Catena 100 (2012) 57–73

Contents lists available at SciVerse ScienceDirect

Catena

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

A micromorphological view through a Namaqualand termitaria (*Heuweltjie*, a Mima-like mound)

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ARTICLE INFO

Article history:
Received 18 September 2011
Received in revised form 6 August 2012
Accepted 9 August 2012

Keywords:
Biogenic calcite
Calcrete
Faecal spherulites
Radial ooids
Sepiolite
Silica cementation

ABSTRACT

'*Heuweltjies*' occur throughout Namaqualand and the western and southern Cape coasts: broad, low-relief termitaria of the harvester termite *Microhodotermes viator* which show different vegetation patterns to the surrounding soils, distinguishable even in satellite images. There is a direct relationship between soil hardpan occurrence and the heuweltjies. Characteristically in the semi-arid areas the hardpans grade outwards from a central sepiolitic petrocalcic horizon laterally through '(petro) sepiolitic/palygorskitic' (variable in the degree of cementation) to the petroduric horizon on the edges, in a landscape in which these hardpans are otherwise absent. The aim of the study was to investigate the genesis of these hardpans associated with the heuweltjie mound, with a particular focus on the build-up of calcite and sepiolite. The micromorphological study examined a transect through a representative sepiolite-bearing heuweltjie on the coast near the Olifants River mouth, and revealed evidence of termite activity in the central (petro)calcic part of the mound. This concentration of calcite and Mg-rich clay in the centre can be explained by termite foraging, as the regionally characteristic Ca- and Mg-rich foliage is moved into the centre of the mound, facilitating the precipitation of calcite and sepiolite as bacterial decomposition and subsequent leaching modify the soil solution in the mound. The increase in coarse/fine ratio from the centre outward showed that accumulation of calcite and sepiolite displaced the original sand matrix by a greater degree than the silica accumulation, consistent with the topographically raised surface in the centre. Limpid yellow, low birefringent nodules, some with pseudo-negative uniaxial interference figures, showed a fibrous nature under ESEM, and their low Ca, and molar Mg/Si ratios of 0.64 to 0.68 (ESEM-EDX) were consistent with sepiolite. The presence of the sepiolite, with its Mg-rich composition and hydrophilic character, together with organic acids generated from the vegetation collected by the termites, is considered to be an explanation for the formation of 'ooids', radial calcite crystals associated with a core of sepiolite. Colourless, non-calcareous, pseudo-uniaxial negative spherulites were present in fresh termite excrement from an active heuweltjie near Stellenbosch. These were either produced in the termite gut itself or had been ingested along with herbivore dung by the termites. The presence of faecal spherulites in termite excrement is significant since it shows that faecal spherulites can be distributed over a wider area than that directly associated with mammalian herbivores.

1. Introduction

'Heuweltjies' (pronounced 'he-u-vill-keys', Afrikaans for small hills) are distinguishable in the field as circular features (usually 10 to 20 m diameter) showing a different vegetation pattern and a slightly raised (1 to 2.5 m) surface, presenting what Laurie (2002) referred to as an "ostrich leather" texture in aerial view. Their zone of occurence is restricted to Namaqualand and the western and southern Cape coasts in the Fynbos and Succulent Karoo biomes, where they occupy 14–25% of the land surface (Lovegrove and Siegfried, 1989; Moore and Picker, 1991). Their distribution is shown in detail by Lovegrove and Siegfried (1986), Moore and Picker (1991) and Picker et al. (2007).

When using Google Earth (http://earth.google.com/) to observe the study area (Fig. 1) between Papendorp and Strandfontein, the heuweltjies become discernable as green circular features at an eye altitude of 2 to 5 km. They represent zones of denser vegetation because of the nutrient cycling into the heuweltjie (Midgley and Hoffman, 1991; Midgley and Musil, 1990) and higher base status of on-mound compared to off-mound soils (Ellis, 2002, 2004). A good example is evident at the location 31° 44′ 10″ S, 18° 14′ 20″ E, between Strandfontein and the heuweltjie in the present study, where the greener vegetation pattern of heuweltjies has persisted through subsequent ploughing and cropping.

Heuweltjies are sometimes described as Mima-like mounds (Cox et al., 1987; Lovegrove and Siegfried, 1986, 1989; Milton and Dean,

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http://dx.doi.org/10.1016/j.catena.2012.08.004

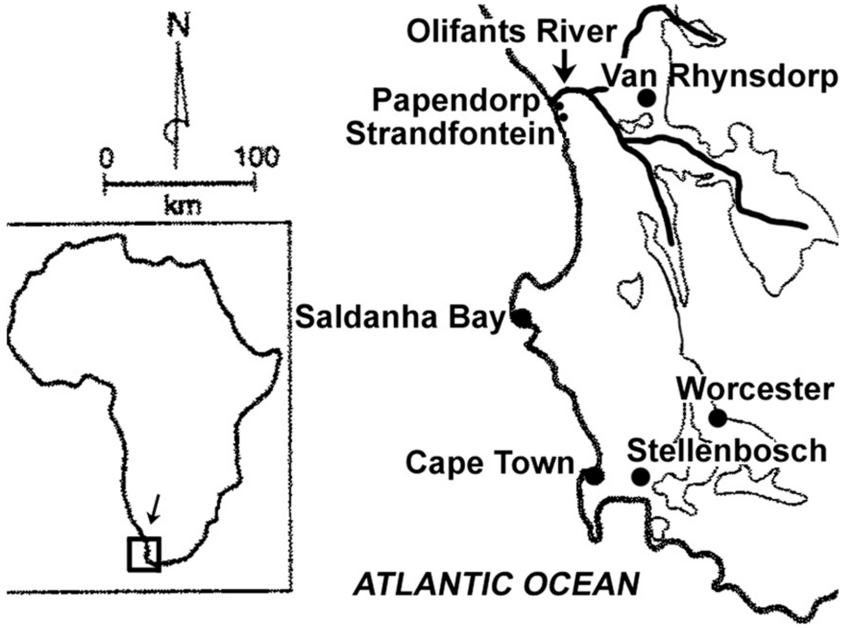

Fig. 1. Location of Papendorp–Strandfontein and Stellenbosch, where heuweltjies were sampled for this study. Modified from Pether et al. (2000).

1990). Numerous origins for Mima mounds have been proposed Washburn, 1988, commonly bioturbation by burrowing rodents (Horwath and Johnson, 2006, 2007; Litaor et al., 1996; Nelson, 1997), and also local groundwater action (Reider et al., 1996). They are similar to heuweltjie soils in their raised surfaces, silica and/or calcium carbonate hardpans, clay-accumulation horizons (Hobsan and Dahlgren, 1998; Spackman and Munn, 1984), as well as their organic matter (nitrogen) enrichment (Hobsan and Dahlgren, 1998; Litaor et al., 1996; Midgley and Musil, 1990). They differ in that the Mima mounds do not contain sepiolite or palygorskite, only smectite, kaolinite (Hobsan and Dahlgren, 1998) and illite (Spackman and Munn, 1984), and we have not observed in heuweltjies the plug or central pipe that was noted by Spackman and Munn (1984) and Reider et al. (1996).

Heuweltjies are thought to be termitaria of the harvester termite *Microhodotermes viator* (Moore and Picker, 1991; Picker et al., 2007), with a contribution from mole rats and other animals (Cox et al., 1987; Laurie, 2002; Lovegrove and Siegfried, 1986; Lovegrove and Siegfried, 1989; Midgley and Hoffman, 1991; Milton and Dean, 1990). Picker et al. (2007) provided evidence for the construction of the heuweltjies by their current *M. viator* occupants.

M. viator is endemic to the Western and Northern Cape, occurring in both summer and winter rainfall regions (Coaton and Sheasby, 1974; Lovegrove and Siegfried, 1986). Their distribution overlaps that of the heuweltjies (Lovegrove and Siegfried, 1986), with the exception of the Ruensveld in the southern Cape, from which heuweltjies are absent (Fey et al., 2010), although it is possible that the heuweltjies have been eroded in this region leaving only the basal layers (Lovegrove and Siegfried, 1986).

Unlike the spire-building *Macrotermes* species that occupy the humid eastern parts of South Africa, *Microhodotermes (Hodotermitidae)* lacks a fungus culture and differs from most termites worldwide by being a detritivore as well as a herbivore, consuming fresh faeces of herbivores and harvesting fresh foliage (Fey et al., 2010).

δ^{14}C ages of heuweltjie calcite fall into two groups: less than ca. 8000 years before present (BP) (Moore and Picker, 1991), and ca. 20 000–35 000 years BP (Coaton, 1981; Midgley et al., 2002; Potts et al., 2009). δ^{14}C dating and trace-fossil evidence was used by Moore and Picker (1991) to argue for the continuous occupation by *M. viator* for at least the last 4000 years near Clanwilliam. Potts et al. (2009) used stable isotope analyses of calcrete associated with a heuweltjie near Worcester to infer paleoclimate and vegetation conditions in the region during the Last Glacial Maximum (LGM). They concluded that the heuweltjie has been present in the landscape for at least the last 36 000 years, with the period of calcrete formation taking place prior to 22 000 years BP due to the subsequent reduction in rainfall after the wetter LGM period.

There is a direct relationship between the soil horizons in the heuweltjie soils, and rainfall (Ellis, 2002): in areas with less than 250 mm rainfall annually, termite activity is presently low and the mounds are characterised by a central petrocalcic horizon. The outer edge and surrounding inter-mound areas are typified by a petroduric horizon, often overlying a deeper petrocalcic horizon. In the drier northern area of Namaqualand, the petrocalcic horizon at the centre of the heuweltjie is sometimes partly replaced with a petroduric horizon. In higher rainfall zones (250 to 450 mm) where termites are more active, calcic horizons are associated with the areas of activity in the centre of the mound, and petroduric or petrocalcic horizons on the perimeter of the mound — even when neither of these occur in surrounding soils. With increasing rainfall, age, or relict termite activity, only a broken (petro) calcic horizon and/or more base-rich soil material can be found on the mounds.

Francis (2008) noted the association of the fibrous clay minerals sepiolite and palygorskite with some of the heuweltjies in the lower rainfall zone (less than 250 mm annual precipitation). Sepiolite and palygorskite are distributed throughout the Namaqualand region (50–250 mm annual precipitation, Desmet, 2007) where they are generally associated with calcareous soils (Francis, 2008; Singer et al., 1995) but their high concentration and formation of distinct coatings up to 5 mm thick on calcic peds appear to be particularly characteristic of the heuweltjie soils. These fibrous clay minerals are concentrated in a zone between the (petro)calcic horizons in the centre of the heuweltjie mound, and the petroduric horizons at the edges, overlapping the calcic horizons.

In this study we focussed on a mound that can be considered typical, with a well developed petrocalcic–sepiolitic (Francis et al., 2012)–petroduric B-horizon variation from the centre of the heuweltjie outwards. The aim of the study was to investigate the genesis of the hardpans associated with the heuweltjie mound, with a particular focus on the build-up of calcite and sepiolite.

2. Materials and methods

2.1. Papendorp–Strandfontein

The Papendorp heuweltjie is located at 31° 42′ 32″ S, 18° 13′ 32″ E, elevation 60 m a.m.s.l., on the south side of the Olifants River mouth, on a road-cut along the R362 between the towns of Papendorp and Strandfontein (Fig. 1), on an undulating coastal plain, sea-facing (west) in natural veld (natural pasture, intermittently used for grazing or has been in the past). Vegetation is the Sandveld bioregion of the Succulent Karoo (Desmet, 2007). Mean annual rainfall for the Papendorp/Strandfontein area is < 150 mm. Termite activity is presently low, increasing after rainfall. Approximately 2 kg bulk sample was taken from each horizon of the Papendorp heuweltjie, as well as undisturbed material for the preparation of thin sections. Soils were classified according to WRB (2006) and the sepiolitic horizons according to Francis et al. (2012). A 10% solution of HCl was used to test for carbonate, 30% H_2O_2 for manganese, and the presence of sepiolite was indicated by a purple reaction of methyl orange (Mifsud et al., 1979).

Slaking tests were based on the WRB (2006) definition of petroduric, petrocalcic and fragic horizons. An intact fragment a few centimetres in diameter was submerged in water, 5 M HCl or 6 M NaOH and gently heated on a waterbath for four days.

Thin sections for optical microscopy from the Papendorp heuweltjie were impregnated with a polyester resin and ground without water, and left uncovered on one side to allow for etching and SEM-EDX work. Micromorphological descriptions followed the scheme of Stoops (2003). Fine grained calcite was identified by effervescence in 1 M HCl under the optical microscope. Calcite was distinguished from calcium oxalate by using 2 M acetic acid: calcium oxalate is insoluble in 2 M acetic acid, whereas both calcium carbonate and calcium phosphate are soluble in this solution (Post, 1985). Uncoated fragments and thin sections were observed before and after etching in 1 M HCl using low vacuum SEM-EDX with a Philips Xl30 ESEM. High vacuum SEM was done on Au-coated fragments using a Leo 1430VP SEM-EDX system.

For XRD analysis of the clay fraction, the bulk samples were air-dried, crushed and passed through a 2 mm sieve. The method was modified from Soil Survey Staff (1996). The <2 μm fraction was separated from the bulk samples by dispersion (shaking briefly by hand, raising the pH to approximately 10 with Na_2CO_3) and settling. The clay suspension was flocculated by addition of $MgCl_2$ after lowering the pH to 5 to 7 with HCl to prevent the precipitation of brucite and/or clay destruction. The clay suspension was then Mg-saturated, concentrated by centrifugation, and sedimented (or smeared; many of the sepiolite-rich samples developed 'mudcracks') onto a glass slide. XRD analyses were done with a stepsize of 0.05° and steptime of 40 s, using a Bruker DD8 Advance Powder Diffractometer with a graphite monochromator, 40 kV and 40 mA. Ethylene glycol was sprayed lightly onto the surface of the Mg-saturated sample slides. TEM-EDAX analyses were performed on the clay fractions using a Philips CM120 Biotwin equipped with EDAX detector.

Soil solution composition was measured in equilibrated saturated paste extracts. The pH of the saturated paste was measured directly. The solution was extracted under vacuum and analysed. Electrical conductivity (EC) was measured using a calibrated conductivity meter; alkalinity, by potentiometric titration to pH 4.5 with 0.01 M HCl; major cations (Ca^{2+}, Mg^{2+}, K^+, and Na^+) by atomic absorption spectroscopy; anions (Cl^-, F^-, NO_2^-, NO_3^-, Br^-, and SO_4^{2-}) by ion chromatography; Si using the blue silicimolybdous acid procedure of Weaver et al. (1968) (described by Hallmark et al., 1982), and P using Bray II (Bray and Kurtz, 1945). Organic carbon was analysed following the Walkley–Black method (Walkley, 1935). NH_4OAc (pH7) extractable bases where analysed using the Büchner funnel method (Soil Survey Staff, 1996), ssir42 is the reference key. Major element leaf and stem analyses of *Cephalophyllum* spp. (Vygies) from the Papendorp–Strandfontein heuweltjie followed the method of Beyers (1962), ashing to 500 °C and acidification with 1:1 HCl(v/v) before dilution with distilled water.

2.2. Stellenbosch

Thin sections were made through unmineralised exit towers (protruding spires approximately 10 cm high, diameter 8 to 10 mm) and frass (excrement) from the surface of an active heuweltjie in Stellenbosch in 2005, in order to assist in the recognition of these features in the mineralised Papendorp heuweltjie, following the assumption that the size and shape of the frass and tunnels would be consistent across the species.

The Stellenbosch heuweltjie is located on the south side of Papegaaiberg (Stellenbosch) above the graveyard in a pine plantation (33° 56′ 15″ S, 18° 50′ 29″ E, elevation 156 m a.m.s.l.). The soil is a non-calcareous, yellow-brown apedal material (kaolinite, illite) developed from granite. Mean annual rainfall for the Stellenbosch area is > 650 mm and so sepiolitic and calcic horizons are absent.

The excrement samples were collected loose and randomly oriented on the sections. Two termite exit towers were sampled, both of which were orientated in cross-section. Thin sections were impregnated with an epoxy resin under vacuum and ground without water.

3. Results

3.1. Profile descriptions

Profile descriptions through a cross-section of the heuweltjie are given in Table 1. The soils of the heuweltjie are typical of those in the arid western parts of South Africa, with a nodular to massive petro-/hypercalcic horizon in the centre of the mound, white, non-calcareous sepiolite coatings on the nodules, and a brown petroduric horizon at the edges (Fig. 2). Between the two is a hard but friable horizon that is composed of light brown, nodular, non-calcareous peds covered by white sepiolite coatings and infillings. These adhered to the wetted tongue, and tested positive for sepiolite with both methyl orange (Mifsud et al., 1979) in the field and later by XRD analysis (Fig. 3). The term 'sepiolitic' was suggested by Francis et al. (2012) to describe non-indurated sepiolite-rich horizons that contain neither sufficient silica nor calcite to be classified as a calcic or duric horizons, particularly with respect to the slaking requirements of these horizons, or as a descriptive prefix where sepiolite dominates the macroscopic features of the horizon. The sepiolitic features were not present in the petroduric horizon at the edge of the heuweltjie (Table 1).

3.2. Clay mineralogy

3.2.1. (Petro)calcic horizons at the centre of the heuweltjie

XRD analyses of the clay fraction (Fig. 3), showed a dominant 1.28 nm peak for the (petro)calcic horizons (samples 2A to 2C) in the centre of the heuweltjie. With the exception of mica, the peaks of its overlying cambic horizon (sample 2.2) were not as well defined. Hay and Wiggins (1980) also found a broad 1.26 to 1.4 nm peak for sepiolite-rich calcretes of the southwestern United States with a similar dominance of sepiolite over palygorskite.

3.2.2. Sepiolitic horizon 7.5 m from the centre of heuweltjie: sample 2D

The clay mineralogy of sample 2D is less clear: it adhered to the wetted tongue, but the darker colour (Table 1) meant that the methyl orange test was only clear on the white, non-effervescent coatings (Fig. 2), where it turned purple suggesting sepiolite. It did not show as clear a sepiolite peak as the (petro)calcic samples 2A to 2C in the centre of the heuweltjie. The major clay peak was broader and centred around 1.4 to 1.5 nm. The 1.28 nm peak became more

Table 1
Profile descriptions from the Papendorp heuweltjie pictured in Fig. 2. South African Classification System: Soil Classification Working Group (1991).

Sample			WRB (2006)	pH†	Munsell		Field texture	Structure	Consisitency			Effervesce HCI	Methyl orange‡	Slake (0 = no, 5 = full)			Water absorption	Roots	Transition	Other features
					Dry	Moist			Dry	Moist	Wet			HCI	NaOH	Water				
Profile "2": centre of the heuweltjie. South African Classification System: Kimberley Form (Orthic A–Red Apedal B–Soft carbonate) and Plooysburg Form (Orthic A–Red Apedal B–Hardpan carbonate)																				
0–0.1 m	2.1	A	Ochric.	7.6	5YR 4/4	5YR 4/6	Medium sand.	Apedal.	Loose.	Loose.	Non-plastic, non-sticky.	None.	Remains orange.				3	Common.	Abrupt, smooth.	Tunnel ~3 cm diameter, few macropores. Bleached; 2 mm crust.
0.1–0.55 m	2.2	Bw	Cambic.	6.9	5YR 5/4	5YR 4/6	Medium sand.	Apedal.	Loose.	Loose.	Non-plastic, non-sticky.	None.	Remains orange.				1	Few.	Abrupt, wavy to tonguing.	Few macropores.
0.55 m	2A	Bk	Calcic.	8.3	5YR 8/2	5YR 7/3	–	Nodular.	Hard.	Friable.	Sl. plastic, sl. sticky.§	Strong.	Purple-pink.	5	5	–	3	Few.	Not reached.	White sepiolite coatings on peds.
Sampled at 1 m depth	2B (sampled 2 m away from 2A. Horizon grades laterally in sample number sequence 2A–2B–2C–2D from centre to edge of heuweltjie in cross-section.)																			
		Bkm	Petrocalcic.	–	5YR 8/2	7.5YR 7/4	–	Massive.	Hard.	Hard-Friable.	Sl. plastic, sl. sticky.§	Strong.	Purple-pink.	4	2	–	>20	Few.	Not reached.	Tunnels ~3 mm wide, 3 cm long; white sepiolite coatings on peds.
	2C (sampled 3.2 m away from 2A. Horizon grades laterally in sample number sequence 2A–2B–2C–2D from centre to edge of heuweltjie in cross-section.)																			
		Bk	Calcic.	–	5YR 8/2	5YR 8/3	–	Nodular.	Hard.	Friable.	Sl. plastic, sl. sticky.§	Strong.	Purple-pink.	4	5	4	3	Few.	Not reached.	Few cracks; common white sepiolite coatings on peds.
	2D (sampled 7.5 m away from 2A. Horizon grades laterally in sample number sequence 2A–2B–2C–2D from centre to edge of heuweltjie in cross-section.)																			
		Bt	Sepiolitic.	–	7.5YR 4/2	7.5YR 4/4	–	Medium blocky.	Hard.	Friable.	Sl. plastic, sl. sticky.§	None	Purple-pink on white coatings.	2–3	4	4	5	Few.	Not reached.	Tunnels ~3 mm wide, 3 cm long; abund. cracks; white sepiolite coatings and infillings on peds
Profile "1": located at edge of heuweltjie, approximately 8 m laterally from 2D. South African Classification System: Garies Form (Orthic A–Red Apedal B–Dorbank)																				
0–0.04 m	1.1	A	Ochric.	8.7	5YR 4.5/6	5YR 3/4	Medium sand.	Apedal.	Loose.	Loose.	Non-plastic, non-sticky.	Slightly on surface of crust.	Remains orange.				3	Common.	Abrupt, smooth.	Few macropores. Bleached, 2 mm thick crust.
0.04–0.15 m	1.2	Bw	Cambic.	8.5	5YR 4.5/6	5YR 4/6	Medium sand.	Apedal.	Loose.	Loose.	Non-plastic, sl. sticky.§	None.	Remains orange.				1	Few.	Abrupt, smooth.	Few macropores.
0.15 m‡–	1.3	Bqm	Petroduric.	9.1	7.5YR 5/6	7.5YR 3.5/4	–	Massive.	Very hard.	Firm.		None.	Remains orange.	0	3–4	–	5	None.	Not reached.	Few fine cracks.

†Saturated paste. ‡Changes to purple-pink in the presence of sepiolite or Mg-smectite (Mifsud et al, 1979). §Sl.: slightly. Water from dropper spreads instantly away along very fine cracks (dendritic pattern).

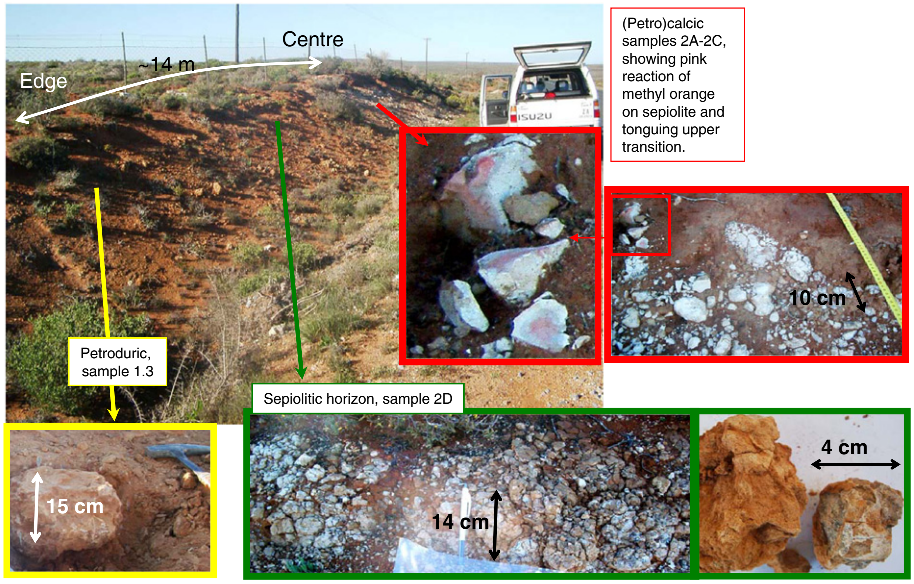

Fig. 2. Photographs of cross-section through heuweltjie. White sepiolite coatings reacted purple-red with methyl orange. Detailed descriptions are given in Table 1.

apparent on glycolation. TEM images (Fig. 4a) of the <0.08 μm fraction from sample 2D showed fibrous minerals to be present, consistent with the presence of sepiolite.

3.2.3. Petroduric horizon at edge

The petroduric horizon (sample 1.3) and its overlying cambic horizon (sample 1.2) showed poorly defined clay peaks. These broad clay peaks could be a function of disordered siliceous coatings masking the clay minerals (Blank and Fosberg, 1991; Flach et al., 1969). Fibrous clay minerals were not apparent (Fig. 4b).

3.3. Micromorphology of termite frass and exit towers: Stellenbosch heuweltjie

The excrement comprised non-calcareous ellipsoids (0.8 × 0.4 mm) and spheres 0.3 to 0.4 mm diameter (Fig. 5a). Each had a massive microstructure, a coarse/fine ratio (where the coarse material was coarser than 5 μm; $c/f_{5\mu m}$) of 1:20 that was considerably finer than any of the samples from the heuweltjie near Papendorp, and an open porphyric coarse/fine (c/f)-related distribution. The coarse material was mostly <30 μm, angular, acicular-prolate fragments that appeared to be silica, many of which were orientated perpendicular to one another (Fig. 5c and d). There were occasional 4 mm spheroidal quartz particles. The micromass appeared to be an organic–clay mixture, and had an undifferentiated to stipple-speckled birefringence fabric (b-fabric). The excrement contained spherulites 8 to 15 *μ*m diameter, non-effervescent with cold 10% HCl, with pseudo-negative uniaxial interference colours (Fig. 5b to d).

The termite exit towers (Fig. 6) had a 6 to 7 mm internal diameter. The wall was 3 to 5 mm thick and had a massive microstructure. They contained considerably more coarse material than the frass ($c/f_{5\mu m}$ ratio 3:1 and a close porphyric c/f-related distribution). The coarse material comprised angular, predominantly spheroidal quartz fragments 0.3 mm to 20 μm diameter. There was no change in composition on either inner- or outer wall surfaces. They were non-calcareous. The micromass appeared to be an organic matter–clay mixture with an undifferentiated b-fabric. It resembled the material shown by Jungerius et al. (1999). The wall included one ellipsoid excrement 0.85 × 0.3 mm (Fig. 6b), identical to the material in the excrement sample. The only spherulites (with pseudo-negative uniaxial interference colours) observed in both of the towers sectioned occurred within this excrement nodule.

Faecal spherulites in herbivore dung are 5–15 μm diameter (Canti, 1997), similar to the 8 to 15 μm diameter for those observed in the Stellenbosch termite excrement, and like those in Stellenbosch, always showed pseudo-negative uniaxial interference colours (Canti, 1998). According to Canti (1997, 1998, 1999) the faecal spherulites are composed of calcium carbonate, however, the Stellenbosch spherulites did not effervesce in cold 10% HCl. No reaction with HCl was observed by Brochier et al. (1992) either. However, Canti (1997) noted that the gas bubbles (but usually only one per spherulite) were clearly evolved, appearing almost immediately on wetting, and so could only be observed by allowing a front of HCl to advance onto dry spherulites in the field of view at high power magnification. This method was employed for the Stellenbosch samples but produced no visible effervescence.

3.4. Micromorphology of the heuweltjie at Papendorp

3.4.1. Cambic (Bw) over (petro)calcic horizons in the heuweltjie centre

The horizon was sampled just below its upper transition (section depth 0.1–0.2 m). It was non-calcareous and had very little clay. It consisted of subangular embayed quartz grains (0.4–0.8 mm and 0.005–0.1 mm diameter bimodal size distribution), which were coated with 0.025 mm thick amorphous iron oxides including hematite (red in oblique incident light). Interped areas and some voids surrounding the peds had much less of the fine (50 to 100 μm) material. Some of the coarser (0.4 to 0.8 mm) material appeared to be wedged in vertically elongated voids (planes, ped margins, channels). The $c/f_{5\mu m}$ ratio was 9:1. Void space was 40% of the section.

3.4.2. (Petro)calcic horizons in the heuweltjie centre

These contained much fewer sand grains (10–20%) compared to the overlying cambic horizon, and virtually no void space, represented by the $c/f_{5\mu m}$ ratio of 1:8. The coarse material appeared similar to the overlying horizon, predominantly quartz grains coated with red (OIL) Fe (hydr)oxides.

A weak to moderately separated granular microstructure was dominant. Granules (‘peloids’; ‘ooids’) were 0.3–0.03 mm diameter. Channels and chambers together formed approximately 10% of the section. Thin planar voids (0.6 mm × 3 cm) were present (~5% of

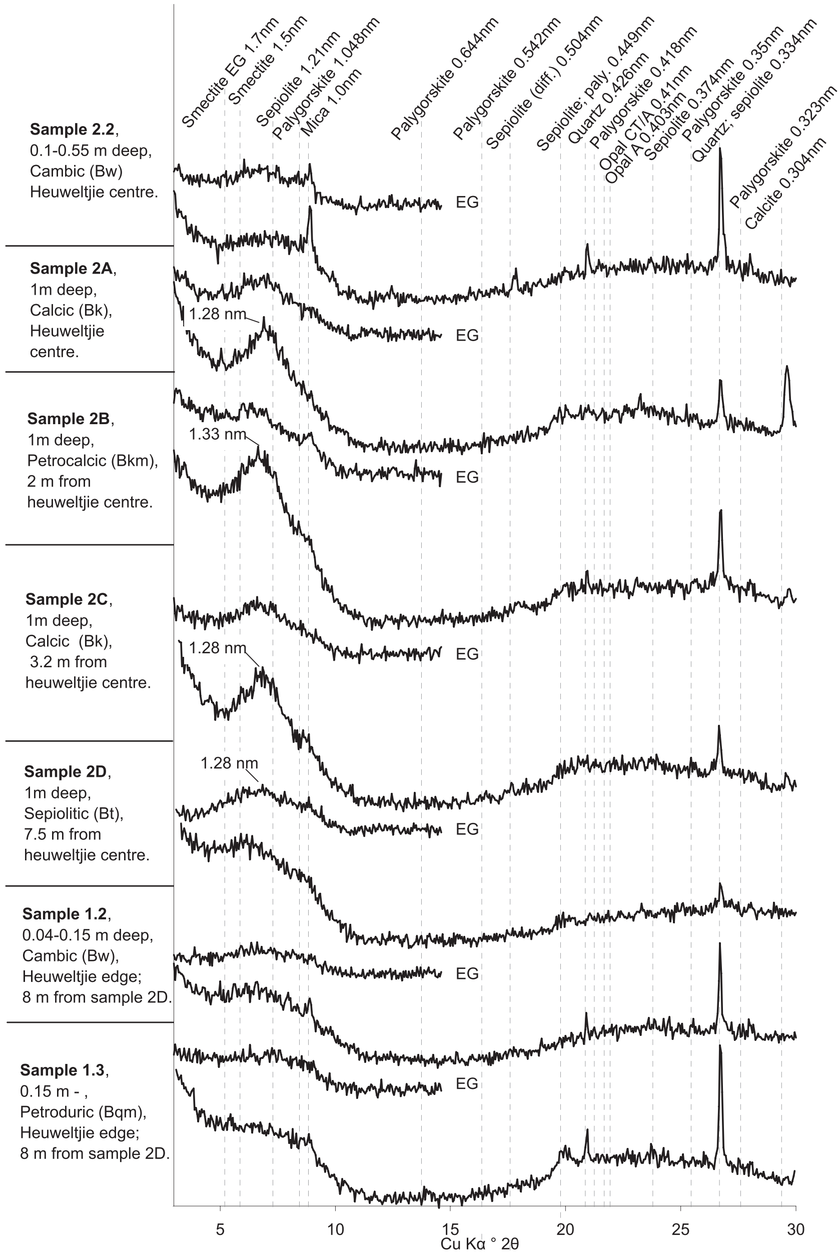

Fig. 3. XRD traces of Mg-saturated, <2 μm fractions of milled samples from Papendorp heuweltjie showing the relative intensities of the mineral peaks. Diff.: diffuse; EG: ethlyene glycol; paly.: palygorskite.

section), some of which contained fine roots in handspecimen and defined a larger scale moderately separated subangular blocky microstructure (comprising approximately 2 cm diameter peds).

The micromass was composed of micrite interspersed with clay, yellow to brown, speckled in plane polarised light (PPL), with Fe (hydr)oxides (yellowish-green under oblique incident light), and accessory dendritic or dispersed Mn oxides (effervesced in cold H_2O_2). A crystallitic b-fabric was dominant (micrite) with secondary granostriated b-fabric comprising clay and micrite. Sample 2B contained less micrite than samples 2A or 2C, and more abundant accessory dendritic or dispersed Mn oxides (40% of section). There were calcic pendants and cappings present (Fig. 7).

Evidence of biological activity could only be found in the (petro) calcic horizons in the centre of the heuweltjie (samples 2A to 2C). Neither the sepiolitic (sample 2D) halfway to the edge, nor the petroduric (sample 1.3) horizons at the edge exhibited such evidence. This is consistent with observations that the centre of the heuweltjie was where the termite activity was concentrated. Tunnels and chambers in the petrocalcic horizons (Fig. 7) were lined with organic matter. Dark ellipsoids (0.8×0.4 mm) appeared to be termite excrement, based on the morphology of the termite excrement from the active heuweltjie in Stellenbosch. Smaller excrement particles in the form of 0.1 to 0.05 mm diameter calcareous spheres were also abundant: within what appeared to be termite excrement; in calcified plant organ residue; and in a tunnel. Plant remains were present in the (petro)calcic horizons: some appeared to be fresh, but most were calcified. Highly birefringent phytoliths were present and composed of calcite, since they dissolved completely in 2 N acetic acid which eliminated the possibility of them being oxalate (Post, 1985). Rectangular silica phytoliths (isotropic) were also present.

3.4.2.1. Limpid yellow pseudo-negative uniaxial sepiolite spherulites and nodules. There were abundant limpid yellow nodules 300 to 70 μm in diameter (labelled (i) in Fig. 8a), some showing pseudo-negative

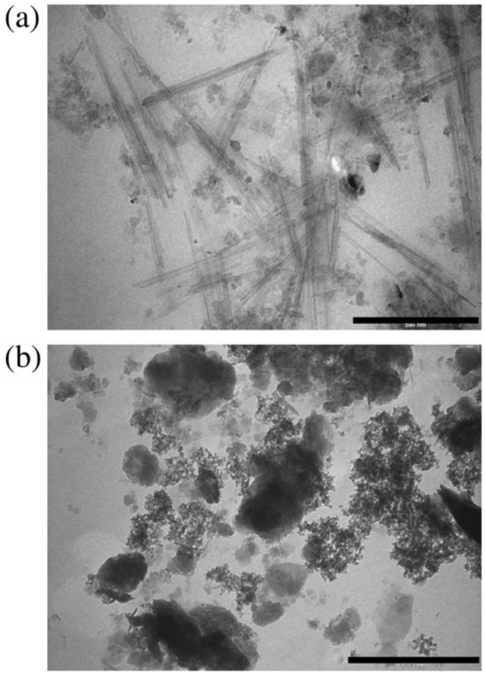

Fig. 4. (a) TEM image from sepiolitic sample 2D showing fibrous clay particles in <0.08 μm fraction. Scale bar 500 nm. (b) <2 mm fraction from petroduric sample 1.3, showing disordered aggregates and no fibrous material. EDAX analysis showed the large platy crystals to have a biotite composition. Scale bar 1 μm.

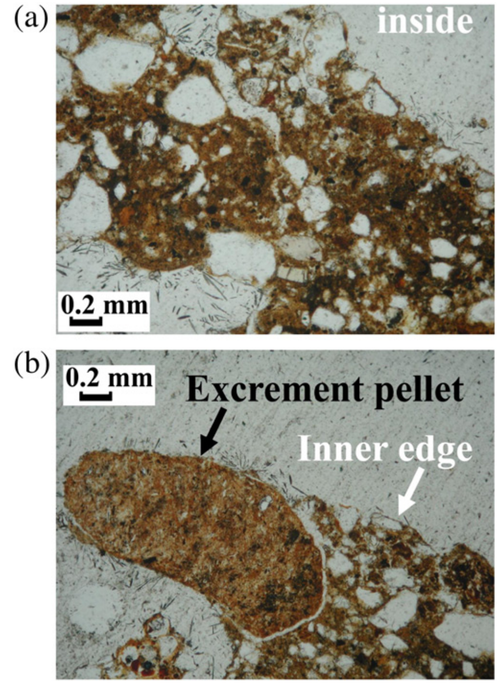

Fig. 6. (a) (b) Photomicrographs (PPL) of cross-section through termite exit towers, composed of subrounded quartz particles in a clay–organic matrix. Collected on the surface of an active heuweltjie on Papegaaiberg (Stellenbosch). Inward side of exit towers indicated. (b) Termite excrement pellet (arrowed) within wall of exit tower.

uniaxial interference figures (thereby meeting Canti's (1997) definition of spherulites as 'crystal aggregations with an approximately circular outline and a permanent cross of extinction in crossed polarised light'), usually with a dark round- or dumbbell-shaped core, and a dark rim between them and the matrix calcite (Figs. 9, 10). Some of the nodules seemed to have undergone 'micritization' which gave them a highly birefringent crystallitic b-fabric in the centre (labelled (ii) and (iii) in Fig. 8a) and which ESEM showed to be acicular calcite and micrite (Fig. 11). Their formation is discussed in Section 4.3.

3.4.2.2. Calcareous ooids and peloids. The granular microstructure that was most strongly developed in the centre of the heuweltjie comprised 0.3 to 0.03 mm diameter granules that resembled 'peloids'

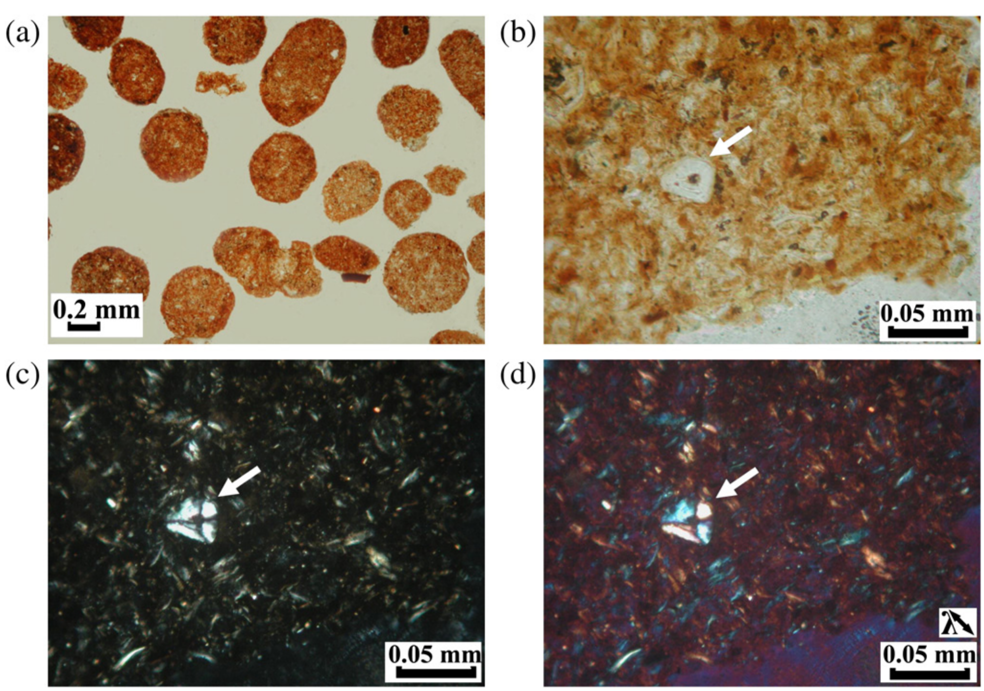

Fig. 5. Photomicrographs of termite frass composed of very fine quartz and organic matter. Collected loose, randomly orientated in resin from surface of active, non-calcareous heuweltjie on the south side of the Papegaaiberg (Stellenbosch).Figs. (b)–(d): Spherulite with pseudo-negative interference figure.(a)–(b) PPL, (c) XPL, (d) λ-plate, fast-direction NW–SE.

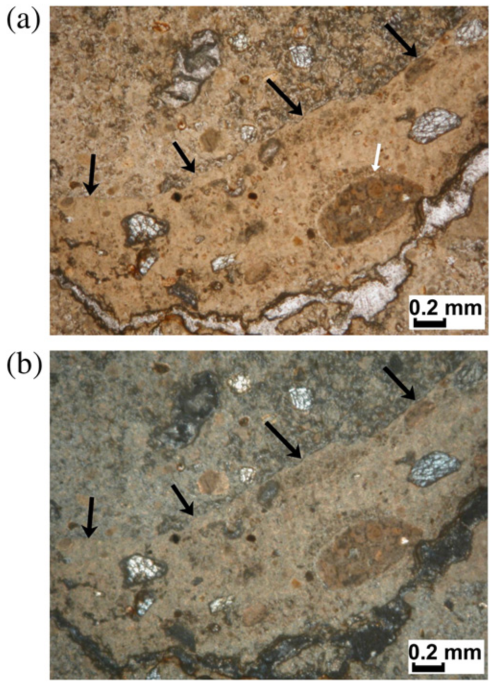

Fig. 7. Photomicrographs of calcite pendent (black arrows) and termite excrement (white arrow) associated with an organic matter-lined tunnel, calcic horizon sample 2C. Way-up is top of page. (a) PPL. (b) XPL.

(Fig. 8), and abundant micrite-coated grains that resembled 'ooids' (Fig. 9). Boggs (1995) defined 'ooid' as a general name for coated carbonate grains (0.02 to 2 mm in size) containing a nucleus (commonly a shell fragment, pellet or quartz grain) surrounded by coatings of fine calcite or aragonite. Most ooids display an internal structure consisting of concentric layers, but some show a radial structure. Boggs (1995) defined 'peloid' as a nongenetic term for carbonate grains composed of micro- or cryptocrystalline calcite/aragonite that did not display distinctive internal structures, generally smaller than ooids (0.03 to 0.1 mm).

The granules in the Papendorp heuweltjie often had a core of limpid yellowish sepiolite under the micrite (Figs. 8 areas (ii) and (iii), 9 (arrowed), 11). In some cases the core seemed to be hollow (Fig. 13). Where orientation could be discerned, the coatings were composed of radially oriented acicular calcite (Figs. 11, 13b). In many cases the radial acicular calcite was contained within concentric envelopes, forming successive layers of calcite (Figs. 9, 11a). Their formation is discussed in Section 4.3.

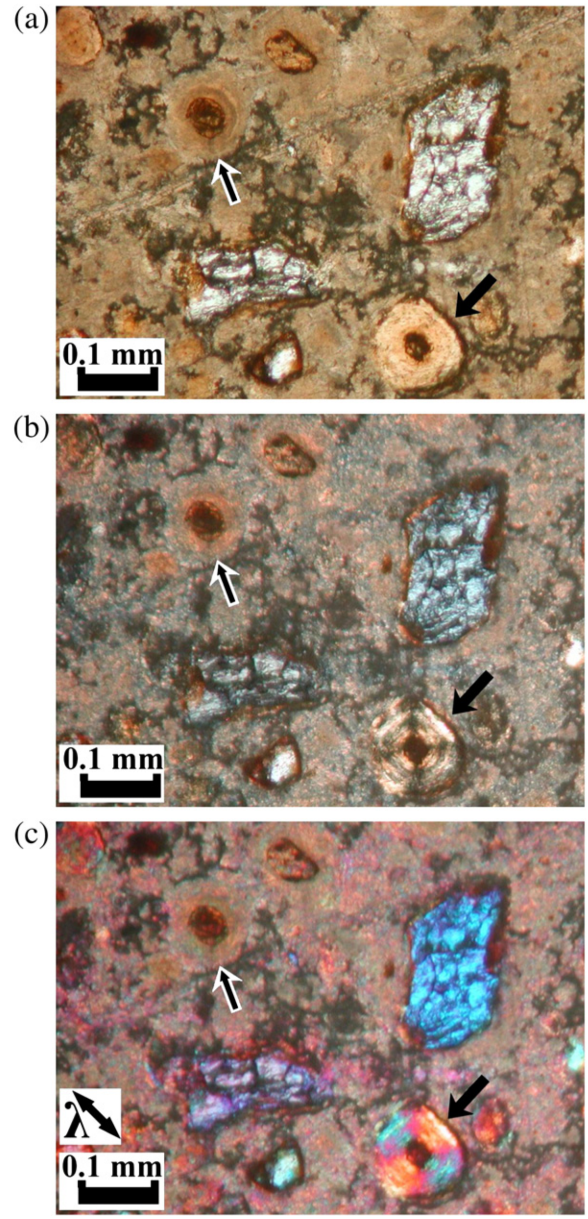

Fig. 9. 'Ooid' showing successive calcite envelopes (arrowed top); limpid yellow nodule (arrowed bottom) with pseudo-negative uniaxial interference figure from calcrete sample 2B, 2 m from centre of heuweltjie. Way-up is top of page. (a) PPL, (b) XPL, (c) XPL, λ-plate, fast-direction NW–SE.

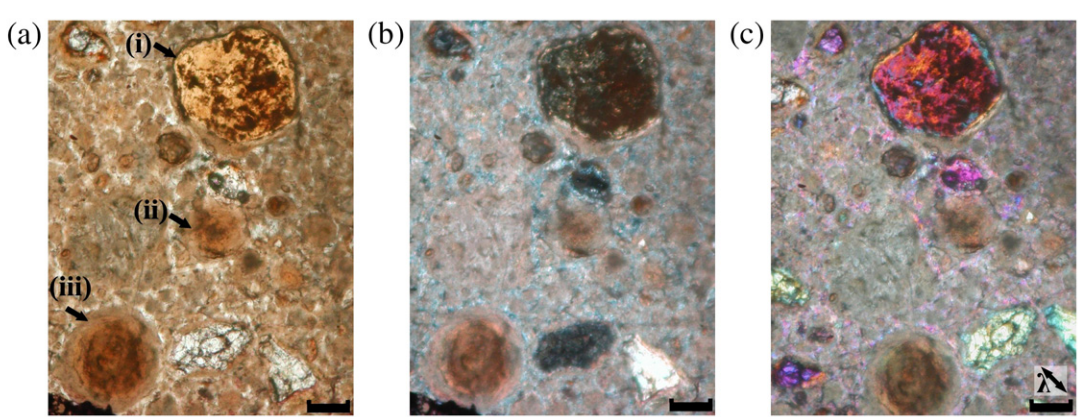

Fig. 8. Calcrete sample 2A in centre of heuweltjie. Photomicrographs correspond with ESEM images in Figs. 11–12. Way-up is to the right, scale 0.1 mm. (a) PPL. (b) XPL. (c) XPL, λ-plate, fast-direction NW–SE.

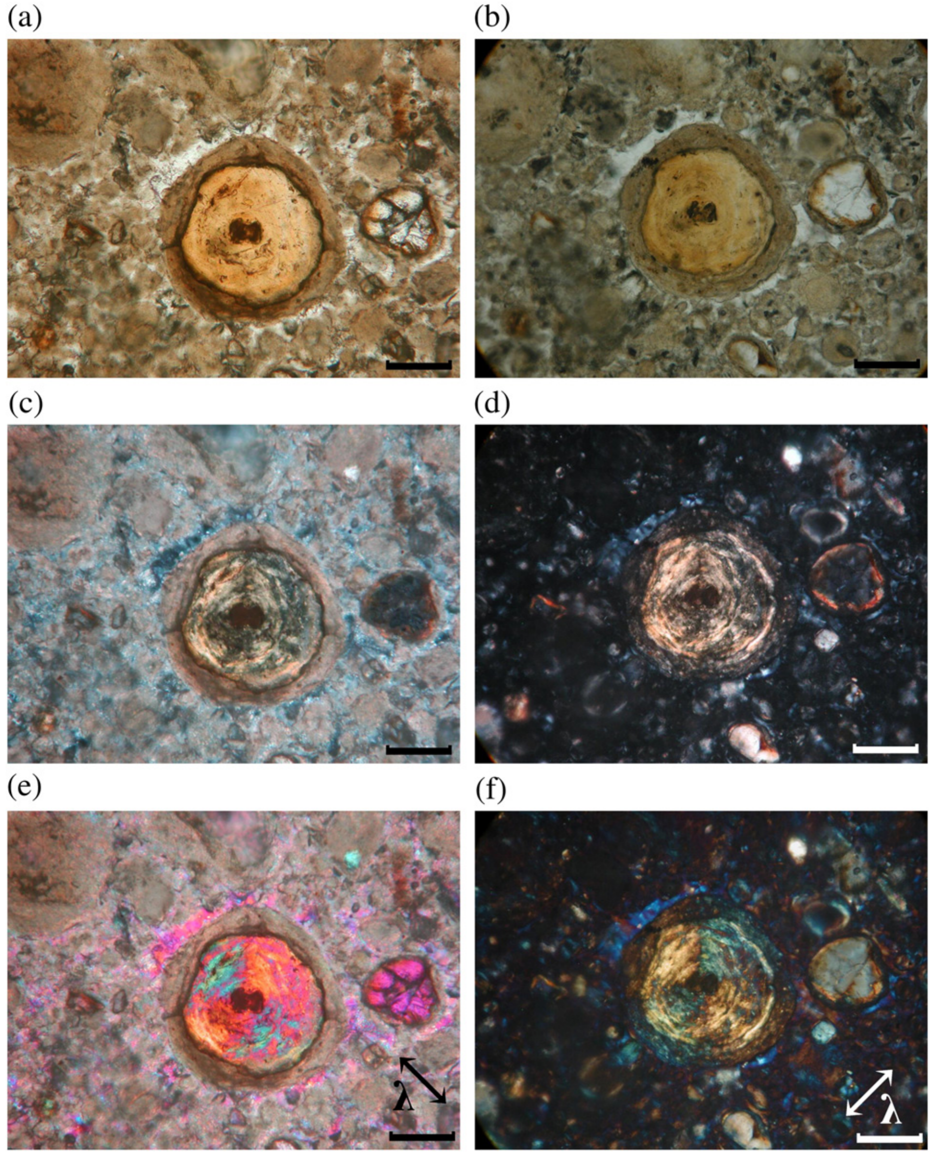

Fig. 10. Photomicrographs showing effect of 1 M HCl etching of on granular microstructure and on a micrite-coated limpid nodule with pseudo-negative uniaxial interference figure (sample 2A, calcrete in centre of heuweltjie). Way-up is top of page, scale 0.1 mm. (a) Before etching, PPL. (b) After etching, PPL. (c) Before etching, XPL. (d) After etching, XPL. (e) Before etching, XPL, λ-plate, fast-direction NW–SE. (f) After etching, XPL, λ-plate, note that fast-direction is opposite to (e).

3.4.3. Sepiolitic horizon midway to edge of heuweltjie (sample 2D)

The coarse material in this portion of the horizon was similar in appearance to coarse material in the (petro)calcic in the centre of the heuweltjie and in the overlying cambic horizons, comprising predominantly quartz grains coated with red (OIL) Fe (hydr)oxides. The coarse/fine$_{5\mu m}$ ratio was 1:2 in contrast to the 1:8 in the (petro) calcic. The horizon contained no calcite. There were neither tunnels nor excrement evident. It displayed a weakly separated vughy to massive microstructure and a pale yellow-brown, mostly limpid grano- and circular striated b-fabric (Fig. 14). The micromass appeared similar to the micromorphological description of sepiolite and palygorskite by Mees (2010). Interwoven domains of oppositely orientated fibres (Figs. 14, 15) were also present. These optically length-slow fibres with low birefringence occurred in domains up to 0.1 mm thick, and showed optical properties consistent with sepiolite (Mees, 2010).

Similar to the petrocalcic horizon in the centre of the heuweltjie, this horizon also contained subangular limpid yellow clay coatings (100 μm diameter) and nodules of the same material. Both the nodules and coatings displayed concentric banding, very low first order interference colours, and pseudo-negative uniaxial interference figures (Fig. 14a–c). Where the central grain was small enough or absent, the nodule and coating took the form of a spherulite under cross-polars but no dark or 'dumbbell' shaped centre was visible. As in the (petro)calcic horizons (samples 2A–2C), these nodules and coatings were non-calcareous. Their formation is discussed in Section 4.3.

3.4.4. Petroduric horizon at heuweltjie edge; sample 1.3

The micromorphology of the petroduric horizon was similar to that of other 'dorbank' in southern Africa (Ellis, 1988; Francis, 2008). The quartz grains were coated with hematite, as they were in the cambic, (petro)calcic and sepiolitic horizons of the heuweltjie. The c/f$_{5\ \mu m}$ ratio was 2:1. The matrix was orange-brown and appeared to be composed of amorphous Fe (hydr)oxides mixed with amorphous silica and clay. There was no micrite. There was a strong grano-, poro- and circular striated pattern (Fig. 16). There were silica and Fe-stained clay compound coatings around channels and vughs. The silica was in places transparent in PPL but in other places it seemed to be coloured

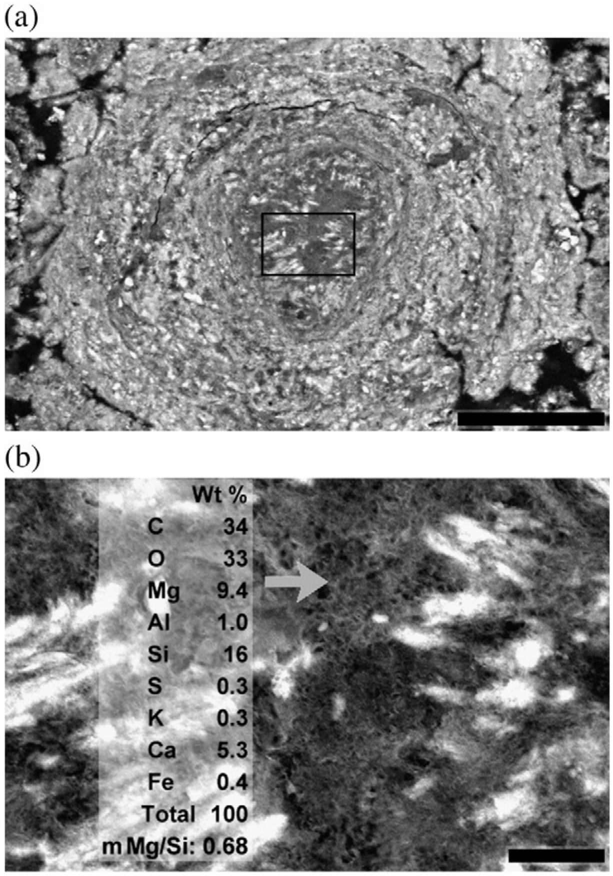

Fig. 11. ESEM-EDX images of the area indicated (ii) on photomicrographs in Fig. 8 (petrocalcic sample 2A, centre of heuweltjie). The core is composed of sepiolite (grey mesh) with radial acicular calcite (white) projecting from the core changing to 'stubby' calcite at the perimeter. Calcite is white; grey colours are lower atomic numbers such as Mg or Si. Mg/Si ratio in EDX analysis is in molar proportions. Pure sepiolite molar Mg/Si ratio is 0.67 (Stoessell, 1988). Way-up is to the right. (a) Scale bar 50 μm, (b) 5 μm.

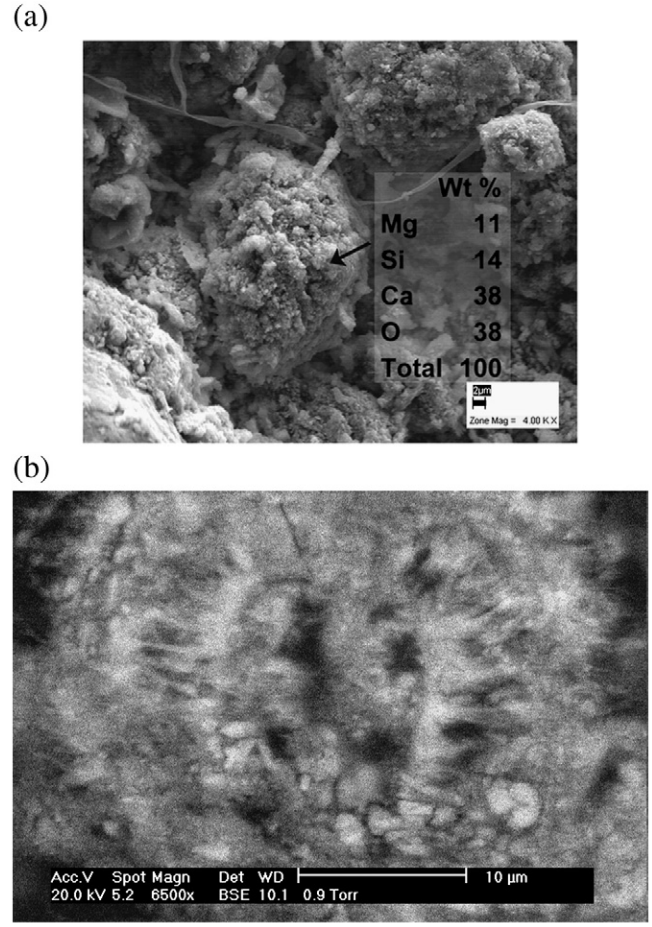

Fig. 13. ESEM images of fragments and thin sections from petrocalcic sample 2A in the centre of the heuweltjie. (a) Fragment of handspecimen showing granular microstructure and micrite coatings. Note hollow centres, and fungal filament. Location of EDAX analysis arrowed. Scale 2 μm. (b) Thin section showing radial acicular calcite and hollow centre. EDAX elemental mapping showed Ca > Si > Mg > Al, which suggested sepiolite was present in addition to calcite. Scale 10 μm.

by iron and mixed with clay. In one case it could be discerned as edge-parallel length-slow (Fig. 17c). Neither limpid clay nodules nor spherulites appeared to be present, unlike the (petro)calcic samples 2A to 2C and sepiolitic sample 2D.

The clay- and/or Fe-enriched coatings appeared to have formed before the silica coatings. In one instance, the silica was concentrated

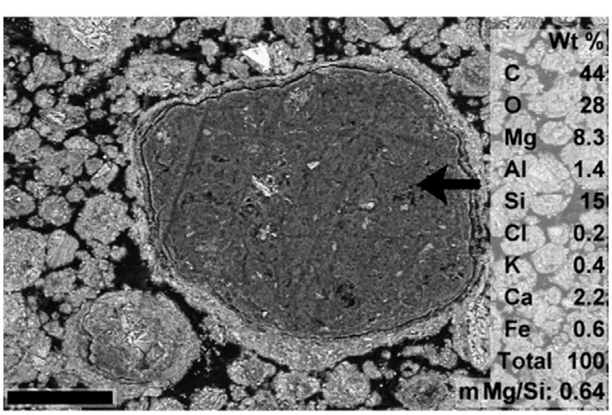

Fig. 12. Petrocalcic sample 2A in the centre of heuweltjie. ESEM image corresponds to area indicated (i) on photomicrographs in Fig. 8. Calcite is white; grey colours are lower atomic numbers such as Mg or Si. Way-up is to the right. Scale bar 100 μm. Mg/Si ratio in EDX analysis is in molar proportions. Pure sepiolite molar Mg/Si ratio is 0.67 (Stoessell, 1988).

on the outside of clay capping a ped (Fig. 16). Silica was generally (but not exclusively) concentrated on the void side of coatings (Fig. 17), similar to that described by Litchfield and Mabbutt (1962) for red-brown hardpans in Western Australia. The strong grano-, poro- and circular striated pattern in the petroduric horizon suggested the illuviation of clay and silica has been a prominent process in the horizon´s formation.

4. Discussion

4.1. Microtopography

The relief observed in the centre of the heuweltjie is a result of displacement of the original loose sand grains by calcium carbonate crystallisation in the matrix, as well as material transported into the heuweltjie by the termites. The greater displacement of sand-sized grains in the (petro)calcic (heuweltjie-centre) compared to the dorbank (petroduric) at the edge is shown by the increasing coarse/fine (c/f) ratio from the centre to the edge. It is also reflected by the open porphyric c/f-related distribution in the centre of the hardpan carbonate of the heuweltjie, the zone of maximum carbonate accumulation, grading through single-spaced porphyric/chitonic due to clay accumulation in the non-calcareous sepiolitic sample 2D, to chito-gefuric in the dorbank (petroduric) at the outer edge. The sand grains of a material similar to the overlying cambic B horizon appeared to have simply moved apart, possibly due to the low

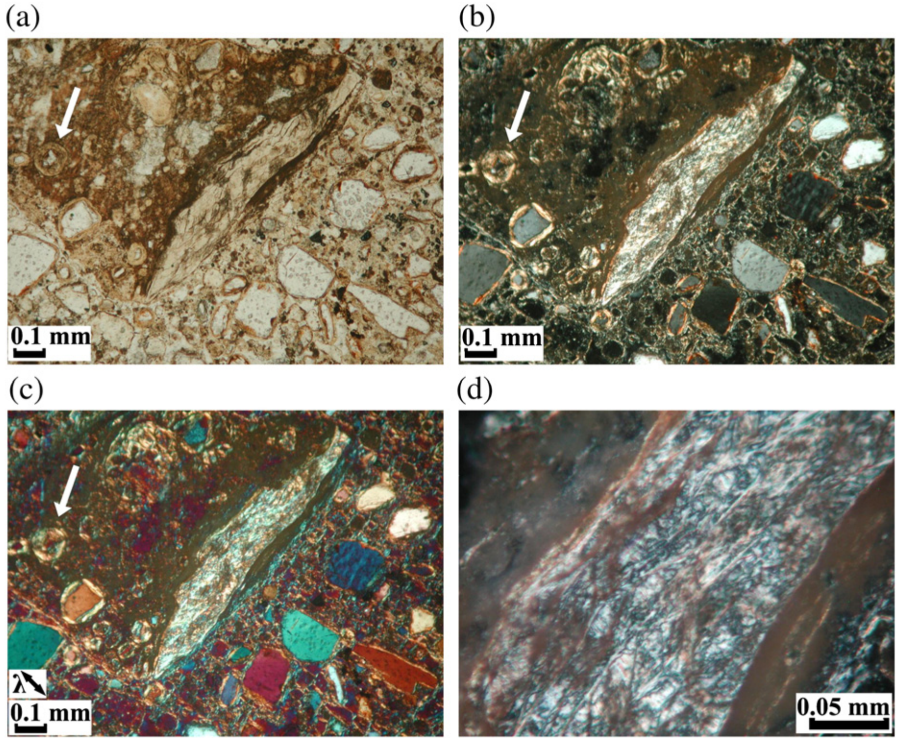

Fig. 14. Photomicrographs of the non-calcareous sepiolitic horizon (sample 2D), 7.5 m from centre of heuweltjie, showing interwoven fibre domains (sepiolite) and a spherical coating forming a pseudo-negative uniaxial interfence figure (arrowed). Way-up is top of page. (a) PPL, (b) XPL, (c) XPL, λ-plate, fast-direction NW–SE. (d) XPL, magnification of (b).

confining pressure of the overlying loose orthic (ochric) A- and neocutanic (cambic) B-horizons. This allowed the vertical expansion that resulted in the typical topographic high in the centre of the heuweltjie. Similar processes have been described in soils of the Okavango Delta, Botswana, where $CaCO_3$ and SiO_2 precipitation resulted in a significant volume increase and topography-rise of the area (McCarthy and Ellery, 1995; McCarthy and Metcalfe, 1990). The higher organic carbon content (Table 2) and the calcium accumulation in the centre of the heuweltjie would also have allowed a more stable soil structure to develop, reducing the soil erosion on the slightly higher centre areas of the mound relative to the surrounding soils.

4.2. Water penetration

The lack of clay and presence of hematite coatings in the cambic horizon (sample 2.2) over the (petro)calcic in the heuweltjie centre indicate a well-drained environment. This is compatible with its lower-pH and the tonguing nature of the transition to the (petro) calcic horizon below (Table 1 and Fig. 2). It is consistent with the vertical distribution of the cations from the A (sample 2.1) to B (sample 2.2) horizons in the centre of the heuweltjie (Table 3), as the B horizon contains greater amounts of the more easily leached Na^+ and K^+ relative to the A (sample 2.1) horizon, and the A horizon contains more of the less easily leached Ca^{2+} and Mg^{2+} than the B horizon.

Calcic pendants and cappings in the (petro)calcic horizons in the heuweltjie centre (Fig. 7) suggest the penetration of water (Brock and Buck, 2005) into the heuweltjie to at least the sampled 1 m depth. In a similarly arid area (Oudtshoorn) after exceptionally heavy rains, the authors observed profiles through two heuweltjies that were wet in all layers up to a depth of about 1.5 m. This suggests that the intense rainfall events are necessary for movement of solutes to the deeper layers of heuweltjies.

4.3. Granules, ooids, peloids and spherulites in the petrocalcic horizons

Those limpid yellow brown nodules displaying pseudo-negative uniaxial interference figures (Figs. 9 and 10) and those which did not (labelled (i) in Fig. 8) appeared to be composed of the same material. The micromorphology of the limpid yellow brown nodules was consistent with that of sepiolite aggregates from Namibian pans (Mees, 1999, 2010). The EDAX analyses showed molar Mg/Si ratios of 0.64 to 0.68, consistent with the molar Mg/Si of 0.667 for sepiolite (Stoessell, 1988). An example is shown in Fig. 12, which is an analysis of the nodule labelled (i) in Fig. 8. Fig. 11, an analysis of the nodule labelled (ii) in Fig. 8, showed a similar molar Mg/Si ratio of 0.68, and additionally revealed a fibrous mesh fabric at the core, consistent with sepiolite.

Calcite spherulites have been commonly observed on laminar calcretes (Verrecchia et al., 1995; Mees, 1999). However, only the micrite-coatings on these limpid yellow nodules with pseudo-negative uniaxial interference figures found in the Papendorp heuweltjie reacted in cold 10% HCl (Fig. 10). They differed from the faecal spherulites in their limpid yellow colour in plane polarised light rather than colourless, and were considerably larger than the 5 to 15 μm faecal spherulites that in herbivore dung (Canti, 1997) and the termite excrement (Section 3.3, compare Figs. 5 and 10).

While chemistry and micromorphology of the limpid yellow brown nodules were consistent with sepiolite, it must be noted that silica (opal-CT) has also been reported to show weak anisotropy in soils. In addition to the 1.2 nm peak in the (petro)calcic samples 2A to 2C, these samples and the silica-cemented petroduric sample 1.3 showed a broad rise in the background at around 0.4 nm (Fig. 3), consistent with amorphous silica (Drees et al., 1989). Broadly similar pedofeatures (although in a massive rather than oriented form) were noted in Sardinia, Italy in > 2.7 Ma buried paleosols (Usai and Dalrymple, 2003). They suggested that these 'milky pedofeatures' were made of different phases of silica such as inorganic opal-A, opal-C and opal-CT, but mainly composed of opal-C. Although silica was the main constituent of the

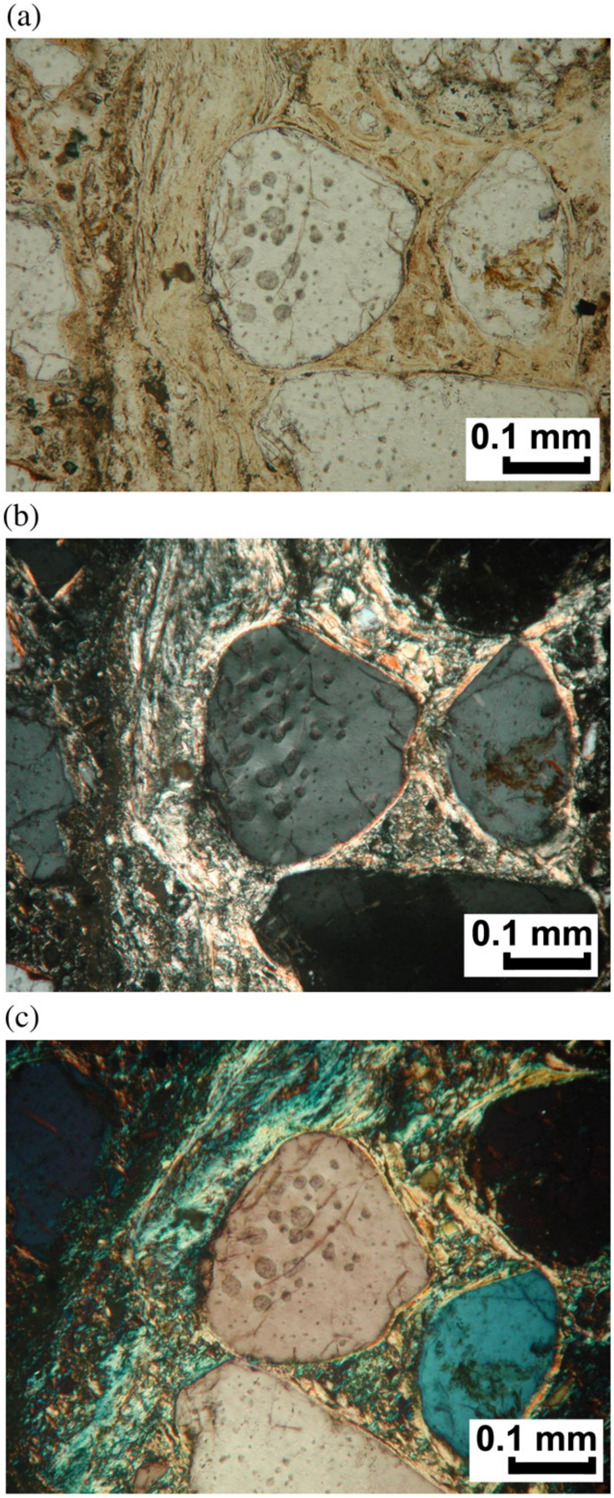

Fig. 15. Photomicrographs from non-calcareous sepiolitic sample 2D, 7.5 m from centre of heuweltjie, showing fibre domains (length slow) in aggregate with sepiolite matrix. Way-up is top of page. (a) PPL, (b) XPL, (c) XPL, λ-plate, fast-direction NW–SE.

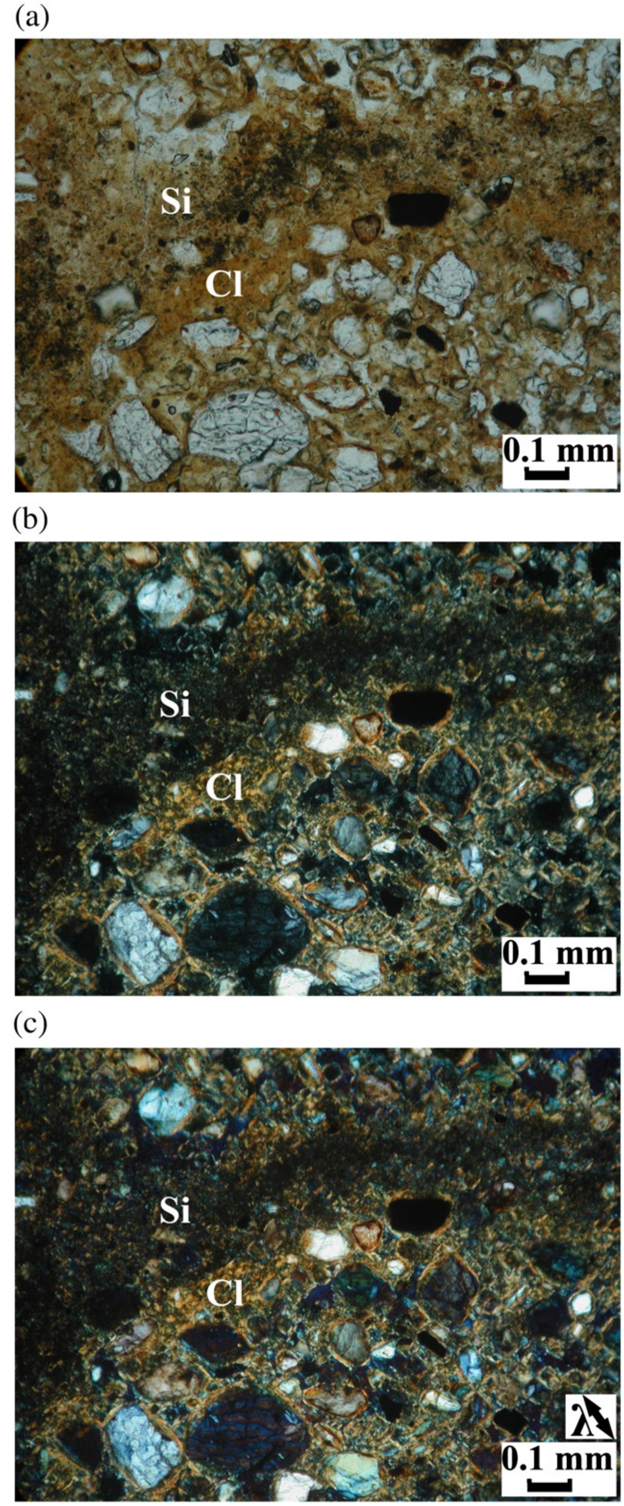

Fig. 16. Photomicrographs of the non-calcareous petroduric horizon sample 1.3, on the edge of the heuweltjie, showing silica (Si) over clay-rich (Cl) zones on a ped capping. Way-up is top of page. (a) PPL, (b) XPL, (c) XPL, λ-plate, fast-direction NW–SE.

'milky pedofeatures' (reaching 67% of the total weight), the remaining constituents were around 25% Al_2O_3, 5% MgO, 2 to 4.6% Fe_2O_3 and 2% CaO, which they attributed to either impurities chemisorbed to silica or to analytical inaccuracy. Gutiérrez-Castorena et al. (2006) also described weak anisotropy in opaline coatings on channels and fissures in the strongly alkaline sediments of the former Texcoco Lake (Mexico City), but suggested that the weak anisotropism could be related to an initial crystallisation of the opal-A to opal-CT (anisotropic domains), or to the presence of fine clay particles oriented according to the flow direction of the colloids (parallel anisotropic streaks).

Pseudomorphic replacement of sepiolite by opal has been noted from deposits in the Madrid Basin, Spain (Bustillo and Alonso-Zarza, 2007; Bustillo and Bustillo, 2000). Bustillo and Alonso-Zarza (2007) proposed that the replacement took place via an initial silicification resulting in an atypical, porous opal, which showed striated birefringence as a consequence of the sepiolite fibrous structure.

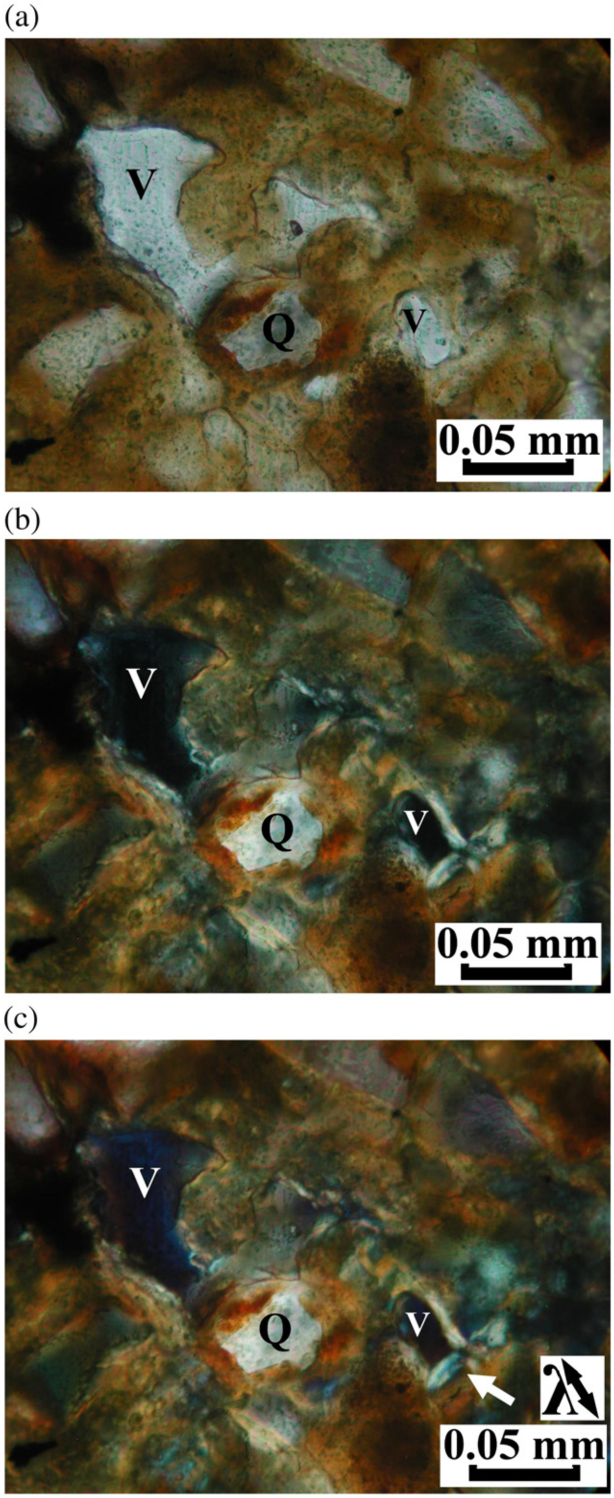

Fig. 17. Photomicrographs of non-calcareous petroduric sample 1.3, heuweltjie edge, showing Fe coating an embayed quartz grain (Q) and silica lining voids (v). Silica length — slow as shown in (c). Way-up is top of page. (a) PPL, (b) XPL, (c) XPL, λ-plate, fast-direction NW–SE.

Both biotic and abiotic processes have been used to explain rounded calcite aggregates, spheres, spherulites ooids and peloids (Bosak et al., 2004; Braissant et al., 2003; Cailleau et al., 2005; Fernández-Díaz et al., 2006; González-Muñoz et al., 2000; Raz et al., 2000; Tracy et al., 1998a,b; Zhou and Chafetz, 2009). Termite activities concentrate organic matter and herbivore dung into the

Table 2
Comparison of soil composition (NH_4OAc (pH7) extractable bases, Bray 2 extractable P, Walkley–Black organic carbon) at the entrance point (off the heuweltjie), and the exit point (near the centre). Sampling was done of the top few cm (pedoderm).

	C	P	Ca	Mg	Na	K
	%	mg kg^{-1}	cmol(+) kg^{-1}			
Intake point (between mounds)	1.2	90	8.5	4.1	8.4	1.7
Outlet point (mound centre)	6.2	127	20.4	23.9	13.1	3.8

mounds (Whitford and Wade, 2002). The granules in this heuweltjie are closely associated with organic/biogenic material, for example the fungal filaments in Fig. 13a and biogenic calcite. Alonso-Zarza and Silva (2002) noted organic material and organic films associated with ooids formed in calcrete containing bee nests in the Canary Islands. They concluded that this occurrence favoured the precipitation of calcite and the adhesion of palygorskite. Seong-Joo and Golubic (1999) noted dumbbell-shaped, dark centres similar to Fig. 10 in 30 to 500 μm spherulites formed in silicified stromatolites (carbonates) in China, and noted that the fabric is similar to that produced by the process of diagenetic granularization or condensation of organic matter as discussed by Knoll et al. (1988).

The terms 'peloid' and 'ooid' are applied descriptively to carbonate sedimentary rocks, usually marine limestones. They were not used in Stoops' (2003) soil micromorphological description scheme, included instead in the concepts of 'granular microstructure' and micrite '(hypo)coatings'.

Peloids and ooids are not restricted to limestones of marine origin. Siesser (1973) referred to them as 'diagenetic ooids/intraclasts' to distinguish them from their marine counterparts, and noted that Quaternary calcretes contain the only known ooids/intraclasts in any South African Cretaceous or Cenozoic rocks. Ooids and peloids have been recorded from pedogenic calcretes in northern Tanzania (Hay and Reeder, 1978); sepiolitic calcretes in the southwestern United States (Hay and Wiggins, 1980); Tarragona, northeastern Spain (Calvet and Julià, 1983); calcretes developed in the Old Red Sandstone of Scotland (Wright et al., 1993); the Kalahari valley (Nash and McLaren, 2003); and calcretes containing bee nests on the Eastern Canary islands (Alonso-Zarza and Silva, 2002). Pellets have been described in soils associated with termites by Stoops (1964) and Mermut et al. (1984). The granular microstructure composed of prolate calcite crystals in the granules set in a sepiolite matrix was present in an old inactive heuweltjie in the Knersvlakte, Namaqualand (Francis, 2008, p. 29).

The ooids in the petrocalcic horizons of the Papendorp heuweltjie displayed a dominantly radial orientation of calcite crystals (Figs. 11, 13b). Davies et al. (1978) concluded that radially orientated calcite ooids are related to a specific type of organo-carbonate interaction involving the formation of organic membranes. Davies et al. (1978) and Ferguson et al. (1978) synthesised ooids in quiet-water conditions which displayed a radial orientation of carbonate crystals, in contrast to those ooids formed in agitated conditions which showed predominantly tangential calcite crystals due to grain collisions.

The most important parameters for the synthesis of the radial quiet water ooids in Davies et al.'s (1978) experiment were: high molecular weight organic components, the presence of Mg in addition to Ca, the presence of carboxylic groups (for example solutions containing humic acids), and a capacity to participate in hydrophobic/hydrophilic interactions. These parameters were critical to membrane formation, and it was the formation of these hydrophilic high molecular-weight organic membranes that was important in the formation of ooids. These membranes formed concentric shells which acted as growth surfaces for carbonate and induced periodicity in carbonate precipitation.

Table 3
Composition of saturated paste extracts from the upper (non-cemented) horizons of the heuweltjie at the centre and the edge. pH was measured in the saturated paste directly.

Sample	Depth	pH	EC	$HCO3^-$	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	Na^+	K^+	Si	SAR[#]
	m		mS/cm	$mmol_c/L$							mmol/L	
Profile "2": centre of the heuweltjie overlying petrocalcic horizon												
2.1 A	0–0.1	7.60	2.60	4.17	17.8	7.17	6.35	7.36	22.0	0.75	0.73	8
2.2 Bw	0.1–0.55	6.88	4.33	1.24	40.3	3.30	1.54	3.08	63.1	1.66	2.17	41
Profile "1": edge of heuweltjie overlying petroduric horizon												
1.1 A	0–0.04	8.67	2.40	4.55	16.7	1.70	2.87	1.84	18.7	2.14	0.52	12
1.2 Bw	0.04–0.15	8.45	2.87	5.54	23.6	1.54	4.71	4.00	35.0	2.59	0.88	17

SAR: sodium adsorption ratio $Na/((Ca+Mg)/2)^{0.5}$.

The mechanism proposed by Davies et al. (1978) for the formation of quiet-water ooids is the best explanation for the formation of ooids with radially arranged calcite crystals in the heuweltjie soils, in view of the number of parallels between the described quiet-water ooid-forming processes and conditions in the sepiolitic (petro)calcic of the Papendorp heuweltjie. It explains the core of sepiolite (Fig. 11), given its strongly hydrophilic character (Alvarez, 1984) and high Mg content, and the dumbbell-shaped, dark centres that appear to be organic and which are similar in appearance to the possibly organic coating between the limpid yellow nodules and the micrite coatings (Figs. 9, 10). The induced periodicity in carbonate precipitation described by Davies et al. (1978) explains the successive acicular layers seen in the ooids and the coatings (Fig. 9A arrowed top). Further support for the hydrophilic/hydrophobic membrane theory of Davies et al. (1978) would be the hydrophobic character of the organic material in the A horizons of Namaqualand soils (Francis et al., 2007). In the heuweltjie, it took longer for a drop of water to penetrate the sandy orthic A horizon than the underlying B horizon (Table 1).

4.4. Organic matter as a source of Ca^{2+}, Mg^{2+} and H^+ for calcite and sepiolite precipitation

The movement of organic matter through the heuweltjie is from the intake point at surface of the periphery or off-mound area, though the heuweltjie via tunnels, to the outlet for frass at the surface near the mound centre (Coaton and Sheasby, 1974; Ellis, 2004; Moore and Picker, 1991). Moore and Picker (1991) observed temporary storage chambers filled with cut vegetation and smaller chambers packed with frass on inhabited mounds excavated in Clanwilliam. Our data show that the soils at the exit point at the centre display higher P, C, and basic cations, especially Ca and Mg, compared to the intake point at the edge (Tables 2 and 3). Increased Ca, Mg, K, P and organic matter has been associated with termite mound soils across a wide range of species and locations (Kaschuk et al., 2006; Okullo and Moe, 2012; Sarcinelli et al., 2009; Watson, 1975). It is also consistent with the micromorphological evidence of the accumulation of organic matter (detailed in Section 3.4.2) that is associated only with the (petro) calcic horizon in the centre of the heuweltjie (samples 2A to 2C). Evidence of organic matter accumulation is absent from both sepiolitic sample 2D and dorbank sample 1.3 on the periphery.

The (petro)calcic horizons occurred only in the centre of the heuweltjie mounds, a feature common to many heuweltjie landscapes such as the Worcester-Robertson area (Potts et al., 2009). Ellis (2002) proposed that the petrocalcic horizon at the centre of the mound formed as the concentration of plant material by termite activity led to the build-up of bases (especially Ca) and silica in the heuweltjies over time; the 'zoogenic origins' approach of Lee and Wood (1971). Watson (1975) showed for *Macrotermes* mounds in the higher rainfall eastern parts of the subcontinent that the calcium enrichment in mound soils was due to calcium-bearing plant material, which was subsequently leached proportionally to the increase in rainfall.

It is conceivable that the concentration of plant material in the centre of the heuweltjie would similarly raise the Mg levels to allow for the concentration of sepiolite (and palygorskite) precipitated within heuweltjies. Data from Midgley and Musil (1990) showed that foliar Mg as well as Ca is high in plants associated with heuweltjies in the Worcester-Robertson valley. These levels are consistent with vegetation Mg-levels in the Strandfontein–Papendorp heuweltjie (Table 4).

This calcite mineralisation in the centre of heuweltjies in an otherwise non-calcareous landscape bears some resemblance to the calcite mineralisation in Iroko trees (*Milicia excelsa*) and surrounding soil in the Ivory Coast and Cameroon (Braissant et al., 2004; Cailleau et al., 2005). These trees contain significant calcium carbonate accumulations within their tissues and are associated with calcium carbonate in their surrounding soils, even though they grow on non-calcareous orthox soils which normally have a pH of 4.3 to 6.0. (Braissant et al., 2004; Cailleau et al., 2005) showed that the calcium carbonate mineralisation in the trees and their surrounding soils is caused by soil bacteria that oxidise the Ca oxalate that is present in the tissues of *M. excelsa* and their surrounding soils. Calcium oxalate (weddellite) was observed in fungus-culturing *Macrotermes* mounds in Mozambique (Dias Pereira and Leal Gomes, 2010) and in the Congo (Mujinya et al., 2011). Although the *Mictotermes viator* resposible for the heuweltjies is not a fungus-culturing species, much of the plant material available to the foraging termites in Namaqualand is enriched in oxalate (A. Milewski, pers. comm., 2007), for example 'vygies' (*Mesembryanthemum* spp.), *Oxalis* spp and *Rumex* spp.

SEM images of the granular microstructure in the petrocalcic horizons in the centre of the heuweltjie shown in Fig. 13a closely resemble the images of the micritic aggregates found both in the soil profile associated with Ca oxalate enriched *M. excelsa* trees, and precipitated experiementally in a *Xanthobacter autotrophicus*-innoculated soil-extract medium (Cailleau et al., 2005).

Given the high nitrogen content as a result of the accumulation of organic matter by termites and its subsequent degradation (Midgley and Musil, 1990), the passive carbonatogenesis induced by several metabolic pathways of the nitrogen cycle described by Castanier et al. (1999) may also be relevant to calcite genesis within the heuweltjie. These induce production of carbonate and bicarbonate ions, and as a metabolic end-product, ammonia, which induces pH increase (Castanier et al., 1999).

Table 4
Leaf and stem analyses of on-mound *Cephalophyllum* spp. (Vygies) from the Papendorp–Strandfontein heuweltjie.

	Ca	Mg	Na	K	Si
	%	%	%	%	ug/g
Leaf	1.90	1.34	3.42	2.45	371
Stem	2.18	0.30	0.50	1.45	399

4.5. Zonation of calcite–sepiolite–silica

Spackman and Munn (1984) used differential leaching to explain why the upper parts of a profile in a mima-like mound in Wyoming contained more Ca^{2+}, and the lower parts more $Mg^{2+}$and Na^{+}. In the heuweltjies, although the plant material concentrated into the centre of the heuweltjie contains high amounts of Ca, Mg, K and Na (Tables 2 and 4), a similar process could lead to a relative concentration Ca and Mg necessary for the formation of calcium carbonate and sepiolite in the topographically raised centres relative to the edges.

The interwoven nature of the sepiolite (Figs. 14, 15) in the sepiolitic horizon suggests that – similar to the (petro)calcic and petroduric horizons – it was neoformed, with the grano- and circular striated b-fabric of the sepiolitic horizon attributable to intergranular crystalisation and the wetting and drying process (Mees, 2010). These were similar to the domains described by Stahr et al. (2000) for a palygorskite-cemented hardpan in Portugal.

The gradual zoning outward from sepiolitic petrocalcic horizons in the topographically raised centre through (petro)sepiolitic horizons (Francis et al., 2012) to petroduric horizons at the lower edges of heuweltjies is very similar to the calcite-palygorskite-silcrete sequence developed in an alluvial fan sequence in Spain. Rodas et al. (1994) suggested that the calcretes (with palygorskite in the clay fraction) precipitated in the proximal part of the alluvial fan, and non-calcareous 'palycrete' formed during the movement of alkaline phreatic waters through the fan, as the precipitation of calcite in the proximal part of the fan shifted the composition of the water to a lower Ca/Mg-ratio and lower CO_3^{2-} in the distal parts. In equivalent terms, the 'proximal' part of the heuweltjie is the centre (Ca–Mg–Si-rich) where calcite precipitation and Ca-depletion result in a zone of sepiolite to precipite midway to the edge (Mg–Si-rich), and finally Mg-depletion due to sepiolite precipitation leading to development of the petroduric zone (Si-rich) at the outer (distal) edge.

Summerfield (1983) noted that silica would only precipitate where the presence of other constituents did not favour the formation of other silicates, and is also consistant with the location of the silica on the outer (void) sides of the Fe-oxides and clay cappings in the petroduric horizon.

4.6. Spherulites in termite frass

According to Fey et al. (2010), South African termite trophic strategies include fungus-culturing, consumption of fresh faeces of herbivores and harvesting of fresh foliage. The sections were cut through a fresh exit tower collected in situ and not from material collected loose at the surface, suggesting it was unlikely to be direct contamination by a passing herbivore. The association of spherulites with the termite excrement may be due to the spherulites' presence in the original herbivore dung, ingested together with the dung by the termite. Another possibility is that the process of digestion in the termite gut may in some way be similar to that of the larger herbivores and their production of calcic spherulites described by Canti (1999). According to Whitford and Wade (2002) much of the decomposition of organic matter in arid ecosystems occurs within the guts of termites as the material ingested by the termites is mineralised by symbionts in the gut.

5. Conclusions

The role of termites in the formation of the heuweltjie is indicated by abundant plant-derived organic material (fresh and calcified organ remains and phytoliths) as well as tunnels and chambers lined with organic matter, and termite excrement that was consistent in size and shape with current *Mictotermes viator* excrement from an active heuweltjie in a higher rainfall zone (Stellenbosch).

We propose that the distinct sequence of calcite-sepiolite-silica enriched horizons in the mound is due to the elevated calcium and magnesium levels and organic matter in foliage collected by the termites into the centre of the mound, followed by the geochemical differentiation of the soil solution leading to the development of the distinct mineral zones. Further work on the geochemical processes within the mounds would aid in understanding the movement of water and solutes through the heuweltjie.

The calcite shows a distinctive micromorphological fabric consistent with that of biotic factors in its precipitation (spherulites, ooids, granules, and possibly micrite aggregates formed by oxalate-consuming bacteria). The zone is typified by the abundance of sepiolite-cored ooids showing radially orientated calcite. This fabric appears to be associated with the precipitation of these minerals associated with accumulation of organic matter.

Colourless, non-calcareous, pseudo-uniaxial negative spherulites were present in fresh termite excrement from an active heuweltjie near Stellenbosch. The presence of faecal spherulites is usually associated with mammalian herbivore dung, and the possibility of the (re)distribution of faecal spherulites by termites in an arid region ecosystem needs to be considered.

Acknowledgements

The thin sections were prepared by M. Antúnez from the University of Lleida, Spain and D. Wilson the University of Cape Town; W. de Clercq constructed a resin impregnator. Electron Microscope images were taken by and E. Spicer and M. L. Francis at the University of Stellenbosch, and B. White at the University of KwaZulu-Natal (Pietermaritzburg campus). N. van der Merwe helped with clay separations; T. Vilakhazi with clay separations and ran some of the samples on the XRD at the Stellenbosch Geology department; R. Bucher performed the XRD analyses at the Ithemba Labs Materials Research Group, Somerset West. Special thanks are owed to A. Mills and A. Milewski for their assistance with the question of oxalate in the vegetation and the foraging of termites, and to M. Fey, project co-supervisor, for his generous help with earlier drafts. Financial support was also provided by grant number 2047381 from the National Research Foundation.

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