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Miocene fluvial systems and palynofloras at the southwestern tip of Africa: Implications for regional and global fluctuations in climate and ecosystems

David L. Roberts [a,*], Lara Sciscio [b], Andy I.R. Herries [c], Louis Scott [d], Marion K. Bamford [e], Chiedza Musekiwa [a], Harilaos Tsikos [f]

[a] Council for Geoscience, PO Box 572, Bellville 7535, South Africa
[b] Department of Geology, University of Cape Town, Rondebosch, South Africa
[c] Australian Archaeomagnetism Laboratory, Department Archaeology, Environment and Community Planning, Faculty of Humanities and Social Science, La Trobe University, Melbourne Campus, Bundoora, 3086, VIC, Australia
[d] Department of Plant Sciences, University of the Free State, Bloemfontein, South Africa
[e] Bernard Price Institute for Palaeontology, School of Geosciences, University of the Witwatersrand, P. Bag 3, WITS 2050, Johannesburg, South Africa
[f] Department of Geology, Rhodes University, Grahamstown 6140, South Africa

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ABSTRACT

High amplitude climate fluctuations have been inferred from marine isotope data in the early Neogene, but few well documented terrestrial records exist from this era to gauge the effects of these high latitude events on continental climates and ecosystems. The extensive, three-dimensional exposures of Miocene fluvial and fluvio-lacustrine sediments in the Rondeberg clay pit near Cape Town provide a unique window on this era. Palaeomagnetic data suggests that the deposits accumulated over a period of <1 Ma. The presence of meso-megathermic palynoforms (Palmae, *Ilex*-type, *Euphorb*-type, Rhamnaceae) and mesothermic (*Podocarpus*-type) palynofloras suggests a humid subtropical/tropical climate. However, abundant charcoal, charred *in situ* tree stumps, overall poor preservation of organics, evidence for upward-drying lacustrine successions and an appreciable *fynbos* presence, point to cyclical periods of drought. We suggest that these climate fluctuations may have been influenced by the orbital pacing seen in the marine isotope record of the earlier Miocene, pointing to a high latitude link with mid-latitude terrestrial climate patterns. Earlier studies of pollen spectra from the nearby, slightly older Noordhoek deposits show cyclical alternations from tropical to cooler climates and more recent biogeochemical work has shown dramatic coincident fluctuations in depositional temperature. These vegetation changes were previously correlated with major global events embracing the entire Neogene from the Oligo–Miocene (late Oligocene to early Miocene) to the Pliocene. We offer a different interpretation, suggesting that the deposits represent a much shorter time interval in the earlier Miocene and that these climate fluctuations may have been influenced by orbital forcing evinced in the marine isotope record. Along the northern west coast, the Arrisdrift vertebrate fossil assemblage in Early–Middle Miocene terrace deposits of the Orange River indicate a tropical climate but possibly less humid than in the south, with more open vegetation patterns. The presence of pedogenic calcretes and gypcretes in the deposits suggests periodic extremes of aridity not seen in south; the current pronounced north-aridity gradient from humid temperate to hyper-arid may have had its inception in the earlier Miocene.

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* Corresponding author. Tel.: +27 0219436731.
E-mail address: droberts@geoscience.org.za (D.L. Roberts).

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1. Introduction

The dominant present day flora (Cape Floristic Region) at the south-western tip of Africa (Fig. 1) is characterised by summer-dry adapted maccia vegetation (*fynbos*). Modern extant families which typify this flora include Asteraceae, Ericaceae, Proteaceae, Restionaceae, Aizoaceae, Iridaceae, Rutaceae and Orchidaceae (Goldblatt and Manning, 2002). During the last few decades it has become apparent from palynological studies of onshore drill core that the *fynbos* was preceded by an early Neogene flora characterised by tropical/subtropical forest elements including palms. Many of these taxa are extinct in the region today and some are no longer found in Africa; overall the floras exhibit a distinct Gondwanan flavour, rooted deep in the past (Coetzee, 1978, 1980; Coetzee and Rogers, 1982; Coetzee, 1983a,b, 1986; Scott, 1995).

Although the Miocene polleniferous organic sediments in the south-western Cape generally have fluvial and fluvio-lacustrine affinities, little attention has been paid to the sedimentation patterns of these depositional systems as a whole in elucidating palaeoenvironments. Fluvial depositional style reflects fluctuations in regional hydrology, climate, catchments, relative sea level and therefore, tectonics. We recognise three basic Miocene fluvial depositional styles along the west coast of South Africa (Models A, B and C; Fig. 2), whose deposits are characterised by a dominance of suspension load (fines) such as at the Rondeberg site north of Cape Town (Fig. 1), mixed load (coarse sands and fines) as at the Noordhoek site (Fig. 1) and bedload gravels at the Orange River site (Fig. 1), respectively. From these three models, we draw inferences concerning the parameters listed above. We focus on three sites in this region exemplifying these depositional models, namely the Orange River in the far north, Noordhoek and a new site (the Rondeberg clay pit), both of which are located near Cape Town in the south (Fig. 1). The inception of the present steep climate gradient along the South African west coast culminating in hyper-aridity around the Orange River in the north has been debated (Coetzee, 1978; Pickford and Senut, 1997) and we compare the Miocene terrace deposits of the Orange River and their diagenesis with their counterparts in the south to investigate this question.

Here we also provide an in-depth study of the Rondeberg clay pit (Model C), situated 60 km north of Cape Town, which offers extensive three-dimensional exposures of Neogene fluvial and fluvio-lacustrine fine sands, silts and clays, not previously reported in the literature. These exposures are complemented by information from a number of drill-holes designed to delimit the extent of the deposits, 10 of which are shown in Fig. 3. Organic-rich horizons have proved to be polleniferous and *in situ* preserved charred tree stumps yielded information concerning fire regime, taxonomy and plant growth patterns. Previous studies of the Neogene polleniferous successions of the south-western Cape were based on drillhole cores (Rogers, 1980, 1982). Importantly, the extensive exposures at Rondeberg allowed palaeomagnetic studies to be conducted, to independently constrain the age and time interval over which the Neogene deposits accumulated. Again, the exposures at Rondeberg provide a wealth of new data in this regard, not available for the vast majority of deposits which are confined to the subsurface. The Rondeberg clays are situated over a major terrain-bounding fault system and faulting observed in the deposits has shed further light on regional neotectonics.

The earlier work on the Neogene palynofloras, particularly at the Noordhoek site near Cape Town (Fig. 1) which hosts the longest and most complete record to date, also brought to light marked fluctuations in plant communities through time. These changes, which indicated alternating more tropical and cooler intervals (Coetzee, 1983a), were considered to embrace the entire Neogene from the Oligo–Miocene to the Pliocene and Quaternary and were correlated with major global events. These included the recovery from the Oligocene glaciation in the early Miocene, the Middle Miocene warm period and subsequent global cooling with increasing thermal isolation of Antarctica. A notable increase in *fynbos* taxa higher in the Noordhoek succession was considered to reflect the advent of the cooler/drier Pliocene climate as the Benguela Cold Upwelling System intensified heralding the transformation to the Quaternary dominance of *fynbos* encountered at the top of the succession (Fig. 1).

Subsequent to the major works of Coetzee (*e.g.* Coetzee, 1983a) on the Miocene palynofloras of the Western Cape, marine cores provided detailed information on global climate fluctuations during the Miocene (Prentice and Matthews, 1988; Zachos et al., 1992; Holbourn et al, 2007). Orbital (Milankovitch) forcing has been inferred from spectral analysis of the marine isotope data and both high frequency precession (23 ka) and obliquity (41 ka) bands are inferred, in addition to lower frequency eccentricity (100–400 ka) beats. The forcing is thought to have been amplified at high latitudes, but few well documented mid-latitude Miocene terrestrial records are available to

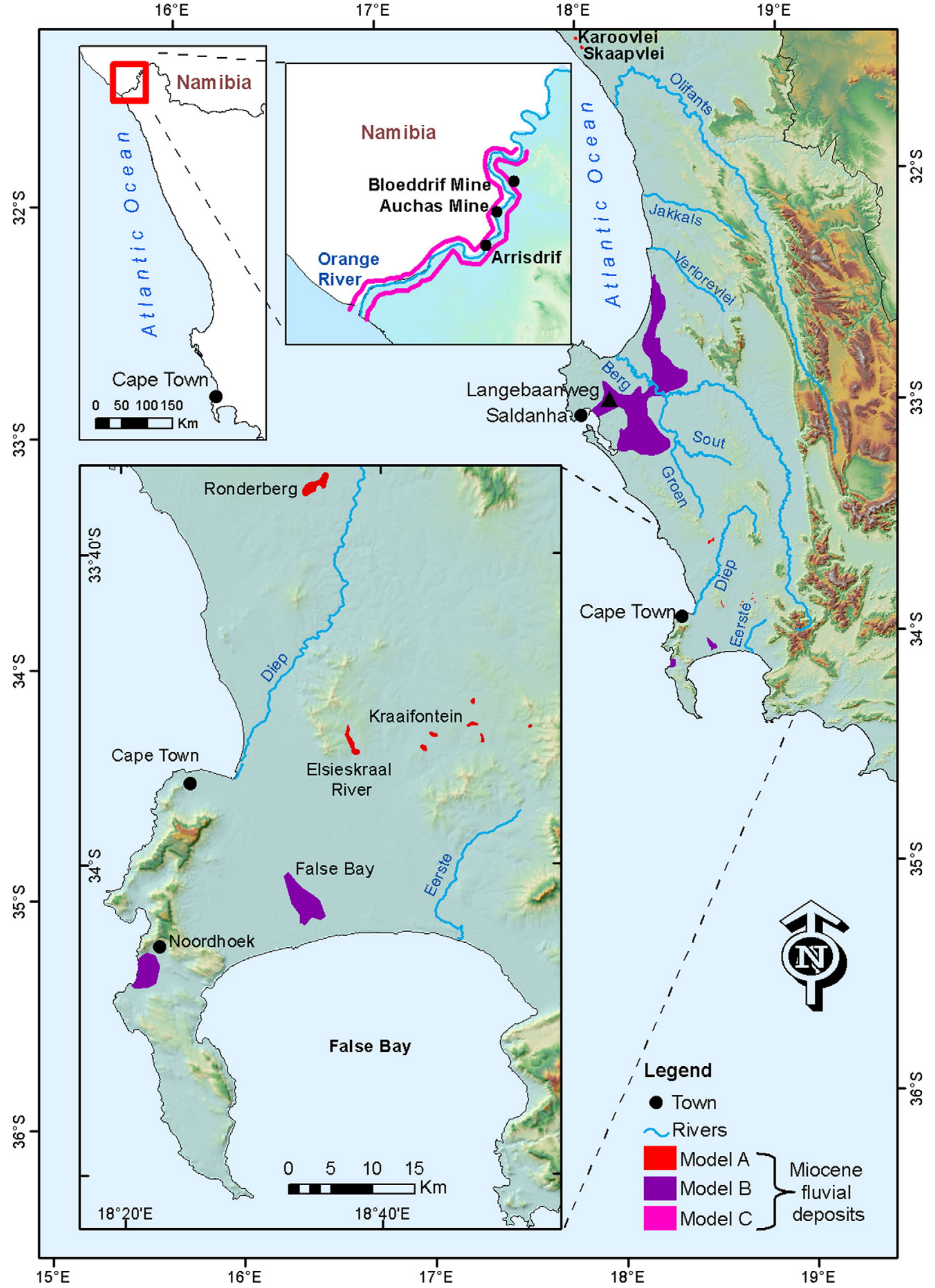

Fig. 1. Distribution of Miocene fluvial deposits and depositional styles (see Fig. 2) along the western South African coastal plane. Models A, B and C are suspension load, mixed bedload/ suspension load and bedload rivers, respectively.

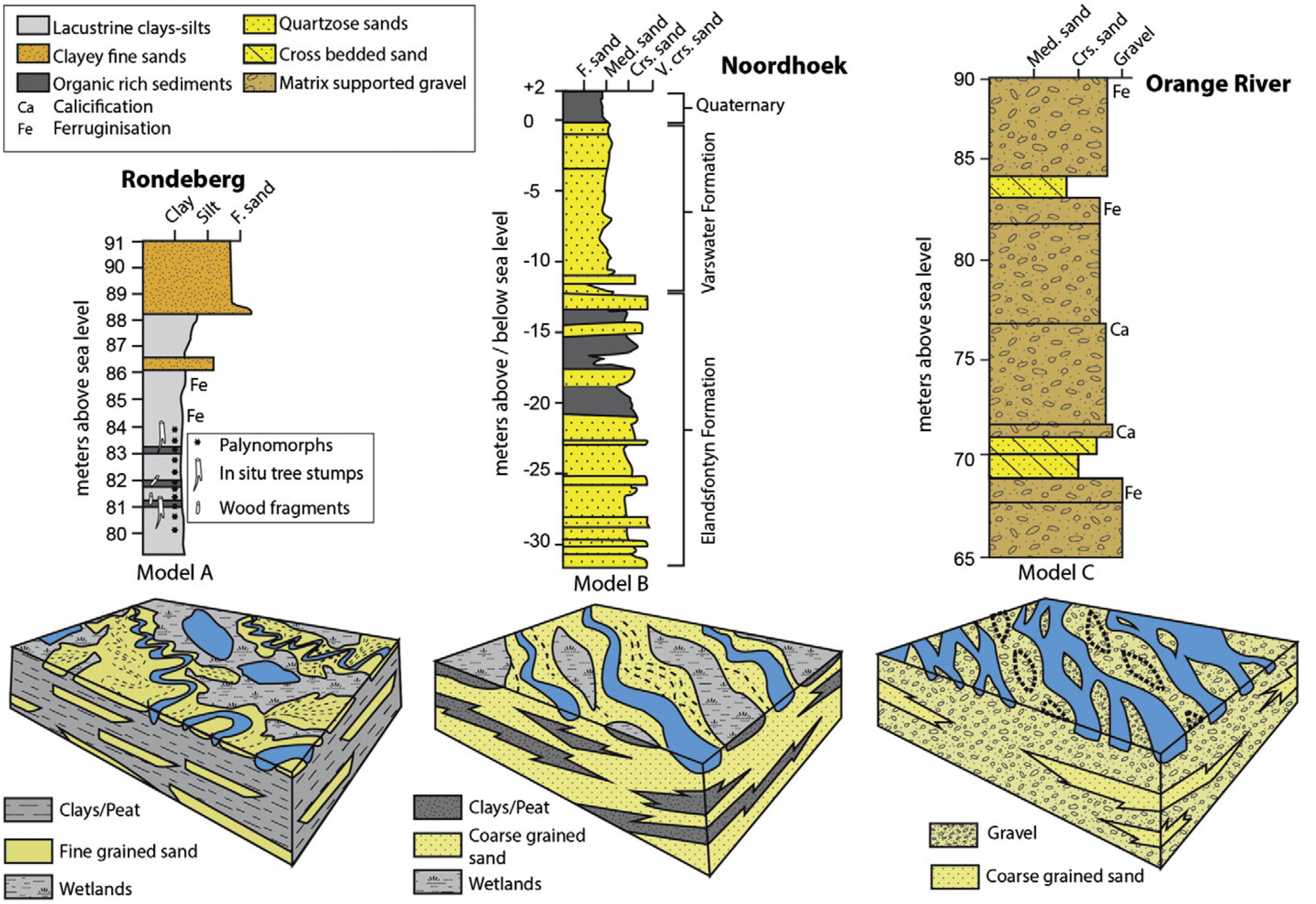

Fig. 2. The three basic Miocene fluvial depositional styles along the west coast of South Africa (Models A, B and C), whose deposits are characterised by: suspension load fines (*e.g.* Rondeberg), mixed bedload/ suspension load consisting of coarse sands and fines/organics (*e.g.* Noordhoek), and a dominance of bedload gravels (Orange River), respectively.

gauge the effects of these high frequency climate shifts on continental climates and ecosystems. As noted above, the Noordhoek succession has been interpreted as embracing the entire Neogene period, but in the absence of an independent chronology and given the evidence for global high amplitude shorter term climate fluctuations, these conclusions require re-examination. In this regard we synthesise

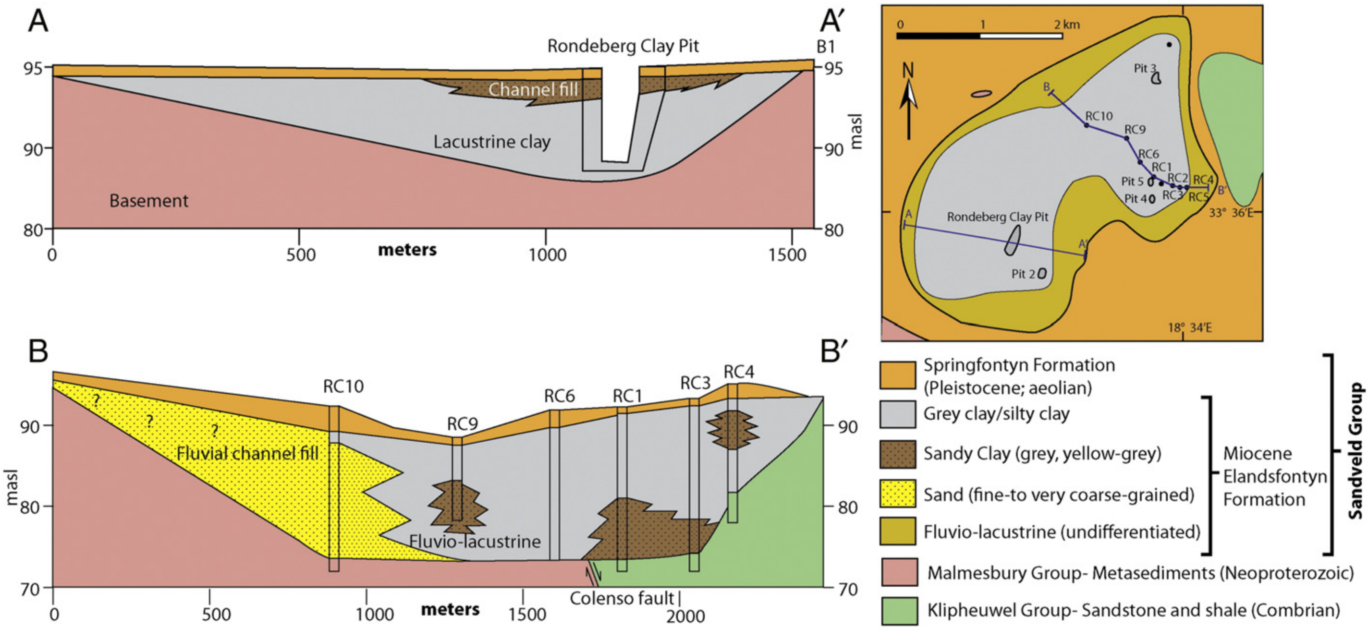

Fig. 3. Geological setting and sedimentary facies of the Rondeberg fluvio-lacustrine deposits (see Fig. 1 for location).

unpublished data from 4 drill-holes to provide a more holistic view of sedimentation patterns in the Noorhoek basin. We also draw on the recent work at this site which provided new stratigraphic and biogeochemically derived depositional temperature data (Sciscio, 2011; Sciscio et al., in preparation).

Much information concerning Neogene fluvial/fluvio-lacustrine systems along the West Coast of South Africa is contained in relatively obscure publications and unpublished reports. Here we synthesise this information and make it available to a wider audience.

In view of the considerations outlined above, the aims of this study are to:

- provide further (detailed) information on fluvial and fluvio-lacustrine depositional style and associated floras from the unique three-dimensional exposures at the Miocene Rondeberg clay pit near Cape Town;
- review the literature on Neogene fluvial and fluvio-lacustrine depositional style along the West Coast of South Africa to evaluate variability in space and time;
- re-evaluate previous correlations of Neogene pollen bearing successions near Cape Town with the global record, in the light of chronological inferences from palaeomagnetic data at Rondeberg, regional sea level history and sedimentation rates;
- compare earlier Miocene river deposits along the southern and northern west coasts to infer the timing of the present extreme west coast climate gradient;
- relate variability in Neogene fluvial systems and palynofloras at the southern tip of Africa to the global record.

2. Geological/geographical setting

The study area extends along the South African West Coast from Cape Town in the south to the Orange River in the north (Fig. 1). A passive intraplate, trailing edge tectono–seismic model has been determined for the mid-latitude southern African coastline, which is also removed from glacio-isostatic influence; the coastal belt therefore constitutes a platform where sea level fluctuations largely reflect glacio-eustacy rather than vertical crustal motions (Tyson, 1999; Goedhart, 2007; Roberts et al., 2011). This platform originated in the late Mesozoic breakup of Gondwana and has since been influenced by repeated Cenozoic marine transgressions (Pether, 1986, 1994). It is bounded on the landward side by the Great Escarpment (Fig. 1) and is sporadically blanketed by late Cenozoic marginal marine and fluvial deposits (Rogers, 1982; Roberts and Berger, 1997; Roberts and Brink, 2002), with the thicker deposits occupying depressions in the Precambrian basement. The depressions were mainly incised by rivers during the Oligocene drawdown in glacio-eustatic sea levels (Rogers, 1982; Roberts et al., 2011). The basement comprises intensely deformed Neoproterozoic metasediments and slightly younger plutons of the Cape Granite Suite (Roberts and Siegfried, in press). Outliers of the resistant Palaeozoic quartzitic sediments of the Cape Supergroup form flat-topped mesas ranging up to ~2100 m in elevation.

The onshore Cenozoic sediments contain a rich geomorphic, sedimentological and palaeontological archive ranging in time from the Miocene to the Holocene, whereas marine Cretaceous strata predominate offshore (Rogers, 1982; Dale and McMillan, 1999; Roberts, 2006). The Cape Town environs and the southern-most west coast currently experience a Mediterranean climate, obtaining almost all rainfall in the winter months from cyclonic polar frontal systems (Tyson, 1999). The dominant (dry) southerly summer winds are generated by the South Atlantic Anticyclone, which migrates southward in the summer. 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 have profoundly influenced patterns of sea surface temperatures and regional climates (Pether, 1994; Cohen and Tyson, 1995; Schumann et al., 1995). Because of the influence of the cold Benguela Upwelling System, 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, with a prominent succulent component. According to Coetzee (1978) and Roberts and Brink (2002), these fundamental atmospheric/oceanographic dynamics have dominated at least since the early Late Miocene (~12–10 Ma).

3. Methods and materials

3.1. Palynology

Standard sample collection techniques for palynology as outlined by Faegri and Iverson (1964) and Traverse (1988) were used. Sample preparation was done *via* standard laboratory methods (Gray, 1965).

Standard palynological extraction techniques were used as outlined by Gray (1965), Traverse (1988) and Erdtman (1969). A total of 35 samples were collected and processed, with only 15 samples yielding palynomorphs of low abundances (<300 grains per slide).

For disaggregation and chemical extraction processes, all RCP samples were washed with distilled water and/or the outer layer is shaved off with a clean sterile knife to remove any contamination. Samples were then crushed into small chips (disaggregation) using a pestle and mortar, and not ground into a fine-powder which can damage palynomorphs and sporomorphs. Powdered weights were recorded, and samples were placed into labelled plastic beakers or test tubes. To remove carbonate and silicates, the samples were treated with HCl (10%) and HF (48%). Sample treatment with HF varied in time from 1 to 3 hours to 48 hours. Samples were then washed with 15 ml 10% hydrochloric acid to precipitate calcium fluoride and this is followed by washing and centrifuging several times with distilled water. Density separation was utilised to remove any heavy minerals present. Palynomorph-containing organic residue was flushed with distilled water. Slide mounting, in glycerol jelly, uses roughly 1 cm^3 of the organic residue collected. All sample preparation was carried out in the Dept. of Plant Sciences, University of the Free State, and slides were labelled and stored in the Geology Department, Rhodes University. Transmitted light microscopy was carried out with a Zeiss light microscope using ×250 and ×1000 (oil immersion) magnifications for palynomorph identifications and counts.

Pollen counts were done on the most promising slides and the general low abundances of palynomorphs allowed a classification of representation to be made by rating each taxon as: 'abundant' (>30 or more grains); 'frequent' (10–30); 'occasional' (<10) and 'rare' (1–2 grains). Palynomorphs were identified from the relevant literature and using the pollen reference collection archived in the Department of Plant Sciences at the University of the Free State. Because of the considerable probable Neogene-age of the Rondeberg deposits, identification was typically to family level and more rarely, to genus. Where identification was uncertain, palynomorphs were described and named according to morphological features.

3.2. Lignified wood

Lignified wood from an *in situ* tree stump from the base of the Rondeberg clay succession was sectioned, mounted on slides and examined microscopically in reflected/transmitted light.

3.3. Biogeochemistry

Branched tetraether membrane lipid extraction was attempted on the most organic-rich horizons (5 samples), using the approach of Huguet et al. (2006), but their tetraether yield was below detection levels.

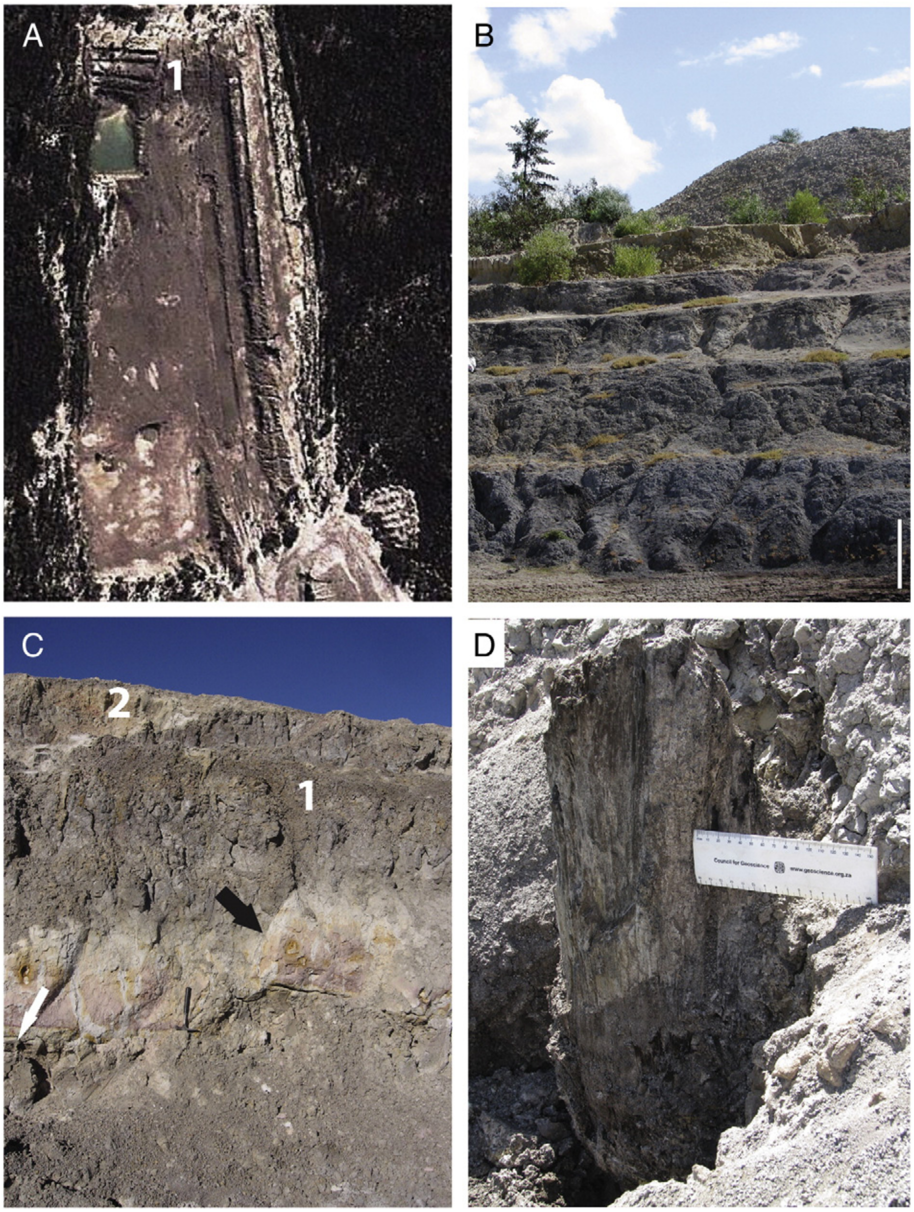

Fig. 4. (A) Satellite image of the Rondeberg clay pit which is ~275 m in length and ~85 m in breadth, showing the locality (1) of the measured section shown in Fig. 2; (B) pollen ferrous lacustrine clays near the base of the succession; (C) Lower rubified palaeosol with a post-depositional normal fault (black arrow), uppermost carbonaceous horizon (white arrow), upper palaeosol (1) and very fine grained, silty channel-fill (2); (D) *in situ* tree stump podocarp-scale in cm.

3.4. Logging of geological sections

Measured sections were logged using standard methods including GPS, compass and a levelling device. A total of 4 sections were logged, 2 at Rondeberg and 2 at the Orange River site.

3.5. Palaeomagnetics

Palaeomagnetic methodology follows that outlined in Herries and Shaw (2011) and Braun et al. (2010). Samples were oriented using a Suunto compass and clinometer and final directions were corrected using local field calculations from Finlay et al. (2010). Samples from the base of the quarry were collected in standard 8 cm^3 palaeomagnetic sample cubes and so only alternating field demagnetisation could be used to isolate the primary remanence. Samples from the upper part of the quarry were block sampled and so were also subjected to thermal demagnetisation. Samples were measured in a zero field room using a high temperature SQUID based magnetometer and demagnetised using an in house built AF demagnetiser and Magnetic Measurements Thermal Demagnetiser (MMTD80). Samples were analysed using principle component analysis and samples with a maximum angular deviation (MAD) of <15 were accepted. Samples with a palaeolatitude of $>45°$ were defined as having Normal polarity. Mineral magnetic measurements (Isothermal Remanence Acquisition, Backfields, Hysteresis Loops and Curie Curves) were undertaken using a Magnetic Measurements Variable Field Translation Balance (VFTB).

4. Rondeberg fluvio-lacustrine succession

4.1. Stratigraphy, sedimentology and geomorphology

A pit excavated for brick clay exposed Miocene fluvial and fluvio-lacustrine deposits (Rondeberg clays) at an elevation of ~100 m above sea-level (asl) near Malmesbury, approximately 60 km north of Cape Town (Figs. 1 and 3). The topography of the region is subdued, with gently rolling hills (coastal peneplain, Fig. 1) comprised of deeply weathered Cambrian and Neoproterozoic sediments. Borehole data demonstrates that the Cenozoic deposits are extensive and underlain by the pre-Cambrian basement. The deposits terminate in the flanks of a low hill in the east, indicating that they are erosional remnants of a once larger deposit. The exposures in the pit, which is situated in the southern part of the Rondeberg deposits, are 275 m in length and 85 m in breadth (Figs. 3 and 4). The deposit is up to ~11 m in thickness and mainly comprises pale yellowish-brown to pale red clays and silty clays with intercalated thin, dark grey to black organic rich horizons. Very fine sands occur at the top of the succession which collectively ranges up to ~11 m in thickness and overall comprises a coarsening upwards succession. These older sedimentation units are unconformably overlain by up to 2.5 m of well sorted, reddish, fine grained quartz sands, typical of the Quaternary aeolian Springfontyn Formation (Fig. 3).

The clayey deposits are generally massive, but certain intervals are well-stratified (Fig. 4) and some individual horizons can be traced over the entire extent of the exposures. Two cycles consisting of an upward decrease in organic content, as reflected in a colour changes from dark grey to yellowish grey and finally to pale red, are apparent. The organic rich horizons occur at ~1.2 m and 3.8 m above the base of the succession (Figs. 2–4). The lower organic horizon is best developed and is up to 0.3 m in thickness, whereas the upper ones consists of several dark, organic rich laminae, cumulatively about 0.2 m thick. Charcoal fragments visible to the naked eye and lignified *in situ* tree stumps occur in the lower and middle organic horizons, the largest (0.5 m) in the lower one (Fig. 4). The very fine, silty and clayey sands at the top of the succession take the form of broad channels fills (up to 35 m in width), in some instances with very thin (<1 cm) coarser lags at the base.

The Rondeberg channel fill deposits consist of very fine, subrounded quartz sands with a silty and clayey matrix as seen microscopically. A lens of similar sediment occurs near the top of the succession. These sediments appear massive with no clearly visible sedimentary structures, suggesting slow deposition and possible homogenisation by burrowing organisns (although no ichnofauna was detected to support this contention).

Similar Neogene clayey deposits have been reported from elsewhere in the region and have been attributed to deposition in quiet settings, such as fluvio-lacustrine and estuarine environments, where the predominantly kaolinitic clays can flocculate out of suspension (Cole and Roberts, 1996, 2000). The notable lateral extent of even very thin beds in the clayey part of the Rondeberg succession is consistent with a quiet, non-erosive lacustrine setting. The organic rich horizons are attributed to shallowing of the lake and establishment of a wetland (backswamp) setting with abundant vegetation. In the west, the lacustrine deposits interfinger with clayey channel fill sands (Fig. 3).

The fine grained channel fills at Rondeberg are consistent with deposition associated with meandering rivers with very low gradients (Miall, 1995 and references therein). The overall coarsening upward motif of the Rondeberg succession is considered to record increasing encroachment of the fluvial channels into the adjacent lake. The channel fills are notably finer-grained than the laterally interfingering sands, illustrating a low carrying capacity of the river and the channel base is not strongly erosive. Since Rondeberg was situated on a coastal plain and given the highly stable tectonic setting, it is probable that glacio-eustatic sea level was a major control of base level and would have played an important role in fluvial sedimentation patterns (Rogers, 1982; Cole and Roberts, 1996, 2000).

The Rondeberg succession overlies a major NW trending fault system (Colenso Fault) and tectonic deformation in the form of minor normal faulting is evident in the south-western part of the pit, but not within the deepest section of the pit where samples were taken (Fig. 4). Since the region represents a stable intraplate, trailing edge tectonic setting with little evidence of neotectonic activity in general (Pether, 1986, 1994), this suggests a considerable antiquity. The Neogene Elandsfontyn Formation of the Sandveld Group (Fig. 2) comprises gravels, coarse-to fine sands, clays and organic clays of fluvial/fluvio-lacustrine origin (Roberts, 2006). We include the Rondeberg deposits in this stratigraphic unit on the basis of sedimentological similarities and Neogene palynological age indications as described below. The only appreciable present drainage in the region of the clay pit is the Diep River 4.7 km to the west and it is likely that the deposits represent palaeo-Diep River sedimentation. The present elevation of the Diep River channel base is ~55 m asl, suggesting some 40–50 m of vertical incision and appreciable eastward migration since deposition of the Rondeberg deposits (Fig. 1).

4.2. Rondeberg floras

4.2.1. Lignified wood

The *in situ* tree stumps occur at different levels within the Rondeberg succession (Fig. 2). Since all the tree stumps appeared similar, only a portion of one of these (the largest) from the lower organic horizon was analysed (Figs. 2 and 4B). The diameter of the *in situ* stump was 45 cm and the piece that was removed for study was 25 × 11 × 5 cm. The wood has been charred by fire on the outside and the interior is very dark brown in colour with the appearance of lignification. Microscopically, the tracheids are approximately square in outline and on average 40 μm in tangential diameter (range 35–45 μm, Fig. 5). No parenchyma tissue or resin canals were seen. No late wood was observed under the microscope so apparently there are no growth rings. Bordered pits 20 μ in diameter occur on the radial walls and are uniseriate and separate. Cross-field pits are 15 μm in diameter and there is one pit per cross field. Although the pits appear simple in Fig. 5, they exhibit a narrow border under oblique light, a feature diagnostic of podocarpoids and taxodioids. Rays are uniseriate and homocellular with smooth, thin walls, ranging from 120 to 510 μm (5–20 cells) high.The tracheid pitting is abietinian (uniseriate or biseriate bordered pits, opposite and not compressed), ray cell walls are smooth and the cross-field pits are podocarpoid in form, all features indicative that the lignified wood belongs to the genus *Podocarpus* (Phillips, 1941). However, it is not possible to distinguish the species on the wood characters alone.

4.2.2. Palynology

Although preservation was generally poor and abundances relatively low in most samples, over specific intervals in the lower part of the succession *i.e.* 1.1 m, 1.76 m and 1.96 m above the base, both preservation and abundances of spores (pteridophytes) and pollen (gymnosperms and angiosperms) showed a notable improvement (Figs. 6–8). The lowermost productive sample unit at 1.1 m contained abundant *Ilex*-type and Rhamnaceae pollen, in addition to *Pellaea*-type (Scott, 1982) and Polypodiaceae fern spores (Fig. 8). Palms including the large and small morphotypes of Coetzee (1984) were low in abundance and Podocarpaceae were recorded, confirmed by the presence of *Podocarpus* wood in growth position just above this horizon. The *fynbos* families Ericaceae and Asteraceae along with the Mutisiae (ancestral Asteraceae, Scott et al., 2006) were present at this level (Figs. 6–8).

The interval of highest abundance and best preservation of palynomorphs was from 1.79 m to 1.96 m, where a general increase in the abundance of Palmae were noted, along with the first appearance of Podocarpaceae, Celastraceae, Euphorbiaceae and Liliaceae. *Fynbos* elements included Asteraceae, Proteaceae (triporate and triangular amb types) and Restionaceae. Various unidentified tricolporate psilate and reticulate pollen forms were also recorded. Above 1.96 m, a decrease in pollen abundance coincides with poorer preservation of individual palynonomorphs; an increase in the frequency of charcoal

Fig. 5. Radial longitudinal section (RLS) of podocarp wood under reflected light. Round, separate bordered pits seen in the lower part of the image (labelled). The diagonal lines across the tracheids (long vertical cells) are part of the wall structure that has partially degraded and should not be confused with spiral thickening. Cross-field pits of the podocarpoid type are visible in the top part of the image as round to oval holes with a narrow border within the square cross-fields.

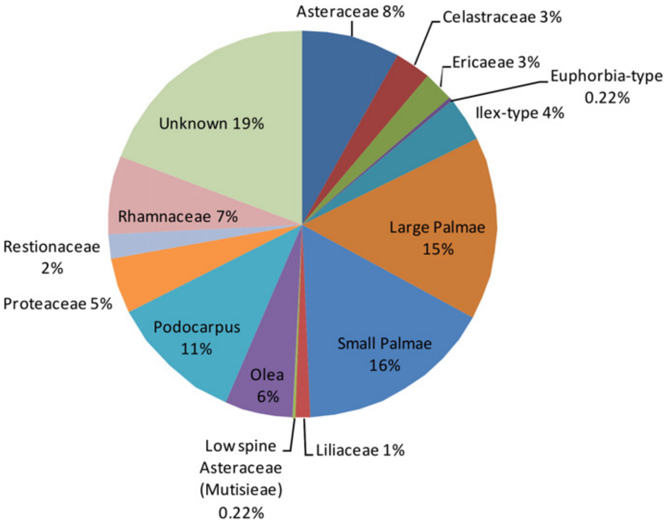

Fig. 7. Pie diagram showing the overall percentage distribution of palynomorph taxa within the Rondeberg succession.

appearance and concentration in samples above this elevation were also recorded.

The overall assemblage at Rondeberg is dominated by Palmae (31%), *Podocarpus*-type (11%), and Rhamnaceae (7%). Typical *fynbos* elements such as Asteraceae (8%), Proteaceae (5%), Restionaceae (2%) and Ericaceae (3%) also form a significant part of the pollen assemblage at Rondeberg, collectively forming ~18% of the total pollen (Fig. 7). The 'unknown' category of palynomorphs accounted for 19% of total pollen counts, indicating a significantly higher floral diversity than inferred from the positively identified forms. The 'unknowns' included palynomorphs of uncertain affinities such as the tricolporate psilate and reticulate morphotypes and was enlarged by the fragmentary nature of many specimens.

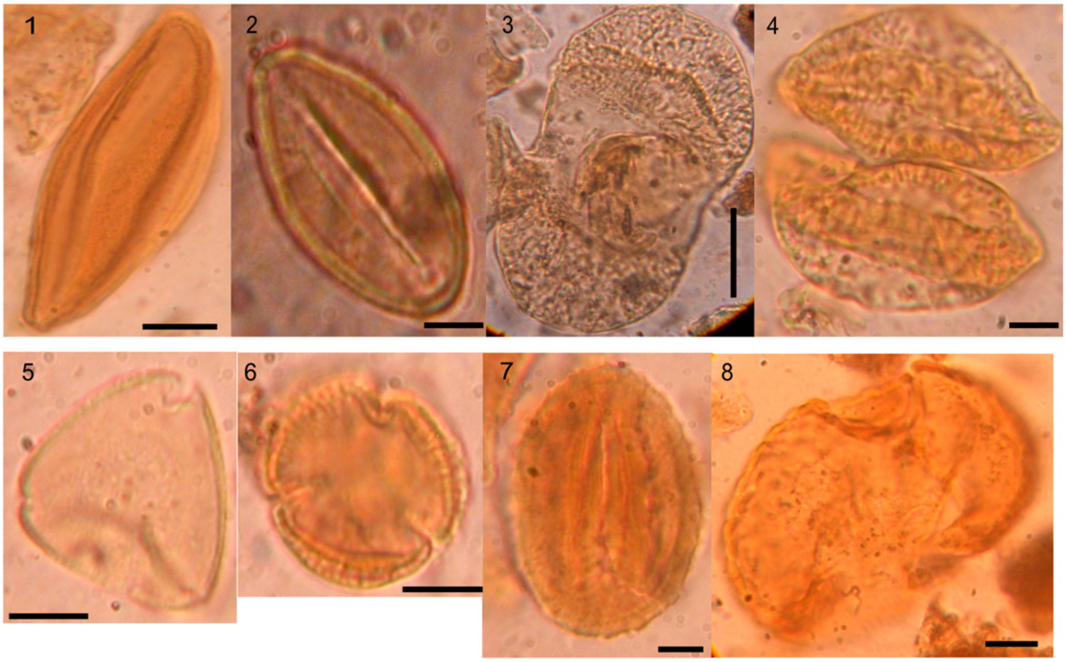

Fig. 6. Selected photomicrographs of Rondeberg palynomorphs which represent tropical (1, 2, 7, and 8) and more temperate (3, 4, 5, and 6) environments. 1: Angiospermae: Arecaceae/Palmae, 'large palm', 2: Arecaceae/Palmae, 'small palm', 3, 4: Gymnospermopsida: Coniferophyta, Podocarpidites, 5: Proteaceae, 6: Oleaceae, *Olea-type*, 7: Tubuliflorae group, *Mutisiae*, 8: Spore: Polypodiaceae, *Polypodiisporites* sp. Scale bar = 10 μm.

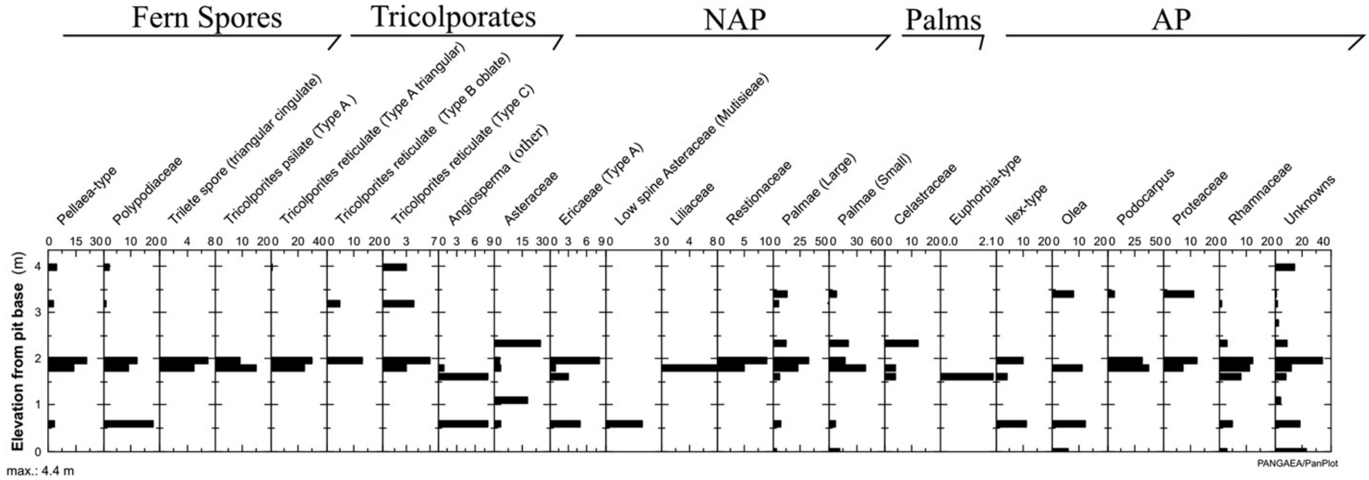

Fig. 8. Total pollen counts for the most productive samples at Rondeberg. Horizons richer in pollen are clearly apparent (see text for more detail). NAP = non-arboreal palynomorphs; AP = arboreal palynomorphs.

4.2.3. Palaeomagnetics

A mixture of single domain magnetite and maghaemite were identified in the samples, as shown by the separation of hysteresis loops and Curie points of ~570 °C–600 °C, in addition to a drop in magnetisation on cooling. Remanence is removed around the same temperature during thermal demagnetisation, indicating that the same minerals are holding the primary remanence. In some samples (e.g. RB08, Fig. S1) the remanence is stable up to 100 mT, whilst in others the remanece is almost entirely removed by 40 mT (e.g. RB04, RB07; Fig. S1). Goethite may also occur in some samples, as indicated by an initial drop in magnetisation below 300 °C during thermal demagnetisation, but high field stability during AF demagnetisation and a transformation from a yellowish brown to reddish brown during heating. On removal of any viscous remanence, all the samples (save one) from Rondeberg record a stable characteristic remanence that indicates a Normal magnetic polarity (Fig. S1; Table 1). The exception is sample RB10, from which different sub-samples contained mixed directions, indicating Normal, Intermediate and Reversed polarities. It is possible that RB10 records a brief excursion from Normal polarity, but the random orientations may also be due to depositional processes. Further sampling would be needed to resolve this question and as such the results from this sample have been discounted.

Table 1
Palaeomagnetic data for the Rondeberg Quarry sediments taken at ~0.5 m intervals from top to bottom. X = samples that fell apart during analysis. ~ = samples without consistent directions.

Sample	Declination	Inclination	No.	K	Palaeolatitude	Polarity
RB17	349.4	−46.8	3	206.9	79.8	N
RB18	357.5	−41.3	3	331.4	80.9	N
RB16	50.6	−47.4	3	39.5	46.6	N
RB15	51.2	−41.8	3	60.2	45.6	N
RB14	349.1	−47.4	3	190	79.8	N
RB12	344.0	−53.0	3	86.2	77.3	N
RB13	346.8	−56.3	3	137.3	78.4	N
RB03	28.9	−24.2	3	34.0	56.9	N
RB04	36.4	−50.4	3	25.7	57.6	N
RB06	36.3	−34.7	3	29.0	47.2	N
RB08	2.2	−45.1	3	111.7	83.1	N
RB11	25.7	−46.0	3	242.3	67.2	N
RB09	X	X	3	X	X	X
RB05	349.5	−50.1	3	679.7	80.9	N
RB07	347.3	−48.7	3	312.7	78.7	N
RB10	~	~	3	~	~	~
RB1	335.9	−26.3	3	49.1	58.8	N
RB2	36.4	−46.1	3	63.0	77.1	N

5. Discussion of the Rondeberg deposits

5.1. Chronology

The upper age limit of the Miocene (fluvial) Elandsfontyn Formation (Figs. 1–4), which is based on stratigraphic inferences, is best constrained at Langebaanweg, situated ~120 km north of Cape Town. Here the formation is separated from overlying Late Miocene marine gravels by a major unconformity (Hendey, 1981; Roberts et al., 2011). The presence of Asteraceae in the Elandsfontyn Formation at both Langebaanweg and Noordhoek places a maximum Oligo–Miocene age on the deposits (Coetzee, 1978; Coetzee and Rogers, 1982). However, Coetzee did not specify whether the Asteraceae found at Langebaanweg were the ancestral Mutisiae type (Fig. 6) already present in the Eocene (Scott et al., 2006) or the later, long-spined form, so there appears to be some uncertainty in this regard. The Noordhoek fluvio-lacustrine succession has been assigned an earlier Miocene age, based on the dominance of taxa characteristic of tropical/subtropical climates (extinct in the region today) and some with a distinct Gondwanan affinity (Coetzee, 1978; Coetzee and Rogers, 1982; Carr et al., 2010). The families Oleaceae and Celastraceae are typical in coastal early Tertiary sediments at Koingnaas on the west coast 500 km north of Cape Town (De Villiers and Cadman, 2001). Both of these taxa are present in the Elandsfontyn Formation at Rondeberg further suggesting a considerable antiquity.

The Rondeberg and Noordhoek/Langebaanweg floras have much in common, and appear to be broadly of similar age (Sciscio, 2011). However, both the Noordhoek and Langebaanweg deposits accumulated under conditions of rising sea levels (Rogers, 1980, 1982) and since the Rondeberg succession was deposited during higher relative sea levels than Noordhoek (Cole and Roberts, 1996, 2000), it is probably slightly younger.

The rubified horizons at Rondeberg do not show evidence of prolonged subaerial exposure such as intense root bioturbation, abundant concretionary structures or post-depositional erosion, characteristic of mature palaeosols (Yaalon, 1971); Fe contents are only slightly higher than in vertically adjacent intervals (Sciscio, 2011). Overall, the succession appears conformable with no major breaks in sedimentation. The 18 palaeomagnetic samples taken at regular intervals (~50 cm) throughout the Rondeberg succession indicated a Normal magnetic polarity. Because of the frequent fluctuations in global polarity over the early earlier Miocene, this does not positively pin down the age of the deposits, although long periods of normal polarity occur at ~10–11 Ma and ~19–20 Ma (Figs. S1 and S2). The data do, however serve to eliminate the intervals of reversed polarity as the possible depositional time. The apparent absence of any major breaks in sedimentation, in conjunction with the consistent normal polarity indicates that the Rondeberg succession accumulated within a single polarity zone. The longest earlier Miocene period of normal polarity is chron C6 at ~20.5–19.3 Ma (Ogg and Smith, 2004), suggesting that this represents the maximum period of accumulation (*i.e.* 0.8 Ma).

5.2. Rondeberg ecosystems and biogeographic links

The predominant massive clays without widespread evidence of root bioturbation, though with laterally persistent organic rich horizons at intervals, probably reflect deeper water (lacustrine/backswamp) suspension deposition and support the notion of a generally humid climate (Freshney et al., 1979). The clays are kaolinitic and likely derived from tropical weathering of the Neoproterozoic Malmesbury Group metapelites (Cole and Roberts, 2000).

However, several considerations point to periodic drier conditions at Rondeberg. These include *in situ* tree stumps of *Podocarpus* at two levels (~2 m and 3.8 m) in the clays, reflecting periodic declines in lake levels (Fig. 2). The high fraction of charcoal (microscopic and macroscopic) in most samples and the observations that the *in situ* stumps are charred, point to frequent fires over the period of accumulation of the lacustrine/backswamp deposits. Fire and other environmental factors such as desiccation during and shortly after deposition would account for generally poor pollen preservation and the lack of preserved membrane lipids (below detection limits). Sequences of upward decreasing organic content in the clays, culminating in reddish, oxidised horizons (Figs. 2 and 3) suggest cyclical, longer term dry periods (the absence of distinct growth rings in the fossil tree stumps does not indicate seasonality). The relatively high proportion of *fynbos* taxa in the pollen spectra further point to periodic cooler, drier periods; the fine grain size of the channel fill deposits are suggestive of low flow rates. Overall the Rondeberg deposits appear to reflect an unstable, rapidly fluctuating climate, ranging from wetter conditions supporting tropical forest to a drier regime with frequent fires and oxidation of organic matter.

The presence of meso-to megathermic forms (Palmae, *Ilex*-type, *Euphorb*-type) and moist mesothermic (*Podocarpus*-type) palynofloras point to a humid subtropical/tropical climate at Rondeberg.The floras range from large trees and shrubs to ferns, suggesting that the landscape in the vicinity of Rondeberg was, at times, at least partially forested. The pollen assemblage resembles counterparts in the older parts of the Miocene sequences at Noordhoek and Langebaanweg (Elandsfontyn Formation) and represents remnants of vegetation that predominated in the southwestern extremity of southern Africa since the earlier part of the Cenozoic (Coetzee, 1980; Coetzee and Rogers, 1982; Coetzee, 1983a, 1983b; Scholtz, 1985; Scott, 1995; De Villiers and Cadman, 2001). This flora is in stark contrast with the present day summer-dry adapted *fynbos* flora, which became increasingly dominant in the region during the Late Miocene (Dupont et al., 2011). This major botanical transition was interpreted by Coetzee (1980, 1983) and Coetzee and Rogers (1982) in terms of changing warm, humid subtropical conditions to a climate similar to that which is currently experienced in the region.

Interestingly, all the woody macro plant materials studied thus far from the various Western Cape Miocene deposits (most recently from Rondeberg) have turned out to belong to the Podocarpaceae, despite pollen from a variety of other arboreal species being present (Theron et al., 1992; Bamford, pers. comm.).This family is also ubiquitous in the Neogene pollen record from the region (Coetzee, 1978; Rogers, 1982; Coetzee and Rogers, 1982; Cole and Roberts, 1996, 2000; Scott, 1995; Sciscio, 2011). The presence of the wood in growth position in lacustrine/palludal sediments at Rondeberg suggests that the Miocene species favoured wetland settings, an environment that would have promoted fossilisation. *Podocarpus* woods usually have indistinct growth rings (Phillips, 1941) even when they grow in seasonal climates. Even so, the absence of any latewood suggests that the tree grew under conditions of sufficient water availability year-round, consistent with a moist setting.

In Africa, the Podcarpaceae are mainly restricted to Afromontane forests (Adie and Lawes, 2009) and at Noordhoek such a situation is feasible because of the local high relief surrounding the wetland (Fig. 9). However, the Rondeberg region in the Miocene constituted a tropical/subtropical low relief coastal plane traversed by meandering rivers and the tree stumps testify to podocarp presence at the site itself, apart from the podocarp pollen. Currently, tropical lowland podocarp species (typically of the genus *Nageia*) may be present in low numbers in species diverse forests, but characteristically they occur where conditions are difficult, such as low nutrient soils and peat swamps. In such localised settings they may have a competitive edge over angiosperms (Morley, 2011). In Africa the species of the genus *Afrocarpus*, is more closely related to *Nageia* (Southeast Asia, India, Japan, Philippines and Indonesia) than to the African representatives of *Podocarpus* (Morley, 2011). Bearing these points in mind as well as the present occurrence of *Afrocarpus falcatus* on the coastal plane of the subtropical southern African east coast (Adie and Lawes, 2009), we suggest that of the two podocarp genera represented in Africa, the podocarps at Rondeberg are more probably of the genus *Afrocarpus*. Because the pollen and wood of the two genera are indistinguishable, palynology and the nature of the fossil wood at Rondeberg can neither confirm nor disprove this hypothesis.

The Mutisiae found at Rondeberg are the first definite representatives of this group from the southern Cape region and are considered an ancestral form of the Asteraceae (Scott et al., 2006; Barreda et al., 2009, 2010). Mutisiae pollen was also found in the Eocene from marine core off the southern West African coast (Scott et al., 2006) and their presence in the Miocene at Rondeberg indicates a long history for this group in the region. Barreda et al. (2009, 2010) contend that an early form of Asteraceae from the Eocene of southern Argentina with morphological links to the Mutisiae, supports a southern Gondwanan origin of Asteraceae and a possible Eocene age of divergence. The Podocarpaceae which have been widely recorded from the Miocene of the southern Cape, represent an ancient and widespread Gondwanan gymnosperm lineage with greatest diversity centring on Australasia and New Caledonia; the group has persisted as part of the *fynbos* biome (Coetzee, 1980, 1983a; Coetzee and Rogers, 1982; Barker et al., 2004).

6. Regional variations in Neogene fluvial systems

It has been recognised that facies-based fluvial models do not necessarily embrace all the variability displayed by ancient and modern river systems and their utilisation can result in over-simplification (*e.g.* Bridge, 1993). Nonetheless, we were able to recognise three distinct fluvial depositional styles along the South African west coast on the basis of the geometry, sedimentology, stratigraphy and palaeontology (Figs. 1 and 2), that broadly conform to basic depositional models described in the literature. Whereas Models A and C are founded on extensive exposures in quarries, Model B is based on subsurface data only.

6.1. Depositional Model A (Rondeberg type)

The Model A fluvial depositional style is exemplified by Rondeberg, described in some detail in Section 4. Low gradient, suspension load meandering rivers were characterised by a dominance of structureless, fine grained channel fill facies, in addition to laminated to massive clayey/organic lacustrine and backswamp facies. Other Model A examples occur to the south of Rondeberg around Kraaifontein and at Elsieskraal River valley (Fig. 1), where the maximum thickness of ~23 m has been recorded; some sites have in the past been exploited for peat/lignite and clays (Theron et al., 1992; Cole and Roberts, 1996,

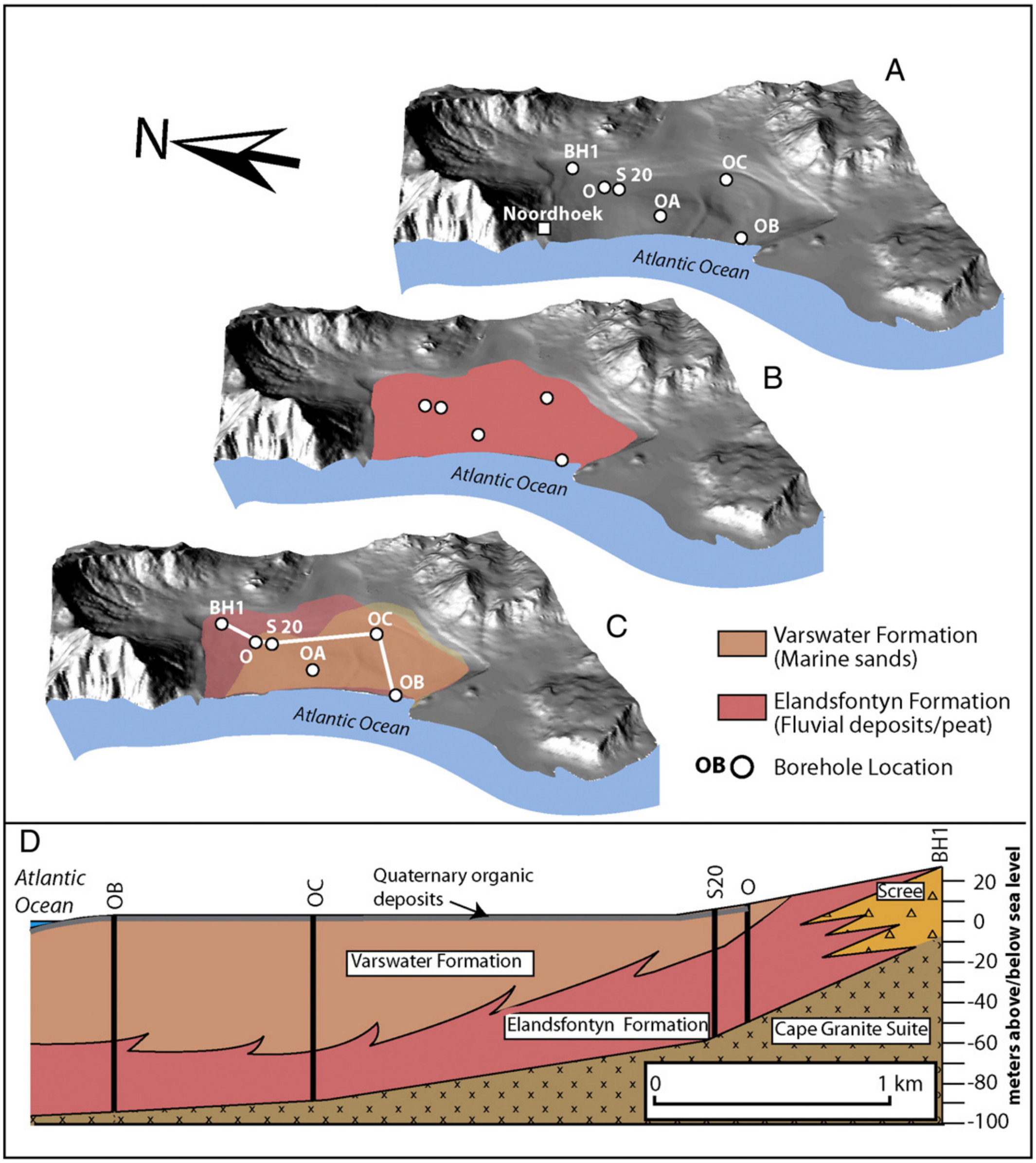

Fig. 9. Three-D model of the Noordhoek Basin showing the Neogene depositional history generated from geological maps and borehole data (see Fig. 1 for context): (A) Oligocene? basement configuration; (B) extent of the fluvial/palludal sediments of the Neogene Elandsfontyn Formation (C) extent of the Neogene marine sediments of the Varswater Formation.

2000). The deposits are situated inland from the coast at elevations between 80 and 135 m asl and unlike Models B and C, show no direct sign of marine influence.

Two Model A type deposits referred to as 'channel clays' (Rogers et al., 1990; Cole and Roberts, 1996, 2000) occur further north at Skaapvlei and Karoovlei near the Olifants River mouth (Fig. 1). All palynological studies on Model A deposits indicate that they also accumulated in the Miocene, displaying the trademark tropical/subtropical elements such as palms and a general scarcity of *fynbos* taxa (Coetzee, 1983a; Theron et al., 1992; Cole and Roberts, 1996, 2000; Sciscio, 2011).

The Model A deposits are thought to have accumulated during high relative sea levels, which promoted high water tables. Unlike Rondeberg where organic matter is generally degraded, relatively thick accumulations (up to 3 m) of peat/lignite/organic clays are preserved at Elsieskraal River valley and in deposits around Kraaifontein pointing to overall wetter conditions (Theron et al., 1992; Cole and Roberts, 1996, 2000). The Model A successions around Cape Town were deposited during a broadly similar time interval, pointing to pronounced shorter term climate fluctuations during the earlier Miocene in this region.

6.2. Depositional Model B (Noordhoek type)

6.2.1. Stratigraphy, sedimentology and geometry

The depositional Model B fluvial style (exemplified by Noordhoek) is characterised by coarse-grained, quartzose channel fill and possible crevasse sands, interfingering with and overlain by overbank/backswamp fines/organics (Fig. 2). An overall upward fining motif is evident, suggestive of lateral channel migration; alternatively this may reflect a decline in slope as the basin was infilled (Fig. 9). These sedimentary characteristics are consistent with a mixed load meandering fluvial style (Rogers, 1980; Timmerman, 1988; Cole and Roberts, 1996, 2000; Roberts et al., 2011). However, a caveat in this interpretation is that all data for the Model B fluvial depositional style comes from subsurface boreholes, with resultant loss of information such as primary sedimentary structures in the uncemented sandy deposits. The sediments accumulated in a coastal embayment probably excavated during the Oligocene regressive phase, extending well below present sea level (Figs. 2 and 9) and also onto the continental shelf as indicated by geophysics (Rogers, 1980, 1982). No major drainage exits into the present wetland at this site, and no evidence exists for a past major river system in the area (Theron et al., 1992), suggesting that sedimentation was *via* a relatively short-headed river(s) rising in the surrounding highlands (Fig. 9).

Other Model B examples occur at False Bay and around Saldanha (Fig. 1). All of these fluvial deposits grade upwards and down dip into marginal marine/estuarine sediments (*e.g.* Fig. 9), probably reflecting rising glacio-eustatic sea levels of the Early Miocene (Cole and Roberts, 1996, 2000). Elevated sea levels exerted a damming effect on groundwaters, causing a general rise in the water table which nurtured widespread wetlands at Noordhoek and around Saldanha (a situation which persists at the present time at Noordhoek). The rate of sea level rise eventually exceeded the fluvial deposition rate, and marine transgression terminated organic accumulation. The Model B fluvial successions are probably slightly older than the Model A deposits (Coetzee, 1983a; Cole and Roberts, 1996, 2000).

A striking contrast in sedimentation patterns between Model A and Model B is the coarse grade of the channel fill sediments in the latter. This may in part reflect the closer proximity of elevated topography at Noordhoek (Fig. 9), but this does not hold for the low relief False Bay and Saldanha environs. We suggest that stream power was greater during deposition of the coastal embayment sites, pointing to an overall higher rainfall regime in the slightly older Model B deposits, further borne out by the relative scarcity of charcoal (Sciscio, 2011; Sciscio et al., in preparation) and lack of evidence of sub-areal exposure that intimate a degree of (intermittent) relative aridity at Rondeberg.

6.2.2. Reinterpretation of the Noordhoek succession chronology

Noordhoek probably represents the longest record of Neogene floras in the region, with a cumulative thickness of organics of up to ~15 m (Fig. 2). The earlier palynological work on these deposits (*e.g.* Coetzee, 1978) brought to light marked fluctuations in plant communities through time, which indicated alternating more tropical and cooler intervals, confirmed by more recent studies which provided biogeochemically derived temperature data (Sciscio, 2011; Sciscio et al., in preparation). These changes were correlated with major global events embracing the entire Neogene from the Oligo–Miocene to the Pliocene as well as the Quaternary (Coetzee, 1978). These events included the recovery from the Oligocene glaciation in the early Miocene, the Middle Miocene warm period and subsequent global cooling with increasing thermal isolation of Antarctica. A notable increase in *fynbos* taxa higher in the Noordhoek succession (pollen zone Lvii, Coetzee, 1978) was considered to reflect the advent of the cooler/drier Pliocene climate as the Benguela Cold Upwelling System intensified (Fig. 1). This event was thought to herald the transformation to the Quaternary dominance of *fynbos* encountered at the top of the succession (Fig. 2).

The fluvial Elandsfontyn Formation at Noordhoek is only ~25 m thick, but was interpreted on the basis of palynological correlation with the global record, to span some 20 Ma (Coetzee, 1978). This yields a mean sedimentation rate of ~1.25 m/Ma which is extremely low (even taking account of sediment compaction), compared with modern peat sedimentation rates in tropical wetlands. Modern sedimentation rates extrapolated over 1 Ma range from 300 to 2550 m/Ma (Page et al., 2006a,b). No major unconformities are evident in the succession revealed in the recent borehole drilled in 2009 (Sciscio, 2011)-or in the previously drilled holes at Noordhoek (Rogers, 1980). The excellent preservation of organic matter seen at Noordhoek (Coetzee, 1978; Sciscio, 2011) is consistent with a persistent high water table and also seems incongruent with the low accumulation rates inferred by Coetzee (1978). When the rapidly deposited coarse sediment intercalated with the fines/peat is included in the calculations, the situation becomes more untenable still. The Elandsfontyn Formation in the Noordhoek succession has the general components of a typical (conformable) fluvial upward fining sequence, with basal gravels and very coarse sands successively overlain by strata with a dominance of finer sands and organic overbank/wetland facies. We suggest that sedimentation occupied a time span similar to Rondeberg (<1 Ma), rather than spanning the entire Neogene and Quaternary.

A further difficulty with Coetzee's (1978) interpretation of the Noordhoek succession is their low elevation (well below sea level, Figs. 2 and 9). No evidence exists at the site for the major Miocene and Pliocene sea level fluctuations seen elsewhere along the west and southern South African coasts. For instance, along the southeast coast, the Knysna lignites of broadly comparable age to Noordhoek (Carr et al., 2010) are situated at 200 m–260 m asl, and the Early to Middle Miocene shallow marine deposits of the Alexandria Formation rises to +300 m (Le Roux, 2000). Closer to Noordhoek, the Langebaanweg site (130 km to the north) boasts an early Pliocene sea level at up to 90 m asl, followed by highstands to 50 and 30 m asl in the mid and Late Pliocene respectively (Rogers, 1980; Pether, 1994; Roberts et al., 2011).

The extension of the Noordhoek succession into the Pliocene was chiefly founded on an increase in *fynbos* taxa in the upper part of the succession (pollen zone L vii of Coetzee, 1978) and was considered to reflect the advent of the cooler/drier Pliocene climate as the Benguela Cold Upwelling System strengthened (Rommerschieren et al., 2011). However, typical *fynbos* elements (Ericaeae, Restionaceae, Proteaceae, Asteraceae) form a higher proportion of the pollen assemblage in the earlier Miocene Rondeberg site (~18%) than at Noordhoek. As we have shown, this reflects an overall drier period at Rondeberg, rather than a major temporal effect, given the brief period of sediment accumulation at this site (<1 Ma). In the 2009 drill-hole core (NH1, Fig. 9) at Noordhoek, Sciscio (2011) reported a high proportion of tropical taxa including palms at the top of the organic rich Elandsfontyn fluvio-paludal succession (Fig. 2). This author found a dominance of *fynbos* only in the Quaternary black soil near the surface of the present Noordhoek wetland (Fig. 9). Thus by analogy with Rondeberg where we have placed constraints on the depositional time span, the higher *fynbos* counts in pollen zone L vii do not necessarily constitute evidence for extension of the deposits into the Pliocene.

It appears that regional sea level histories, sedimentation rates, organic preservation and fluvial depositional style are incompatible with Coetzee's (1978) contention that the Noordhoek succession spanned the entire Neogene. According to our new interpretation, the major vegetation changes represent migration events of plant communities driven by relatively brief climate fluctuations; the underlying forces are considered in Section 7.

6.3. Depositional Model C: Orange River

The Orange River is the largest drainage along the southern African west coast and forms the northwestern boundary of South Africa (Fig. 1). It has an extensive inland catchment of nearly 1 million km^2, reaching the Drakensberg escarpment about 2000 km inland (Rogers et al., 1990; De Wit, 1999). The Orange River system essentially originated in the Jurassic (~190 Ma), possibly as a consequence of crustal deformation associated with mantle plume activity (Cox, 1989; Vita-Finzi, 2012). The present exit into the Atlantic was established at ~85 Ma, with subsequent epeiric uplift at ~65 Ma, resulting in a superimposed system deeply incised into bedrock. During the Oligocene, the river may have exited at the present Olifants River mouth some 370 km to the south, subsequently reverting to its present position in the Oligo–Miocene (Dingle and Hendey, 1984). A large fan delta has accumulated offshore from the present river mouth (Corbett and Burrell, 2001).

The presence of economic diamond deposits in the Miocene Orange River terrace gravels has spurred research into their nature and origins over the past few decades. The following analysis of these strata is based on this literature, as well as observations made by one of us (DLR) during a field mapping exercise in 2006 at the Bloeddrif diamond mine, situated 48 km from the present river mouth (Table S1). The older (Early to Middle Miocene) terrace strata reach up to ~90 m above the present river level (arl) and clasts range up to up to boulder-size (Rogers et al., 1990; De Wit, 1999; Corbett and Burrell, 2001); clasts up to 2 m in diameter were observed by us at Bloeddrif Mine. Typically, the gravels are polymict, comprising a mixture of poorly sorted, locally derived angular to subangular first cycle clasts plucked and entrained from bedrock, in addition to multi-cycle, well rounded material (De Wit et al., 1997; Jacob et al., 1997). The gravels as observed by us mostly comprised locally derived palaeo-Proterozoic quartzite, lavas, dolomite, white vein quartz and granite, along with rarer 'heavy' clasts, including banded iron formation, cherts, jasper, agate, epidote and diamonds. These exotic lithologies testify to erosion and transport from the deep hinterland (Dingle and Hendey, 1984; De Wit et al., 1997; Corbett and Burrell, 2001). The gravels are rarely clast-supported and typically have a matrix consisting of fine gravel to coarse sand and sorting is generally poor.

The terrace gravels are considered to represent a braided gravelly, bedload dominated palaeo-Orange River (De Wit et al., 1997; Jacob et al., 1997; Corbett and Burrell, 2001). At Bloeddrif Mine, we observed erosively-based coarse gravel bodies conforming to channel lags previously described. Lensoidal convex upwards gravel bodies interfinger with and grade laterally into poorly sorted, medium to very coarse sands, which are gravelly in part and laminated or cross-stratified (Figs. 2 and 10B). Such features are interpreted as downstream-fining channel bar deposits (Jacob et al., 1997), confirming prior observations and interpretations. Low angle stratified coarse sands and sandy gravels with complex internal structures (Fig. 10C) may represent a coarse grained point bar (Blacknell, 1982; Jacob et al., 1997).

The lack of carbonaceous paludal/lacustrine facies in the Orange River sediments is in striking contrast to their Miocene counterparts (Model A and B fluvial systems of the Elandsfontyn Formation) in the south. The only palaeontological window into the chronology of and climate under which the palaeo-Orange River terrace sediments

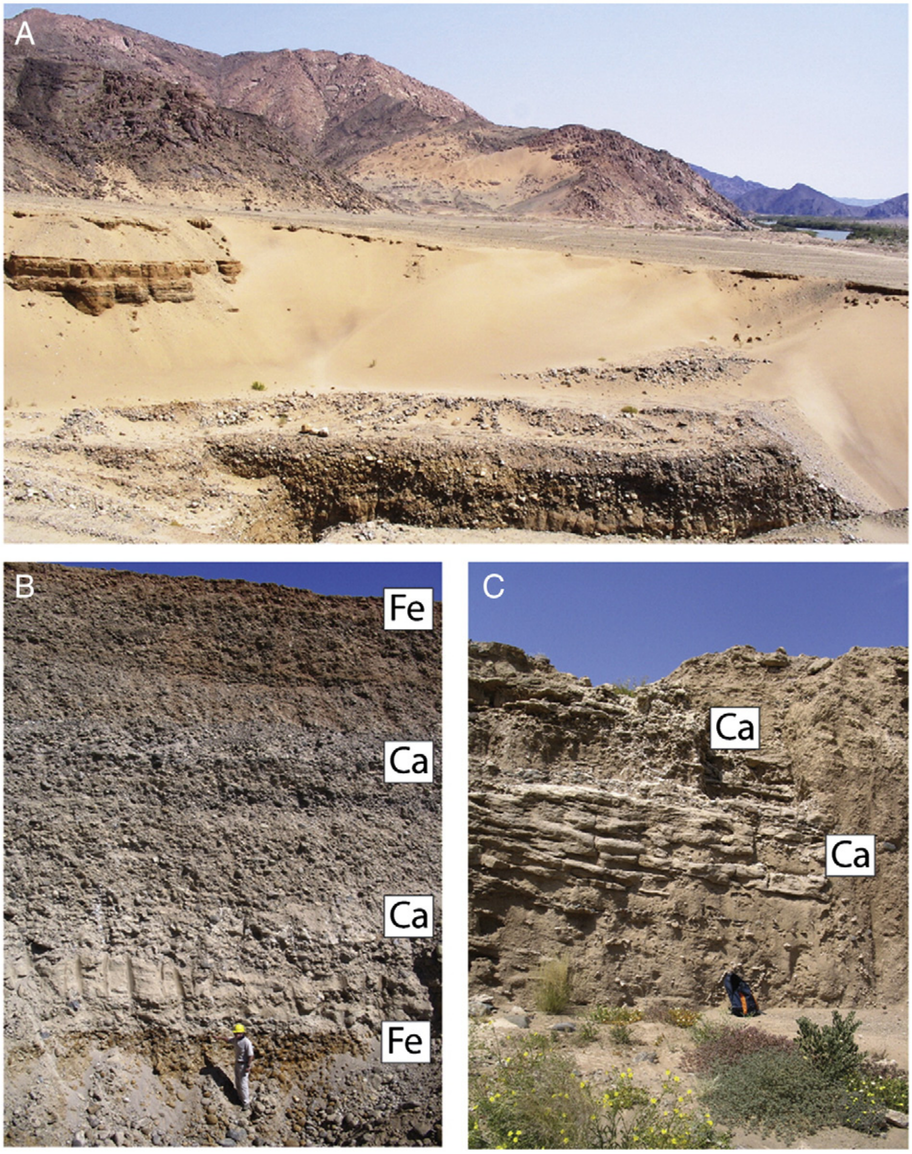

Fig. 10. Miocene Orange River terrace gravels at Bloeddrif diamond mine (Fig. 1): (A) Terrace gravels (foreground) in the present hyper-arid setting with the extant river visible at top right; (B) stacked terrace gravels with coarse sand lens above the figure at bottom centre; (C) calcretised terrace sandy gravels. 'Fe' and 'Ca' refer to feruginous and calcareous cementation/palaeosols respectively.

accumulated in this region comes from the Arrisdrift and Auchas vertebrate/plant fossil sites, situated ~45 km and ~42 km upstream from the river mouth respectively (Fig. 1). The fossils indicate an early to Mid-Miocene age (~20–14 Ma) and at Arrisdrift were associated with estuarine deposits at ~45 m above river level (Corvinus and Hendey, 1978; Pickford, 1998; Pickford and Senut, 2000). The assemblages indicate that a tropical-subtropical climate prevailed, but appears to have been less humid than in the south at that time, with more open vegetation patterns (Corvinus and Hendey, 1978; Pickford, 1998; Pickford and Senut, 2000; Bamford, 2003).

Of special note in terms of Miocene climate fluctuations associated with the Orange River terrace sedimentation, is the presence of pedogenic features, noted by us in several mining faces at Bloeddrif Mine (Figs. 2 and 10). In the measured profile at Bloeddrif Mine, calcareous and ferruginous palaeosols alternate within the 35 m thick section (Figs. 2 and 10). In particular, penecontemporanous (intercalated) pedogenic calcretes displaying characteristic features such as calcareous rhizoliths, suggest periodic aridity during intervals of non-deposition. In the southern African context, calcareous palaeosols may form under a range of climate regimes, depending on factors such as drainage, seasonality of rainfall, ambient temperatures and nature of the host lithology (Netterberg and Caiger, 1983). Generally, such pedogenic features develop where annual rainfall is <550 mm. Calcrete evolution may take place over periods in the order of a few hundreds of thousands of years (Candy et al., 2004). Large gypsum crystals (up to 40 mm) were observed in basal gravels overlying basement rocks on Bloeddrif Mine, suggesting evaporative conditions and formation of a briny lake (Chen, 1997). Ferruginous palaeosols tend to form under tropical/subtropical climates, but also in temperate regions (McFarlane, 1976). Ferricrete formation occurs through groundwater leaching of iron-rich minerals in the soil in reducing, acidic environments, followed by precipitation of iron and silicates in colloidal form as oxy-hydroxides in more oxidising, less acidic conditions. A widely quoted prerequisite for their genesis is an alternating moisture cycle, such as a seasonal rainfall regime. The presence of both calcic and ferruginous pedogenic horizons within the same profile suggests significant climate oscillations during the accumulation of the Orange River terrace deposits. Amongst the Model A and B fluvial systems in the south, only the Rondeberg succession contains (ferruginous) pedogenic horizons, as noted by us in Sections 4 and 5. Overall, patterns of pedogenesis in the Orange River terrace gravels and evidence for evaporative conditions suggest a significantly more arid Miocene climate than in the south.

The Orange River depositional style contrasts with the suspension load and mixed load meandering styles (Models A & B respectively) of the Elandsfontyn Formation in the south. The coarser grade of the palaeo-Orange River deposits partly reflects the vast catchment, but a steeper gradient inherited from Late Mesozoic to Early Cenozoic uplft may also have played a role. In common with the Elandsfontyn Formation, aggradation in the Orange River valley occurred under a regime of rising earlier Miocene relative sea levels (Rogers et al., 1990; De Wit, 1999; Corbett and Burrell, 2001).

7. Global context of west coast Miocene climate

The view that the earlier Miocene was a period of consistently reduced Antarctic ice volume (*e.g.*, Zachos et al., 1992; Zachos et al., 2001) with only transiently increased ice volume represented by heavy isotope excursions (Mi events of Miller et al., 1991, Fig. 11) has been challenged. Ice-volume estimates for the early Miocene (23–17 Ma) were determined by applying calibrations to high-resolution $\delta^{18}O$ records from ODP Sites 1090 (located in the Cape Basin south of the study area) and 1218 in the tropics (Pekar and DeConto, 2006). These calibrated records indicate that ice-volume ranged between 50% and 125% of the present day East Antarctic Ice Sheet during most of the earlier Miocene (23–17 Ma) with ice maxima corresponding to the Mi events. Such variability in ice volume was attributed to fluctuations in deep-water temperatures and circulation patterns near Antarctica, possibly instigated by deepening of the Drake Passage (Pekar and DeConto, 2006). Additionally, shorter period stable oxygen isotope fluctuations are superimposed on broader trends in the marine record of this period. Spectral analysis of the isotope data reveals orbital (Milankovitch) forcing in high frequency precession (23 ka) and obliquity (41 ka) bands, as well as the lower frequency eccentricity (100 and 400 ka) beats (Prentice and Matthews, 1988; Pekar and DeConto, 2006; Holbourn et al., 2007). At Rondeberg, overall drier conditions are reflected in degraded organics and frequent fires relative to the other nearby Model A occurrences (Fig. 1), where organics are well preserved throughout (Cole and Roberts, 2000). These observations suggest medium term climate variability during the earlier Miocene in our study area. Periodic lacustrine desiccation at Rondeberg, alternating with thriving tropical forest vegetation is indicative of shorter term climatic fluctuations. Thus the fluvio-lacustrine record at the southern tip of Africa underpins the concept of global climate instability during the earlier part of the Miocene recorded in the marine archive.

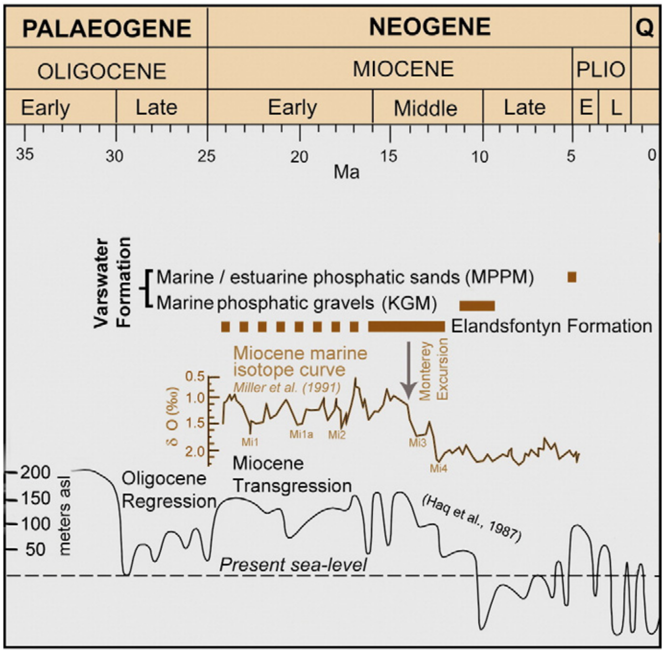

Fig. 11. Miocene marine isotope curve from ODP site 608 showing (glacial) Mi events and the sequence stratigraphic sea level curve of Haq et al. (1987). MPPM = Muishond Fontein Phosphatic Sand Member; KGM = Konings Vlei Gravel Member (Roberts et al., 2011).

We further suggest that the warmer/cooler climate fluctuations reflected in the pollen zones at the slightly older Noordhoek site were also driven by shorter term influences such as orbital forcing, rather than longer term major reorganisations of ocean and atmosphere throughout the Neogene (Fig. 11), as previously considered by Coetzee (1978, 1983a). Her interpretation, offered prior to publication of the detailed earlier Miocene marine record, is also incongruent with modern tropical wetland sedimentation rates (see Section 6.2.2) as well as established relative sea level histories. Our new interpretation points to a strong influence of short term climatic events (possibly originating at high latitudes) on the continental record in the temperate/subtropical zone at the southwestern tip of Africa.

The present steep north–south aridity gradient along the west coast (Fig. 12A) is considered to have originated in the later Miocene with indications of increased cold upwelling in marine core and the inception of the Namib Desert at ~14–13 Ma (Siesser, 1980; Senut and Pickford, 1995; Dupont et al., 2011; Rommerschieren et al., 2011). These events correspond with the global cooling marked by the Monterey Excursion (Fig. 11), correlated with expansion of the East Antarctic ice cap (Holbourn et al., 2007). The earliest indication from terrestrial deposits for the existence of the present Mediterranean climate pattern along the southern west coast was the documentation of the winter rainfall dune snail *Trigonephrus globulus* in early Late Miocene (~12–10 Ma) coastal aeolianites of the Prospect Hill Formation. These deposits were formed by southerly winds related to the South Atlantic Anticyclone, responsible for cold upwelling in the Benguela System (Roberts and Brink, 2002). However, the evidence of arid climate pedogenesis in the Early to Middle Miocene Orange River terrace gravels testifies to a significantly drier climate in the north extending notably further back in time. The present aridity gradient (Fig. 12A) is mainly a consequence of the northward attenuation of the (winter) polar frontal systems embedded in the westerly winds (Tyson, 1999). This suggests an Early to Middle Miocene inception of westerly polar airflows, which would have been enhanced since the inception of the circumpolar current, probably in the Oligocene (Lawver and Gahagan, 2003).

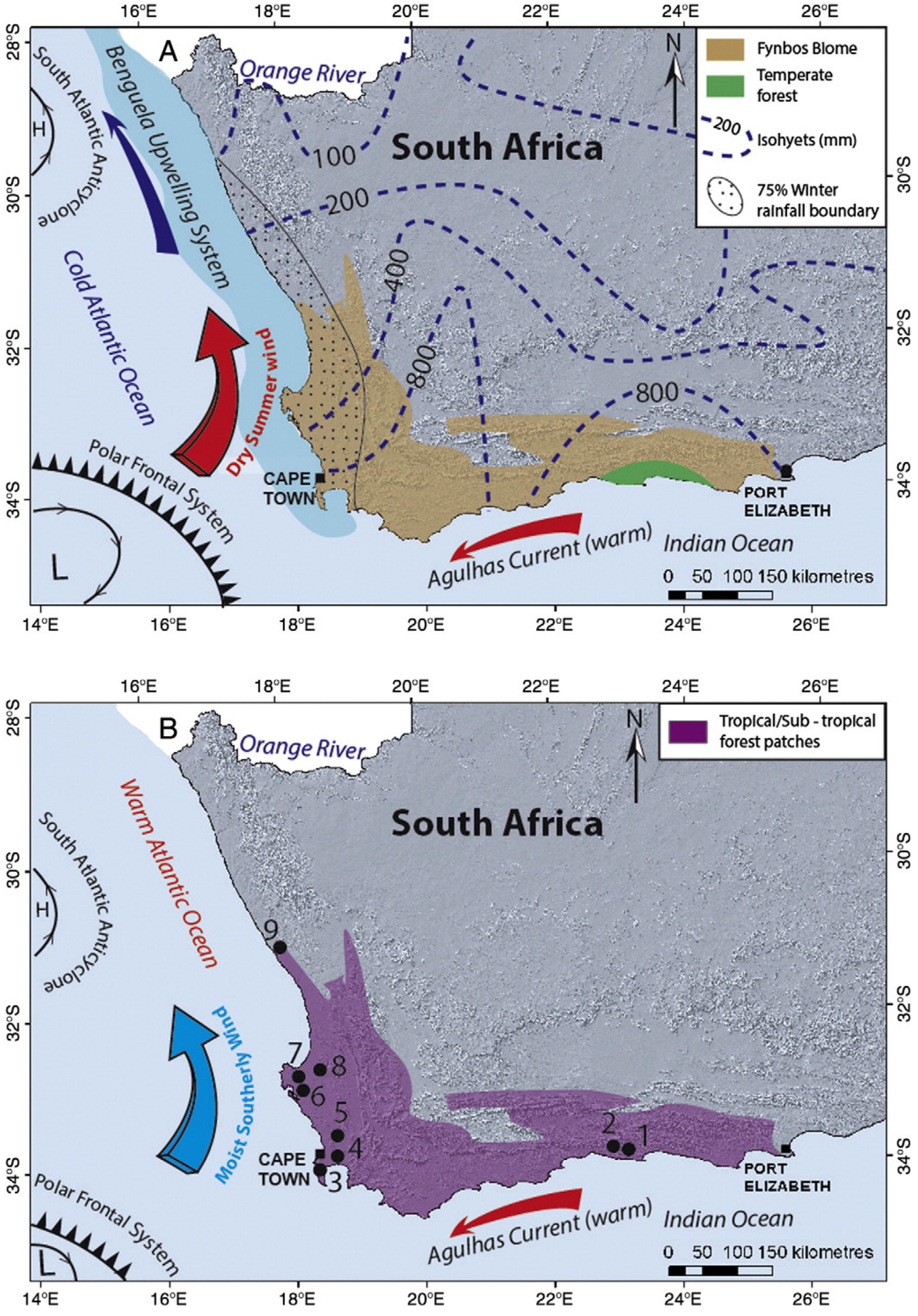

Fig. 12. A) Generalised present annual rainfall patterns in southwestern South Arica. The steep climate gradient from moist south affected by winter polar frontal systems, to hyper-arid north is clearly apparent; B) Schematic reconstruction of Miocene climate systems and vegetation patterns. Poleward migration of climate belts during the generally warmer Neogene and decreased southerly wind velocity weakened the Benguela System, with consequent increased monsoonal (summer) precipitation. The numbered dots indicate sites where Miocene tropical/ subtropical elements have been reported: ; 1 & 2= Knysna; 3= Noordhoek; 4=Cape Flats;5=Rondeberg);5; 6=Elandsfontyn (Rogers, 1980); 7 = Langebaanweg area; 8=Berg River; 9=Olifants River area.

The later Miocene interval which followed the Monterey Excursion, correlated with expansion of the East Antarctic ice cap as noted above between 14 and 13 Ma, has apparently left little onshore imprint in terms of fluvial deposition along the west coast. The overall decline in glacio-eustatic sea levels of this period (Fig. 11) was probably associated with fluvial incision rather than deposition as was the case in the Oligocene (Roberts et al., 2011). At the Langebaanweg site situated ~130 km north of Cape Town (Fig. 1), later Miocene phosphatic marine deposits of the Koningsvlei Gravel Member, (KGM, Fig. 11) rise to ~18 m asl and contain evidence of repeated sea level fluctuations (Tankard, 1976a,b; Hendey, 1981; Roberts et al., 2011). Phosphate authigenesis has been linked to a strengthening Benguela System (Tankard, 1976a, b; Hendey, 1981) and accords with the fall in west coast SST and diversification of arid adapted taxa such as the Aizoaceae at the expense of humid climate taxa, as seen in offshore cores (Dupont et al., 2011; Rommerschieren et al., 2011). Thus the global marine isotope record which points to high frequency growth and decay of polar ice throughout the Miocene Epoch, finds expression along the west coast of South Africa. The same can be said for the Pliocene succession at Langebaanweg, including the Muishond Fontein Member (MPPM) of the Varswater Formation (Fig. 11), where ephemeral streams repeatedly incised phosphatic marine/estuarine sediments as a consequence of base level changes related to sea level fluctuations. Orbital forcing as a possible cause for these shorter term events was cited by Roberts et al. (2011).

8. Miocene neotectonics

Disparate viewpoints have been expressed concerning Miocene neotectonics along the South African west coast, mostly involving interpretations of the relative contributions of eustacy and tectonism to the currently observed elevations of Late Tertiary marine deposits. Most authors have gravitated to either one of these mechanisms, but a few have invoked both (Roberts et al., 2011). A Neogene marginal downwarp along the southern west coast has been inferred (Krige, 1927; Tankard, 1976a,b; Dingle et al., 1983) based on perceived variations in elevation of marine deposits along the coast. Partridge and Maud (1987, 2000) followed suite, citing the Miocene terrestrial deposits at Noordhoek at ~50 m below present sea level (Coetzee, 1978; Rogers, 1982; Coetzee and Rogers, 1982) as evidence of Miocene coastal marginal subsidence. In contrast, Compton et al. (2006) invoked marginal Miocene uplift, based on offshore studies of marine sediments. 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 Miocene raised estuarine terraces along the Orange River (~45 m above msl) dating from the Early Miocene (Pickford, 1998).

Hendey (1981), Pether (1994, and Pether et al., 2000) cited the equivalence in ages and elevation of the Late Tertiary 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 in determination of terrace elevations. Pickford (1998) was in agreement with 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. Roberts and Brink (2002) further confirmed this view, noting that all west coast Miocene marine deposits occurred below 50 m and providing new evidence for Pliocene sea levels along the southern and northern at the widely accepted elevations around the globe (Roberts et al., 2011).

The extensive development of Oligo–Miocene fluvial deposits (Elandsfontyn Formation) extending well below present sea level (Fig. 2) at several localities along the 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 deposition of the Elandsfontyn Formation, culminating in marine transgression over the fluvial deposits (Fig. 9) — consistent with the Oligocene–Miocene transition. According to this scenario, which is congruent with the global eustatic record, it is unnecessary to invoke either major uplift or downwarping of the southwestern tip of Africa as previously mooted. Moreover, if the correlation of the Rondeberg fluvio-lacustrine deposits with the palaeo-Diep River (Fig. 1) is correct (Section 4), only minor incision (few tens of metres) has occurred since the Miocene, most of which may be accounted for by the lowered eustatic sea levels of the Piocene and Pleistocene. This further supports the concept of tectonic stability in the region.

9. Conclusion

Three categories of Miocene fluvial systems are developed along the South African west coast: the first comprises meandering, suspension load/lacustrine systems dominated by fines, situated on a low relief, stable coastal plane at higher elevations of 80–130 m asl; the second consists of mixed bedload and suspension-load rivers whose deposits extended below present sea level in coastal embayments; and the third is represented by the Orange River terraces in the north, reaching ~80 m asl and comprising a gravel dominated braided river system.

The Rondeberg clay pit 60 km northeast of Cape Town exemplifies the first type, comprising a succession of clays, silts and very fine sands deposited on a low relief coastal plane. The presence of meso-megathermic palynoforms suggests a humid subtropical/tropical climate in the earlier Miocene, contrasting with the summer-dry adapted *fynbos* of today. However, abundant charcoal, charred *in situ* tree stumps, overall poor preservation of organics and evidence for pedogenesis in the lacustrine deposits, point to cyclical periods of drought. Palaeomagnetic data suggests that the deposits accumulated over a period of <1 Ma. We suggest that these climate fluctuations may be related to orbital forcing identified in the marine record.

The Noordhoek succession exemplifies the second type of fluvial system. Short-headed rivers with greater stream power deposited coarse channel fill sands, interfingering with organic backswamp facies. Earlier palynological work indicated climate fluctuations between tropical and (moist) cooler conditions and were previously correlated with major global events embracing the entire Neogene. This inferred climate variability has recently been underpinned by biogeochemical studies, but we invoke shorter term, possibly orbital cyclicity as the driving force. This conclusion is in keeping with (rapid) modern sedimentation rates observed in tropical wetlands, excellent preservation of organics at Noordhoek and regional sea level histories.

The gravel dominated Miocene Orange River deposits testify to greater stream power relative to Rondeberg and Noordhoek, but this was linked to the vast palaeo-Orange River drainage basin and steeper gradients associated with tectonic events. Pedogenesis in the gravels testifies to periodic aridity of an intensity not seen in the Miocene fluvial systems in the south. The present steep, south to north climate gradient along the west coast is rooted in the cold Benguela Upwelling System, mitigated in the south by the (winter) polar frontal systems (Fig. 12A). We suggest on the basis of evidence from west coast Miocene fluvial systems that this climate system had its inception in the more distant past than previously considered. During orbitally driven cooler periods, both the Benguela and polar frontal systems may have strengthened, leading periodically to conditions similar to today (but overall still more moist).

Both the Noordhoek-type and palaeo-Orange River deposits exhibit transition to marine/estuarine conditions and are strongly aggradational, indicative of rising sea level. We suggest that in both instances this may have related to the major Oligo–Miocene glacio-eustatic event (Fig. 11). During the earlier Miocene, the marine and onshore records indicate warmer SST and climate and probably for most of this period climatic belts had shifted southwards. This resulted in a dominant monsoonal rainfall pattern in contrast to the polar frontal systems of the present time. Consequently, during the Miocene much of the present *fynbos* region comprised tropical forest – or as suggested by Du Pont et al. (2001) – a mosaic of these vegetation types (Fig. 12B). Overall, the Miocene fluvial systems at the southern tip of Africa bear testimony to the influence of major global events as well as shorter term cyclical forcing originating at high latitudes (East Antarctica).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.earscirev.2013.05.001.

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