Quaternary Science Reviews xxx (xxxx) xxx

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Geological and soil maps of the Palaeo-Agulhas Plain for the Last Glacial Maximum

Hayley C. Cawthra [a, b, *], Richard M. Cowling [b], Sergio Andò [c], Curtis W. Marean [b, d]

[a] Geophysics and Remote Sensing Unit, Council for Geoscience Western Cape Office, PO Box 572, Bellville, 7535, South Africa
[b] African Centre for Coastal Palaeoscience, Nelson Mandela University, PO Box 77000, Port Elizabeth, Eastern Cape 6031, South Africa
[c] Department of Earth and Environmental Sciences, University of Milano Bicocca, PO Box 20126, Piazza della Scienza 4, Milan, Italy
[d] Institute of Human Origins, School of Human Evolution and Social Change, PO Box 872402, Arizona State University, Tempe, AZ 85287-2402, USA

ARTICLE INFO

Article history:
Received 18 February 2019
Received in revised form
4 June 2019
Accepted 24 July 2019
Available online xxx

Keywords:
Cape south coast
South Africa
Pleistocene geological map
Pleistocene soil map
Submerged landscape
Palaeolandscape
Marine geology

ABSTRACT

The South African Cape South Coast is bordered by one of the broadest continental shelves in Africa. The Agulhas Bank, inshore shelf and presently exposed coastal plain make up the Palaeo-Agulhas Plain (PAP), though our area of study extends beyond this limit and as far inland as the first mountain belt. Quaternary sea levels have been significantly lower than at present for ~90% of the Pleistocene, exposing a terrestrial ecosystem on what is now the submerged shelf. The presently drowned component makes up 94% of the total area of the PAP. Past work has hypothesised a contrast in character of this submerged landscape when compared to the subaerial environment. Here, we assimilate newly-acquired geophysical and geological datasets to produce geological- and soil maps from the Last Glacial Maximum on a scale of 1:750,000, covering an area of ~55,000 km. Three broad geomorphic zones are defined, including the Western section from Cape Agulhas to Cape Infanta, the Central section from Cape Infanta to Knysna and the Eastern section extending eastward of Knysna. We demonstrate that Mesozoic sedimentary deposits crop out near the surface on this current-swept shelf and soils derived from siltstone and shale bedrock are prominent when the coast is up to 64 km distant from the modern shoreline at its maximum point. Beyond this, weathered limestone dominates the substrate sequences on the Agulhas Bank. We show that the submerged landscape was a unique terrestrial environment and that there is no exact modern-day analogue in the region other than a small (~70 km^2) area located at the edge of the Agulhas Plain near Cape Agulhas, and map major contrasts in the geological, topographic and edaphic nature of the landscape from the onshore to the offshore. The expansion of this plain is coupled with exaggerated floodplains, meandering shallowly incised rivers and wetlands. The submerged shelf is dominated by fertile soils compared to the dissected onshore belt, and extensive calcareous dunefields extending up to 10 km inland from their associated palaeoshorelines covered much of the emergent shelf. Sedimentary bedforms may have obstructed or slowed drainage as suggested by leached palaeosols and carbonate mixing observed in petrographic thin sections and grain mounts. The data show a low-relief "plains" landscape, which contrasts strongly to the topographically complex contemporary coastal foreland.

1. Introduction

Following the onset of the Quaternary glacial-interglacial climate cycles, sea level has shifted between a maximum lowstand depth of 130 m below and a maximum highstand elevation of 13 m above contemporary sea level approximately every 100 thousand years since 900 thousand years before the present (ka) (Bintanja et al., 2005; Lisiecki and Raymo, 2005). During most of this time (~90%) sea level has been significantly lower than present, exposing a now submerged terrestrial ecosystem of what is now the continental shelf. The ~800 km long Cape South Coast, extending from Cape Hangklip in the west to Port Elizabeth in the east, represents a tract of relatively dissected coastal foreland bordered at its landward geographic limit by the Cape Fold Belt and at the seaward margin by the Indian Ocean (Fig. 1). This region has

* Corresponding author. Geophysics and Remote Sensing Unit, Council for Geoscience Western Cape office, PO Box 572, Bellville, 7535, South Africa.
E-mail address: hcawthra@geoscience.org.za (H.C. Cawthra).

https://doi.org/10.1016/j.quascirev.2019.07.040
0277-3791/

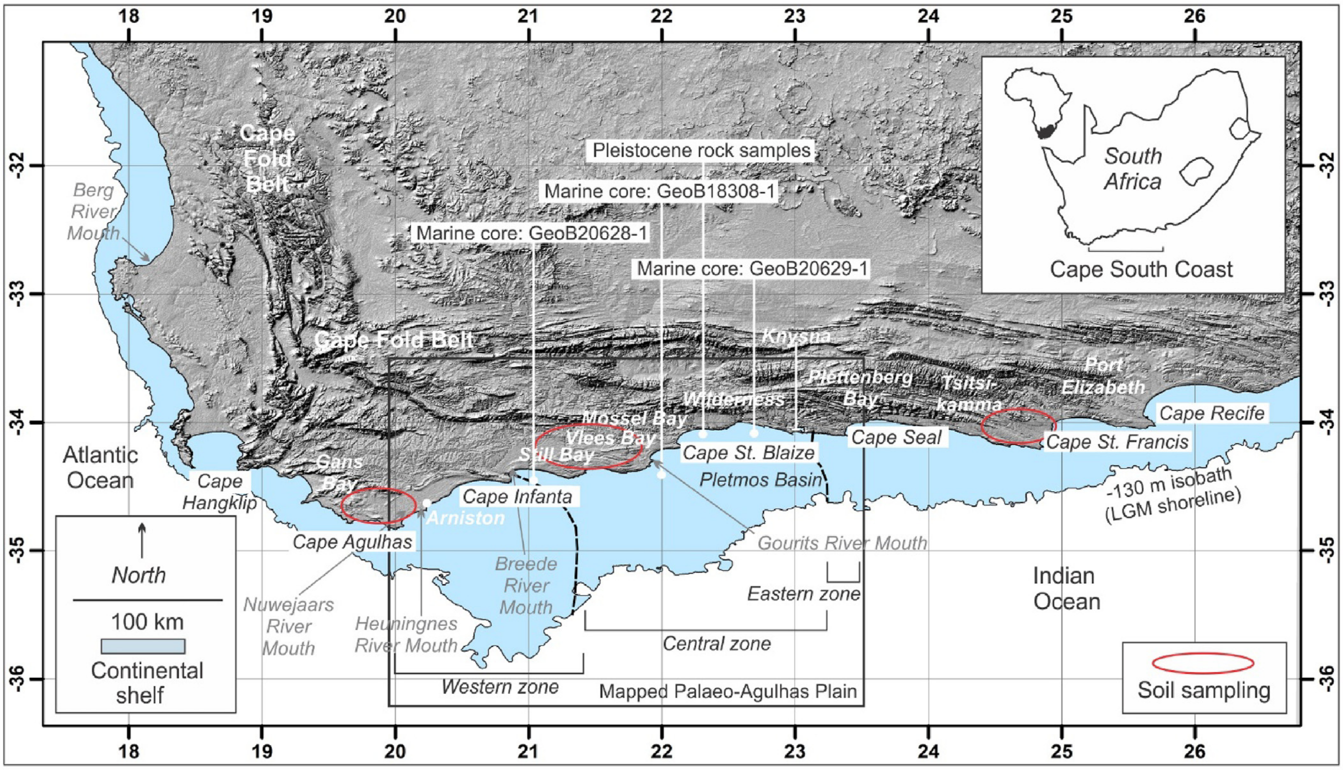

Fig. 1. Locality of the study area, with background data the SRTM 90 m grid (Jarvis et al., 2008). The Pletmos and Bredasdorp basins are sub-basins of the Outeniqua Basin. Onshore soil sampling and verification was undertaken within the zones illustrated as red ellipses. The mapped area of the PAP is shown, with its Western-, Central and Eastern zones. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

been divided into four broad-scale geological and geomorphic provinces (Birch, 1978). These distinct coastal regimes, which are separated by sediment-free areas of exposed bedrock near headlands and promontories, are Cape Town to Cape Agulhas; Cape Agulhas to Cape Seal; Cape Seal to Cape St. Francis and Cape St. Francis to Cape Recife. We focus on Cape Agulhas to Cape Seal in this study and refer to this submerged palaeoscape as the Palaeo-Agulhas Plain (PAP) (after Marean et al., 2014).

The unique PAP likely played a key role in Middle- and Late Pleistocene hominin development (Marean, 2010; Marean et al., 2014). The Cape South Coast holds a diverse array of endemic plants (Cowling and Holmes, 1992; Goldblatt and Manning, 2002; Cowling et al., this volume; Grobler et al., this volume) and shows evidence of systematic shellfish exploitation and reliance on the coastal area by prehistoric people (Marean et al., 2007; Jerardino, 2010; Jerardino and Marean, 2010; Langejans et al., 2012; De Vynck et al., this volume). Faunal records suggest that a range of ungulates occupied the landscape during glacial periods (Klein, 1983; Faith, 2011) and likely grazed on the now-submerged landscape (Copeland et al., 2016; Hodgkins et al., this volume). Specifically, sea-level fluctuations during the Pleistocene had a profound effect on the entire Cape South Coast environment (Dingle and Rogers, 1972; Van Andel, 1989; Fisher et al., 2010; Cawthra et al., this volume '*a*'). During full glacials when the continental shelf was completely exposed, the PAP was likely a refuge for hominin and ungulate populations (Roberts et al., 2008; Marean et al., 2014; Cawthra et al., 2015; Helm et al., 2018a; b; this volume; Compton, 2011; Oestmo et al., this volume). Perhaps as a result of that, many important African Middle Stone Age (MSA) sites occur in the area (Deacon, 1995; Marean et al., 2000; Henshilwood et al., 2002; Marean, 2010).

Previous workers have hypothesised that the PAP lacks an exact modern analogue (Van Andel, 1989; Compton, 2011; Cawthra, 2014; Copeland et al., 2016) except for aspects of the subaerially exposed Agulhas Plain near Bredasdorp (Marean et al., 2014) on the Agulhas Plain (Thwaites and Cowling, 1988). Along the Cape South Coast, rocks of the Cape Fold Belt that dominate the modern coastal plain generally do not extend more than ~3 km offshore, and as a result the shelf gradient and morphology has been shown to significantly differ to the present coastal plain (Cawthra et al., 2015).

On the Cape South Coast, there is a geological preservation bias towards the Pleistocene rather the Holocene (e.g., Roberts et al., 2012) and this has allowed a unique view into the Pleistocene. To this end, we have invested in describing in detail the submerged shelf for the last eight years, in the attempt to capture the character of this submerged environment. Through marine geoscience surveys, we have pieced together fragments of information remnant of three glacial periods (MIS 6, 4, 2). Using modern marine geophysical mapping techniques the offshore submerged landscape and its deposits can now be mapped in ultrahigh-resolution [with multibeam echosounder data from a continental shelf, within a decimetre] (e.g., Cawthra et al., 2015) and sampled (e.g., Hahn et al., 2017; Cawthra et al., 2018) and inform us of how the margin has evolved over glacial to interglacial cycles of the Quaternary Period.

The primary objective of this work was to use recent work undertaken in data integration (de Wet, 2013), and seafloor mapping with modern techniques in marine geophysics (Cawthra et al., 2014, 2015; 2019/this volume '*b*') and integrate these results with archival data (Dingle and Rogers, 1972; Dingle and Siesser, 1975; Birch, 1980; Dingle et al., 1983; Martin and Flemming, 1986; Gentle, 1987) to create a base from which to derive a geological map. The hypothesis that we test is that the adjacent continental shelf on the PAP contains a richer-than-onshore ecosystem and fertile plains. Using the geological substrate as a base, we interpret soil distribution on the submerged landscape. We anticipate that this basis can be applied in the study of past vegetation, climate and palaeoenvironmental considerations.

This paper presents geological and soil maps for the LGM and although numerous palaeo-topographic maps exist of the LGM globally, to the best of our knowledge, this is a first published attempt of its kind. The geographic area under consideration extends from Cape Agulhas to Plettenberg Bay, and as far north as the first mountain belt bordering the coastal plain (Langeberg/Outeniqua ranges). The southernmost edge of the map extent is the −130 m global LGM shoreline (after Waelbroeck et al., 2002; Clark et al., 2009). Regional seafloor maps of the Cape South Coast are not unknown (e.g. Dingle and Siesser, 1975; Gentle, 1987) but with modern mapping methods, we have improved technologies and techniques to study the seafloor and tightened the scale from 1:5,000,000 to 1:750,000. With the recent advancement in methods for seafloor mapping and sampling, as well as in geochronology, we are now able to project back to the LGM.

2. Regional setting

The ~800 km long South Coast of the Cape Floristic Region, the Cape South Coast, represents a tract of relatively low-relief but nonetheless dissected coastal plain bordered at its landward geographic limit by the Cape Fold Belt that rises up to 3000 m and at the seaward margin by the Indian Ocean (Fig. 1). The fragmentation of Gondwana in the South Coast region and the opening of the South Atlantic commenced in the Early Cretaceous (~136 Ma) as South America was sheared westward along the Agulhas-Falkland Fracture Zone (Martin and Hartnady, 1986; Eagles, 2007). This rifting was accompanied by extensive mafic igneous activity along the entire west coast of Southern Africa, from the Walvis Ridge in the north, to the Cape Peninsula in the south (Day, 1986; Trumbull et al., 2007). Compressional Cape Fold Belt faults were subsequently reactivated as listric extensional faults (Paton et al., 2006; Stankiewicz et al., 2007), and the newly created accommodation space in basins (e.g. the Outeniqua Basin) was filled with clastic sediments of the Uitenhage Group (~145–130 Ma). Offshore, arcuate normal faults bounded several graben and half graben structures that became the depocentres for terrigenous sediment sourced from the onshore areas (Brown et al., 1995; Broad et al., 2006; Tinker et al., 2008a, b). Of relevance to this work, are deposits belonging to the Bredasdorp and Pletmos sub-basins of the Outeniqua Basin.

The basement geology in the area investigated consists of Ordovician to Silurian quartz arenites of the Table Mountain Group (TMG) sandstone units and Devonian age Bokkeveld Group shales. Anticlines in the arenaceous deposits of the TMG sandstones form a series of west-east trending headlands (Martin, 1985; Rogers, 1971) and near the modern coast, erosion of the Bokkeveld shales in the synclines has led to formation of the coastline characterised by a series of eastward-opening log-spiral bays that extend for approximately 20–40 km between adjacent west-east trending rocky headlands.

Offshore, the bulk of the Neogene sediments exposed on the outer Agulhas Bank are loosely consolidated Mio-Pliocene limestones, cemented phosphatic rocks and ferricretes (Dingle et al., 1983; Parker and Siesser, 1972; Rogers, 1971) (Fig. 2). Underlying the Neogene sediments are deposits of Mesozoic sediments (Dingle et al., 1983), laid down during the fragmentation of Gondwana. A shallow seaward dip of Mesozoic and early Cenozoic deposits has resulted in the distribution of inner shelf Cretaceous units and outer shelf Neogene outcrops.

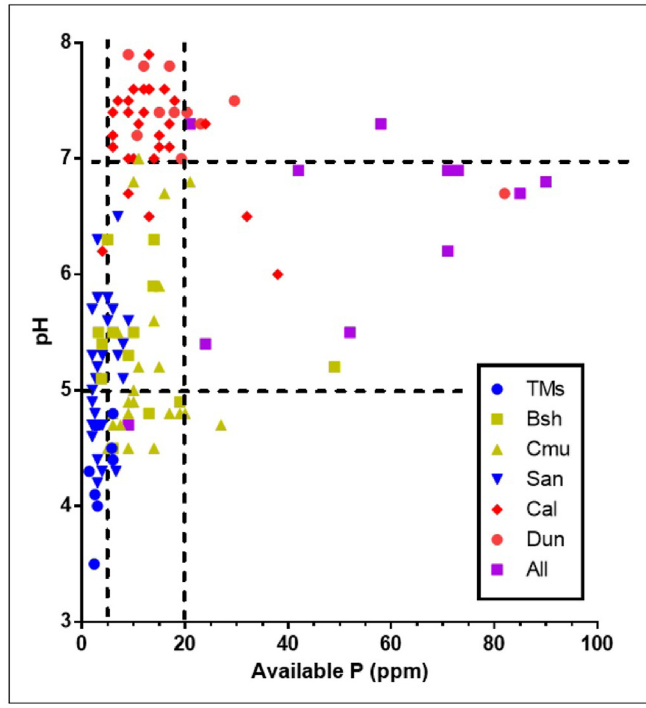

Fig. 2. Scattergram of soil pH (KCl) and available P (Bray No. 1) from 123 sites on the predominant geologies of the coastal plain of the Cape south coast (Fig. 1). Vertical dotted lines separate soils of low (0–5 ppm), moderate (5–20 ppm) and high (>20 ppm) fertility status while the horizontal line separates alkaline from neutral and acid soils. The geology abbreviations are as follows: TMs = Table Mountain Group quartzitic sandstone, Bs = Bokkeveld shale, Cmu = Cretaceous mudstone, San = Neogene aeolianite (acid to neutral and supporting fynbos), Cal = Neogene calcarenite and calcrete, Dun = Holocene dunes, All = alluvium. Bray No. 1 is a standard technique to measure the amount of plant available phosphorus in the soil. Phosphorus is extracted from the soil using Bray No 1 solution as extractant. The extracted phosphorus is measured colourimetrically based on the reaction with ammonium molybdate and development of the 'Molybdenum Blue' colour. The absorbance of the compound is measured at 882 nm in a spectrophotometer and is directly proportional to the amount of phosphorus extracted from the soil. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Along the coastal plain, Cenozoic deposits of the Bredasdorp Group are composed of early Pliocene marine calcarenites of the De Hoopvlei Formation, calcified aeolianites of the late Pliocene Wankoe Formation and aeolianites of the Upper Pleistocene Waenhuiskrans Formation (Malan, 1990). In contrast with the West Coast, shore parallel dune cordons ('barrier dunes') constitute the dominant southern coast dunefield morphology, especially in the central area of the PAP (Tinley, 1985; Illenberger, 1996; Roberts and Brink, 2002; Bateman et al., 2004, 2011; Roberts et al., 2008, 2009). The predominantly westerly dune building winds are generally weaker than the southerlies along the West Coast. Critically, significant rainfall frequently accompanies the (winter) westerly dune building winds of the South Coast. The resulting propensity for vegetation colonisation inhibits onshore dune migration and promotes vertical dune aggradation (e.g., Tinley, 1985). Holocene coastal dunes on the Cape South Coast vary in form. In the Wilderness region are the compound mega-parabolic dunes that reach 94 m in height, with superposed smaller parabolic and transverse dunes (Martin, 1962; Tinley, 1985; Illenberger, 1996; Bateman et al., 2004). Similar to the Still Bay dunefields about 140 km to the west, the main regional dune building wind regime was westerly, associated with cyclonic polar frontal systems (as at the present time)

(Roberts et al., 2013).

The Holocene sediment wedge is a quasi-continuous unconsolidated sediment feature stretching approximately 1500 km from the east to the south coast along the inner to mid shelf (Martin and Flemming, 1986). The major source of terrigenous sediment supply is by fluvial discharge from major rivers, which would have been substantial contributors to the sediments blanketing this ancient plain when exposed (Hahn et al., 2017, 2018). Physiography and ocean currents are described in Cawthra et al. (this volume b).

3. Methods

3.1. Mapping and sampling strategy

We draw upon data from marine geophysical surveys and sampling campaigns, as well as archival data. Recently acquired bathymetric, seismic and geological data are described below, and historical archived data were made digital and georeferenced (from Dingle and Siesser, 1975; Gentle, 1987; Birch, 1980) to compile a seamless dataset as a basis for interpretation.

The **archival data** is derived from the products of the first South African offshore mapping programme, which ran from 1967 to 1975 under the auspices of the South African Committee for Oceanographic Research (SANCOR), which was a marine geological research group made up of the Geological Survey, Council for Scientific and Industrial Research and the University of Cape Town. During this time, the entire South African continental shelf was covered as a reconnaissance survey that produced a grid of single-beam bathymetric lines and sediment samples, as well as shallow sub-bottom profiles and geological sampling in selected areas. By 1973, bathymetric maps on a scale of 1: 5,000,000 covering the shelf and upper slope between Port Elizabeth and the Kunene River had been created (Dingle, 1973) and in 1975 the regional survey of the Southern African continental shelf was completed (Dingle and Siesser, 1975). A total of 1744 archived surficial samples were obtained in this endeavor and many originated from the Agulhas Bank. The next gridding exercise undertaken that brought together all known and available bathymetric data for the South African continental shelf was carried out by de Wet (2013).

The **recent data** for this project were acquired from 2011 to 2016. A map showing all geophysical surveys, sampling and coring locations for our work which has been conducted since 2011 is presented in Cawthra et al. (this volume '*b*'). One full-coverage geophysical survey of Mossel Bay and Vlees Bay was carried out by our team which included multibeam echosounder, side-scan sonar boomer and pinger sub-bottom profiling, to a depth of 60 m below Mean Sea Level (bMSL) (details in Cawthra et al., 2015). Following this, four regional sub-bottom profiling investigations were carried out. A total of 245 sub-bottom profiles (~1500 line km of data) have been collected in this area (details in Cawthra et al., 2019/this volume '*b*'). On each of these profiles, positions of aeolianites, river channels, floodplain deposits and lagoons were digitized. In order to produce a map of the LGM, the modern marine sediments were removed and the Pleistocene units considered to project from a 3D linear representation, to a 2D gridded surface (geological map). Sediment grab sampling and scuba diving surveys allowed seafloor surface outcrops to be sampled (details in Cawthra et al., 2018) and a total of six marine vibrocores were taken over two marine expeditions for the RAiN project (Regional Archives for Integrated iNvestigations) in ancient river valleys and lagoons from the R/V Meteor (Ekau and participants, 2014; Zabel and participants, 2017; Hahn et al., 2017 and Cawthra et al., this volume 'b').

3.2. Geological map compilation

All datasets described above were integrated in GIS. Where geological structures and features were identified, they were digitized in AutoCAD Map3D. Because these index points were scattered across the study area and often only along mapped lines, in order to create a seamless map, we extrapolated along strike to generate geological units. Once we derived a map extending across the area of study, topologies were built in AutoCAD and exported as a single-layer shapefile. This shapefile was imported into ArcGIS where the maps were created, with lithostratigraphic definitions representing unique geological and sedimentological units. The onshore geological data which was merged with the offshore data is from the Council for Geoscience 1:250,000 database. We refined the descriptions and ages in this database after field surveys and an exercise in 'ground-truthing' the presently exposed portions of the PAP. The maps are displayed on a scale of 1:750,000 to accommodate for the relatively large geographic area.

3.3. Soil mapping and projection

To derive soil descriptors that can differentiate between major vegetation types, we compiled data from 129 sites on the texture, depth and nutrient status of soils derived from different geologies present on the contemporary coastal plain. Data were derived from Cowling (1983) and Singels (2013). Nutrient status was characterised using available phosphorous (P) (Bray No. 2) and pH (in KCl) since these measures effectively differentiate infertile (0–5 ppm P), moderately fertile (5–20 ppm) and fertile (>20 ppm) soils on the one hand (Schloms et al., 1983; Cramer et al., 2014), and pH identifies alkaline soils of marine (pH > 7) and terrestrial origin that are neutral (pH 5–7) or acid (pH < 5) (Fig. 2). Soils were also categorized as deep (>30 cm) and shallow (<30 cm). The clay content was used to differentiate soils into three categories, namely sands, loams and clays (Foth, 1990). Thus each geology was allocated a corresponding soil type based on depth, pH, fertility and texture (Supplementary Material, Table 1). This yielded 9 soil types ranging from deep, neutral, highly fertile clay to shallow, acid, highly infertile sand. There are no outcrops of Alphard Complex volcanics or appropriate terrigenous muds on the onshore coastal platform. We assumed that both of these substrata would yield deep, neutral, fertile clays (cf Brady, 1974). There is also no offshore equivalent of the Neogene terrace gravels mapped on the PAP. Given that these gravels overlie Cretaceous mudstone, we categorized their associated soils as shallow, neutral, moderately fertile loams. Map compilation was carried out as per the method for the geological map.

3.4. Petrographic and mineralogical data

Petrographic analysis of thin sections from Pleistocene rock samples (aeolianite and cemented beach deposits) from both the modern shoreline and continental shelf was undertaken using transmitted light microscopy, in particular to study matrix clay minerals (Fig. 1B). The thin sections were studied using a Nikon Petrographic microscope at magnifications of 5x, 10x and 20x to study the carbonate cements and diagenetic phases. Photographs presented are shown under plane polarised light, as well as under crossed polariers to enhance features within the carbonate cements. To determine composition of the matrix material, selected sub-samples of rocks were analysed by Scanning Electron Microscope (SEM) and Element Dispersive Spectrography (EDS) at the University of Cape Town.

Heavy minerals were analysed from marine cores, with specific focus on the identification of minerals derived from soils

Table 1
Descriptions of geological units and associated soil types mapped in the area.

Group	Lithostratigraphy	Geological description	Texture	Fertility	pH	Depth	Soil description
	Mud belt	Terrigenous muds derived from rivers	CLAY	HIGH	NEUTRAL	DEEP	Deep neutral highly fertile clay
	River channel/ floodplain/lagoon	Alluvium	LOAM	HIGH	NEUTRAL	DEEP	Deep neutral highly fertile loam
Bredasdorp	Strandveld	Unconsolidated dune sand	SAND	MODERATE	ALKALINE	DEEP	Deep alkaline moderately fertile sand
	Cobbles	Late Pleistocene palaeobeaches	SAND	MODERATE	ALKALINE	SHALLOW	Shallow alkaline moderately fertile sand
	Calcareous sands	Strandveld and Waenhuiskrans Formations	SAND	MODERATE	ALKALINE	DEEP	Deep alkaline moderately fertile sand
	Waenhuiskrans	Consolidated to semi-consolidated aeolianite (calcarenite) calcareous sand, calcrete lenses	SAND	MODERATE	ALKALINE	DEEP	Deep alkaline moderately fertile sand
	Klein Brak	Sand/sandstone, calcarenite, gravel/conglomerate	SAND	MODERATE	ALKALINE	DEEP	Deep alkaline moderately fertile sand
	Pleistocene cover sands	Light-grey to red sandy soil	SAND	LOW	ACIDIC	DEEP	Deep acidic low-fertility sand
	Wankoe	Grey-weathering, massive or large-scale cross-bedded calcarenite and calcareous sandstone	SAND	MODERATE	ALKALINE	SHALLOW	Shallow alkaline moderately fertile sand
	Neogene limestone	Marine limestone, occasional calcrete	SAND	MODERATE	ALKALINE	SHALLOW	Shallow alkaline moderately fertile sand
	De Hoopvlei	Calcarenite and calcareous sandstone with scattered pebble and coquinite layers	SAND	MODERATE	ALKALINE	SHALLOW	Shallow alkaline moderately fertile sand
	Calcrete	Calcrete and hardpans	SAND	MODERATE	ALKALINE	SHALLOW	Shallow alkaline moderately fertile sand
	Relict sand and gravel	Reworked gravel pavement remnant of palaeobeaches	LOAM	MODERATE	NEUTRAL	SHALLOW	Shallow neutral moderately fertile loam
	Terrace gravels	High-level terrace gravel	LOAM	MODERATE	NEUTRAL	SHALLOW	Shallow neutral moderately fertile loam
Alphard Complex	Alphard Complex soils	Volcanic soils	CLAY	HIGH	NEUTRAL	DEEP	Deep neutral highly fertile clay
	Alphard Complex	Tuff, trachyte, basalt	CLAY	HIGH	NEUTRAL	DEEP	Deep neutral highly fertile clay
	Grahamstown	Silcrete	LOAM	MODERATE	NEUTRAL	SHALLOW	Shallow neutral moderately fertile loam
Uitenhage	Buffelskloof	Conglomerate, subordinate sandstone, siltstone and mudstone	LOAM	MODERATE	NEUTRAL	DEEP	Deep neutral moderately fertile loam
	Kirkwood	Variegated (reddish-brown and green) silty mudstone & sandstone, subordinate grey shale	LOAM	MODERATE	NEUTRAL	DEEP	Deep neutral moderately fertile loam
	Enon	Conglomerate, subordinate lenticular sandstones and claystones	LOAM	MODERATE	NEUTRAL	DEEP	Deep neutral moderately fertile loam
	Robberg	Sandstone, subordinate conglomerate, breccia and shale	LOAM	MODERATE	NEUTRAL	DEEP	Deep neutral moderately fertile loam
Witteberg	Weltevrede	Shale, siltstone, quartzitic sandstone, micaceous sandstone	LOAM	MODERATE	NEUTRAL	SHALLOW	Shallow neutral moderately fertile loam
Bokkeveld	Bidouw	Mudrock, siltstone, micaceous sandstone, occasional sandstone beds/dark grey mudrock, quartz wacke	LOAM	MODERATE	NEUTRAL	SHALLOW	Shallow neutral moderately fertile loam
	Ceres	Mudrock, siltstone, grey shale, fine-grained sandstone/ feldspathic arenite, wacke	LOAM	MODERATE	NEUTRAL	SHALLOW	Shallow neutral moderately fertile loam
Table Mountain	Baviaanskloof	Fine- to medium-grained, dark to light grey, feldspathic sandstone, shale	SAND	LOW	ACIDIC	SHALLOW	Shallow acidic low-fertility sand
	Rietvlei	White, siliceous, feldspathic sandstone, subordinate mudrock in places	SAND	LOW	ACIDIC	SHALLOW	Shallow acidic low-fertility sand
	Skurweberg	Thick-bedded, medium- to coarse-grained, cross-bedded, white-weathering, quartzitic sandstone	SAND	LOW	ACIDIC	SHALLOW	Shallow acidic low-fertility sand
	Goudini	Brownish-weathering, quartzitic sandstone, subordinate shale and siltstone	SAND	LOW	ACIDIC	SHALLOW	Shallow acidic low-fertility sand
	Cedarberg	Shale, siltstone, subordinate sandstone	LOAM	MODERATE	NEUTRAL	SHALLOW	Shallow neutral moderately fertile loam

(*continued on next page*)

Please cite this article as: Cawthra, H.C et al., Geological and soil maps of the Palaeo-Agulhas Plain for the Last Glacial Maximum, Quaternary Science Reviews, https://doi.org/10.1016/j.quascirev.2019.07.040

Table 1 (*continued*)

Group	Lithostratigraphy	Geological description	Texture	Fertility	pH	Depth	Soil description
	Pakhuis	Mudstone (diamictite) or sandstone containing scattered pebbles, cobbles and boulders	SAND	LOW	ACIDIC	SHALLOW	Shallow acidic low-fertility sand
	Peninsula	Quartzitic sandstone, minor conglomerate and shale	SAND	LOW	ACIDIC	SHALLOW	Shallow acidic low-fertility sand
	Cape Granite Suite	Granite/gneissic granite and granodiorite/coarse-grained, porphyritic, biotite-rich gneissic granite	LOAM	MODERATE	NEUTRAL	DEEP	Deep neutral moderately fertile loam
	Kaaimans/Malmesbury	Phyllite, shale, slate, schistose grits/quartzite/feldspathic quartzite with calc-silicates	LOAM	MODERATE	NEUTRAL	DEEP	Deep neutral moderately fertile loam

(hematite), present in the sedimentary record. Heavy minerals separated from a quartered aliquot of the bulk sample in the broad 15–500 μm grain size range. These samples were obtained through wet sieving by centrifuging in polytungstate (2.90 g/cm^3) and recovered by partial freezing with liquid nitrogen. Under a polarizing microscope, 200 to 250 transparent heavy minerals were point counted at a suitable regular spacing on grain mounts. Specific key minerals in trace portions (e.g. hematite) embedded in Canada Balsam, were also checked in the entire grain mount area to describe the surficial texture of Fe-oxides encountered in the studied sediments. An inVia Renishaw Raman spectrometer, equipped with a green laser 532 nm and a 50x LWD objective, was an additional tool utilised for a robust identification of single minerals and to identify the composition of light minerals where Fe-oxides were deposited and crystalized (Andò and Garzanti, 2013). The ZTR index, expressing the "chemical durability" of the suite (Garzanti et al., 2018), is the sum of zircon, tourmaline and rutile over total transparent heavy minerals and it can be useful to define recycling of sediments. Heavy-mineral concentration, calculated as the volume percentage of total (HMC) and transparent (tHMC) heavy minerals, ranges from extremely poor ($HMC \leq 0.1$), very poor ($0.1 \leq HMC \leq 0.5$) poor ($0.5 \leq HMC \leq 1$) and moderately poor ($1 \leq HMC \leq 2$), to rich ($5 \leq HMC \leq 10$), very rich ($10 \leq HMC \leq 20$) and extremely rich ($20 \leq HMC \leq 50$). In all analysed samples corrosion features were assessed systematically following the classification of surface textures in Andò et al. (2012). Heavy minerals are listed in order of abundance throughout the text.

4. Results

4.1. Geoscience

Our mapped area incorporates two distinct components: the extant coastal forelands and the submerged landscape of the PAP. We define three broad zones within the PAP based on the distribution of geological deposits: the western area that extends from Cape Agulhas to Cape Infanta/Breede River Mouth, the central PAP from Cape Infanta to Knysna and the eastern PAP from Knysna onwards; within the scope of this study only extending as far east as Plettenberg Bay. The mapped part of the submerged PAP presented in this work covers an area of 37,108 km^2 (Fig. 3) and makes up 66% of the total study region area and 94% of the PAP that includes the modern coastal plain. The total onshore mapped landmass from the coastline to the mountains and from Cape Agulhas to Plettenberg Bay amounts to 18,098 km^2 but there is only 70 km^2 of the true Agulhas Plain currently exposed above water, in the Cape Agulhas area. Seismic profiles and sampled geological units have been ground-truthed and described (Cawthra et al., this volume 'b').

From the mountains to the modern coast, basement architecture on the Cape South Coast is dominated by sequences of the Palaeozoic Cape Supergroup which consist of Kaaimans Group shale and phyllite, Cape Granite Suite plutons, the TMG sandstones, Bokkeveld Group shales, Witteberg sandstones and Uitenhage Group sandstones, claystones and conglomerates (Fig. 3). On the seafloor the substrate to Quaternary units is composed dominantly of claystones and siltstones of the Uitenhage Group, and on the outer shelf, Neogene limestones. Although pre-Mesozoic deposits are relatively underrepresented on the seafloor, Silurian Skurweberg Formation of the TMG constitutes the sea cliffs at prominent headlands mapped in this study. The Alphard Banks Complex is a unique outcrop on the seafloor. Cenozoic deposits on the seafloor are dominated by aeolianites and calcretes for older successions and muddy, sandy and calcareous sedimentary deposits laid down by recent marine processes.

Aeolianite and cemented beach material is preserved at depth bands of 120–130 m, 100–95 m, 80–75 m, 67–62 m, 45–38 m and 25 m (Cawthra et al., 2018, this volume '*b*'). Relict river channels and their floodplains are extremely broad and shallowly incised on the PAP (Cawthra et al., 2015, this volume '*b*') and the Gourits River splays into a delta near the LGM shoreline (Cawthra et al., this volume 'b'; Fig. 3). There is a clear topographic and lithological contrast between the onshore and offshore components of the PAP. On the submerged platform, extensive dunefields extend across the defined isobaths listed above. Sub-bottom profiling has shown that these dunes are laterally expansive and do not reach substantive heights (all less than 10 m). The central region is characterised by extensive submerged aeolianites as well as a thick accumulation of sediments and these deposits occupy ~40% of entire South Coast budget.

4.2. Distribution of soil types on the Palaeo-Agulhas Plain

We identified and mapped nine broad soil units in the study area (Fig. 4). Here we focus on the offshore soils; the subaerial soils (Fig. 1) are described by Schloms et al. (1983) and Thwaites and Cowling (1988). The bulk of the PAP soils are either fertile (26%) or moderately fertile (70%); infertile soils cover a small portion (4%), mainly in the southwest (Supplementary Material, Table 2) where they are associated with TMG quartzitic sandstone (Fig. 3). This contrasts with the contemporary coastal foreland where the corresponding proportions are 5% (fertile), 57% (moderately fertile) and 38% (infertile). The proximal half of the PAP includes large areas of relatively fertile clay and loam soils derived from Uitenhage sediments, gravels, terrigenous muds and, in the west, volcanic rocks and Bokkeveld shale. Covering about one third of this relatively clay-rich landscape are large blocks of coastal dunes, with deep, calcareous sands. Today this soil type is associated with Late Pleistocene and Holocene dunes which cover a relatively small area

Please cite this article as: Cawthra, H.C et al., Geological and soil maps of the Palaeo-Agulhas Plain for the Last Glacial Maximum, Quaternary Science Reviews, https://doi.org/10.1016/j.quascirev.2019.07.040

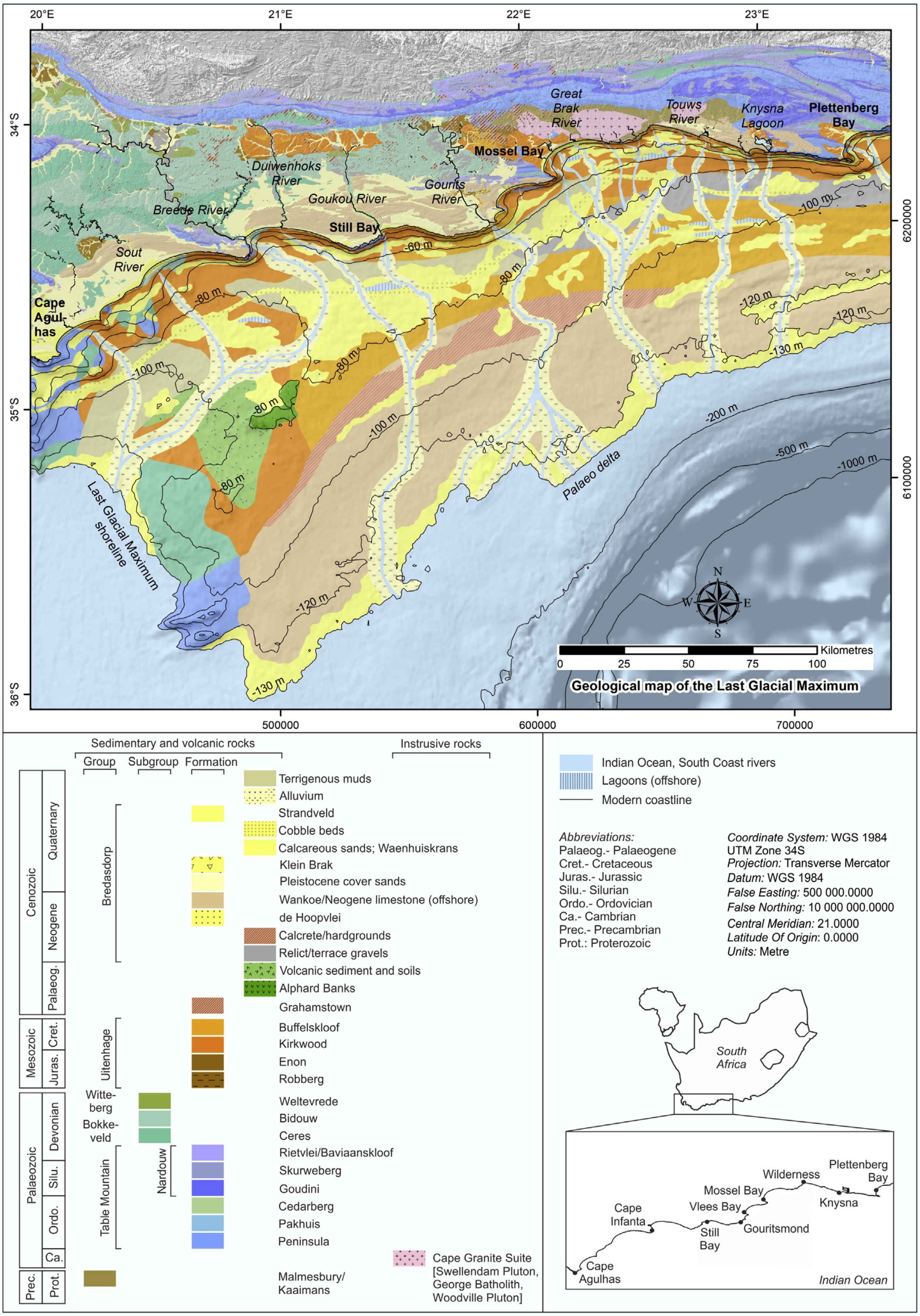

Fig. 3. Geological map for an average glacial period on the PAP, extending from Cape Agulhas to Plettenberg Bay and from the Cape Fold Belt mountains to 130 m BMSL.

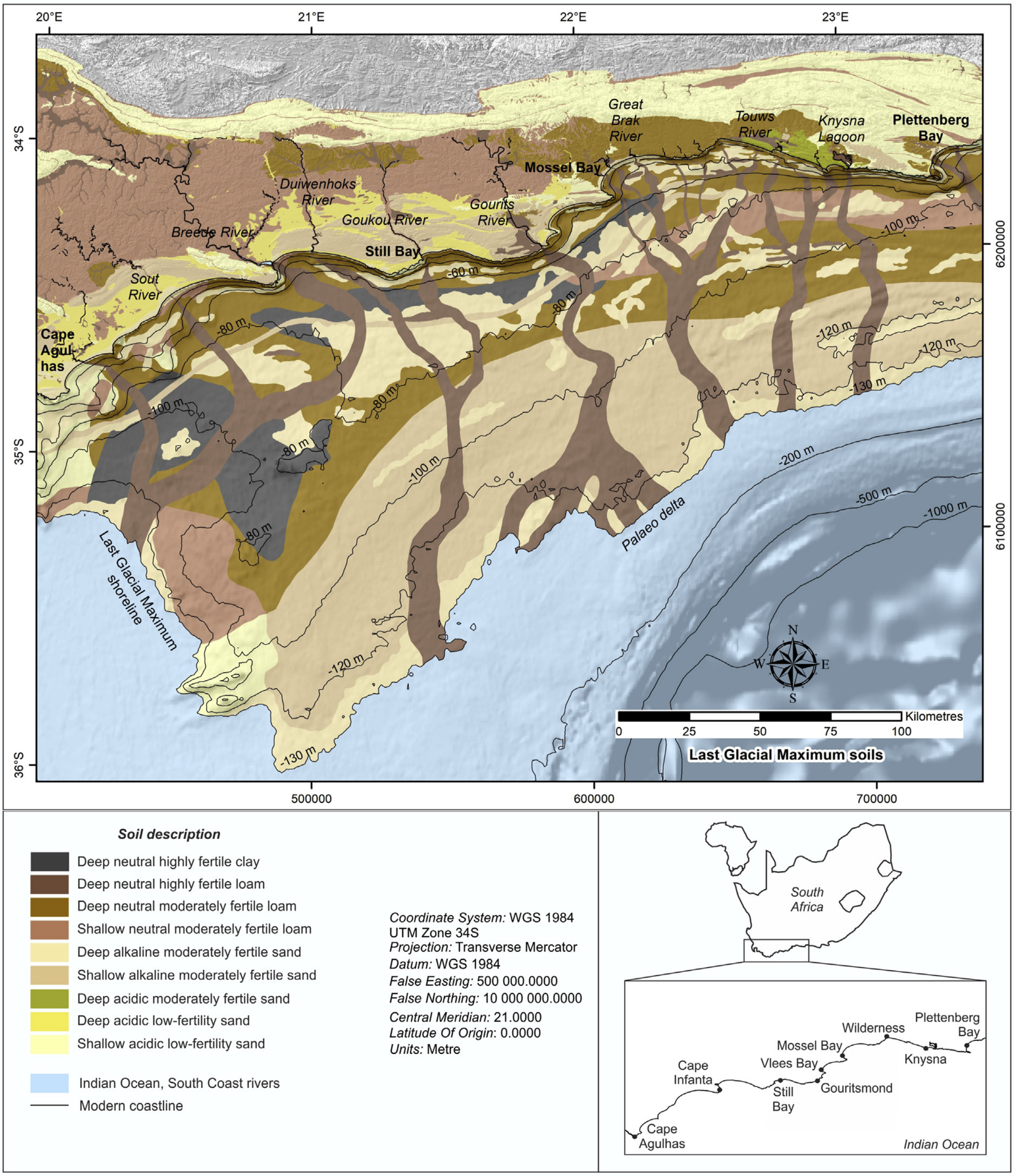

Fig. 4. Soil map for an average glacial. The geographic area follows that of the geological map and nine soil types and their spatial distribution are shown. These units' characteristics are detailed in Supplementary Data Table 2.

(2013 km^2). The distal portion of the PAP is dominated by shallow, alkaline sands associated with Neogene limestone and associated calcretes, covering 15,126 km^2, an area 7,5 times the area these soils occupy on the contemporary coastal plain. The LGM coastline on the PAP is mantled with a relatively large band of coastal dune sands. Alluvium-filled river valleys provide a large area of fertile loams, a soil type with a very restricted distribution on the dissected coastal plain where valleys tend to be steep and narrow. Overall, soils of the PAP are more fertile and deeper than those of the contemporary coastal plain. Additional maps of soil texture, fertility, pH and depth are presented in Supplementary Data Figs. 1–4.

4.2.1. Mineralogy of sampled soils on the shelf

We have sampled (i) elements of PAP soils in marine sediment cores (Fig. 5) and (ii) using matrix material from geological samples on the continental shelf (Fig. 6), investigated their influence on the coastal littoral environment through transmitted light petrography. The cored sediment samples (Fig. 5) show a presence of Hematite derived from soils on the submerged landscape.

Table 2
Percentage coverage of soil units on the Palaeo-Agulhas Plain.

ONSHORE		
Soil Description	Area (km^2)	Area (% of onshore)
Deep acidic low-fertility sand	1659	8,71506619
Deep acidic moderately fertile sand	181	0,950830006
Deep alkaline moderately fertile sand	280	1,470897247
Deep neutral highly fertile loam	938	4,927505779
Deep neutral moderately fertile loam	2847	14,95587308
Shallow acidic low-fertility sand	5588	29,35490649
Shallow alkaline moderately fertile sand	1552	8,152973314
Shallow neutral moderately fertile loam	5991	31,47194789
Total	**19036**	**100**
Not represented onshore: Deep neutral highly fertile clay		
OFFSHORE		
Soil Description	**Area (km^2)**	**Area (% of offshore)**
Deep alkaline moderately fertile sand	6485	17,47601595
Deep neutral highly fertile clay	2780	7,491646006
Deep neutral highly fertile loam	6919	18,64557508
Deep neutral moderately fertile loam	7350	19,80704969
Shallow acidic low-fertility sand	1396	3,761992023
Shallow alkaline moderately fertile sand	9864	26,58186914
Shallow neutral moderately fertile loam	2314	6,235852107
Total	**37108**	**100**
Not represented offshore: Deep acidic low-fertility sand and Deep acidic moderately fertile sand		
PALAEO-AGULHAS PLAIN		
Soil Description	**Area (km^2)**	**Area (%)**
Deep neutral highly fertile clay	2780	4,951553149
Deep neutral highly fertile loam	7857	13,99437162
Deep neutral moderately fertile loam	10197	18,16222571
Shallow neutral moderately fertile loam	8305	14,79231975
Deep alkaline moderately fertile sand	6765	12,04937304
Shallow alkaline moderately fertile sand	11416	20,33342833
Deep acidic moderately fertile sand	181	0,322385295
Deep acidic low-fertility sand	1659	2,954901681
Shallow acidic low-fertility sand	6984	12,43944144
Total	**56144**	**100**

Transmitted-light microscopy on thin sections from rocks of known ages sampled offshore of the Great Brak River (Cawthra et al., 2018) indicates two matrix phases and demonstrate evidence for soil material, which complements the presence of marine-core hematite (Fig. 6).

4.2.1.1. Authigenic smectite. Authigenic clays occur in two dominant diagenetic phases in the study area (Fig. 6A–C). Firstly, the alteration of rims at grain boundaries is generally associated with feldspar and lithic clasts. Secondly, authigenic smectite is associated with widespread pore-filling. SEM-EDS analysis indicated the composition of this material to likely be smectite, as peaks of Si, Al, Mg and Fe were noted with additional Ti in select samples (Fig. 6A).

4.2.1.2. Carbonate-organic mixed matrix. This cement type consists of carbonate, siliciclastic mud and organic material mixed in different proportions. In plane-polarised light, this material presents a brown colour, while under crossed polarisers, evenly dispersed points of high birefringence colours occur in an almost opaque mass (Fig. 6D and E).

5. Discussion

5.1. Geoscience

5.1.1. Interpretation of the Mesozoic bedrock sequences

Bedrock/basement sequences were known from literature (e.g., summarized in Dingle et al., 1983), but the Mesozoic units on the inner- and mid-shelf required correlation for our investigation. During the fragmentation of Gondwana, normal faults on the seafloor have down-faulted basement sequences and resulting grabens are filled with deposits of the Uitenhage Group. Sedimentation patterns that developed during the accumulation of the Cretaceous and younger drift succession were controlled by the availability of seafloor accommodation space generated by tectonic subsidence on the continental margin (McMillan, 2003). Lower Cretaceous Synrift units are represented onshore by the Robberg, Enon and Kirkwood Formations. Early graben fill of Synrift I sediments in the Pletmos Basin date to the Kimmeridgian and consist of thick aggradational fluvial sediments in the north and marginal marine sediments in the south (Broad et al., 2006) (Fig. 7). Our correlation of seismic units preserved on the upper continental shelf in this study with the Mesozoic Enon and Kirkwood Formations of the Uitenhage Group were based on retrograding reflector geometry identified on sub-bottom profiles collected between 2011 and 2016, and spatial correlation to the onshore and deep offshore regional stratigraphy. Upper Cretaceous deposits are linked to the offshore extent of the Buffelskloof and Hartenbos Formations of the Uitenhage Group (Viljoen and Malan, 1993; Muir et al., 2017a,b; Viljoen and Cawthra, 2019), or the marine distal Agulhas Formation (Dingle et al., 1983). These Upper Cretaceous units exposed on the shelf in this study area are most likely claystones and were sampled in part offshore of the Breede River (Cawthra et al., this volume 'b').

5.1.2. Soils on the Palaeo-Agulhas Plain

Our soil categorization assumes that there was sufficient time

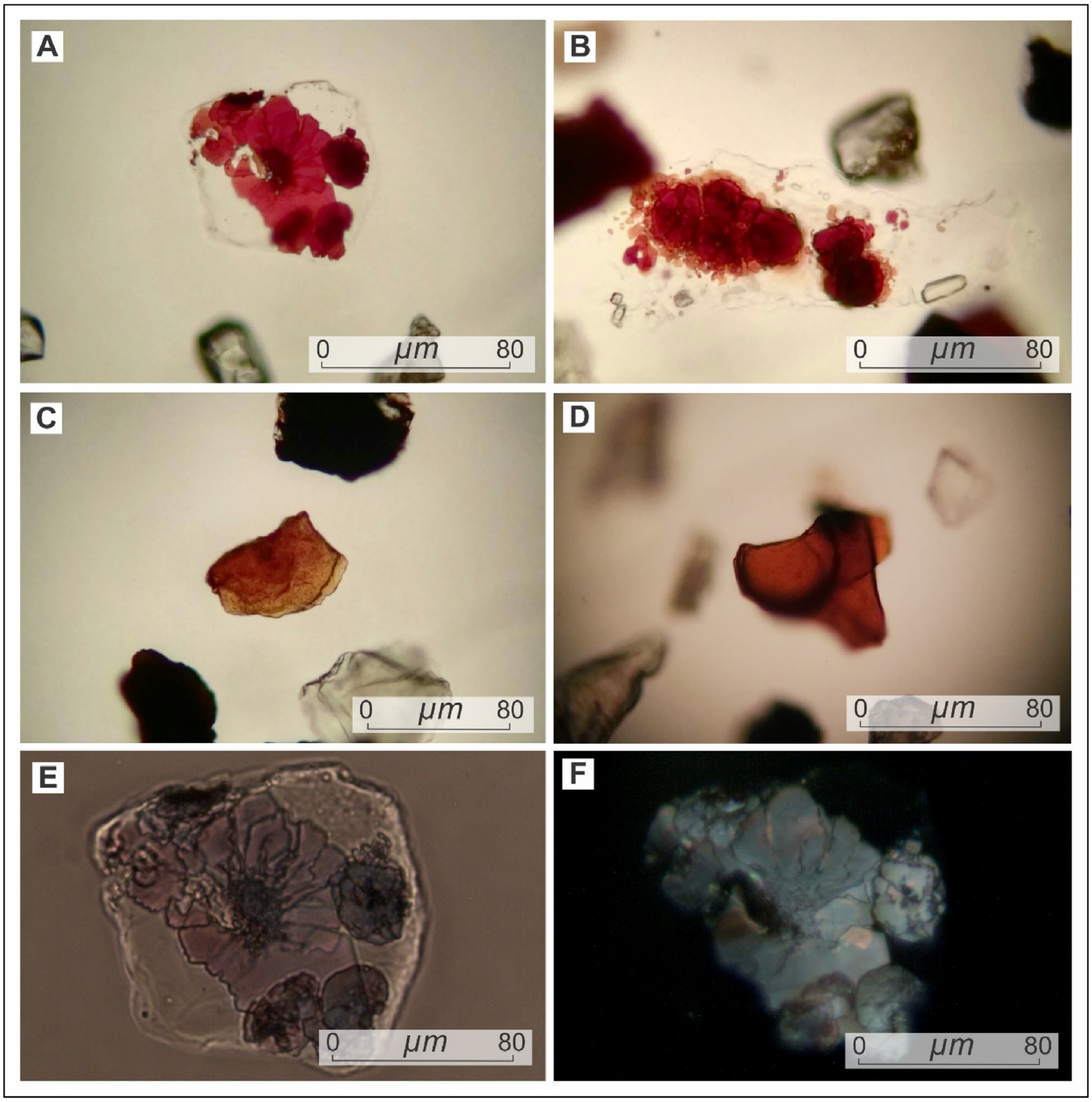

Fig. 5. A. Red flower of hematite on detrital muscovite from core GeoB18308-1. **B.** Spherules of hematite on phyllosilicates from core GeoB18308-1. **C.** ECT2-1 Gourits River below brown reddish aggregates of iron oxides. (All photos collected by a camera connected with a polarizing microscope, with a 20x objective, in grain mounts embedded in Canada Balsam). **D.** Angular hematite from core GeoB18308-1. **E.** Flower of hematite under transmitted light**. F.** Flower of hematite under reflected light. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

on the exposed PAP between major transgressions for residual (i.e. in situ) soils to develop. We interpret the soil material in cemented Pleistocene rocks to represent palaeosols on the landscape, as this association is clearly evident in this region (e.g., Roberts et al., 2008; Oestmo et al., 2014; Jacobs et al., this volume). During any given glacial-interglacial cycle, time for soil development would be greatest on the proximal parts of the PAP and least at its distal extent. Removal and re-deposition of terrestrial sediment by repeated sea-level fluctuations through the Quaternary has modified unconsolidated sediments on the shelf with each glacial-interglacial cycle. Therefore the Pleistocene cover sands that support Sand Fynbos (Cowling et al., this volume) and are dominant on the modern coastal plain, are poorly represented on the submerged shelf. Rather, calcareous sediments dominate the submerged portion of the PAP. The mild glacial temperatures compared to other parts of the world at the time of the LGM (e.g., Cowling et al., this volume), increased summer rainfall and flat terrain of the PAP would have been conducive to weathering and soil formation (Van Breemen and Buurman, 2002). Thus, we would expect the development of duplex soils in clay-rich landscapes, and podzols on the Table Mountain Group erosional surfaces of the southwest (Schloms et al., 1983). It is unlikely that there was sufficient time for the deeply weathered paleosols of the current coastal forelands to develop on the PAP; these palaeosols hark back to the warm, wet climates of the Mio-Pliocene (Hendey, 1983). It is also likely that there was insufficient time between major transgression for the weathering of calcareous sands - via the leaching of lime, releasing of iron and clay movement – to produce the apedal, red to yellow, acid and infertile sands of the contemporary coastal forelands (Schloms et al., 1983). The deep and fertile alluvial soils of the PAP's wide river valleys – a striking feature barely replicated on the contemporary coastal foreland – were likely deep, apedal loams. We posit that the fossil soils on the submerged portion of the PAP must be less than 100 ka in age on average, given the exposure between interglacial periods. Mature palaeosols have developed on coastal calcarenites over periods similar to the duration of shelf

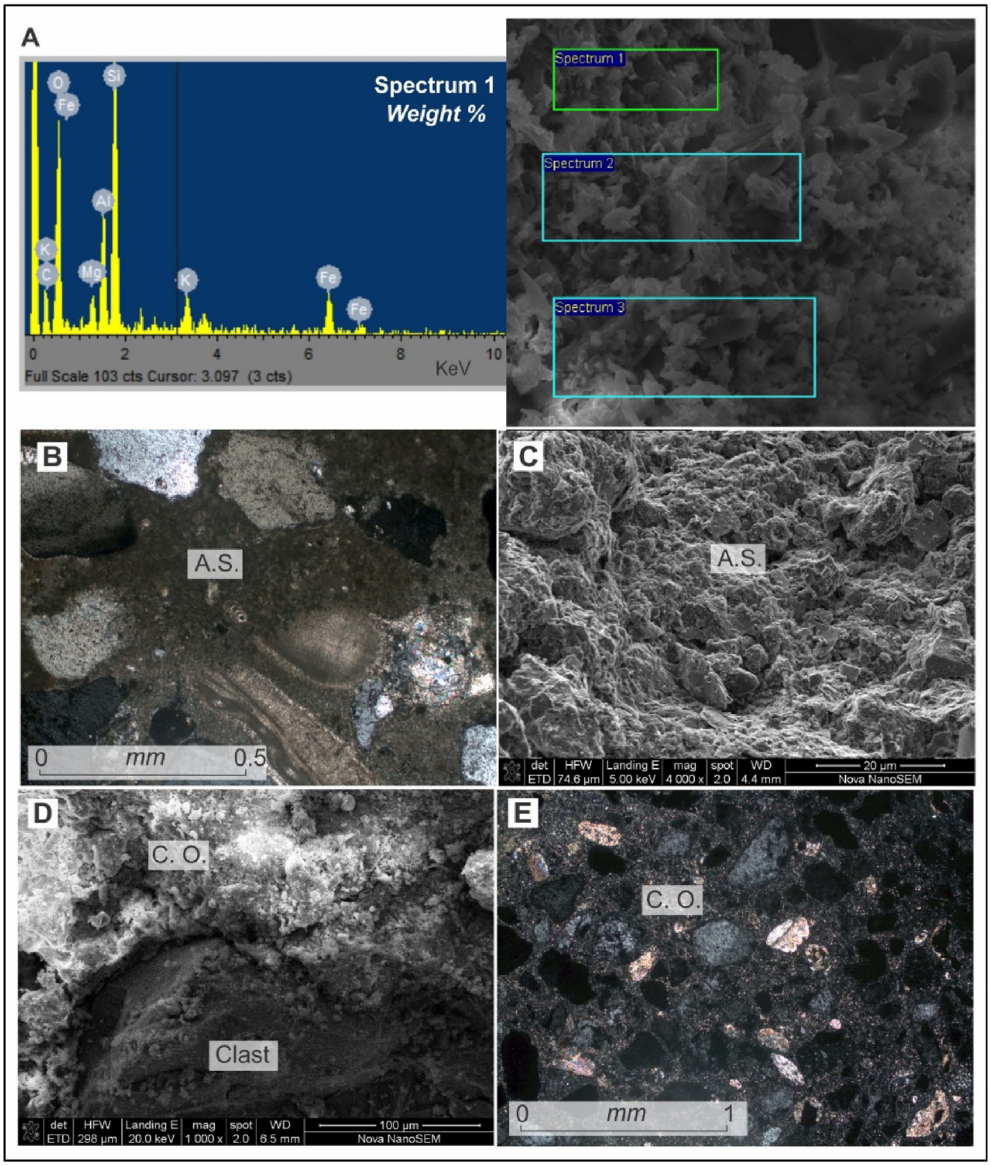

Fig. 6. A. SEM-EDS plot showing elements present and relative distribution as a weight percent for an authigenic smectite dominated matrix **B, C.** Transmitted light- and SEM microscopy showing the pore infilling diagenetic cement of the authigenic smectite (A.S.) infill. **D, E.** Carbonate-organic (C.O.) mixed matrix.

exposure and in comparable contexts, such as in Bermuda (Hearty, 2002), Southwestern and Southern Australia (Brooke et al., 2003) and the Mediterranean (Frechen et al., 2002).

Our model of the soils of the PAP suggests a considerably more fertile landscape than the contemporary coastal foreland. The proximal half of the PAP was dominated by relatively fertile, clay-rich soils which, under a regime of regular fire, would have supported Renosterveld or Grassland during glacials (Cowling et al., this volume). The shift to Grassland requires an increase in the proportion of summer rain, which was predicted to be the case for the eastern part of the central PAP during the LGM. Given the level topography of the PAP, it is likely that these duplex soils experienced seasonal waterlogging (Schloms et al., 1983), which would also have favoured the development of Grassland (Cowling and Potts, 2015). The Grasslands of the PAP were a productive, C4-grass dominated system (Cowling et al., this volume) that supported large numbers of plains game, including both small and large bodied extinct ungulates, as well as extant grassland species uncommon to the Cape (Venter et al., this volume). Pleistocene MSA and Later Stone Age (LSA) sequences found along the Cape South Coast were dominated by large and medium-sized ungulates (both extinct and extant) that are typical of open-habitat migratory ecosystems (Klein, 1983). These glacial age fauna have been described from Nelson Bay Cave and Klasies River (Klein, 1983) and open-habitat species at Pinnacle Point (Rector and Reed, 2010) include black wildebeest (Connochaetes gnou), hartebeest (*Alcelaphus buselaphus*), springbok (*Antidorcas marsupialis*), zebra (Equuscf. quagga), and the extinct giant buffalo (Syncerus antiquus). Glacial age LGM grazers at Nelson Bay Cave show a mixed C3 and C4 diet (Sealy, 1996) and the MIS6 PP30 ungulates also show a mixed C3 and C4 diet (Hodgkins et al., this volume).

These clay-rich regions are partially mantled by widespread dunefields of coastal origin (Cawthra et al., 2019; this volume '*a,b*'); here soils were likely deep, moderately fertile, calcareous sands which supported in the LGM a mosaic of Subtropical Thicket and Fynbos (Cowling et al., this volume). Much of the distal shelf supported shallow, calcareous sands derived from Neogene limestone. These alkaline and moderately fertile sands are predicted to have

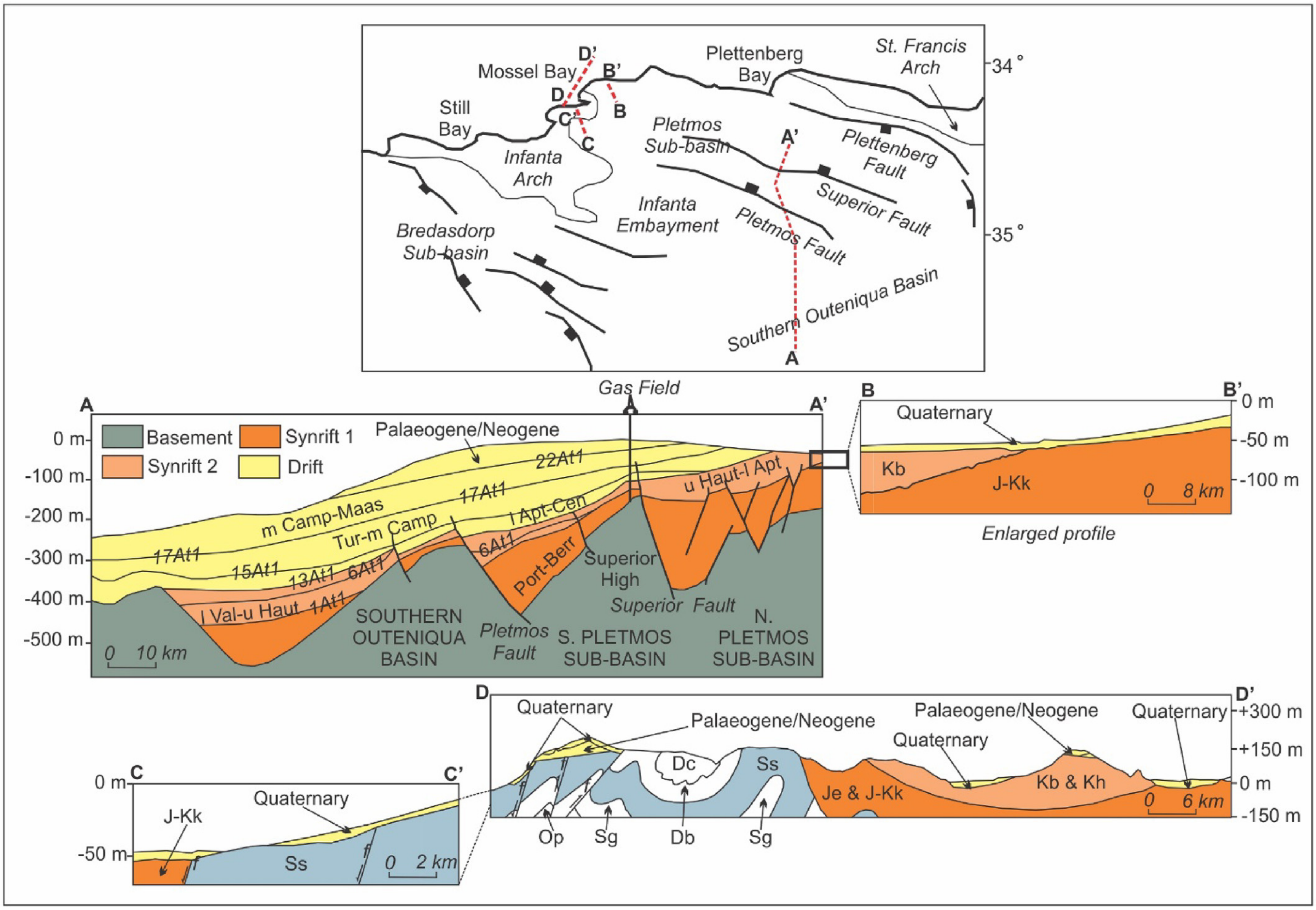

Fig. 7. Sub-bottom configuration of the bedrock of the Palaeo-Agulhas Plain, with correlated units from this study linked to local and regional stratigraphy. The profiles are linked according to the depths of outcrops within the Pletmos Basin in the case of A and B, although the lines are spatially spread apart. The location of profiles are plotted on the structural geological setting of the south coast (modified from Broad et al., 2006). A – A′ covers the deep units and profile B – B′ the shallow stratigraphy (modified from Cawthra et al., 2019/ this volume '*b*'). Profile C – C′ is from this study, profile D – D′ is simplified from the onshore Council for Geoscience 1:50,000 geological map 3422AA (Mossel Bay) (Viljoen and Malan, 1993). Abbreviations of units: Op: Ordovician Peninsula Formation, Sg: Silurian Goudini Formation, Ss: Silurian Skurweberg Formation, Db: Devonian Boplaas Subgroup, Dc: Devonian Ceres Subgroup, Je: Jurassic Enon Formation, J-Kk: Jurassic – Cretaceous Kirkwood Formation, Kb: Cretaceous Buffelskloof Formation, Kh: Cretaceous Hartenbos Formation. Abbreviations of Mesozoic stages: Port: Portlandian, Berr: Berriasian, Val: Valanginian, Haut: Hauterivian, Apt: Aptian, Cen: Cenomanian, Tur: Turonian, Camp: Campanian, Maas: Maastrichtian.

supported Limestone Fynbos, a distinctive and endemic-rich (Willis et al., 1996) fynbos type, now confined to Bredasdorp Formation calcarenites on the contemporary coastal plain (Cowling and Heijnis, 2001). Given the higher winter rainfall in the western PAP (Cowling et al., this volume), the large benches of TMG that outcrop there were likely covered in skeletal podzols, included areas of sluggish drainage – as occurs today on similar topography west of Cape Agulhas - and supported Sandstone Fynbos. The fertile alluvium of the major river valleys supported Savanna (Cowling et al., this volume), a productive environment that would have supported large numbers of game, including giraffe, black rhinoceros, African elephant, hippopotamus, bushbuck and kudu (Helm et al., 2018a; this volume).

5.1.3. Evidence for soil in the submerged record

Marine vibrocores taken on this shelf are detailed in Hahn et al. (2017) and Cawthra et al. (this volume '*b*') and we have conducted further analyses to determine evidence for soils on the now submerged landscape. This was achieved through the presence of hematite in Holocene sediments, although we acknowledge that it is difficult to assess the effect and extent of recycling studying the petrography and mineralogy of modern and ancient sediments. Only applying a quantitative approach, looking the presence of key minerals eroded from soils and coupling this information with the absolute and relative abundance of stable and ultrastable heavy minerals (e.g. ZTR index, the sum of zircon, tourmaline, and rutile over total transparent heavy minerals; Hubert, 1962), do we have a chance to detect the information encoded in sedimentary deposits. The grain mounts were analysed for the heavy mineral contents and also traces of specific minerals such as hematite, were detected and documented. In previous studies (Hahn et al., 2017, 2018) mineralogy of samples from the study area in the Gourits River valley and offshore is fully described, and Fe-oxides were recognized by optical microscope and confirmed by Raman spectroscopy. These oxides are in the shape of flowers and spherules on detrital colorless phyllosilicates (muscovite) (Fig. 5A–D). This observation suggests a recycling of such grains from soil profiles and their transport from palaeo-drainage networks to the present site on the shelf. Smear slides from Meteor expedition M123 in samples GeoB20629-1 and GeoB20628-1 (for location: see Fig. 1 and Cawthra et al., this volume 'b') were also studied and Fe-oxides were encountered only in sample GeoB20628-1. The core sample GeoB18308-1 (10–12 cm), represents the most uppermost deposit of silt and sand (15–500 μm), but heavy-mineral concentration is moderately poor (HMC 1.3% weight and ZTR 19, Hahn et al., 2017). It contains 6% of Fe-oxides (hematite), in the heavy fraction and two clear flowers of hematite have been documented, (Fig. 5D and E). The distribution of silt, as evidenced from marine cores, was incorporated into the mapping of floodplain material (Fig. 3).

The mixed carbonate-organic matrix noted in petrographic thin sections from rock samples from the seafloor is associated with younger geological units and is ascribed to an association with the LGM floodplains described by Cawthra et al. (2019/this volume '*b*'). The transgression of sea level from MIS 2—1 is characterised petrographically by the presence of an organic-carbonate mixed cement observed in thin sections. The presence of organic matter in the calcite cement suggests that the waters from which the calcite cement precipitated had abundant dissolved and particulate organic matter, typical of soils and tannin rich waters seen today in the low-lying coastal wetlands or 'vleis'. This attests to the presence of water-saturated sedimentary stratigraphy and can perhaps be extended to consider the presence of wetlands associated with floodplain sediments as described from the seismic record (Cawthra et al., this volume 'b').

For older exposures, there is evidence in petrographic thin sections from Pleistocene aeolianite and beachrock samples that suggest a wet environment, with spatially extensive palaeosols associated with coastal dunes. Evidence for wetness is suggested as smectite clays have formed the matrix of calcarenite rocks in Pleistocene deposits from MIS 7—MIS 5d (115.4 ± 7 ka) (Cawthra et al., 2018) and we attribute leaching to moisture in the system. The red colouration in the fine grained matrix of the authigenic smectite diagenetic phase is interpreted to be caused by small percentages of iron, likely Fe^{3+}, derived from hinterland weathering. The Fe^{3+} can be present as colloids or preserved on clay minerals, or associated with organic matter (e.g., Flügel, 2004). The proposed introduction of this material into the littoral zone may relate to transport via solution phases associated with compaction, as the coastal sediments in this area contain inter-granular voids. The mixing of clay minerals with carbonate is likely in the study area, given the prevalence of rubified palaeosols in the region on the contemporary coast, such as described by Roberts et al. (2008) at Still Bay. We interpret the presence of authigenic smectite to be a result of palaeosols overlying neocoastal dunes, much like the present-day environments at Vlees Bay and Suidekruis, to the west and east of Mossel Bay. The Vlees Bay palaeosols have been dated to ~50 ka, 74 ka, ~90 ka and 120 ka (Smith et al., 2018). This cluster of dune ages is prolific along the coast and these can be directly linked to the adjacent offshore rocks. Cawthra et al. (this volume a) propose that there were stages of stabilization, marked by palaeosol development, interrupted by phases of aeolian activity which covered mature ecosystems.

Diagenetic phases described in this study are therefore both dominated by post-depositional cements, including late-stage presence of organic matter in a reducing environment interpreted to be associated with (1) an abundance of water seeping through the unconsolidated sediments of the shelf to deposit the mixed carbonate-organic matric material, and (2) the likelihood for dissolved material from overlying palaeosols have entered dune deposits where tannin rich waters may result in organic matter included in calcite cements. Meteoric diagenesis generally showed that in the vadose zone, water was concentrated at grain contacts and in the phreatic zone water filled the pores.

5.2. *Relict terrestrial features on the Palaeo-Agulhas Plain*

5.2.1. *Rivers, estuaries and floodplains*

Fluvial systems have been mapped by Cawthra et al. (2019/this volume '*b*') and mechanisms for subsequent infill are explored. Here, we have projected this information derived from linear sub-bottom profiles to a 2D map. Offshore expressions of most modern rivers extended onto the continental shelf during sea-level lowstands but demonstrate a different character of being shallowly incised but associated with extensive floodplains (Fig. 3). Incised river channels have also previously been described in this area in the first investigations undertaken. A thin veneer of sediment, filling bedrock depressions, and within a buried river channel was described by Birch (1978) off Struis Bay. The Gourits River's well-developed sediment wedge on the seafloor (~10 km wide and 85 km long), extends west of the river mouth (Birch, 1980). The trend is explained by Rogers *pers. comm*. to be a result of the fine grained nature of suspended sediments (from argillaceous Karoo basement in the catchment) and the summer rainfall-related flooding of the river in association with strong westerly coastal currents in summer. The floodplain of the Gourits River on the PAP is up to 18 km wide (Cawthra et al., this volume 'b'; Fig. 3) and the composition of this floodplain is important in considerations of vegetation reconstructions (Cowling et al., this volume) and for Pleistocene faunal implications (e.g., Copeland et al., 2016).

On the modern Agulhas Plain, the region east and north of Cape Agulhas, the Heuningnes River meanders across a low-relief landscape and we propose that this is an example (on a smaller scale) of the likely flow pattern of the submerged fluvial systems on this shelf. The Nuwejaars River on the Agulhas Plain (Fig. 1) feeds the permanent lakes Voelvlei and Soetensdalvlei, perched on well-cemented calcarenite (Carr et al., 2006) and the Sout River terminates against a cemented dune ridge (Fig. 3). What we now know from the geological datasets is that relict river channels were shallowly incised and had extremely broad floodplains and anastomosing channels that can form on low gradient plains. Seismic lines intercepting the palaeo-Gourits point towards a delta when sea level was lower than −110 m and these data show the first documentation of any delta in this region. Deltas and flooded habitats are considered to be a unique source of aquatic resources to people and animals (e.g., Wrangham et al., 2009). The coastal exploitation described at Pinnacle Point (Marean et al., 2007; Jerardino and Marean, 2010) can be supplemented with proof for water resources at the coast for most of the lowstand record. This addresses an additional attraction of the PAP and contributes to the confluence of factors that make this environment unique and productive.

5.2.2. *Wetlands and lagoons*

Extensive wetlands and lagoon environments existed on the PAP (Cawthra et al., 2014, this volume '*b*'). Seismic data revealed the presence of bathymetric depressions containing low-reflectance sediments at dominant depths of 30—40 m, 50—60 m, 75—80 m and ~105 m BMSL across the entirety of the South Coast shelf between Still Bay and Wilderness. These, based on core samples obtained from the inshore deposits (Cawthra et al., this volume 'b'), are interpreted to represent both interdune deposits and back-barrier sediments. They occur in close association with fluvial systems. There are several examples on the modern coastline, both connected to the marine environment (e.g., Swartvlei at Wilderness) and totally disconnected (e.g., Rietvlei at Still Bay), This shelf environment is suggested to have been a locally water-saturated environment as a function of its Mesozoic substrate and adjacent hard-rock foreland (e.g., Marean et al., 2014; Rishworth et al., 2019) and this interpretation is supported by evidence from the carbonate cements in Pleistocene rocks on the PAP analysed in this study. The Agulhas Plain comprises a complex array of soils and wetlands and has been suggested by Cowling (1990) to represent a likely analogue for the vegetation expression expected during glacials when the shelf is exposed. Most of the plant species present are associated with alkaline environments (Cowling and Holmes, 1992) that would have been widespread on the now submerged shelf and this is articulated in Grobler et al. (this volume).

6. Conclusions

We have reconstructed major physical elements of a completely submerged and extinct terrestrial ecosystem. Sea level reached a maximum depth of 130 m BMSL during the LGM and the geological data demonstrate a greatly expanded plain. We show the PAP, for the most part, lacks an exact modern analogue and contrasts sharply with the subaerially exposed Cape South Coast. It was a fertile flat plain while the current Cape Floristic Region landscape is infertile and has high topographic heterogeneity. Wetlands and floodplains were present and broad, shallowly incised river channels carved what would have been a sweeping coastal plain. Laterally extensive floodplains were infilled, and overspilled, with sediment into the channels carved during former occupations of the shelf. Extensive dunefields, extending up to 10 km inland from their associated palaeoshorelines, covered much of the emergent shelf. The seismic stratigraphic record, as well as the diagenetic features, attest to a water table close to the surface. The sedimentary bedforms may have obstructed or slowed drainage as suggested by leached palaeosols and carbonate mixing observed in petrographic thin sections and grain mounts. The mineralogical fingerprint represents an independent proxy for provenance studies in modern and very recent time and terrestrial signals in marine sediment archives can be used for paleoclimatic reconstruction. Aeolianite ridges and cemented deposits are remnant of former glacial periods and this suggests that coastal barrier systems were rapidly cemented by carbonate diagenesis during Pleistocene sea-level oscillations.

The wetter plain may have been able to support a different suite of vegetation. The PAP is suggested to have been a suitable habitat for animals and people alike. Humans need water and wetlands and coastal lakes are considered here to be an important feature of the landscape on the emergent shelf during glacials. This study has showed what the river systems looked like and how they were likely to respond to lowstand conditions.

Acknowledgements

Marine geophysical surveys were funded by the National Geographic Society Expeditions Council (EC482-10) and the South African Council for Geoscience (ST-2011-1139). Michael MacHutchon, Wilhelm van Zyl and Willem Kupido from the Council for Geoscience are thanked for assistance with marine geophysical data collection. Sediment coring and Parasound data collection were financially supported by the Bundesministerium für Bildung und Forschung (BMBF, Bonn, Germany) within the projects "Regional Archives for Integrated Investigation (RAiN)" and PI Dr Matthias Zabel (University of Bremen) is gratefully acknowledged in this regard. This paper was first drafted whilst HC was a visiting junior fellow of the Hanse-Wissenschaft Kolleg in Delmenhorst from November 2017—January 2018. Two anonymous reviews are gratefully acknowledged for their comments and suggestions that improved the quality of this manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2019.07.040.

References

Andò, S., Garzanti, E., 2013. Raman spectroscopy in heavy-mineral studies. In: Sediment Provenance Studies in Hydrocarbon Exploration and Production. Geological Society, London, p. 386. Special Publications.

Andò, S., Garzanti, E., Padoan, M., Limonta, M., 2012. Corrosion of heavy minerals during weathering and diagenesis: a catalogue for optical analysis. Sediment. Geol. 280, 165—178.

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. Quat. Sci. Rev. 23 (14—15), 1681—1698.

Bateman, M.D., Carr, A.S., Dunajko, A.C., Holmes, P.J., Roberts, D.L., McLaren, S.J., Bryant, R.G., Marker, M.E., Murray-Wallace, C.V., 2011. The evolution of coastal barrier systems: a case study of the Middle-Late Pleistocene Wilderness barriers, South Africa. Quat. Sci. Rev. 30 (1—2), 63—81.

Bintanja, R., van de Wal, R.S.W., Oerlemans, J., 2005. Modelled atmospheric temperatures and global sea levels over the past million years. Nature 437, 125—128.

Birch, G., 1978. The Bathymetry and Geomorphology of the Inner Shelf between Cape Seal and Cape Recife, vol. 11. Joint Geological Survey/University of Cape Town Technical Report, pp. 118—121.

Birch, G.F., 1980. Nearshore quaternary sedimentation off the South coast of SA (Cape Town to Port Elizabeth), 20pp Geol. Surv. Bull. 67.

Brady, N.C., 1974. The Nature and Properties of Soils, eighth ed. Macmillan, New York.

Broad, D.S., Jungslager, E.H.A., McLachlan, I.R., Roux, J., 2006. Offshore Mesozoic basins. In: Johnson, M.R., Annhauser, C.R., Thomas, R.J. (Eds.), The Geology of South Africa. Geological Society of South Africa, Johannesburg/Council for Geoscience, Pretoria, pp. 553—571.

Brooke, B.P., Woodroffe, C.D., Murray-Wallace, C.V., Heijnis, H., Jones, B.G., 2003. Quaternary calcarenite stratigraphy on Lord Howe Island, southwestern Pacific Ocean and the record of coastal carbonate deposition. Quat. Sci. Rev. 22 (8—9), 859—880.

Brown Jr., L.F., Benson, J.M., Brink, G.J., Doherty, S., Jollands, A., Jungslager, E.H.A., Keenan, J.H.G., Muntingh, A., van Wyk, N.J.S., 1995. Sequence stratigraphy in offshore South African divergent basins: an atlas on exploration for cretaceous lowstand traps by Soekor (Pty) Ltd. AAPG Stud. Geol. 41.

Carr, A.S., Thomas, D.S., Bateman, M.D., 2006. Climatic and sea level controls on Late Quaternary eolian activity on the Agulhas Plain, South Africa. Quat. Res. 65 (02), 252—263.

Cawthra HC, Frenzel P, Hahn A, Compton J, Gander L, Zabel M., This Volume 'b'. Seismic Stratigraphy of the Broad, Low-Gradient Continental Shelf of the Palaeo-Agulhas Plain, South Africa. Quaternary Science Reviews Special Publication on the PalaeoAgulhas-Plain.

Cawthra, H.C., 2014. The Marine Geology of Mossel Bay. Ph.D. thesis. University of Cape, Town, 283 pp.

Cawthra, H.C., Anderson, R.J, de Vynck, J., Fisher, E.C., Jacobs, Z., Jerardino, A., Kyriacou, K., Marean, C.W. This Volume 'a'. Migration of Pleistocene Shorelines across the Palaeo-Agulhas Plain and the Influence of Intertidal Resources on Human Subsistence. Quaternary Science Reviews Special Publication on the PalaeoAgulhas-Plain.

Cawthra, H.C., Bateman, M.D., Carr, A.S., Compton, J.S., Holmes, P.J., 2014. Understanding Late Quaternary change at the land—ocean interface: a synthesis of the evolution of the Wilderness coastline, South Africa. Quat. Sci. Rev. 99, 210—223.

Cawthra, H.C., Compton, J.S., Fisher, E.C., MacHutchon, M.R., Marean, C.W., 2015. Submerged terrestrial landscape features off the South African south coast. In: Harff, J., Bailey, G., Lüth, F. (Eds.), Geology and Archaeology: Submerged Landscapes of the Continental Shelf, vol. 411. Special Publication of the Geological Society of London, pp. 219—233.

Cawthra, H.C., Jacobs, Z., Compton, J.S., Fisher, E.C., Karkanas, P., Marean, C.W., 2018. Depositional and sea-level history from MIS 6 (Termination II) to MIS 3 on the southern continental shelf of South Africa. Quat. Sci. Rev. 181, 156—172.

Cawthra, H.C., Frenzel, P., Hahn, A., Compton, J., Gander, L., Zabel, M., 2019. Seismic stratigraphy of the broad, low-gradient continental shelf of the Palaeo-Agulhas Plain, South Africa. PeerJ Preprints 7, e27757v1. https://doi.org/10.7287/peerj.preprints.27757v1.

Clark, P.U., Dyke, A.S., Shakun, J.D., Carlson, A.E., Clark, J., Wohlfarth, B., Mitrovica, J.X., Hostetler, S.W., McCabe, A.M., 2009. The last glacial maximum. Science 325 (5941), 710—714.

Compton, J.S., 2011. Pleistocene sea level fluctuations and human evolution on the southern coastal plain of South Africa. Quat. Sci. Rev. 30 (5—6), 506—527.

Copeland, S.R., Cawthra, H.C., Fisher, E.C., Lee-Thorp, J.A., Cowling, R.M., le Roux, P.J., Hodgkins, J.M., Marean, C.W., 2016. Strontium isotope investigation of ungulate movement patterns on the Pleistocene Paleo-Agulhas Plain of the greater Cape Floristic region, South Africa. Quat. Sci. Rev. 141, 65—84.

Cowling, R.M., 1983. Phytochorology and vegetation history in the south eastern Cape, South Africa. J. Biogeogr. 10, 393—419.

Cowling, R.M., 1990. Diversity Components in a Species-Rich Area of the Cape Floristic Region. Journal of Vegetation Science 1 (5), 699—710.

Cowling, R.M., Heijnis, C.E., 2001. Broad habitat units as biodiversity entities for conservation planning in the Cape Floristic Region. South Afr. J. Bot. 67, 15—38.

Cowling, R.M., Holmes, P.M., 1992. Flora and vegetation. In: Cowling, R.M. (Ed.), The Ecology of Fynbos. Nutrients, Fire and Diversity. Oxford University Press, Cape Town.

Cowling, R.M., Potts, A.J., 2015. Climatic, edaphic and fire regime determinants of biome boundaries in the eastern Cape Floristic Region. South Afr. J. Bot. 101, 73–81.
Cowling, R.M., Potts, A.J., Franklin, J., Midgley, G.F., Engelbrecht, F.A., Marean, C.W., This Volume. Describing a Drowned Pleistocene Ecosystem: Last Glacial Maximum Vegetation Reconstruction of the Palaeo-Agulhas Plain. Quaternary Science Reviews Special Publication on the PalaeoAgulhas-Plain.
Cramer, M.,D., West, A.G., Power, S.C., Skelton, R., Stock, W.D., 2014. Plant ecophysiological diversity. In: Allsopp, N., Colville, J.F., Verboom, G.A., Cowling, R.M. (Eds.), Fynbos: Ecology, Evolution, and Conservation of a Mega-diverse Region. Oxford University Press.
Day, R.W., 1986. Magnetometric Mapping of the False Bay Dolerites, vol. 16. Joint Geological Survey/University of Cape Town Marine Geoscience Unit Technical Report, pp. 217–227.
De Vynck, J.C., Difford, M., Anderson, R., Marean, C., Cowling, R., Hill, K. This Volume. The Resilience to Human Foraging of Intertidal Resources on the South Cape Coast of South Africa and the Implications for Pre-historic Foragers. Quaternary Science Reviews Special Publication on the PalaeoAgulhas-Plain..
de Wet, W., 2013. Bathymetry of the South African Continental Shelf. Unpublished MSc thesis. University of Cape, Town.
Deacon, H.J., 1995. Two Late Pleistocene-Holocene Archaeological Depositories from the Southern Cape, South Africa. The South African Archaeological Bulletin, pp. 121–131.
Dingle, R.V., 1973. The geology of the continental shelf between Luderitz and Cape Town (Southwest Africa), with special reference to Tertiary strata. J. Geol. Soc. 129 (4), 337–362.
Dingle, R.V., Rogers, J., 1972. Pleistocene palaeogeography of the Agulhas Bank. Trans. R. Soc. S. Afr. 40, 155–465.
Dingle, R.V., Siesser, 1975. Geology of the Continental Margin between Walvis Bay and Ponta Do Ouro. Government Printer, 1pp.
Dingle, R.V., Siesser, W.G., Newton, A.R., 1983. Mesozoic and Neogene Geology of Southern Africa. Balkema, Rotterdam, 375pp.
Eagles, G., 2007. New angles on South Atlantic opening. Geophys. J. Int. 166, 353–361.
Ekau, E., cruise participants, 2014. Training and Capacity Building Cruise – Cruise No. M102 - December 6 - December 23, 2013 - Le Port (Ile de la Reunion) - Walvis Bay (Namibia), M102. DFG-Senatskommission für Ozeanographie, METEOR-Berichte, 68 pp.
Faith, J.T., 2011. Ungulate community richness, grazer extinctions, and human subsistence behavior in southern Africa's Cape Floral Region. Palaeogeogr. Palaeoclimatol. Palaeoecol. 306 (3–4), 219–227.
Fisher, E.C., Bar-Matthews, M., Jerardino, A., Marean, C.W., 2010. Middle and late Pleistocene paleoscape modeling along the southern coast of South Africa. Quat. Sci. Rev. 29, 1382–1398.
Flügel, E., 2004. Microfacies of Carbonate Rocks: Analysis, Interpretation and Application. Springer-Verlag, Berlin, Heidelberg, New York, 976pp.
Foth, H.D., 1990. Fundamentals of Soil Science, eighth ed. John Wiley & Sons, Canada.
Frechen, M., Neber, A., Dermann, B., Tsatskin, A., Boenigk, W., Ronen, A., 2002. Chronostratigraphy of aeolianites from the Sharon coastal plain of Israel. Quat. Int. 89 (1), 31–44.
Garzanti, E., Dinis, P., Vermeesch, P., Andò, S., Hahn, A., Huvi, J., Limonta, M., Padoan, M., Resentini, A., Rittner, M., Vezzoli, G., 2018. Dynamic uplift, recycling, and climate control on the petrology of passive-margin sand (Angola). Sedi-ment. Geol. 375, 86–104.
Gentle, R.I., 1987. The geology of the inner continental shelf and Agulhas Arch: CT to PE. Geol. Surv. Bull. 20, 129pp.
Goldblatt, P., Manning, J.C., 2002. Plant diversity of the Cape region of southern Africa. Ann. Mo. Bot. Gard. 281–302.
Grobler, A., Cawthra, H.C., Potts, A., Cowling, R.M., This Volume. Plant Diversity of Holocene Dune Landscapes in the Cape Floristic Region: the Legacy of Pleistocene Sea-Level Dynamics? Quaternary Science Reviews Special Publication on the PalaeoAgulhas-Plain.
Hahn, A., Schefuß, E., Andò, S., Cawthra, H.C., Frenzel, P., Kugel, M., Meschner, S., Mollenhauer, G., Zabel, M., 2017. Southern Hemisphere anticyclonic circulation drives oceanic and climatic conditions in late Holocene southernmost Africa. Clim. Past 13, 649–665.
Hahn, A., Miller, C., Andò, S., Bouimetarhan, I., Cawthra, H.C., Green, A., Radeff, G., Schefuß, E., Zabel, M., 2018. Eastern South African provenance study: a toolbox for interpreting inorganic and organic marine signals. G-Cubed (Geochemistry, Geophysics, Geosystems) 17pp.
Hearty, P.J., 2002. Revision of the late Pleistocene stratigraphy of Bermuda. Sedi-ment. Geol. 153 (1–2), 1–21.
Helm, C.W., Cawthra, H.C., Cowling, R.M., De Vynck, J.C., Marean, C.W., McCrea, R.T., Rust, R., 2018a. Palaeoecology of giraffe tracks in Late Pleistocene aeolianites on the Cape south coast. South Afr. J. Sci. 114 (1/2), 2017-0266, 8 pages.
Helm, C.W., MacCrae, R., Lockley, M.G., Cawthra, H.C., Thesen, G.H.H., Mwankunda, J., 2018b. Late Pleistocene vertebrate trace fossils in the Gou-kamma nature reserve, Cape south coast, South Africa. Palaeontol. Africana 52, 89–101.
Hendey, Q.B., 1983. 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 Afr. Natl. Sci. Program, 75, pp. 35–61.
Henshilwood, C.S., D'Errico, F., Yates, R., Jacobs, Z., Tribolo, C., Duller, G.A.T., Mercier, N., Sealy, J.C., Valladas, H., Watts, I., Wintle, A.G., 2002. Emergence of modern human behavior: middle Stone Age engravings from South Africa. Science 295, 1278–1280.
Hodgkins, J., Marean, C.W., Venter, J., Richardson, L., Roberts, P., Zech, J., Difford, M., Copeland, S.R., Keller, H.M., Thorp, J.A., This Volume. An Isotopic Test of the Seasonal Migration Hypothesis for Large Grazing Ungulates Inhabiting the Palaeo-Agulhas Plain (South Coast, South Africa).
Hubert, J.F., 1962. A zircon-tourmaline-rutile maturity index and the interdepen-dence of the composition of heavy minerals assemblages with the gross composition and texture of sandstones. J. Sediment. Petrol. 32, 440–450.
Illenberger, W.K., 1996. The geomorphic evolution of the Wilderness dune cordons. South Africa. Quat. Int. 33, 11–20.
Jacobs, Z., Jones, B., Cawthra, H.C., Henshilwood, C., Roberts, R. This Volume. The Chronological, Sedimentary and Environmental Context for the Archaeological Deposits at Blombos Cave, South Africa. Quaternary Science Reviews Special Publication on the PalaeoAgulhas-Plain.
Jarvis, A., Reuter, H.I., Nelson, A., Guevara, E., 2008. Hole-filled SRTM for the globe version 4. available from the CGIAR-CSI SRTM 90m database. http://srtm.csi.cgiar.org.
Jerardino, A., 2010. Large shell middens in Lamberts Bay, South Africa: a case of hunter–gatherer resource intensification. J. Archaeol. Sci. 37 (9), 2291–2302.
Jerardino, A., Marean, C.W., 2010. Shellfish gathering, marine paleoecology and modern human behavior: perspectives from cave PP13B, Pinnacle Point, South Africa. J. Hum. Evol. 59, 412–424.
Klein, R.G., 1983. Palaeoenvironmental implications of Quaternary large mammals in the fynbos region. In: Deacon, H.J., Hendey, Q.B., Lambrechts, J.J.N. (Eds.), Fynbos Palaeoecology: A Preliminary Synthesis. South African National Scien-tific Programmes Report No 75. Mills Litho, Cape Town, pp. 116–138.
Langejans, G.H., van Niekerk, K.L., Dusseldorp, G.L., Thackeray, J.F., 2012. Middle stone age shellfish exploitation: potential indications for mass collecting and resource intensification at Blombos cave and Klasies River, South Africa. Quat. Int. 270, 80–94.
Lisiecki, L.E., Raymo, M.E., 2005. A Pliocene–Pleistocene stack of 57 globally distributed benthic δ18O records. Paleoceanography 20, 1003–1020.
Malan, J.A., 1990. The Stratigraphy and Sedimentology of the Bredasdorp Group, Southern Cape Province. Unpublished M.Sc. Thesis, University of Cape, Town, South Africa.
Marean, C.W., 2010. Pinnacle point cave 13B (western Cape province, South Africa) in context: the Cape Floral kingdom, shellfish, and modern human origins. J. Hum. Evol. 59 (3–4), 425–443.
Marean, C.W., Abe, Y., Frey, C.J., Randall, R.C., 2000. Zooarchaeological and tapho-nomic analysis of the Die Kelders cave 1 layers 10 and 11 middle stone age larger mammal fauna. J. Hum. Evol. 38 (1), 197–233.
Marean, C.W., Bar-Matthews, M., Bernatchez, J., Fisher, E., Goldberg, P., Herries, A.I.R., Jacobs, Z., Jerardino, A., Karkanas, P., Minichillo, T., Nilssen, P.J., Thompson, E., Watts, I., Williams, H., 2007. Early human use of marine resources and pigment in South Africa during the Middle Pleistocene. Nature 449, 905–908.
Marean, C.W., Cawthra, H.C., Cowling, R.M., Esler, K.J., Fisher, E.C., Milewski, A., Potts, A.J., Singels, E., De Vynck, J., 2014. Stone age people in a changing South African greater Cape Floristic region. In: Allsopp, N., Colville, J.F., Verboom, T. (Eds.), Ecology and Evolution of Fynbos: Understanding Megadiversity. Oxford University Press, Oxford, pp. 164–199.
Martin, A.R.H., 1962. Evidence relating to the Quaternary history of the Wilderness lakes. S. Afr. J. Geol. 65 (1), 19–42.
Martin, A.K., 1985. The Geology of the Seafloor between the Mossel Bay/Stilbaai Coast and the EM and FA Drill Sites. Marine Geoscience division National Institute for Oceanology Council for Scientific and Industrial Research report C/SEA, p. 8510.
Martin, A.K., Flemming, B.W., 1986. The Holocene shelf sediment wedge off the south and east coast of South Africa. In: Knight, R.J., McLean, J.R. (Eds.), Shelf Sands and Sandstones, vol. 2. Canadian Society of Petroleum Geologists Memoir, pp. 27–44.
Martin, A.K., Hartnady, C.J.H., 1986. Plate tectonic development of the southeast Indian Ocean: a revised reconstruction of East Antarctica and Africa. J. Geophys. Res. 91, 4767–4786.
McMillan, I.K., 2003. Foraminiferally defined biostratigraphic episodes and sedi-mentation pattern of the Cretaceous drift succession (Early Barremian to Late Maastrichtian) in seven basins on the South African and southern Namibian continental margin. South Afr. J. Sci. 99 (11/12), 537–576.
Muir, R.A., Bordy, E.M., Reddering, J.S.V., Viljoen, J.H.A., 2017a. Lithostratigraphy of the Enon Formation (Uitenhage group), South Africa. S. Afr. J. Geol. 120 (2), 273–280.
Muir, R.A., Bordy, E.M., Reddering, J.S.V., Viljoen, J.H.A., 2017b. Lithostratigraphy of the Kirkwood Formation (Uitenhage group), including the Bethelsdorp, col-chester and Swartkops members, South Africa. S. Afr. J. Geol. 120 (2), 281–293.
Oestmo, S., Janssen, M., Cawthra, H.C., This Volume. Applying Brantingham's Neutral Model of Stone Raw Material Procurement to the Pinnacle Point Middle Stone Age Record, Western Cape, South Africa. Quaternary Science Reviews Special Publication on the PalaeoAgulhas-Plain.
Oestmo, S., Schoville, B.J., Wilkins, J., Marean, C.W., 2014. A middle stone age paleoscape near the pinnacle point caves, Vleesbaai, South Africa. Quat. Int. 350, 147–168.
Parker, R.J., Siesser, W.G., 1972. Petrology and origin of some phosphorites from the South African continental margin. J. Sediment. Res. 42 (2), 434–440.
Paton, D.A., Macdonald, D.I.M., Underhill, J.R., 2006. Applicability of thin or thick

skinned structural models in a region of multiple inversion episodes, southern. South Afr. J. Struct. Geol. 28, 1933–1947.
Rector, A.L., Reed, K.E., 2010. Middle and late Pleistocene faunas of Pinnacle Point and their paleoecological implications. J. Hum. Evol. 59 (3–4), 340–357.
Rishworth, G., Cawthra, H.C., Perissinotto, R., 2019. Peritidal stromatolites as indicators of stepping-stone freshwater resources in the palaeo-Agulhas landscape. Quaternary science reviews special publication on the PalaeoAgulhas-plain. https://doi.org/10.1016/j.quascirev.2019.03.026.
Roberts, D.L., Brink, J.S., 2002. Dating and correlation of Neogene coastal deposits in the western Cape (South Africa): implications for Neotectonism. S. Afr. J. Geol. 105 (4), 337–352.
Roberts, D.L., Bateman, M.D., Murray-Wallace, C.V., Carr, A.S., Holmes, P.J., 2008. Fossil elephant trackways, sedimentation and diagenesis in OSL/AAR-dated Late Quaternary coastal aeolianites: Still Bay, South Africa. Palaeogeogr. Palaeoclimatol. Palaeoecol. 257, 261–279.
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 (1–2), 24–38.
Roberts, D.L., Karkanas, P., Jacobs, Z., Marean, C.W., Roberts, R.G., 2012. Melting ice sheets 400,000 yr ago raised sea level by 13 m: Past analogue for future trends. Earth Planet. Sci. Lett. 357–358, 226–237.
Roberts, D., Cawthra, H., Musekiwa, C., 2013. Dynamics of late Cenozoic aeolian deposition along the South African coast: a record of evolving climate and ecosystems. Geol. Soc. Lond. Specl. Publ. 388 (1), 353–387.
Rogers, J., 1971. Sedimentology of Quaternary Deposits on the Agulhas Bank. Unpublished MSc Thesis, University of Cape, Town.
Schloms, B.H.A., Ellis, F., Lamprechts, J.J.N., 1983. Soils of the Cape coastal platform. In: Deacon, H.J., Hendey, Q.B., Lamprechts, J.J.N. (Eds.), Fynbos Palaeoecology: a Preliminary Synthesis. South African National Scientific Programmes Report 75. CSIR, Pretoria, pp. 70–86.
Sealy, J., 1996. Seasonality of rainfall around the Last Glacial Maximum as reconstructed from carbon isotope analyses of animal bones from Nelson Bay Cave. South Afr. J. Sci. 92, 441–444.
Singels, E., 2013. Underground Storage Organs of Plants as a Food Source for Pleistocene Hunter-Gatherers in the Southern Cape. MSc thesis, University of Stellenbosch.
Smith, E.I., Jacobs, Z., Johnsen, R., Ren, M., Fisher, E.C., Oestmo, S., Wilkins, J., Harris, J.A., Karkanas, P., Fitch, S., Ciravolo, A., 2018. Humans thrived in South Africa through the Toba eruption about 74,000 years ago. Nature 555 (7697), 511.
Stankiewicz, J., Ryberg, T., Schultze, A., Lindique, A., Weber, M.H., de Wit, M.J., 2007. Results from the wideangle seismic refraction lines in the southern Cape. Inkaba yeAfrica special volume. S. Afr. J. Geol. 110, 407–418.
Thwaites, R.N., Cowling, R.M., 1988. Soil- vegetation relationships on the Agulhas Plain, South Africa. Catena 15, 333–346.
Tinker, J.H., de Wit, M.J., Brown, R., 2008a. Mesozoic exhumation of the southern Cape, South Africa, quantified using apatite fission track thermochronology. Tectonophysics 455, 77–93.
Tinker, J.H., de Wit, M.J., Brown, R.W., 2008b. Linking source and sink: evaluating the balance between onshore erosion and offshore sediment accumulation since Gondwana break-up, South Africa. Tectonophysics 455, 94–103.
Tinley, K.L., 1985. Coastal Dunes of South Africa. National Scientific Programmes Unit: CSIR.
Trumbull, R.B., Reid, D.L., de Beer, C., van Acken, D., Romer, R.L., 2007. Magmatism and continental breakup at the west margin of southern Africa: a geochemical comparison of dolerite dikes from NW Namibia and the Western Cape. S. Afr. J. Geol. 110, 477–502.
Van Andel, T.H., 1989. Late Pleistocene sea levels and human exploitation of the shore and shelf of southern South Africa. J. Field Archaeol. 16, 133–155.
Van Breemen, N., Buurman, P., 2002. Soil Formation. Springer Science & Business Media.
Venter, J.A., Brooke, C., Marean, C.W., Fritz, H., This Issue. Large Mammals of the Palaeo-Agulas Plain: Conceptual Reconstruction of Large Mammal Assemblages and Their Habitats. Quaternary Science Reviews Special Publication on the PalaeoAgulhas-Plain.
Viljoen, J.H.A., Cawthra, H.C., 2019. Lithostratigraphy of the Buffelskloof Formation (Uitenhage group), South Africa. Accepted to South Afr. J. Geol. 122 (1), 97–104.
Viljoen, J.H.A., Malan, J.A., 1993. Die geologie van die gebeide 3421BB Mosselbaai en 3422AA Herbertsdale. Toeligting tot blaaie 3421BB en 3422AA, Skaal 1: 50 000. Geologise Opname van Suid-Afrika, 79pp.
Waelbroeck, C., Labeyrie, L., Michel, E., Duplessy, J.C., McManus, J.F., Lambeck, K., Balbon, E., Labracherie, M., 2002. Sea-level and deep water temperature changes derived from benthic foraminifera isotopic records. Quat. Sci. Rev. 21 (1–3), 295–305.
Willis, C.K., Lombard, A.T., Cowling, R.M., Heydenrych, B.J., Burgers, C.J., 1996. Reserve systems for limestone endemic flora of the Cape lowland fynbos: iterative versus linear programming. Biol. Conserv. 77 (1), 53–62.
Wrangham, R., Cheney, D., Seyfarth, R., Sarmiento, E., 2009. Shallow-water habitats as sources of fallback foods for hominins. Am. J. Phys. Anthropol.: Offic. Publ. Am. Associat. Phys. Anthropol. 140 (4), 630–642.
Zabel, M., cruise participants, 2017. Climate Archives in Coastal Waters of Southern Africa - Cruise No. M123 - February 03 - February 27, 2016 - Walvis Bay (Namibia) - Cape Town (Rep. Of South Africa). Issn: 2195-8475. DFG-Senatskommission für Ozeanographie, Bremen, 50 pp.