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THE SIGNIFICANCE OF CALCRETES AND PALEOSOLS ON ANCIENT DUNES OF THE WESTERN CAPE, SOUTH AFRICA, AS STRATIGRAPHIC MARKERS AND PALEO-ENVIRONMENTAL INDICATORS

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Summary

Two types of geological strata are exposed within the interdunal deflation bays of Geelbek in the Western Cape of South Africa: 1) Multiple layers of hardpan calcrete date to the Pleistocene, and 2) Several ancient dunes show the development of paleosols dating to the Late Pleistocene and Holocene. The unvegetated mobile dune fields of Geelbek are situated within a landscape of vegetated fossil dunes and open windows into the paleoclimate, landscape history and prehistoric settlement of the West Coast region. All of the former land surfaces are associated with Stone Age artifacts and appear to have been occupied under more humid conditions than today. While the exposed calcrete layers reflect complex cycles of soil formation, erosion and karstification under changing climatic regimes, the paleosols of the overlying ancient dunes reflect formation under a different set of climatic conditions and varying time spans. The unique characteristics of these soil horizons make them useful as stratigraphic markers.

Key Words

Paleoecology, paleopedology, coastal dunes, South Africa, Pleistocene, Holocene

1.0 Introduction

Paleosols associated with ancient dunes represent past cycles of alternating arid and humid climates. The paleosols indicate climatic change on both regional and global scales and are useful in reconstructing the paleoecological development of a landscape and its potential for human occupation. In the Western Cape of South Africa between Cape Town and the Olifants River vegetated paleodunes and active coastal dunes are subdivided by a sequence of paleosols that are associated with calcretes.

While ancient strata are inaccessible in densely vegetated areas, several plumes of longitudinal and transversal dunes create deflation hollows that serve as windows into the past and offer access to information about former climates and human behavior. The paleosols are associated with cultural layers of the Stone Age and indicate that several phases of humidity higher than today existed during the late Middle and Upper Quaternary. Paleopedological investigations at Geelbek, about 90 km north of Cape Town, accompanied archaeological investigations (Kandel *et al.*, 2003) and focus on the genesis, stratigraphy and paleoclimatic importance of calcretes and paleosols in ancient dunes. This paper presents the initial results of the paleopedological investigations.

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One aim of the paleopedological investigation is to develop a chronology of the paleosols and calcretes and thereby shed light on the archaeological significance of artifacts which are found within and on these paleosol horizons. The origin of stone artifacts and faunal remains found embedded within a specific horizon is relatively straightforward. However, deflation by wind and other erosional processes has often projected artifacts from several different paleosols onto a single surface, resulting in superimposed scatters of artifacts from multiple periods of occupation that have nonetheless retained their basic spatial integrity. The paleopedological results presented here offer the best possibility to unravel the nature and sequence of the former landscapes in which humans lived.

2.0 Study Area and Methods

The mobile, inland dune plume at Geelbek (about 33°10' S; 18°09'E, location see Fig. 1 in Kandel et al., this volume) is situated near the Atlantic Ocean within the West Coast National Park and covers an area of about 4 km². The climate today is semiarid Mediterranean with predominant winter precipitation of about 270 mm per year. Predominant summer winds from the south-southwest (Flemming, 1977) create both transverse and barchanoid peaks up to 40 m in height and interspersed valleys which are oriented perpendicular to the main wind direction (Tinley, 1985). Multiple measurements of the borders of several deflation hollows in the Geelbek Dunes have documented dune movement of up to 25 meters per annum over the *sandveld*, with an estimated mean of 10 meters per year (Kandel *et al.* 2003). Franceschini (2003) correlates the departure of the dunes from the coast with the mid-Holocene marine transgression, a well-documented high sea level at approximately 6 ka BP (Miller, 1993). This interpretation stands in contrast to more traditional interpretations that generally correlate coastal dune formation with drops in sea level, such as during the last glacial maximum. At this time vast sand flats on the broad continental shelf along the Southern African coast laid exposed, providing parent material for the dunes (Deacon, 1983; Tinley, 1985; Lancaster, 1987).

Table 1. Geelbek. Range of texture (soil samples free of carbonate) and carbonate content of mobile dunes.

	% Medium Sand 630 – 200 µm	% Fine Sand 200 – 63 µm	% Fines < 63 µm	Carbonate mass %
Yellowish white dunes (Mobile dune a)	12 - 23	57 - 96	4 - 8	23 - 36
Dark yellow dunes (Mobile dune b)	22 - 37	61 - 77	1 - 2	8 - 13

Mobile dune a: average of 6 samples
Mobile dune b: average of 3 samples

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The texture of the mobile dunes is dominated by medium and fine sand (Table 1). Mineralogically, the dunes consist mainly of quartz with a relatively high percentage of calcium carbonate (8–36 mass %.) The carbonates occur as sand-sized fragments of shells and older calcretes, the latter having been reworked by abrasion of submarine outcrops and erosion at cliffs. The content of carbonate correlates with the color of the mobile dunes. The longitudinal dunes in the eastern and central part of the dune plume of Geelbek display a yellowish-white color and higher concentrations of calcium carbonate (23–36 mass %), while the dunes at the western margin of the plume show a brownish-yellow color and a lower carbonate content (8–13 mass %). The darker dunes are colored by aeolian sand that deflated from the erosion of the adjacent, vegetated, ancient dunes, for example, after an extensive bush fire. The electrical conductivity and the amount of water-soluble salts in the mobile dunes are low (100–150 mg kg^{-1}). Among the water-soluble ions extracted from the mobile dune sand, Cl^-, SO_4^{2-}, Na^+ and Mg^{2+} show the highest concentrations, indicating a marine source for the sand, as seawater has the highest concentration of these ions.

The inland dune plume of Geelbek is situated in a 3-4 km wide belt of older coastal dunes (de la Cruz, 1978) extending along the Atlantic Coast from Cape Town in the south to the Olifants River in the north. In contrast to the mobile dune field of Geelbek, which forms a 'local desert,' the ancient dunes are densely vegetated by shrubby fynbos (fine bush) vegetation. The natural shrub vegetation is restricted to the protected area of the West Coast National Park. Outside the National Park grazing and agriculture have destroyed most of the natural vegetation. The relief of the ancient dunes undulates with an elevation difference of between 50 and 100 m separating the peaks and troughs. Coastal cliffs along Langebaan Lagoon expose a vertical sequence of ancient dunes, which are subdivided by several horizons of calcrete (Knox, 1977; Theron et al., 1992). Near the modern land surface the ancient coastal dunes are capped by a fragmented bank of calcrete that follows the hilly relief of the dunes. The calcrete is covered by a younger aeolian sand sheet and shallow dunes on which a weak Cambic Arenosol developed under recent climatic conditions.

A calcrete layer also forms the base of the mobile dune field at Geelbek and outcrops in the interdunal deflation bays. An ancient dune, in which a Cambic Arenosol is developed, underlies the basal calcrete. The ancient dune with the paleosol is exposed in profiles of karst basins which frequently dissect the calcrete bank (Fig. 1). The calcrete is covered by a sequence of two immobile ancient dunes with paleosols and the recent mobile dunes. The paleosols of the ancient dunes are the primary focus of this paleopedological study.

After detailed survey and profile investigations, representative samples were taken from each soil horizon. Particle-size distribution was determined by sieving after the dissolution of carbonates with HCl

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and the fine fraction (< 63 µm) was calculated by mass difference. Chemical analysis of pH, EC, C_{org} and pedogenic oxides (Fe, Mn, Si, Al) followed the procedures of Schlichting et al. (1995). Soil classification and designation of soil horizons is based on the FAO-legend (FAO-UNESCO 1989).

3.0 Results and Discussion

3.1 Calcrete

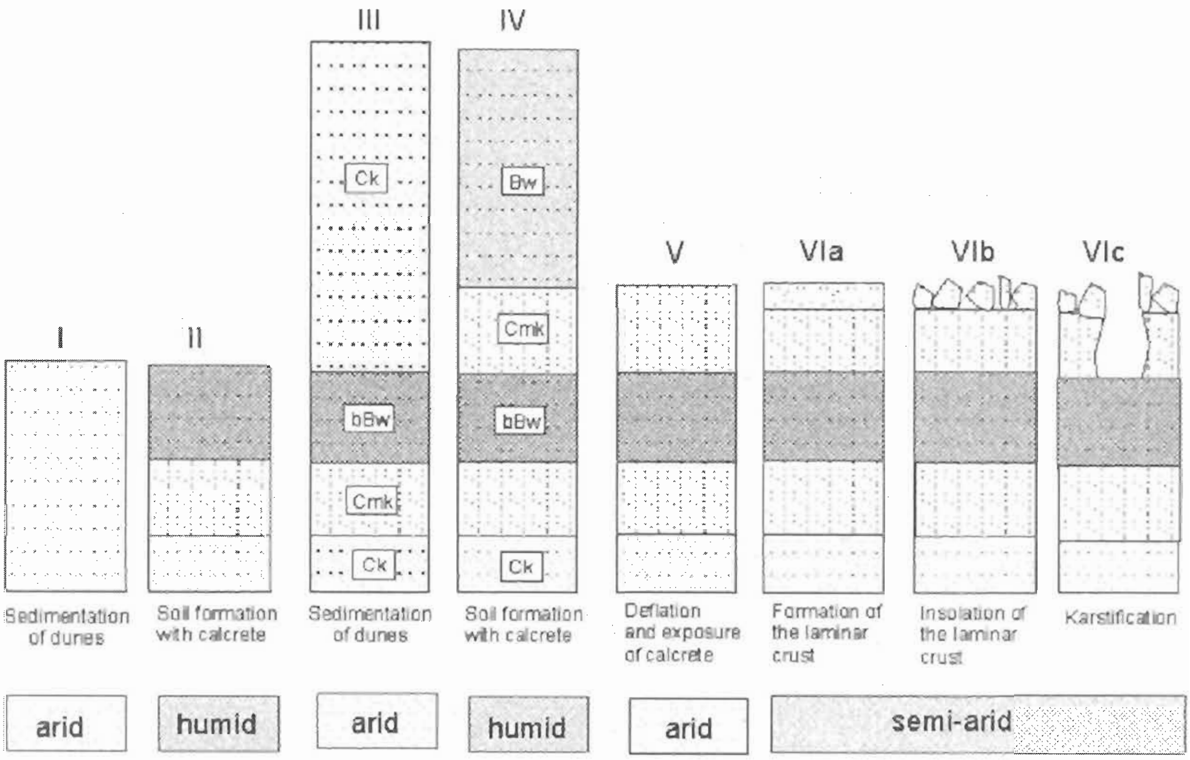

Fig. 1. Geelbek. Stages of calcrete development.

Hardpan calcrete forms the basis of the interdunal deflation bays of Geelbek. The macro- and micromorphological characteristics of the hardpan calcretes of the study area and the adjacent coastal region as the basis for a genetic interpretation were intensively studied by Netterberg (1969) and Knox (1977). The morphological characteristics and the genesis of calcretes in Namibia were also investigated in detail by Eitel (1994). The results from Geelbek show that calcrete displays a sequence of horizons with typical characteristics due to its polygenetic development. These characteristics are also revealed by calcrete that is exposed within the interdunal deflation bays (Fig. 1). Calcrete developed as a subsoil horizon of a paleosol. A semi-humid to semi-arid climate caused decalcification of the dune sand during the wet season and re-precipitation of carbonates within the deeper parts of the sediment during the dry season. Over the course of soil formation the growth of vegetation and an increased weathering of silicates led to the formation of fines that in turn impeded the leaching of bicarbonate to deeper parts of the dune. Continuous enrichment of calcium carbonate led to cementation of the upper part of the horizon (Fig. 1, stages I and II). A rapid climatic change to more arid conditions could have caused the sedimentation of younger calcareous dunes, which covered the paleosol before it was destroyed by deflation or erosion. A new cycle of calcrete formation could begin during a subsequent period with more humid conditions (Fig. 1, stages III and IV).

In the case of slowly increasing aridity and/or limited availability of aeolian sand, the paleosol surface remained exposed for a long period. The calcrete was subsequently exposed by deflation or erosion of the decalcified, and thus less stable, soil material (Fig. 1, stage V). During long periods at the surface the exposed calcrete dissolved during rainy periods and was re-precipitated as carbonate during dry periods. This alternating cycle resulted in the formation of a very hard, dense, laminar 'upper crust' (Cmk1 horizon) of yellowish-gray color at the exposed calcrete surface (cf. Eitel, 1994; Fig. 1, stage VIa), which in Geelbek is up to 10 cm thick.

Below the laminar upper crust, a hard, white, massive 'lower crust' (Cmk2 horizon) displays the coherent structure of the original calcrete. This horizon is frequently dissected by vertical cracks and root channels, partly filled with coarse crystalline secondary carbonates, that could have precipitated during the formation of the upper crust by deep infiltration of dissolved bicarbonates. In Geelbek the total thickness of the upper and lower crust, which together form the hardpan calcrete (de la Cruz 1978), varies between 40 and 80 cm. As the concentration of calcium carbonate decreases with increasing depth, the hardpan calcrete gradually changes into a soft, white carbonate enrichment horizon. The thickness of this 'powder calcrete' (de la Cruz 1978) varies from 30 cm to more than 1 m. In places hard, thick, vertically orientated rhizo-concretions composed of carbonate, some with diameters up to 5 cm and more, extend from the hard crust down into the soft enrichment horizon. These concretions indicate that during the formation of the calcretes, the soil surface was vegetated by trees or shrubs and that the calcrete originally developed within the rooted zone.

The vegetation assisted in the formation of calcrete. Due to acidification which resulted from the formation of organic acids and the respiration of roots and microorganisms, carbonates dissolved in the upper soil horizons. Leaching of dissolved bicarbonates was, however, hampered by interception and transpiration, which limited the amount of gravitational water. A specific depth of accumulation cannot, however, be estimated because shrubs and trees in a semi-arid climate develop a deep reaching root system.

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Table 2. Geelbek. Mass balances of calcium carbonate accumulation in calcretes, standardized to a total profile thickness of 1 m and thickness of the related decalcified zone which must have existed in the overlying dune sand.

Profile	Horizon	Depth (cm)	Bulk density ($g\ cm^{-3}$)	Carbonate content (mass %)	Carbonate mass ($kg\ m^{-3}$)	Carbonate accumulation, based on carbonate content of dune a ($kg\ m^{-3}$)	Carbonate accumulation, based on carbonate content of dune b ($kg\ m^{-3}$)	Thickness (m) of the decalcified zone, based on carbonate content of dune a	Thickness (m) of the decalcified zone, based on carbonate content of dune b
GC 1	Cmk1	0 - 5	2.21	63.1	1,275	795	1,115	1.66	6.97
	Cmk2	- 20	2.47	70.3					
	Ck	-100	2.11	56.1					
GC 3	Cmk1	0 - 8	2.46	71.6	1,020	540	860	1.13	5.38
	Cmk2	- 50	2.09	49.1					
	Ck	-100	1.93	46.3					
GP 7	Cmk1	0 - 10	2.34	63.3	1,236	756	1,076	1.58	6.73
	Cmk2	- 40	2.30	46.4					
	Ck	- 100	2.39	53.5					
Mobile dune a)	C	0 - 100	1.60	30.0	480				
Mobile dune b)	C	0 - 100	1.60	10.0	160				

Location of the profiles:
GC1: Road bank at the road from Geelbek to the south coast of Langebaan Lagoon (33° 13' 22.6" S; 18° 6' 46.9" E)
GC3: Geelbek, deflation bay "Rhino" (33° 10' 43.3" S, 18° 09' 08.5" E)
GP 7: Geelbek, interdunal deflation bay "Stone Ring" (33° 10' 46.6" S, 18° 09' 30.3" E)
Mobile dune a: average of 6 samples from the yellowish white dunes, 23 – 36 mass% $CaCO_3$
Mobile dune b: average of 3 samples from the dark yellow dunes, 8 – 12 mass% $CaCO_3$
Calcrete horizons: Cmk1: laminar upper crust; Cmk2: coherent massive lower crust; Ck: soft carbonate enrichment horizons

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Based on the analytical data from three selected calcrete profiles, mass balances of the calcium carbonate accumulation were calculated, taking into account the carbonate content and bulk densities of the calcareous mobile dunes and the calcrete horizons (Table 2). Standardized to the uppermost meter of calcrete, the bulk masses of accumulated calcium carbonate are similar at differing locations in the Geelbek area. According to the variation of the primary $CaCO_3$ content of the mobile dunes between 8 and 36 mass %, the thickness of the decalcified zone may have varied between one and several meters.

Stone Age artifacts and animal bones embedded in calcrete were either projected from the former land surface onto the calcrete surface during the course of erosion of the former paleosol, deposited directly on the bare calcrete surface during the beginning of karstification or were present in the sand before soil development began at the depth of precipitation of calcium carbonate.

Further physical weathering by insolation frequently caused fragmentation of the upper part of the calcrete (Fig. 1, stage VI b) which assisted infiltration of rainwater through the resultant cracks. Continuous dissolution of the bare calcrete along the cracks caused the formation of extensive karst basins that dissected the calcrete and in some places exposed the underlying ancient dune with a bBw horizon of a fossil Cambic Arenosol (Fig. 1, stage VI c).

Some of the presently exposed calcretes contain coarse fragments of an older calcrete, an indication of the complex history of the landscape. This phenomenon can be explained by repeating cycles of sand deposition, soil and calcrete formation, soil erosion, karstification, redistribution of calcrete fragments and renewed dune deposition.

The occurrence of calcrete at different elevations, as well as the variance in composition, color and intensity of karstification, indicates that calcretes of differing age form the foundation of the deflation bays. The absolute dating of samples of the hardpan calcrete confirms these different ages. The vegetated, ancient, coastal dunes outside the mobile dune field of Geelbek consist of several ancient dune complexes of possibly Middle Pleistocene age, which are subdivided by hardpan calcrete horizons. These became dissected by broad valleys following erosion by runoff water. Thus, calcretes of dissimilar age were exposed at different elevations along the slopes of the valleys. Finally the younger Late Pleistocene and Holocene ancient dunes (AD I and AD II, see below) and the modern dune field were deposited on top of the exposed calcretes of the older dunes, which again became exposed in the young deflation valleys.

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Netterberg (1978) and Eitel (1994) discuss the possibilities and difficulties of absolute dating of calcretes. Difficulties in obtaining dates arise from the fact that the unweathered dune sand of Geelbek contains sand-sized fragments of older calcrete. Furthermore, the dissolution and re-precipitation of carbonates that affected the hardpan calcrete after its exposure caused formation of secondary carbonates of indeterminate age. Absolute dating therefore is only successful if micromorphological investigations can prove that the samples are free of older calcrete fragments and secondary carbonates.

The dates for each sample gained by the application of two independent dating methods indicate separate phases of calcrete formation at ca. 250, 150 and 65 ka BP. These preliminary data from Stephan Woodborne of the CSIR in Pretoria result from both IRSL dating of the sand matrix of the calcrete and U-series dating of the calcium carbonate. Until more precise chronological control is established for the Geelbek Dunes, the assumption that the hardpan calcrete is of Pleistocene age seems justified.

Netterberg (1969) and de la Cruz (1978) discuss the paleoclimatic significance of calcrete. The formation of calcrete is very sensitive to climatic conditions such as the amount of rainfall, the rate of evapo-transpiration and wind speed. Netterberg (1969) suggests that calcrete occurring in South Africa in areas receiving less than 500 mm of annual rainfall, such as Geelbek, can be considered fossil. According to the distribution of calcareous soils in South Africa, the occurrence of hardpan calcrete is restricted to warm, semiarid areas that receive less than 550 mm of annual rainfall.

3.2 Pleistocene and Holocene Ancient Dunes and Paleosols

The karstified basal calcrete is overlain by two ancient dunes (AD) of Upper Pleistocene (AD I) and Holocene (AD II) age in which paleosols have developed in the absence of calcrete formation. Profiles in karst depressions of the basal calcrete show that in some places the calcrete covers an older ancient dune of Middle Pleistocene age (AD 0, Figs. 1 and 2). The ancient dunes illustrate characteristics of paleosol formation that allow their use as stratigraphic markers. Furthermore they can be interpreted according to the paleoclimatic conditions during the period of soil formation.

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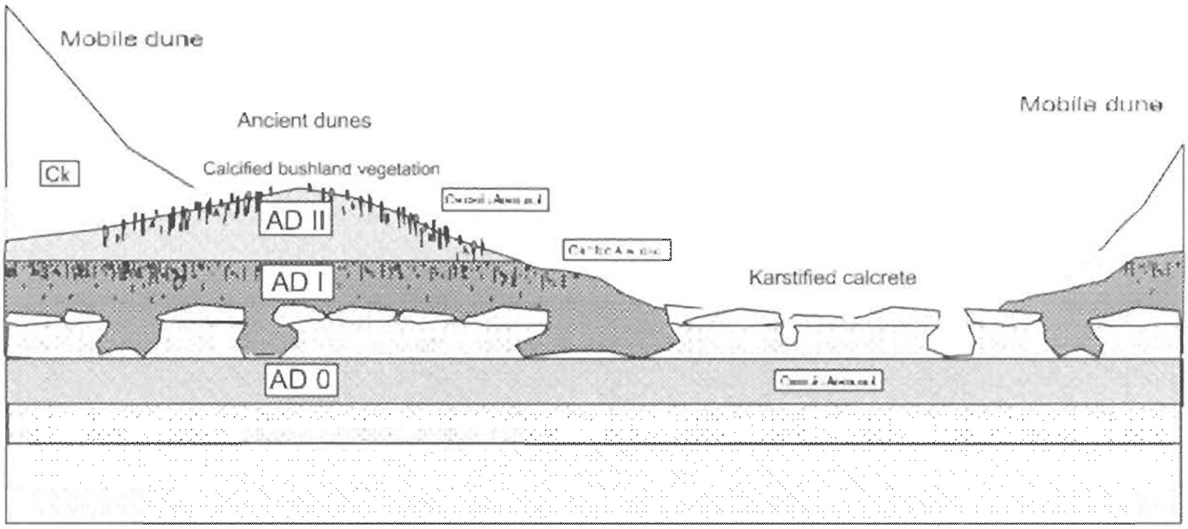

Fig. 2. Geelbek. Cross section of a deflation bay in the dune field. The basal karstified calcrete is covered by two different ancient dunes with paleosols and mobile longitudinal dunes.
AD 0: Pleistocene ancient dune older than the basal calcrete. In some places a brown Bwk horizon of a fossil Cambic Arenosol is developed directly underneath the calcrete, which shows an irregular accumulation of secondary carbonate due to the infiltration of bicarbonate from the calcrete above.
AD I: Pleistocene ancient dune above the basal calcrete, with an up to 2 m thick decalcified, brown (7.5YR 6/4) bBw horizon of a fossil Cambic Arenosol
AD II: Holocene ancient dune with a weakly weathered, brownish yellow (10YR 7/4) bBwk horizon of a fossil Cambi-calcaric Arenosol, which is strongly enriched by secondary carbonates, filling insect burrows and root channels. Former roots of bushes, which pass through the paleosol, and fragments of stems and branches, which cover the soil surface, are partly or completely calcified.
Ck: Mobile dunes: Light yellow, calcareous fine sand

3.2.1 Paleosol in the ancient dune, AD 0

The paleosol AD 0 in the ancient dune below the basal calcrete consists of a ca 1 m thick, brown (10YR 6/3) bBw horizon that was infiltrated by secondary carbonates from the overlying hardpan calcrete. The decreasing concentration of $CaCO_3$ with depth from the upper boundary of the paleosol and the formation of pedogenic Fe and Mn-oxides and amorphous silica prove that the bBw horizon was originally decalcified by the leaching of carbonates, which caused the weathering of silicates (Fig. 3). Decalcification of the topsoil and subsoil horizons led to the formation of an enrichment horizon of calcium carbonate below the bBw horizon (Fig. 3) which gradually developed into a lower hardpan calcrete (Figs. 1 and 2). The paleosol represents a long period of semi-arid conditions in which the depth of decalcification was restricted by the low amount of rainfall. Nonetheless, the length of the period of soil formation sufficed to cause intensive weathering of silicates in the decalcified topsoil and subsoil horizons.

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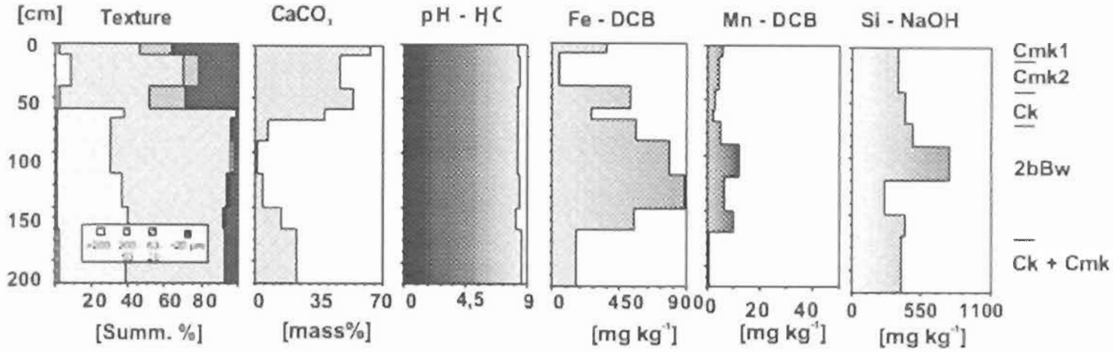

Fig. 3. Geelbek. Physical and chemical characteristics of the fossil Cambic Arenosol developed in AD 0. (Stratigraphic position shown in Figs. 1 and 2.)

3.2.2 Paleosol in the ancient dune, AD I

The paleosol in AD I is a strongly weathered Cambic Arenosol up to 2 meters thick. The soil horizons are free of carbonates, and weathering of silicates has brought about the dark brown (7.5YR 5/4) color. The analytical data presented in Fig. 4 show that the amount of fines (< 63 μm) is very low and ranges from 3–5 mass % in all horizons. Although all paleosol horizons are free of calcium carbonate, the soil horizons display pH values around 8, which result from a low concentration of soluble salts (< 100–200 mg kg^{-1}, mainly Na salts) in combination with a low buffer capacity. Sea spray and deposition by rain are assumed to be the source of the salts. The pedogenic iron and manganese oxides and amorphous silica (Fig. 4) which were formed by weathering of silicates in an acid environment indicate that the soil formation occurred under rather humid climatic conditions, causing decalcification and acidification of the ancient dune. The depth of decalcification exceeds 2 m in the investigated profiles down to the base of the dune. Therefore, the formation of an enrichment horizon of calcium carbonate and the formation of a hardpan calcrete below the bBw horizon was not possible. According to Netterberg (1969) hardpan calcretes occur in areas that receive less than 550 mm annual precipitation and calcification is generally absent in areas with an annual rainfall of more than 800 mm (de la Cruz, 1978). Therefore the decalcified, comparatively strongly weathered paleosol developed on AD I represents a long period of semi-humid to humid climate.

Unfortunately an IRSL date of the ancient dune, which could delimit the period of soil formation, is not available. But in some localities the paleosol surface of AD I is characterized by an associated, brown-stained, sub-fossil, faunal assemblage and a Later Stone Age lithic assemblage (Kandel et al. this volume).

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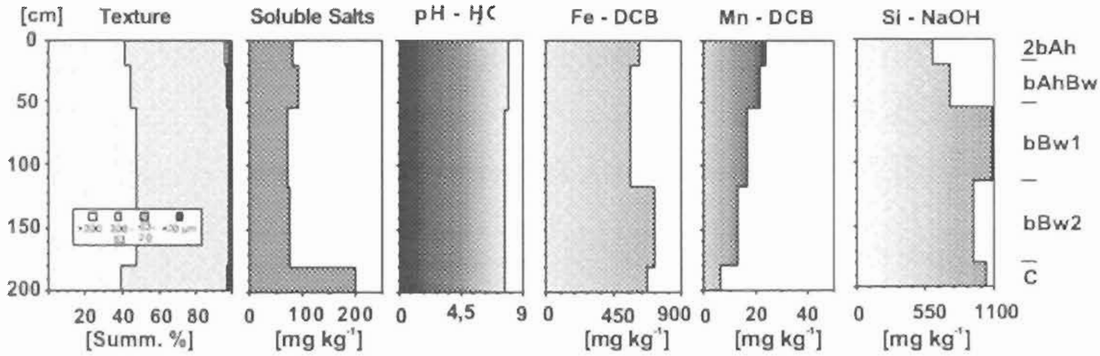

Fig. 4. Geelbek. Physical and chemical characteristics of the fossil Cambic Arenosol developed in AD I. (Stratigraphic position shown in Figs. 1 and 2.)

3.2.3 Paleosol in the ancient dune, AD II

The paleosol in ADI is overlain by the younger ancient dune (AD II), on which a fossil Calcaric Arenosol has formed. Both the bAh horizon and the underlying, weakly weathered bBw-Ck horizon of light orange (10YR 7/4) color contain carbonates, mainly in the form of calcified roots and small nodules. The carbonate content (about 2 mass %, Fig. 5) of the soil horizons is distinctively lower than the carbonate content of the recent mobile dunes (8–36 mass %). Based on the weak weathering of silicates, the initial stage of a bBw horizon indicates a rather short period in which the subsoil must have been free of carbonates. The concentration of carbonates in insect burrows and pores indicates that the major part of the carbonates accumulated by re-calcification. Furthermore, a diagenetic transformation of the former dune vegetation into calcified wood (roots and lower part of stems) is a unique characteristic of AD II. The presence of calcified wood shows that the leaching of bicarbonate from the recent, mobile dunes must have caused both the fossilization of the wood and the secondary enrichment of the paleosol horizons with calcium carbonate. Therefore, the paleosol of AD II indicates a short period of humidity higher than today but distinctively lower than the humid period during which the Cambic Arenosol developed on AD I.

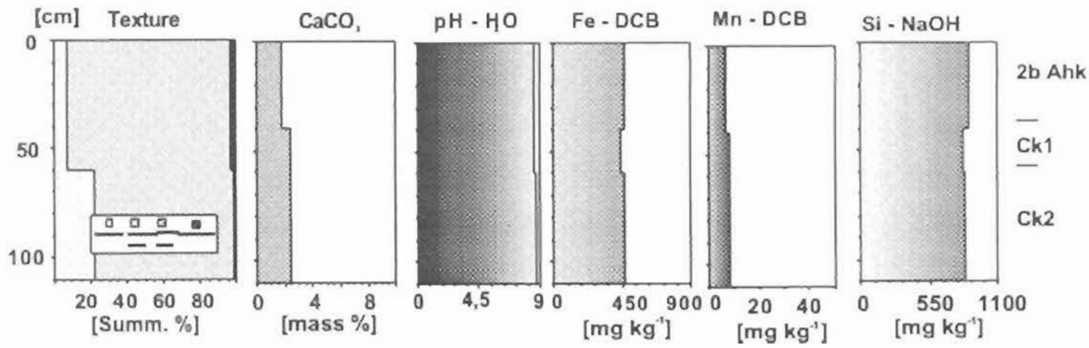

Fig. 5. Geelbek. Physical and chemical characteristics of the fossil Cambi-calcaric Arenosol developed in AD II. (Stratigraphic position shown in Figs. 1 and 2.)

Prehistoric ceramics have been documented on AD II, thus providing a maximum age of 1900 BP, the time when ceramics first occur in the southwestern Cape (Deacon and Deacon 1999.) Preliminary IRSL dates of 5 to 6 ka appear to be reliable for the deposition of the sand in AD II. This shows, that the recent mobile dunes, which cover AD II to a thickness of 10–30 meters approached the study area after 1900 BP.

4.0 Conclusions

The preliminary results of paleopedologic analyses used in conjunction with archaeological data have been successfully applied to reconstruct patterns of ancient geological processes, paleoenvironments and the history of archaeological settlement in the Geelbek region. The calcretes and Arenosols that developed on ancient dunes at Geelbek have unique characteristics and can be used as both stratigraphic marker horizons and paleoclimatic indicators. Stratigraphically the paleosols indicate phases in which deposition of aeolian sand and migration of the dunes was not possible because a cover of dense vegetation anchored the dunes. The shift to more arid climatic conditions caused the beginning of another phase of dune sedimentation and migration.

The degree to which the availability of aeolian sand at the coast, affected marine streams, transgression and regression phases, influenced the inland migration of the dunes apart from the paleoclimate is not yet clear. But since the dunes remain mobile under modern climatic conditions, the paleosols indicate phases of higher annual precipitation than today. Apart from the intensity of decalcification and weathering of silicates due to the degree of humidity, the period of soil formation also must be taken into account. A short period with high humidity may yield the same soil characteristics as a long period of arid climatic conditions. A more detailed interpretation will only be possible in future investigations when the further application of dating methods for soil components and sediments allows a limitation of the absolute ages of the paleosols.

5.0 Acknowledgements

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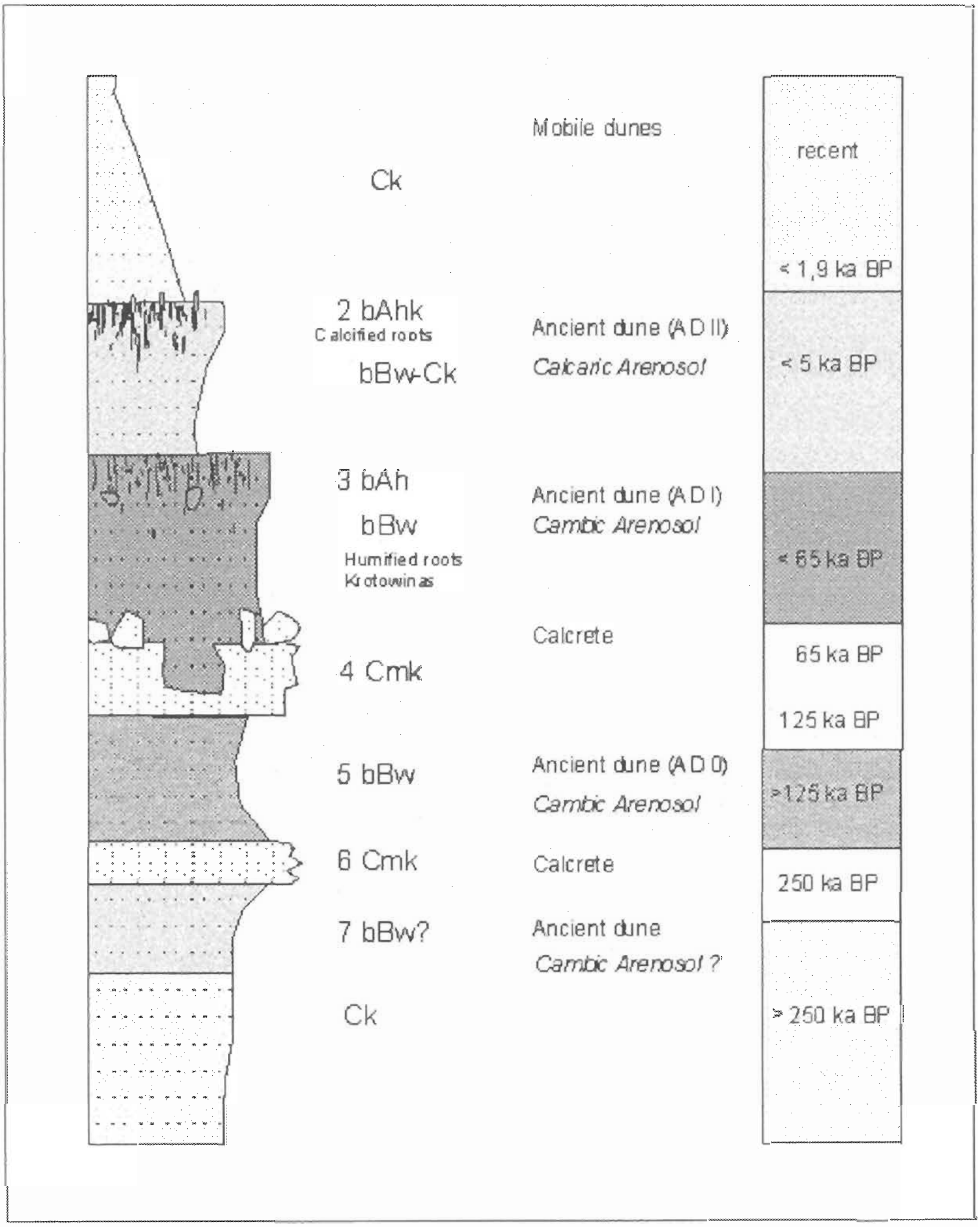

Fig. 6 Geelbek. Idealized stratigraphic sequence of ancient dunes, calcretes and paleosols with an estimation of the absolute ages of the calcretes and ancient dunes based on preliminary dating results.

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