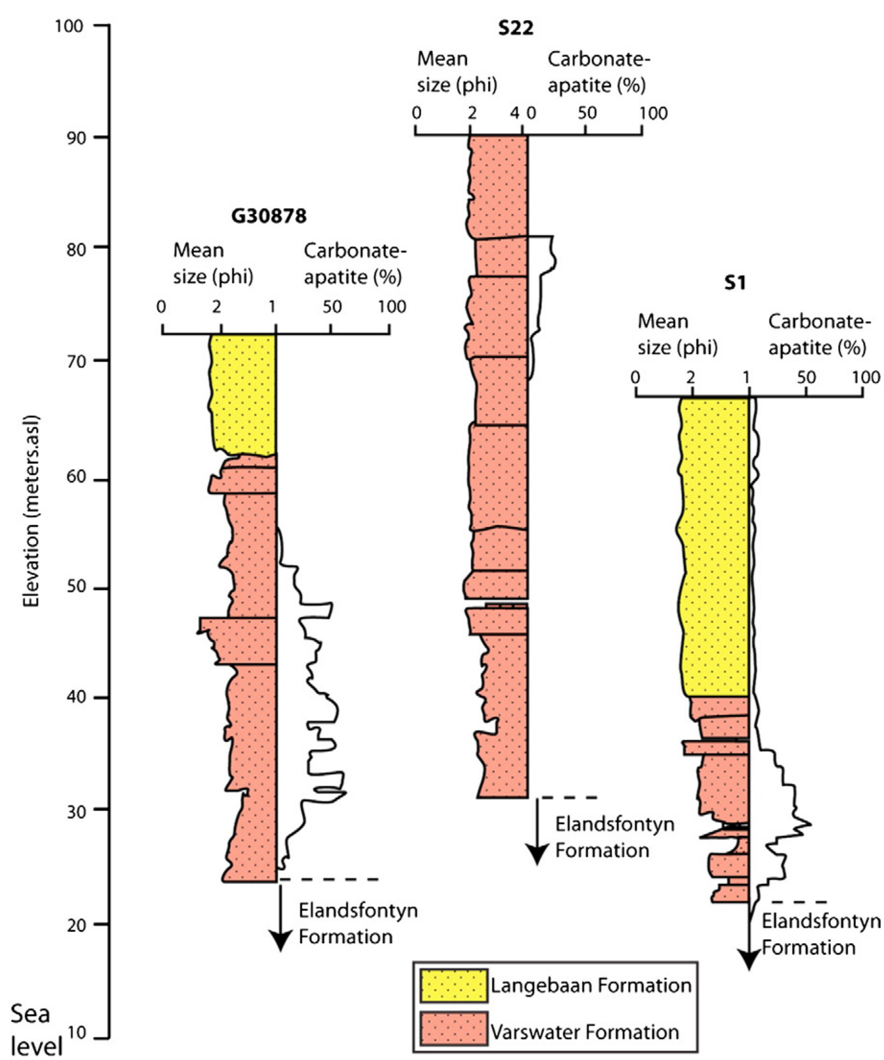

Fig. 16. Borehole logs from the Geelbek (S22 and G30878)and LBW (S1) Embayments showing the Varswater Formation rising to ~90 m asl, as opposed to ~50 m at LBW.

7.3.2. LQSM and MPPM

No sedimentation is apparently recorded at LBW during the latest Miocene, which was dominated by lowstands (Figs. 3 and 13). During this time the KGM underwent intense surficial weathering and ferruginisation (Fig. 7A) and was succeeded by the upper Varswater Formation. The configuration of the palaeoshoreline at 30 m asl which corresponds to the elevation of the main fossilferous interval (Fig. 3) is shown in Fig. 13. As noted by Hendey (1981a, 1982) LBW was situated near the estuary mouth at this time, which was ~4 km wide. Because the marine molluscan faunas of the LQSM and KGM are from tidal flat and open rocky coastal settings respectively, it is difficult to compare them in terms of sea temperature indications. The LQSM does however contain unequivocal cold water taxa such as *Chiton nigroviriscense* and *Tricolia capensis* which may suggest colder waters than the KGM (Hendey, 1981a). Both the KGM and LQSM are reported to contain *Donax serra* (Hendey, 1981a), the cold water form common in the Quaternary, but according to Pether (pers. com., 2010), this species of *Donax* is a new, as yet unnamed form. The small dune snail *Trachycystis* cf. *capensis* of the family Endodontidae was found in the LQSM (Hendey,1981a) and is presently common to the coastal dunes of the west and southern costs (Barnard, 1954; Van Bruggen, 1978, 1982) suggesting the presence of dunes in the area. Pollen from peaty material in the LQSM and phytoliths recovered from the LQSM suggests a flora and therefore climate, with some similarities to the Miocene Elandsfontyn Formation (Fig. 12), but with more emphasis on summer-dry adapted *fynbos* (Scott, 1995; Rossouw et al., 2009).

Previous attempts have been made to refine the chronology of the fossil bearing upper Varswater Formation at LBW by comparing the sea level history archived in these strata with the global record (Hendey, 1981a,b). The composite marine isotope curve of Zachos et al. (2001) indicates a eustatic sea level highstand centering on ~7.5 Ma, but this age is outside the upper faunal age limit of ~7 Ma for LBW indicated by Hendey (1981a) and the subsequent faunal estimates discussed in Section 5. No major highstand is inferred for this period in the global sequence stratigraphic record of Vail and Hardenbol (1979), subsequently updated by Haq et al. (1987). We concur with Rogers (1980, 1982) and Hendey, 1981a,b) that the major Early Pliocene transgression shown by both of these authors and indicated in the marine isotope record (Figs. 14 and 15) is the most probable eustatic event underlying the upper Varswater transgressive episode.

Sequence stratigraphic curves indicate a major Early Pliocene transgression of up to ~90 m asl at ~5 Ma (Vail and Hardenbol, 1979) and ~4.8 Ma (Haq et al., 1987). These data approximately match the maximum relative elevation (~90 m) of the upper Varswater Formation at Elandsfontyn (Figs. 6 and 16) in the Geelbek Embayment basin adjacent to LBW (Rogers, 1982; Roberts 2006d) and the central biochronological age inferred for this succession (Hendey 1981a,b). The climatic shift underpinning this glacio-eustatic event may have been the gradual shoaling of the Isthmus of Panama, which partitioned the Atlantic and Pacific Oceans and intensified the North Atlantic Deep Water Circulation (Haug and Tiedemann, 1998). The age model for these stratigraphically inferred sea level curves is based on microfossil zones (Miller, 1992). The uncertainties attached to such biochronologies are reflected in the ~0.2 Ma age difference for the Early Pliocene highstand between the two curves.

Subsequent studies of $\delta^{18}O$ trends from benthic foraminifera in marine cores (a proxy for glacio-eustatic sea level) have chronologies more tightly constrained by orbital tuning and magnetostratigraphy e.g. Pacific marine core 865 (Shackleton, 1995). The composite marine isotope curve of Zachos et al. (2001) and the LR04 stack comprising 57 global records of Lisiecki and Raymo (2005), reduces the uncertainties attached to single marine cores. The marine isotope curve shown in Fig. 15 is a composite of Lisiecki and Raymo (2005) which, because it ends at ~5.2 Ma is supplemented by the data of Shackleton (1995). The palaeomagnetic studies outlined in Section 3, in tandem with the marine isotope data may further constrain the age of the upper Varswater Formation. The three samples from the lower, middle and upper parts of the MPPM near pit HW1 all clearly indicated normal remanent polarity (Table 2; Figs. 4 and 5). Three other samples in friable sands from the northern area of the mine, adjacent to the dig site and HW1 (Fig. 4) were also analysed in 2001 and gave the same result (Verosub, pers. com., 2002). The normal polarity is thought to represent an early diagenetic remanence, penecontemporaneous with deposition (see Section 4). A marine isotope curve shows a generally isotopically light phase (sea level highstand) extending from ~5.5 to 5.1 Ma (Zachos et al. 2001), which also corresponds with alkenone derived high SST (Fig. 15). This is the age range for the highstand corresponding to the upper Varswater Formation transgression, as broadly indicated by the biochronological ages. Using only the isotopically inferred sea level data, the age of the upper Varswater Formation could thus range from ~5.5 to 5.1 Ma (Fig. 15). However, the only interval with normal polarity in this age range is the Thvera chron, whose age has been refined by radiometric dating to 5.235–4.997 Ma (Ogg and Smith, 2004).

The LQSM comprises a mix of marginal marine and terrestrial facies as noted previously, passing upwards into the marine/estuarine MPPM. The MPPM itself is generally homogeneous with little suggestion of shoaling upwards at LBW or at other localities where the succession is more complete e.g. Elandsfontyn (Fig. 16). The rate of sea level rise apparently matched sedimentation rates, resulting in stacked sedimentary facies. These considerations suggest that in the upper Varswater Formation the transgressive facies have been preserved, a conclusion also reached by Hendey (1981a). Onshore late Tertiary shallow marine deposits along the West Coast typically grade upwards into progressively more proximal environments (Fig. 10), characteristic of prograding shorelines and are essentially regressive in nature (Pether, 1986; 1994a,b), but the deposits at LBW apparently form an exception to this generalisation.

Taking account of the normal polarity, the upper Varswater Formation transgression presumably corresponds to the period of high sea levels embracing sea level cycles T7–T3 (Fig. 15), the lightest isotope phase of the Thvera Chron. The vertebrate fossils in the LQSM and MPPM are concentrated within an abbreviated stratigraphic interval, between ~26 and 30 m asl (Fig. 3). Since the upper Varswater Formation rises to 90 m asl (Fig. 16), this suggests that the fossils accumulated at an early stage in the Early Pliocene transgression, possibly slightly younger than sea level cycle T7. This provides a central age estimate of ~5.15 Ma for the LQSM and MPPM fossils at LBW, with an error factor of $\pm$0.1 Ma reflecting the uncertainties of the various age models for the sea level curves and other factors, such as the rate of marine transgression. This age is consistent with the stratigraphically derived global sea level data of Vail and Hardenbol (1979) and Haq et al. (1987) as shown in Fig. 14. In this way we provide semi-quantitative confirmation of Hendey's (1981b) correlation of LBW with events of the basal Pliocene.

8. Taphonomy

Since the inception of the WCFP in 1998, excavations (ongoing) have been conducted in the river channel 3aN in the MPPM in the northern sector of E Quarry (Fig. 4). Numerous large mammalian bones have been exposed, mainly of the short necked giraffid *Sivatherium hendeyi* which form the centrepiece of the *in situ* fossil display (Fig. 2). Abundant smaller vertebrates have been recovered from the gravel matrix by sieving, including micromammals, avians, reptiles and amphibians (Matthews, 2004, 2005, 2006; Smith and Haarhoff, 2006; Van Dijk, 2006). This highly concentrated bonebed appears to have formed as an ill-sorted lag in river channel 3aN (Figs. 2 and 4), with the bones having little apparent preferred orientation. In this respect, the deposits are similar to those described

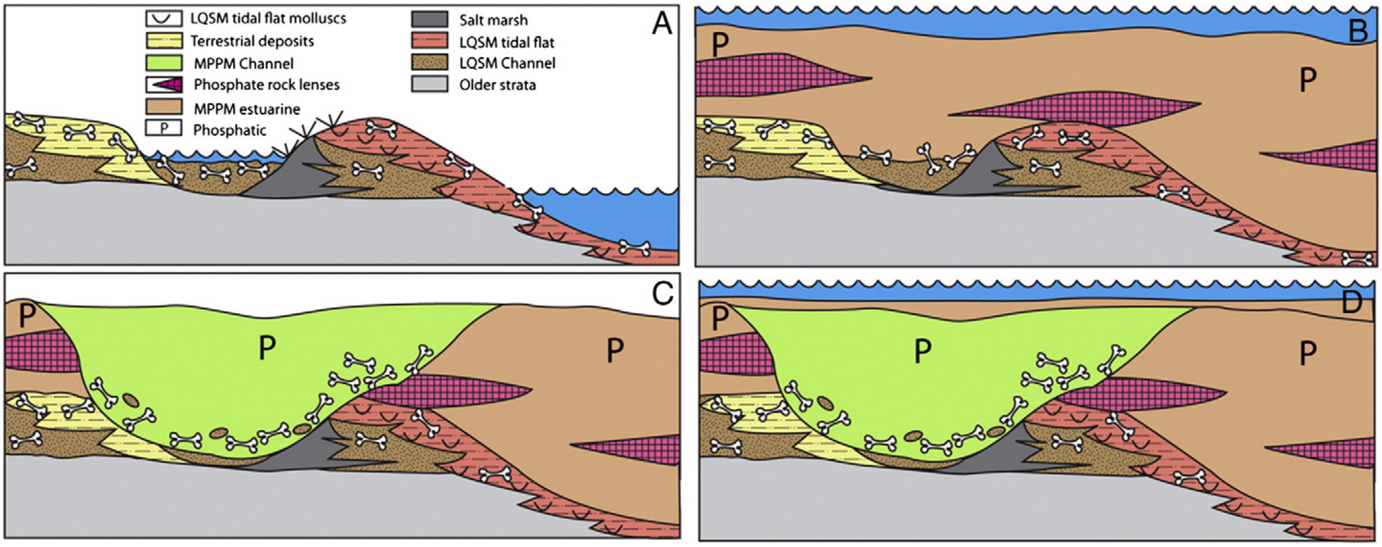

Fig. 17. Conceptual model explaining the fossil occurrences in the LQSM and MPPM: A), Terrestrial to marginal marine palaeontological settings of the LQSM (~25 m asl); B), MPPM Estuarine conditions with phosphate authigenesis with further transgression to ~30 m asl; C), Glacio-eustatic regresssion to below 25 m and incision of ephemeral streams and concentration of fossils from different environments in channel lag; D), transgression and a return to Estuarine conditions (MPPM).

by Hendey (1976a, b, 1981a) from nearby excavations in this channel, as well as the adjacent (younger) channel 3aS.

The bonebed is overlain by a stacked sequence (~3 m thick) of similar fossiliferous channel fills (Fig. 3), the uppermost of which extends as a thin lag for several tens of metres to the west. There is no visible floodplain, backswamp or other facies suggestive of a perennial river associated with these channel facies. The gradient of the channel base is steep (~5°) compared with <1° for the modern Berg River and for the West Coast coastal plain in general, e.g. Keyser (1972). Hendey (1981a) indicated that the 3aN stream flowed intermittently southwestward (Fig. 4), an interpretation bolstered by the structure contours on the base of the MPPM (Tankard, 1974) and regional slope.

The presently exposed bonebed lag underpins this interpretation, strongly suggesting that the 3aN river was short-headed, ephemeral and out of equilibrium with the contemporaneous base level, rather than representing the large, perennial palaeo-Berg River. A likely source for such a short-headed stream at that time may have been the embayment in the granite hills situated southwest of St Helena Bay, which apparently sourced a tributary to the palaeo-Berg River during deposition of the Elandsfontyn Formation (Figs. 1 and 6). The rubification of the dig site river channel deposits, also noted elsewhere in E Quarry (Dingle et al., 1979) and evidence for possible trampling of the bones (Smith and Haarhoff, 2006), suggests an interval of sub-aerial exposure subsequent to deposition.

Fig. 18. Bone bed (Channel 3aN) at the dig site with sivathere rib bone apparently deformed and fractured post-depositionally.

Hendey (1980) indicated that the estuarine facies of the MPPM is virtually barren of fossils and recent surveys of extensive exposures in the various mine workings have yielded no fossil material (Haarhoff pers. com., 2010). Even intensive winnowing of these deposits would be unlikely to yield the concentrations of fossils seen in the channel lags. Hendey (1976a, 1976b) suggested that the many of the fossil remains of the MPPM were reworked from the underlying LQSM, whereas others were carried in from outside the estuarine system. This scenario would explain the large numbers of macro-fossils and diversity of micro-faunas in the dig site deposits. It is also consonant with the greater diversity of faunas in the LQSM compared to the MPPM. Of the 121 vertebrate fossil species from the upper Varswater Formation listed in Hendey (1981a), only 19 are unique to the MPPM, whereas 49 are found only in the LQSM. The reconstructed isopachs for the LQSM illustrate that the member is generally thin (0.5–3 m) but also that the thickness trends are erratic. However, it is not clear whether this represents post-depositional erosion or the effects of the underlying topography.

We suggest on the basis of the evidence outlined above that the fossils of the channel lags in the MPPM accumulated during a (brief) eustatic lowstand, when ephemeral streams incised through the MPPM estuarine deposits and into the upper part of the LQSM (Fig. 17). Eustatic sea level fluctuations were modulated during the Early Pliocene by both precession (~20 ka) and obliquity (~40 ka) cycles, as indicated by marine stable isotopes (Lisiecki and Raymo, 2005). The stream was activated on several occasions during the lowstand as indicated by the stacked channel fills, as well as the age difference between the channels 3aN and 3aS (Hendey, 1981a). Fossils eroded out of the LQSM were concentrated as lag deposits at the channel base, supplemented by surficial bones scavenged by the stream external to the estuary, as well as groups of animals (sivatheres in channel 3aN) possibly killed by the flood events which caused fluvial incision (Hendey, 1981a).

As a consequence of local topographic effects associated with the phosphorite rock (Hendey, 1981a; Smith and Haarhoff, 2006) and sudden loss of stream power characteristic of ephemeral streams, the bones were dumped as an ill-sorted and unaligned deposit. The time interval required for the initial basal Pliocene marine transgression and regression subsequent to deposition of the LQSM suggests a significant age difference between this unit and the MPPM fossiliferous channel fills. The more derived character of certain taxa in the MPPM noted by Hendey (1981a) may represent the remains brought in from outside the estuarine system, which may therefore be younger than any fossil in the LQSM. The taxa common to both units may be chiefly those eroded out of the LQSM. Biogeochemical studies of bones of the same species from either member of the upper Varswater Formation would assist in further resolving the issue of provenience of the MPPM fossils.

The MPPM attains a maximum elevation of ~50 m asl at LBW, but rises to ~90 m in the Geelbek Embayment as noted above. The heavily pedocreted upper surface of the member at LBW (Fig. 8A) indicates a long period of subaerial exposure and erosion, but the same applies at localities such as Elandsfontyn where the formation is much thicker and situated at up to ~90 m asl, as noted above. In support of the concept of major erosion of the Varswater Formation at LBW, we have noted bones in the dig site which were deformed and fractured post-depositionally, indicative of pressure much greater than could have been applied by the overburden of only some 4 m which existed prior to mining operations. The type of damage is in some instances also inconsistent with fracturing associated with trampling (Fig. 18).

The Avontuur Member of the northern West Coast (50 m shoreline succession, Figs. 10, 15) contains mammalian faunal elements (suids in particular), suggestive of broad affinity to LBW (Hendey, 1981a; Pether, 1994a; Pickford and Senut, 1997). However, it is noteworthy in this discussion that Hendey (1981a) found that the seal *Homiphoca capensis* from the Avontuur Member is a more derived form than any of the Varswater Formation specimens and therefore younger. Differences in the molluscan fauna between the 90 and 50 m terraces also indicate a substantial temporal difference (Pether, 1994a). The most likely candidate in the marine isotope record for the 50 m highstand occurs at ~4.4 Ma on the composite curve and for Pacific site 865 (Fig. 15), although this is somewhat older than the ~50 m mid-Pliocene highstand shown by Haq et al. (1987). The maximum elevation of the Varswater Formation in the Papkuils and Duynefontyn Embayments to the north and south of LBW is also at ~50 m asl (Rogers, 1980, 1982). We suggest that the upper part of the Varswater Formation at LBW and the occurrences to the north and south were truncated by the later ~50 m highstand.

9. Plio-Pleistocene history at LBW

9.1. Langebaan Formation aeolianites

Calcareous aeolian deposits along the West Coast range in age from Miocene (Prospect Hill Formation) to Pleistocene (Langebaan Formation) and Holocene (Witzand Formation) and take the form of dune plumes orientated parallel to the prevailing southerly (summer) winds (Roberts and Brink, 2002; Rogers, 1980, 1982; Roberts et al., 2009). The aeolianites form by calcification of calcareous sand deflated from a sandy beach and the fundamental control on the development of plumes is the spatial and temporal stability of the source beaches. Beach development corresponds with basement lows, with rocky shorelines forming over basement highs. Dune sediments are mainly preserved during highstands and early regression, whereas erosion takes place during transgressions. Because of the long term stability of source beaches and sea level fluctuations, the dune plumes are complex in terms of their architecture and chronology, reflecting multiple periods of sedimentation (Roberts and Brink, 2002; Roberts et al., 2009; 2000). Fossil plumes in the vicinity of LBW (Saldanha Bay and Geelbek plumes) conform to this pattern and are exceptionally large in scale, with former extending for 28 km onshore (Fig. 1).

The cemented calcareous deposits overlying the MPPM at LBW (Figs. 8A and 16) attain a maximum thickness of 27.5 m as intersected in borehole S1 on Anyskop (Rogers, 1980, 1982). As noted in Section 5, they bear all the characteristics of the coastal calcareous aeolianites constituting the Langebaan Formation, and form part of the large Saldanha plume (Fig. 1) as shown on the geological map of Visser and Schoch (1973). The deposits at LBW were also interpreted as coastal aeolianites by Tankard (1974), Hendey (1976a, b), Rogers (1980, 1982) and Dale and McMillan (1999). Hendey (1981a) revised his earlier interpretation of the Anyskop deposits, suggesting (albeit tentatively) that they may represent on offshore barrier formed as the Early Pliocene transgression proceeded to an elevation of ~70 m (the height of Anyskop). Evidence cited for this new vision was the anomalous elevation of Anyskop – the highest hill in the immediate area without a core of granite – and the presence of 'fresh' specimens of the foraminiferan *Anomalina*, a deeper water (shelf) form.

Onshore terminations of landward transgressing active dunefields rise to over 50 m above the surrounds at localities such as Wilderness on the southern Cape coast (Illenberger, 1996). Such features are preserved in the geological record when the plume or part thereof is starved of sand and undergoes calcification (Bateman et al, 2004; Roberts et al., 2000). An example of a calcified brinkpoint rises to 30 m at Cape Point, south of Cape Town (personal observation). The large Saldanha plume emanating from Saldanha Bay extends almost as far inland as the Berg River, a distance of 28 km. A tongue of this plume impinges onto the LBW site (Fig. 1), terminating abruptly in the area of LBW. The most conservative explanation of the Anyskop hill is that it represents the fossilised brinkpoint of a tongue of the Saldanha dune plume, which explains its relative topographic prominence in the area.

The foraminifera of the Anyskop and Highwall deposits were re-examined by Dale and McMillan (1999), who found no *Anomalina* and related the assemblage at Anyskop to that found in aeolianites (Diazville Member) exposed in the Lower Quarry at Prospect Hill, Saladanha dated by Roberts and Brink (2002) to Plio-Pleistocene and conformably overlying marine deposits of the 30 m shoreline. We concur with this correlation which is strengthened by the identical dune snail assemblage at both sites, comprising *Trigonephrus globulus* and *Phortion occidentalis* (van Bruggen, 1982). This age also tallies with the Plio-Pleistocene vertebrate fossil assemblage recovered from Anyskop by Hendey himself (Hendey, 1981a). We also draw attention to the unconformable contact separating the Langebaan Formation with the underlying Mio-Pliocene MPPM, marked by intense pedogenesis of the MPPM (Fig. 8A), indicative of a lengthy time break between the two units (Dingle et al., 1979). The interpretation of the Anyskop deposits as an Early Pliocene marine barrier seems untenable on the basis of sedimentology, stratigraphy, palaeontology and chronology.

The aeolianites in the Lower Quarry at Prospect Hill rest conformably on shelly, upper shoreface to foreshore marine sediments at up to 28 m amsl (Roberts and Brink, 2002). The zone fossils *Donax rogersi* and *Fissurella glarea* of the well documented Plio-Pleistocene transgression to ~30 m asl (Hondeklip Bay Member, Fig. 10) are both present in these deposits (Roberts and Brink, 2002). We suggest that the Anyskop aeolianites also relate to this highstand, on the basis of the correlation of Anyskop with the Prospect Hill Lower Quarry aeolianites founded on macro- and microfossils. The fossiliferous Baard's Quarry fluvial sediments 2 km east of LBW with an inferred age of Plio-Pleistocene (Hendey, 1981a) may also relate to this highstand which is widely recorded around the globe (Dowsett et al., 1996; 1999).

The co-occurrence of *P. occidentalis* and *T. globulus* at LBW is apparently anomalous. *T. globulus* inhabits the semi-arid to arid, typically winter rainfall environments of the southwestern coastal region of South Africa (Connolly, 1939), whereas extant members of the genus *Phortion* prefer forested settings (van Bruggen, 1982). Possibly, *P. occidentalis* represents a peripheral isolate which adapted to a more arid climate possibly by having a large, uncommonly thick shell (van Bruggen, 1982).

9.2. Springfontyn Formation quartz sands

The two OSL ages presented in Table 3 are the first obtained for the uncemented aeolian quartz sands (Springfontyn Formation) in this region and serve to complete the chronology of the Late Cenozoic succession at LBW. The age of ~180 ka (OIS 6) of the lower sample demonstrates a considerable antiquity (Middle Pleistocene). This age is stratigraphically consistent with the minimum Acheulian age for the underlying Langebaan Formation noted previously from which it was derived (see Section 3). The upper sample was taken from the sand ridges flanking the blowout (Fig. 4), comprising sand scoured and redeposited from deeper in the succession and shows a latest Holocene age (0.3 ka). This probably records the time when the blowout was formed and the older OSL age reset.

10. Conclusion

A passive intraplate, trailing edge tectono-seismic model applies to West Coast of South Africa, which is also removed from glacial influence and has experienced no Cenozoic volcanic activity. Consequently, rates of vertical crustal motion are low and Late Cenozoic shoreline datums both inform about the pattern of (global) glacio-eustatic sea levels and facilitate correlation with the global record. Essentially, Oligo-Miocene sea levels were well below the present datum and Pliocene transgressions to ~90, 50 and 30 m asl at ~5.1, 4.5 and 3.3 Ma respectively are recorded at LBW and surrounds.

Sedimentation at LBW essentially tracks the major regional and global climatic/oceanographic trends of the Late Cenozoic. Deposition was initiated in the Oligo- Miocene by the meandering palaeo-Berg River, which deposited upward fining successions in previously excavated valleys, as sea level rose from well below the present datum. Palynomorphs indicate a sub-tropical setting with abundant palms, but with a significant component of sclerophytic *fynbos* taxa heralding the transformation to a drier, seasonal climate (Coetzee and Rogers, 1982). Continued marine transgression caused a general rise in the water table and the landscape around LBW was dominated by wetlands, and later by estuarine conditions (LCSM). Marine regression resulted in subaerial weathering of the LCSM, later truncated by the marine KGM, deposited during the fluctuating sea levels of the Middle–Late Miocene transition. Phosphate authigenesis was initiated at this time (KGM), following the global cooling recorded in marine cores (Monterey Excursion) peaking at 12 Ma, which saw burgeoning cold upwelling in the Benguela system. The KGM was subject to lengthy (possibly ~5 Ma) subaerial weathering during the Late Miocene lowstands.

The Early Pliocene global warm period, probably commensurate with the shoaling of the Isthmus of Panama, witnessed a rise in sea level to a relative elevation of ~90 m asl along the South African West Coast. The earlier part of this transgression (to 30 m asl) initiated a return to fluvio-estuarine conditions at LBW (LQSM and MPPM). The sediments of these members exposed by mining at LBW constitute only a small part of extensive deposits extending 14 km inland within the LBW Embayment. The fossils, representing the diverse Mio-Pliocene faunas of the region were initially deposited in the fluvio-estuarine LQSM. During punctuated , probably orbitally driven marine regressions ephemeral streams incised through the MPPM and reworked fossils from the upper LQSM. Catastrophic floods associated with the ephemeral streams killed entire groups of animals such as sivatheres and their remains contributed to the channel lags, in addition to bones scavenged by the streams from outside the estuarine system. The floras from the silty facies of the LQSM are strongly influenced by the local marsh setting, but also suggest an increase in summer drought adapted *fynbos* taxa relative to the Miocene. Stable isotope studies of herbivore teeth indicate a dominant C3 vegetation.

Biochronological insights from more recent faunal studies summarised here, including the micromammals broadly support Mio-Pliocene age for LBW. The penecontemporaneous normal polarity determined for the MPPM allowed a refined correlation of the 90 m transgressive event at LBW with the global sea level record (Cycle T7). As a result the inferred age of fossils themselves was narrowed to 5.15 ± 0.1 Ma. The Varswater Formation deposits, which rise to ~90 m asl to ~90 m near LBW witness the Early Pliocene sea level maximum, similar to the elevation suggested by global sequence stratigraphic studies. Extensive melting of the cryosphere is implied, along with stearic effects such as thermal expansion of the oceans. At LBW itself and several other localities along the West Coast, the formation was truncated by a subsequent middle Pliocene highstand which reached 50 m asl, also recorded in global sea level curves (e.g. Haq et al., 1987).

The late Pliocene highstand at 3.3-3 Ma to ~30 m asl widely recorded around the globe (Dowsett et al., 1996; 1999), again saw the Atlantic shoreline approaching LBW. With progressive global cooling in the later Pliocene, culminating in the initiation of northern hemisphere glaciations, sea levels declined once more and during early regression the strengthening winds of the cooler Plio-Pleistocene formed extensive dunefields over the region. A tongue of the major Saldanha Bay dune plume just impinged on LBW, and the fossil brinkpoint formed the hill known as Anyskop immediately south of LBW. Early and Middle Stone Age people at times occupied the elevated area around Anyskop, leaving their stone artefacts as testimony of their presence. The final depositional phase at LBW comprised the red aeolian quartz sands (Springfontyn Formation) derived from reworking of leached soil profiles in the Langebaan Formation aeolianites. An OSL age of ~180 ka represents the oldest thus far recorded for such quartz sands along the West Coast.

This study has further emphasised the profound regional and global significance of LBW in terms of the prolific, diverse and exceptionally well preserved vertebrate fauna, as well as the detailed climatic and oceanographic history preserved there. The subsurface map of the upper Varswater Formation shows that the mining excavations at LBW have sampled only a small fraction of the total volume of the deposits. Future mining or dedicated investigations will undoubtedly reveal further palaeontological/geological riches. The nearby site of Baard's Quarry should be a future focus of study as its Plio-Pleistocene age helps bridge the temporal divide between the Pliocene LBW and the oldest Quaternary site of Elandsfontyn (~1 Ma) in the region.

References

Adams, J.W., Hemingway, J., Kegley, A.D.T., Thackeray, J.F., 2007. Luleche, a new paleontological site in the Cradle of Humankind, North-West Province, South Africa. J. Hum. Evol. 53, 751–754.

Barnard, K.H., 1954. A Beginner's Guide to South African Shells. Maskew Miller, Cape Town.

Bateman, M.D., Holmes, P.J., Carr, A.S., Horton, B.P., Jaiswal, M.K., 2004. Aeolianite and barrier dune construction spanning the last two glacial–interglacial cycles from the southern Cape coast, South Africa. Quatern. Sci. Rev. 23, 1681–1698.

Bernor, R.L., 2006. A contribution to understanding the evolutionary history of the Langebaanweg 'E' quarry hipparion. Eurygnathohippus cf. baardi. Afr. Nat. Hist. 2, 180.

Bernor, R.L., Scott, R.S., Fortelius, M., Kappelman, J., Sen, S., 2003. Systematics and evolution of the Late Miocene hipparions from Sinap, Turkey. In: Fortelius, M., Kappelman, J., Sen, S., Bernor, R.L. (Eds.), The Geology and Paleontology of the Miocene Sinap Formation, Turkey. Columbia University Press, New York, pp. 220–281.

Birch, G.F., 1979. Phosphatic rocks on the western margin of South Africa. J. Sed. Res. 49, 109–121.

Boisserie, J.-R., 2006. Langebaanweg: a unique window on early hippopotamid evolution in southern Africa. Afr. Nat. Hist. 2, 181–182.

Boné, E., Singer, R., 1965. Hipparion from Langebaanweg, Cape Province, and a revision of the genus in Africa. Ann. S. Afr. Mus. 48, 273–397.

Carrington, A.J., Kensley, B.F., 1969. Pleistocene molluscs from the Namaqualand coast. Ann. S. Afr. Mus. 52, 189–223.

Coetzee, J.A., 1978. Climatic and biological changes in south-western Africa during the Late Cenozoic. In: van Zinderen Bakker, E.M., Coetzee, J.A. (Eds.), Palaeoecology of Africa and the Surrounding Islands, 10, pp. 13–29.

Coetzee, J.A., 1980. Tertiary environmental changes along the south-western African Coast. Palaeontol. Africana 23, 197–203.

Coetzee, J.A., 1983. Palynological studies and vegetation history of the fynbos. In: Deacon, H.J., Hendey, Q.B., Lambrechts, J.J.N. (Eds.), Fynbos Palaeoecology: A Preliminary Synthesis. South African National Scientific Programmes Report No. 75.

Coetzee, J.A., Rogers, J., 1982. Palynological and lithological evidence for the Miocene palaeoenvironment in the Saldanha region (South Africa). Palaeogeogr. Palaeoclimatol. Palaeoecololy 39, 71–85.
Cohen, A.L., Tyson, P.D., 1995. Sea surface temperature fluctuations during the Holocene off the south coast of Africa: implications for terrestrial climate and rainfall. Holocene 5, 304–312.
Cole, D.I., Roberts, D.L., 1996. Lignite from the western coastal plain of South Africa. Afr. J. Earth Sci. 23, 95–117.
Compton, J.S., Franceschini, G., Wigley, R., 2006. A Proposed Neogene Synthesis of the West Coast and West Coast Fossil Park African Natural History 2,182.
Connolly, M., 1939. A monographic treatise of South African non-marine Mollusca. Ann. S. Afr. Mus. 33, 1–660.
Dale, D.C., McMillan, I.K., 1999. On the Beach. Field Guide to the Late Cainozoic Micropaelontological History of the Saldanha Region, South Africa. 127 pp.
Davies, O., 1973. Pleistocene shorelines in the Western Cape and South-West Africa. Ann. Natal Mus. 21, 719–765.
Denys, C., 1987. Rodentia and Lagomorpha. Fossil rodents (other than Pedetidae) from Laetoli. In: Leakey, M.D., Harris, J.M. (Eds.), Laetoli, a Pliocene site in Tanzania. Clarendon Press, Oxford, pp. 118–170.
Denys, C., 1989. Phylogenetic affinites of the oldest East African Otomys (Rodentia, Mammalia) from Olduvai Bed I. N. Jb. Geol. Palaont. Mh. 12, 705–725.
Denys, C., 1994a. Nouvelles espèces de Dendromus (Rongeurs, Muroidea) à Langebaanweg (Pliocene, Afrique du Sud) consequences stratigraphiques et paléoécologiques. Palaeovert. 23, 153–176.
Denys, C., 1994b. Diet and dental morphology of two coexisting Aethomys species (Rodentia) in Mozambique, implications for diet reconstruction in related extinct species from South Africa. Act. Ther. 39, 357–364.
Denys, C., 1996. Olduvai rodent faunas: Palaeoecological and palaeobiogeographical affinities: a comparison between East and South African Plio-pleistocene faunas. Darmstädter Beitr. Naturgeschichte 6, 247–261.
Denys, C., 1999. Of mice and men: evolution in East and South Africa during Plio-Pleistocene times. In: Bromage, T.G., Schrenk, F. (Eds.), African Biogeography, Climate Change and Human Evolution. Oxford University Press, New York, pp. 216–226.
Dingle, R.V., Lord, A.R., Hendey, Q.B., 1979. New sections in the Varswater Formation (Neogene) of Langebaan Road, south-western Cape, South Africa. Ann. S. Afr. Mus. 78, 81–92.
Dingle, R.V., Siesser, W.G., Newton, A.R., 1983. Mesozoic and Tertiary Geology of Southern Africa. Balkema, Rotterdam. 375 pp.
Douglas, B.C., 1997. Global sea rise: a redetermination. Surv. Geophys. 18, 279–292.
Dowsett, H.J., Barron, J., Poore, R.Z., 1996. Middle Pliocene sea surface temperatures: a global reconstruction. Mar. Micropaleontol. 27, 13–25.
Dowsett, H.J., Barron, J.A., Poore, R.Z., Thompson, R.S., Cronin, T.M., Ishman, S.E., Willard, D.A., 1999. Middle Pliocene Paleoenvironmental Reconstruction. PRISM 2, USGS Open File Report, pp. 99–535.
Du Pont, L.M., Schneider, R., Schmüser, A., Jahns, S., 1999. Marine-terrestrial interaction of climate changes in West Equatorial Africa of the last 190,000 years. Palaeoecol. Afr. 26, 61–84.
Erasmus, L., 2005. Virtual reconstruction of stratigraphy and landscapes in the West Coast Fossil Park region. M.Sc. Thesis, 313pp. University of Cape Town, South Africa.
Erasmus, L., 2005. Virtual reconstruction of stratigraphy and past landscapes in the West Coast Fossil Park region. MSc. thesis, University of Stellenbosch, 69 pp.
Flower, B.P., Kennett, J.P., 1993. Relations between Monterey Formation depositition and Middle Miocene global cooling: Naples Beech Section, California. Geology 21, 877–880.
Franz-Odendaal, T. 2002. Analysis of dental pathologies in the Pliocene herbivores of Langebaanweg and their palaeoenvironmental implications. Unpublished Ph.D. thesis, University of Cape Town, South Africa.
Franz-Odendaal, T.A., 2006. Analysis of the dental pathologies in the Pliocene herbivores of Langebaanweg and their paleoenvironmental implications. Afr. Nat. Hist. 2, 184–185.
Franz-Odendaal, T.A., Solounias, N., 2004. Comparative dietary evaluations of an extinct giraffid (Sivatherium hendeyi) (Mammalia, Giraffidae, Sivatheriinae) from Langebaanweg, South Africa (early Pliocene). Geodiversitas 26 (4), 675–685.
Franz-Odendaal, T.A., Lee-Thorp, J.A., Chinsamy, A., 2002. New evidence for the lack of C4 grassland expansions during the Early Pliocene at Langebaanweg, South Africa. Paleobiology 28, 378–388.
Gentry, A.W., 1970. Appendix. The Langebaanweg Bovidae. In: Hendey, Q.B. (Ed.), A Review of the Geology and Palaeontology of the Plio/Pleistocene Deposits at Langebaanweg, Cape Province: Ann. S. Afr. Mus., 56, pp. 114–117.
Gentry, A.W., 1974. A new genus and species of Pliocene boselaphine (Bovidae, Mammalia) from South Africa. Ann. S. Afr. Mus. 65, 45–188.
Goedhart, M., 2007. Seismicity along the southern Cape Fold Belt. South Africa, Association with Geological Structures, and Early Holocene Reactivation of the Kango Fault. Abstract, 17th Inqua Congress, Cairns, Australia, p. 142.
Gresse, P.G., 1988. Washover boulder fans and reworked phosphorite in the Alexander Bay Formation. S. Afr. Jorrnal Geol. 91, 308–391.
Grine, F.E., Ungar, P.S., Teaford, M.F., 2006. Was the early Pliocene hominin *'Australopithecus' anamensis* a hard object feeder? S. Afr. J. Sci. 102, 301–310.
Haarhoff, P., 2006. The West Coast Fossil Park (incorporating the Langebaanweg palaeontological site). Afr. Nat. Hist. 2, 177.
Haile-Selassie, Y., 2006. The suid *Nyanzachoerus australis* and biochronology of the Langeberg Quartzose Sand Member (LQSM), Langebaanweg. SA. Afr. Nat. Hist. 2, 185.
Hallam, C.D., 1964. The geology of the coastal diamond deposits of southern Africa. In: Haughton, S.H. (Ed.), Geology Some Ore Deposits Southern Africa, 2, pp. 671–728.
Haq, B.U., Hardenbol, J., Vail, P.R., 1987. Chronology of fluctuating sea levels since the Triassic. Science 235, 1156–1167.
Harris, J.M., White, T.D., 1979. Evolution of the Plio-Pleistocene African Suidae. Trans. Am. Philisophical Soc. 69, 1–28.
Haug, G.H., Tiedemann, R., 1998. Effect of the formation of the Isthmus of Panama on Atlantic Ocean thermohaline circulation. Nature 393, 673–676.
Haughton, S.H., 1926. On some new mollusca from Tertiary beds in the west of the Cape Province. Trans. R. Soc. SA 13, 159–162.
Haughton, S.H., 1928. Appendix: The palaeontology of the Namaqualand coastal deposits. In: Wagner, P.A., Merensky, H. (Eds.), The Diamond Deposits on the Coast of Little Namaqualand. Transactions of the Geological Society of South Africa, 31, pp. 1–41.
Haughton, S.H., 1931. The Late Tertiary and Recent deposits of the West Coast of South Africa. Trans. Geol. Soc. SA 34, 19–58.
Hendey, Q.B., 1969. Quaternary vertebrate fossil sites in the southwestern Cape Province. S. Afr. Archaeol. Bull. 24, 96–105.
Hendey, Q.B., 1970a. A review of the geology and palaeontology of the Plio/Pleistocene deposits at Langebaanweg. Cape Province 56, 75–117.
Hendey, Q.B., 1970b. The age of the fossiliferous deposits at Langebaanweg, Cape Province. Ann. S. Afr. Mus. 56, 119–131.
Hendey, Q.B., 1972a. A Pliocene ursid from South Africa. Ann. S. Afr. Mus. 59, 115–132.
Hendey, Q.B., 1972b. The evolution and dispersal of the Monachinae (Mammalia, Pinnipedia). Ann. S. Afr. Mus. 59, 99–113.
Hendey, Q.B., 1972c. Further observations on the age of the mammalian fauna from Langebaanweg, Cape Province. Palaeoecol. Afr. 6, 172–175.
Hendey, Q.B., 1972d. Palaeontological investigations in the southwestern Cape Province. Palaeoecol. Afr. 6, 171–172.
Hendey, Q.B., 1974a. The Late Cenozoic Carnivora of the south-western Cape Provnce. Ann. S. Afr. Mus. 63, 1–369.
Hendey, Q.B., 1974b. Faunal dating of the late Cenozoic of Southern Africa, with special reference to the Carnivora. Quatern. Res. 4, 149–161.
Hendey, Q.B., 1975. Relationships of North American hyaenas. S. Afr. J. Sci. 73, 187.
Hendey, Q.B., 1976a. The Pliocene fossil occurrences in 'E' Quarry, Langebaanweg, South Africa. Ann. S. Afr. Mus. 69, 215–247.
Hendey, Q.B., 1976b. Fossil Peccary from the Pliocene of South Africa. Science 192, 787–789.
Hendey, Q.B., 1977. Fossil bear from South Africa. S. Afr. J. Sci. 73, 112–116.
Hendey, Q.B., 1978a. Late Tertiary Hyaenidae from Langebaanweg, South Africa, and their relevance to the phylogeny of the family. Ann. S. Afr. Mus. 76, 265–297.
Hendey, Q.B., 1978b. Late Tertiary Mustelidae (Mammalia, Carnivora) from Langebaanweg, South Africa. Ann. S. Afr. Mus. 76, 329–357.
Hendey, Q.B., 1978c. The age of the fossils from Baard's Quarry, Langebaanweg, South Africa. Ann. S. Afr. Mus. 75, 1–24.
Hendey, Q.B., 1980. *Agriotherium* (Mammalia, Ursidae) from Langebaanweg, South Africa, and relationships of the genus. Ann. S. Afr. Mus. 81, 1–109.
Hendey, Q.B., 1981a. Palaeoecology of the late Tertiary fossil occurrences in "E" Quarry, Langebaan Road, South Africa, and a reinterpretation of their geological context. Ann. S. Afr. Mus. 84, 1–104.
Hendey, Q.B., 1981b. Geological succession at Langebaanweg, Cape Province, and global events of the late Tertiary. S. Afr. J. Sci. 77, 33–38.
Hendey, Q.B., 1981c. Origin of the giant panda. S. Afr. J. Sci. 76, 179–180.
Hendey, Q.B., 1982. Langebaanweg: A Record of Past Life. South African Museum, Cape Town. 71 pp.
Hendey, Q.B., 1983a. Cenozoic geology and palaeogeography of the Fynbos region. In: Deacon, H.J., Hendey, Q.B., Lambrechts, J.J.N. (Eds.), Fynbos Palaeoecology: A Preliminary Synthesis. South African National Scientific Programmes Report No. 75, pp. 35–60.
Hendey, Q.B., 1983b. Palaeoenvironmental implications of the Late Tertiary vertebrate fauna of the Fynbos region. In: Deacon, H.J., Hendey, Q.B., Lambrechts, J.J.N. (Eds.), Fynbos Palaeoecology: A Preliminary Synthesis. South African National Scientific Programmes Report No. 75, pp. 100–115.
Hendey, Q.B., 1983c. Palaeontology and palaeoecology of the Fynbos region: an introduction. In: Deacon, H.J., Hendey, Q.B., Lambrechts, J.J.N. (Eds.), Fynbos Palaeoecology: A Preliminary Synthesis. South African National Scientific Programmes Report No. 75, pp. 87–99.
Hendey, Q.B., 1984. Southern African late Tertiary vertebrates. In: Klein, R.G. (Ed.), Southern African Prehistory and Paleoenvironments. A.A. Balkema, Rotterdam, pp. 81–106.
Hendey, Q.B., Deacon, H.J., 1977. Studies in Palaeontology and Archaeology in the Saldanha region. Trans. R. Soc. SA 42, 371–381.
Hendey, Q.B., Dingle, R.V., 1990. Onshore sedimentary phosphate deposits in south-western Africa. In: Burnett, W.C., Riggs, S.R. (Eds.), Phosphate Deposits of the World, Vol. 2. Cambridge University Press, Cambridge, pp. 200–206.
Hendey, Q.B., Repenning, C.A., 1972. A Pliocene phocid from South Africa. Ann. S. Afr. Mus. 59, 71–98.
Herbert, T.D., Schuffert, J.D., 1998. Alkenone unsaturation estimates of Late Miocene through Late Pliocene sea-surface temperatures at Site 9581. In: Firth, J.V. (Ed.), Proceedings of the Ocean Drilling Program, Scientific Results159T, pp. 17–21.
Holbourn, A.E., Kuhnt, W., Simo, J.A., Li, Q., 2004. Middle Miocene isotope stratigraphy and paleoceanographic evolution of the northwest and southwest Australian margins (Wombat Plateau and Great Australian Bight). Palaeogeogr. Palaeoclimatol. Palaeoecol. 208, 1–22.
Hooijer, D.A., Maglio, V.J., 1974. Hipparions from the Late Miocene and Pliocene of northwestern Kenya. Zool. Trans. 134, 1–34.
Illenberger, W.K., 1996. The geomorphic evolution of the Wilderness dune cordons, South Africa. Quatern. Int. 33, 11–20.
Jacobs, Roberts, 2009. Last Interglacial Age for the Nahoon fossil human footprints, Southeast Coast of South Africa. Quat. Geochronol. 4, 160–169.

Kandel, A.W., Walker, S.J., Conard, N.J., 2006. Near-coastal settlement dynamics at the Anyskop Blowout, an archaeological locality at Langebaanweg, South Africa. African Natural History 2, 186.
Kensley, B.F., 1972. Pliocene marine invertebrates from Langebaanweg, Cape Province. Ann. S. Afr. Mus. 60, 173–190.
Kensley, B.F., 1977. A second assemblage of Pliocene invertebrate fossils from Langebaanweg, Cape. Ann. S. Afr. Mus. 72, 189–210.
Keyser, U., 1972. The occurrence of diamonds along the coast between the Orange River Estuary and the Port Nolloth Reserve. Bulletin of the Geological Survey of South Africa 54. 23 pp.
Krige, A.V., 1927. An examination of the Tertiary and Quaternary changes of sea-level in South Africa, with special stress on the evidence in favour of a recent world-wide sinking of ocean-level. Ann. Univ. Stellenbosch 5, 1–81.
Kurten, B., 1971. Age of Mammals. Weidenfeld and Nicolson, London.
Lehmann, T., 2006. Langebaanweg aardvarks: phylogenetic and palaeogeographical implications. African Natural History. 187–188.
Lisiecki, L.E., Raymo, M.E., 2005. A Pliocene–Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records. Paleoceanography 20, PA1003.
Maglio, V.J., 1973. Origin and evolution of the Elephantidae. Trans. Am. Philos. Soc. 63, 1–149.
Maglio, V.J., Hendey, Q.B., 1970. New evidence relating to the supposed Stegolophodont ancestry of the Elephantidae. S. Afr. Archaeol. Bull. 25, 85–87.
Manegold, A., 2009. Die Bedeutung von Vogelfossilien für paläoökologische Rekonstruktionen am Beispiel der Avifauna von Langebaanweg (Unteres Pliozän, Südafrika). Vogelwarte 47, 314–315 [On the significance of bird fossils for palaeoecological reconstructions on the example of the avifauna of Langebaanweg (early Pliocene, South Africa)]..
Matthews, T., 2005. The taxonomy and taphonomy of the micromammals from LBW, 'E' Quarry, South Africa. Unpublished Research Report Prepared for the Palaeontological Scientific Trust (P.A.S.T).
Matthews, T., 2006. A review of the Muridae of Langebaanweg (Mio-Pliocene, west coast, South Africa). Afr. Nat. Hist. 2, 188–189.
Matthews, T., 2004. The taphonomy and taxonomy of Mio-Pliocene and late Middle Pleistocene micromammals from the Cape west coast, South Africa. Unpublished PhD dissertation, University of Cape Town, South Africa.
Matthews, T., and Stynder, D. D. In press. An analysis of two Myosorex species (Soricidae) from the Mio-Pliocene site of LBW (West coast, South Africa) using geometric morphometrics and linear measurements. doi:10.1016/j.geobios.2010.07.003.
Matthews, T., Denys, C., Parkington, J.E., 2006. An analysis of the mole rats (Mammalia: Rodentia) from Langebaanweg (Mio-Pliocene, South Africa). Geobios 39 (6), 853–864.
Matthews, T., Denys, C., Parkington, J.E., 2007. Community evolution of Neogene micromammals from LBW 'E' Quarry and other west coast fossil sites, southwestern Cape, South Africa. Palaeogeogr. Palaeoclimatol. Palaeoecol. 245, 332–352.
Middleton, X., 2000. The sedimentology and stratigraphy of Varswater Quarry, Langebaanweg. BSc Honours dissertation, Geology Dept. UCT.
Middleton, X., 2006. Rare-earth and trace element geochemistry of the phosphorites and phosphatic sands of Varswater Quarry, Langebaanweg. Afr. Nat. Hist. 2, 189.
Miller, A.J., 1992. Large-scale ocean–atmosphere interactions in a simplified coupled model of the midlatitude wintertime circulation. J. Atmos. Sci. 49, 273–286.
Mol, D., 2006. The Langebaanweg locality: an important site for a better view of the evolutionary history of the mammoths. Afr. Nat. Hist. 2, 190.
Ogg, J.G., Smith, A.G., 2004. The geomagnetic polarity timescale. In: Gradstein, F.M., Ogg, J.G., Smith, A.G. (Eds.), A Geological Timescale. Cambridge University Press, pp. 63–86.
Olson, S.L., 1984. A hamerkop from the early Pliocene of South Africa (Aves: Scopidae). Proc. Biol. Soc. Wash. 97, 736–740.
Olson, S.L., 1994. Early Pliocene grebes, button-quails and kingfishers from South-Western Cape Province, South Africa. (Aves, Podicepididae, Turnicidae, Halcyonidae). Ann. S. Afr. Mus. 104, 49–61.
Olson, S.L., Eller, K.G., 1989. A new species of painted snipe (Charadriformes: Rostratulidae) from the early Pliocene at Langebaanweg, Southwestern Cape Province. Ostrich 60, 118–121.
Partridge, T.C., Maud, R.R., 1987. Geomorphic evolution of South Africa since the Mesozoic. S. Afr. J. Geol. 90, 179–208.
Partridge, T.C., Maud, R.R., 2000. Macro-scale geomorphic evolution of southern Africa. Partridge. In: Partridge, T.C., Maud, R.R. (Eds.), The Cenozoic of Southern Africa. Oxford Monographs on Geology and Geophysics No. 40, pp. 3–18.
Pether, J., 1986. Late Tertiary and early Quaternary marine deposits of the Namaqualand coast, Cape Province: new perspectives. S. Afr. J. Sci. 82, 464–470.
Pether, J., 1994a. Molluscan evidence for enhanced deglacial advection of Agulhas water in the Benguela Current, off southwestern Africa. Palaeogeogr. Palaeoclimatol. Palaeoecol. 111, 99–117.
Pether, J., 1994b. The sedimentology, palaeontology and stratigraphy of coastal-plain deposits at Hondeklip Bay, Namaqualand, South Africa. M.Sc. Thesis, 313pp. University of Cape Town, South Africa.
Pether, J., Roberts, D.L., Ward, J., 2000. Deposits of the West Coast. In: Partridge, T.C., Maud, R.R. (Eds.), The Cenozoic of Southern Afica. Oxford Monographs on Geology and Geophysics, 40, pp. 33–54.
Pickford, M., 1998. Onland Tertiary marine strata in southwestern Africa: eustacy, local tectonics and epeirogenesis in a passive continental margin. S. Afr. J. Sci. 94, 5–8.
Pickford, M., 2005. Orycteropus (Tubulidentata, Mammalia) from Langebaanweg and Baard's Quarry, Early Pliocene of South Africa. C.R. Palevol 4, 715–726.
Pickford, M., 2006. Southern Africa — a cradle of evolution Langebaanweg. Afr. Nat. Hist. 2, 191.
Pickford, M., Senut, B., 1997. Cenozoic mammals from coastal Namaqualand, South Africa. Palaeontol. Africaner 34, 199–217.
Pickford, M., Mein, P., Senut, B., 1994. Fossiliferous Neogene karst fillings in Angola, Botswana and Namibia. S. Afr. J. Sci. 90, 228–231.
Rich, P.V., 1980. Preliminary report on the fossil avian remains from late Tertiary sediments at Langebaanweg (Cape Province), South Africa. S. Afr. J. Sci. 76, 166–170.
Rich, P., Haarhoff, P., 1985. Early Pliocene Coliidae (Aves, Coliiformes) from Langebaanweg, South Africa. Ostrich 56, 20–41.
Roberts, D.L., 2006a. Lithostratigraphy of the Sandveld Group. S. Afr. Committee Stratigr. Lithostratigraphic Ser. 9, 25–26.
Roberts, D.L., 2006b. Lithostratigraphy of the Elandsfontyn Formation. S. Afr. Committee Stratigr. Lithostratigraphic Ser. 9, 25–26.
Roberts, D.L., 2006c. Lithostratigraphy of the Prospect Hill Formation (Sandveld Group). S. Afr. Committee Stratigr. Lithostratigraphic Ser. 9, 17–20.
Roberts, D.L., 2006d. Lithostratigraphy of the Varswater Formation (Sandveld Group). S. Afr. Committee Stratigr. Lithostratigraphic Ser. 9, 27–31.
Roberts, D.L., 2006e. Lithostratigraphy of the Langebaan Formation (Sandveld Group). S. Afr. Committee Stratigr. Lithostratigraphic Ser. 9, 9–12.
Roberts, D. L., Siegfried, P., In Press. The Geology of the Saldanha, Vredenburg and Velddrif Environs. Coucil for Geoscience, Pretoria.
Roberts, D.L., Berger, L., 1997. Last interglacial c.117 kyr human footprints, South Africa. S. Afr. J. Sci. 93, 349–350.
Roberts, D.L., Brink, J., 2002. Dating and correlation of Neogene coastal deposits in the Western Cape, South Africa: implications for Neotectonism. S. Afr. J. Geol. 105, 337–352.
Roberts, R.G., Galbraith, R.F., Yoshida, H., Laslett, G.M., Olley, J.M., 2000. Distinguishing dose populations in sediment mixtures: a test of optical dating procedures using mixtures of laboratory-dosed quartz. Radiat. Meas. 32, 459–465.
Roberts, D.L., Botha, G.A., Maud, R.R., Pether, J., 2007a. Coastal Cenozoic deposits. In: Johnson, M.R., Anhaeusser, C.R., Thomas, R.J. (Eds.), The Geology of South Africa. : Geological Society of South Africa. Johannesburg/Council for Geoscience, Pretoria, pp. 605–628.
Roberts, D.L., Botha, G.A., Maud, R.R., Pether, J., 2007b. Coastal Cenozoic deposits. In: Johnson, M.R., Anhaeusser, C.R., Thomas, R.J. (Eds.), The Geology of South Africa. : Geological Society of South Africa. Johannesburg/Council for Geoscience, Pretoria, pp. 605–628.
Roberts, D.L., Bateman, M.D., Murray-Wallace, C.V., Carr, A.S., Holmes, P.J., 2009. West Coast dune plumes: climate driven contrasts in dunefield morphogenesis along the western and southern South African coasts. Palaeogeogr. Palaeoclimatol. Palaeoecol. 271, 28–31.
Rogers, A.W., 1905. An Introduction to the Geology of the Cape Colony. Longmans, Green and Co, London, UK. 463 pp.
Rogers, J., 1980. First report on the Cenozoic sediments between Cape Town and Eland's Bay. Geological Survey of South Africa, Report No. 1980-136. 136 pp.
Rogers, J., 1982. Lithostratigraphy of Cenozoic sediments between Cape Town and Eland's Bay. Palaeoecol. Afr. 15, 121–137.
Rogers, J., 2006a. Sedimentology of Late Cenozoic sediments of the Varswater Formation in the Varswater Quarry at Langebaanweg, Western Cape Province, South Africa. Afr. Nat. Hist. 2, 192.
Rossouw, L., Stynder, D.D., Haarhoff, P., 2009. Evidence for opal phytoliths preservation in the Langebaanweg 'E' Quarry Varswater Formation and its potential for palaeohabitat reconstruction. S. Afr. J. Sci. 105, 1–5.
Sanders, W.J., 2006. Comparative description and taxonomy of proboscidean fossils from Langebaanweg, South Africa. Afr. Nat. Hist. 2, 196.
Sanders, W.J., 2007. Taxonomic review of fossil Proboscidea (Mammalia) from Langebaanweg, South Africa. Trans. R. Soc. SA 62, 1–16.
Schumann, E.H., Cohen, A.L., Jury, M.J., 1995. Coastal sea surface temperature variability along the South coast of South Africa and the relationship to regional and global climate. J. Mar. Res. 53, 231–248.
Sciscio, L., 2011. Neogene deposits along the southwest coast of South Africa: understanding the palaeoclimate through proxies. MSc Thesis (Unpublished) Rhodes University, Grahamstown, South Africa.
Scott, L., 1995. Pollen evidence for vegetational and climate change in southern Africa during the Neogene and Quaternary. In: Vrba, E.S., Denton, G.H., Partridge, T.C., Burckle, L.H. (Eds.), Palaeoclimate and Evolution with Special Emphasis on Human Origins. Yale Unversity Press.
Sénegas, F., Avery, D.M., 1998. New evidence for the murine origins of the Otomyinae (Mammalia, Rodentia) and the age of Bolt's Farm (South Africa). S. Afr. J. Sci. 94, 503–507.
Shackleton, N.J., 1995. New data on the evolution of Pliocene climatic variability. Glob. Climate Change 38, 242–248.
Siesser, W.G., 1978. Age of phosphorites on the South African continental margin. Mar. Geol. 26, 17–28.
Siesser, W.G., 1980. Late Miocene origin of the Benguela Upswelling System off Northern Namibia. Science 208, 283–285.
Siesser, W.G., Dingle, R.V., 1981. Tertiary sea level movements around southern Africa. Journal 89, 523–536.
Simpson, G.G., 1971. Fossil penguin from the Late Cenozoic of South Africa. Science 171, 1144–1145.
Smith, P.J.R., 1971. Langebaan phosphate deposits. Honours Project, University of Cape Town (unpublished), 38 pp.
Smith, R.M.H., Haarhoff, P., 2006. Sedimentology and taphonomy of an Early Pliocene Sivathere Bonebed at Langebaanweg, Western Cape Province, South Africa. Afr. Nat. Hist. 2, 197.

Stidham, T.A., 2006. Parrots (Aves: Psittaciformes) from the Miocene Varswater Formation, Langebaanweg, South Africa. Afr. Nat. Hist. 2, 198–199.
Stidham, T.A., 2008. The importance of Diamantornis eggshell (Aves: Struthionidae) in the age and correlation of the Prospect Hill Formation. SA S. Afr. J. Of Geol. 111, 459–461.
Strauss, W.L., 1957. Saldanha man and his culture. Science 125, 973–974.
Stynder, D., 2009. Tooth crown form as an indicator of niche partitioning among Late Miocene/Early Pliocene hyenas from 'E' Quarry, Langebaanweg, South Africa. Palaeogeogr. Palaeoclimatol. Palaeoecol. 283, 148–159.
Tankard, A.J., 1974. Varswater Formation of the Langebaanweg–Saldanha area, Cape Province. Trans. Geol. Soc. SA 77, 263–283.
Tankard, A.J., 1975a. The marine Neogene Saldanha Formation. Trans. Geol. Soc. SA 7, 257–264.
Tankard, A. J., 1975b. The late Cenozoic History and Palaeoenvironments of the coastal margin of the south-western Cape Province. Ph.D. thesis (Unpublished), Rhodes University, Grahamstown, 1–353.
Tankard, A.J., 1976a. Pleistocene history and coastal morphology of the Ysterfontein–Eland's Bay area, Cape Province. Ann. S. Afr. Mus. 69, 73–119.
Tankard, A.J., 1976b. Cenozoic sea level changes: a discussion. Ann. S. Afr. Mus. 71, 1–17.
Tankard, A.J., Rogers, J., 1978. Late Cenozoic palaeoenvironments on the west coast of southern Africa. J. Biogeogeography 5, 319–337.
Theron, J.N., Gresse, P.G., Siegfried, H.P., Rogers, J., 1992. The geology of the Cape Town Area. Explanation of 1:250 000 Sheet 3318. Geological Survey of South Africa, Pretoria. 140 pp.
Timmerman, L., 1985. Preliminary report on the geohydrology of the Grootwater Primary Aquifer Unit between Yzerfontein and the Madder River. Report, South African Department of Water Affairs, (unpublished), 30pp.
Timmerman, L., 1988. Regional hydrogeological study of the lower Berg River area, Cape Province, South Africa. Ph.D. thesis, Geology Department, State University of Ghent, Belgium (unpublished) 236 pp.
Tyson, P.D., 1999. Late-Quaternary and Holocene palaeoclimates of southern Africa: a synthesis. S. Afr. J. Geol. 102, 335–349.
Ungar, P., Merceron, G., Scott, R.S., 2006. Dental microwear of bovids from Langebaanweg: evidence for diet and paleoecology. Afr. Nat. Hist. 2, 199–200.
Vail, P.R., Hardenbol, J., 1979. Sea level changes during the Tertiary. Oceanus 22, 71–79.
Van Bruggen, A.C., 1978. Land molluscs. In: Werger, M.J.A., Dr W, Junk (Eds.), Biogeography and Ecology of Southern Africa. The Hague, pp. 463–513.
Van Bruggen, A.C., 1982. *Phortion occidentalis n.* sp., an extinct endodontoid land snail from Late Tertiary deposits at Langebaanweg, Cape Province. S. Afr. J. Sci. 78, 108–111.
Van Dijk, D.E., 2006. Langebaanweg anuran bones and associated biology. Afr. Nat. Hist. 2, 184.
Visser, H.N., Schoch, A.E., 1973. The geology and mineral resources of the Saldanha Bay area. Memoir Geological Survey of South Africa 63. 150 pp.
Weldeab, S., Lea, D.W., Schneider, R.R., Andersen, N., 2007. 155,000 years of West African monsoon and ocean thermal evolution. Science 316, 1303.
Werdelin, L., 2006. The position of Langebaanweg in the evolution of Carnivora in Africa. Afr. Nat. Hist. 2, 201–202.
Zachos, J., Pagani, M., Sloan, L., Thomas, E., Billups, K., 2001. Trends, rhythms, and aberrations in global climate 65 Ma to Present. Science 292, 686–693.