Distinguishing pedogenic and non-pedogenic silcretes in the landscape and geological record

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ABSTRACT

Silcrete is a type of duricrust formed by the near-surface accumulation of secondary silica within a soil, sediment, rock or weathered material. A variety of models of formation have been put forward, involving silicification in both pedogenic and non-pedogenic settings. The resulting silcrete types differ in terms of their macroscale characteristics, micromorphology, areal extent and behavioural properties. Such differences have significant implications in a range of geological, geomorphological, archaeological and engineering contexts, making the correct identification of silcrete type of considerable importance. This paper reviews the properties of pedogenic, groundwater, drainage-line and pan/lacustrine silcretes, and identifies many characteristics that may be diagnostic. It also discusses a number of more problematic macro- and micro-scale features common to both pedogenic and non-pedogenic silcretes. It concludes with a short checklist to aid the future identification of different silcrete types in the landscape and geological record.

Keywords: Duricrust; groundwater silcrete; pedogenic silcrete; micromorphology; silicification; puddingstone; sarsen

1. Introduction

Silcrete is a variety of highly indurated duricrust formed as a result of the near-surface accumulation of secondary silica within a soil, sediment, rock or weathered material (cf. Summerfield, 1983c; Milnes and Thiry, 1992). It is particularly widespread in Australia (e.g. Thiry and Milnes, 1991) and southern Africa (e.g. Summerfield, 1982, 1983a), where it is commonly found outcropping in association with ancient land surfaces. Silcrete also occurs as more spatially limited outcrops, as a surface lag or as isolated boulders in many other areas, including western Europe (see Nash and Ulliyott, 2007 and references therein). The sarsens and puddingstones of the southern UK are a good example of the latter. Silcrete is also widely documented in geological contexts from borehole data (e.g. Rogers, 1980; Basile-Doelsch et al., 2005).

Four main types of silcrete are recognised in the literature (Milnes and Thiry, 1992; Nash and Ulliyott, 2007) (Fig. 1.). The most widespread, in terms of areal extent, are *pedogenic silcretes* (Fig. 2.). These develop within soil profiles as the result of a succession of phases of silica dissolution and recrystallisation caused by multiple episodes of water infiltration and percolation (e.g. Thiry, 1978, 1988; Thiry et al., 2006). Other silcrete types are often grouped together, for convenience, as *non-pedogenic* varieties (Fig. 3.). Of these, *groundwater silcretes* form under phreatic conditions through silicification at or close to a water table, or at zones of groundwater outflow (e.g. Callen, 1983; Thiry et al., 1988; Thiry and Milnes, 1991; Thiry et al., 2015). *Drainage-line silcretes*, in contrast, develop as a result of the silicification of alluvial fills in contemporary or former fluvial systems (e.g. Young, 1978; van der Graaff, 1983; Leckie and Cheel, 1990; Nash et al., 1998; Shaw and Nash, 1998). A final variant, termed *pan/lacustrine silcrete* by Nash and Ulliyott (2007), forms as a result of the silicification of sediments at the margins of ephemeral lake basins (e.g. Goudie, 1973; Summerfield, 1982; Bustillo and Bustillo, 1993; Armenteros et al., 1995; Nash and Shaw, 1998; Bustillo and Bustillo, 2000).

Silcretes develop in a variety of landscape settings and over different timescales (Thiry, 1999). Investigations in Australia and South Africa, for example, show that pedogenic silcrete formation is directly associated with the development of palaeosurfaces (e.g. Mountain, 1952; Langford-Smith, 1978; Wopfner, 1978; Mountain, 1980; Summerfield, 1983a; Alley, 1998); thus the silcrete effectively forms on or very close to a former land surface. Silicification in this context proceeds over potentially large areas and at timescales of $>10^6$ years via the gradual progradation of the silcrete profile into the landscape (Thiry and Milnes, 1991; Milnes and Thiry, 1992). In contrast, non-pedogenic

silcrete development may be more localised, and is often controlled by the position of the local water table; while this would imply an overlying palaeosurface, the silcrete itself does not mark the position of the former land surface (e.g. Callen, 1983; Nash and Ulliyott, 2007). Formation may also be much more rapid. Studies at Fontainebleau (Paris Basin), for example, reveal superposed groundwater silcrete lenses developed during phases of landscape incision, with individual lenses forming in the order of 30,000 years (Thiry et al., 1988; Thiry, 1999).

The above processes of silcrete formation lead to end-products that differ in terms of their macro- and micro-scale characteristics (see Figs 2. and 3.), areal extent and behavioural properties. Such differences have significant implications in a range of geological, geomorphological, archaeological and engineering contexts, making the correct identification of silcrete type of considerable importance.

As an illustration, the misidentification of a pedogenic silcrete as non-pedogenic could be problematic to the formulation of models of landscape evolution, primarily due to the differences in the geomorphological context of, and time required for, profile development noted above. It would also impact upon palaeoenvironmental interpretations. Pedogenic silcrete formation is thought to be restricted to areas of past or present tropical to subtropical climate with alternating wet and dry seasons or periods, whereas non-pedogenic silcretes may have formed in a variety of environmental settings and under climates ranging from cold to arid (e.g. Milnes and Thiry, 1992; Ulliyott et al., 1998; Webb and Golding, 1998; Thiry et al., 2015). Many interpretations of UK silcretes (e.g. Summerfield and Goudie, 1980; Jones, 1999; Lovell, 2015) have inferred, by analogy with southern African and Australian pedogenic silcretes, that they formed as part of an extensive stable palaeosurface under tropical or sub-tropical conditions. However, other studies (Ulliyott et al., 1998, 2004, 2015; Ulliyott and Nash, 2006) indicate that the majority of sarsens and puddingstones are non-pedogenic in origin, and hence could have formed in different palaeoclimatic contexts. Further, detailed studies of sarsen boulders and debris in plough soil, older buildings and in archaeological contexts suggest that, at least for some areas (e.g. Salisbury Plain and the eastern South Downs; Green, 1997; Ulliyott et al., 2004), silcrete distribution was patchy rather than continuous.

From an applied perspective, misidentification of silcrete type could generate problems for basin analysis and sequence stratigraphy. Pedogenic silcretes form within soil profiles that may transect a number of formations on stable basement or basin-marginal areas (Thiry, 1978; Callen, 1983; Milnes and Thiry, 1992) and indicate a hiatus or unconformity,

whereas non-pedogenic silcrete is normally either intraformational or develops within the host material long after deposition. The characterisation of aquifers and hydrocarbon reservoirs, and the development of engineering ground models (e.g. Fookes et al., 2013), also requires the accurate identification of silcrete type. Although the lateral continuity of silcrete bodies is often hard to determine, particularly where an original outcrop has been broken up by erosion, pedogenic silcretes are usually more extensive than other types (Thiry and Milnes, 1991). They may also be thicker and, because of their profile characteristics (Section 2), more permeable than non-pedogenic varieties. Finally, there is growing evidence from the archaeological literature that pedogenic silcrete has different knapping properties to non-pedogenic, the former requiring heat treatment prior to use in stone tool manufacture (Brown et al., 2009; Schmidt et al., 2013) while the latter is workable untreated (Nash et al., 2013). Consequently it is essential that studies trying to provenance artefacts are able to recognise differing silcrete types at their source outcrops.

While the literature on silcrete is relatively large, and there have been a number of useful reviews that include descriptions of silcrete properties (e.g. Milnes and Thiry, 1992; Thiry, 1999; Nash and Ulliyott, 2007), few of these have adequately synthesised the macro- and micro-scale differences between silcrete types worldwide. The aim of this study is to establish criteria for distinguishing between pedogenic and non-pedogenic silcretes, both in the field and in the geological record. We also identify areas of remaining uncertainty that would benefit from additional research.

2. Characteristics of pedogenic silcretes

Pedogenic silcretes exhibit a number of diagnostic characteristics. Foremost amongst these is the presence of a complex profile organisation, with macro- and micromorphology varying consistently throughout. 'Typical' pedogenic profiles can be differentiated into two sections at the macroscale. The upper part is usually highly indurated and features well developed vertical jointing, giving a columnar appearance (Goudie, 1973; Thiry, 1978; Wopfner, 1978; Callen, 1983; van der Graaff, 1983; Thiry, 1988; Dubroeuq and Thiry, 1994; Ballesteros et al., 1997; Thiry, 1999; Thiry et al., 2006) (Fig. 2a-c); this may be overlain by a pseudo-brecciated or, less commonly, a pseudo-nodular horizon. Macroscopic geopetal ('way up') features, including laminated drapes, and/or cap-like or drip-like forms (Fig. 2b) are widely documented (Thiry, 1978; Summerfield, 1981; Callen, 1983; van der Graaff, 1983; Webb and Golding, 1998; Baele et al., 2012). The lower section of the profile often exhibits a nodular or granular appearance and is typically less

consistently cemented (Thiry, 1978; Watts, 1978; Thiry, 1981; Milnes and Twidale, 1983; Summerfield, 1983b).

When viewed in thin-section, pedogenic silcretes exhibit a number of microfabrics (Fig. 4) indicative of the role of soil-forming processes in their formation (e.g. abundant cutans, caps and eluvial structures, nodules/glaebules [Fig. 4a-b]; Thiry, 1999), with primary features of the parent material normally obliterated during the silicification process. Geopetal structures comprising alternating lamellae of silica and titania (e.g. Frankel and Kent, 1938; Taylor, 1978; Thiry, 1978, 1988; Terry and Evans, 1994; Curlík and Forgác, 1996), or silica with iron or manganese oxides and clays (Ballesteros et al., 1997; Thiry et al., 2006), are frequently well developed and abundant. These illuvial or 'colloform' features (Fig. 4b-f) occur in a variety of forms, often as vertically-stacked concave-upward cusps apparently infilling voids or dissolution features (Summerfield, 1983c), as conical or cap structures on top of host sediment clasts or silcrete fragments, or as drip-like features beneath clasts (Thiry, 1978, 1981; Callen, 1983; van der Graaff, 1983; Thiry, 1988; Thiry and Milnes, 1991). In UK silcretes, illuvial features comprising alternating lamellae of silica and titania have only been reported from sarsens and puddingstones on the East Devon Plateau (Isaac, 1983).

The micromorphology of pedogenic silcrete indicates an interplay between dissolution and percolation throughout the profile (Milnes and Thiry, 1992). Dissolution and eluviation features dominate the upper part of profiles, while illuvial structures typify the lower horizons (Thiry, 1978; Watts, 1978; Thiry, 1981; Milnes and Twidale, 1983; Summerfield, 1983b; Thiry and Ben Brahim, 1990; Kendrick and Graham, 2004). The origin of this differentiation is unclear, but appears to be related to gravitational movement of solutions under alternating wet and dry conditions.

While the macro- and micro-scale features described above are common to all pedogenic silcretes, there may be variations in mineralogy, geochemistry and cements between profiles. Two predominant types of pedogenic silcrete have been identified. The first exhibit profiles where microquartz is the dominant cement, with enrichment in titania usually identified as 'leucoxene' or anatase (e.g. Thiry, 1978, 1988). Upwards increases in the crystallinity of silica cements, often termed vertical ripening, is commonly observed at the profile scale in this type, with quartz cements present in addition to microquartz in upper sections and opaline silica more typical at the base (Thiry and Millot, 1987). The second type of pedogenic silcrete exhibits predominantly opaline cements, contains goethite and hematite, sometimes alunite, and retains clay minerals (e.g. Meyer and Pena

dos Reis, 1985; Thiry and Turland, 1985; Ballesteros et al., 1997; Thiry, 1999). Evidence of vertical ripening may also be apparent (Ballesteros et al., 1997), with microquartz and chalcedony cements present in upper parts of the profile.

3. Characteristics of non-pedogenic silcretes

In contrast to pedogenic silcretes, the majority of non-pedogenic silcrete varieties display both a much simpler profile structure and micromorphology (Fig. 3). Groundwater, drainage-line and pan/lacustrine silcretes typically occur as discontinuous lenses (Fig. 3a), or as tabular sheets, that can be superposed (Senior and Senior, 1978; Wopfner, 1983; Meyer and Pena dos Reis, 1985; Thiry et al., 1988; Basile-Doelsch et al., 2005; Lee and Gilkes, 2005). They may form in weathered or unweathered materials (Wopfner, 1983; Thiry and Milnes, 1991), and are typically more massive (Thiry, 1999) and lack the systematic jointing of pedogenic varieties (Thiry and Millot, 1987) (Fig. 3b). Concretionary pillow-like, mammiform or botryoidal shapes (referred to as 'cockades' and 'glerps' in the Australian literature) are common, and have been attributed to progressive or centripetal cementation (Callender, 1978; Ruxton and Taylor, 1982; Thiry and Marechal, 2001). Similar features are reported in UK silcretes (e.g. Boswell, 1916, 1927; Davies and Baines, 1953; Hepworth, 1998).

Variations in macromorphology do, however, occur, and shapes may be very irregular in some host materials. For example, groundwater silcretes developed in limestones in the Paris Basin, where silicification is related to karstic systems, take an irregular form (Ménillet, 1988; Thiry, 1999; Thiry and Ribet, 1999). Similarly, groundwater silcretes at Stuart Creek, Australia, appear as amoeboid masses where they are developed within shales but as more massive or tuberous bodies in fluvial sands (Thiry and Milnes, 1991). Drainage-line silcretes (Fig. 3c) vary in shape from tabular to nodular (Shaw and Nash, 1998), while pan/lacustrine silcretes (Fig. 3d) may be irregularly shaped, lenticular or nodular (e.g. Armenteros et al., 1995; Ringrose et al., 2005).

In line with their profile characteristics, the micromorphology of non-pedogenic silcretes is typically simple (Fig. 5), with host material structures and fabrics generally retained (Milnes and Thiry, 1992). Geopetal features are uncommon but can occur (Callender, 1978). Unlaminated titaniferous caps, for example, have been documented on clasts within groundwater silcretes in eastern Australia (Taylor and Ruxton, 1987) and in sarsens and puddingstones from the southern UK (Ulliyott et al., 2004; Ulliyott and Nash, 2006; Ulliyott et al., 2015) (Fig. 5d). Colloform structures with cusped titania-rich laminae have been documented in groundwater silcretes from Australia (Taylor and Ruxton, 1987;

Webb and Golding, 1998), but are rare; poorly developed colloform structures are also known from the UK (Ulliyott et al., 2015) (Fig. 5c). Cap structures and laminar fabrics are considered further in Section 4.

Silica mineralogy is very variable within non-pedogenic silcrete cements, but vertical sequences of ripening are rarely documented. The presence of length-slow chalcedony and/or enhanced levels of moganite (>20 wt.%) may indicate the formation of some examples under evaporitic conditions (Folk and Pittman, 1971; Heaney, 1995). Non-pedogenic silcretes can contain a variety of matrix minerals in addition to silica; this depends both on the nature of the host material and on the conditions of silicification. For example, transitions between silcrete and calcrete are frequently observed (Nash and Shaw, 1998; Nash et al., 2004). Levels of TiO₂ may be significant, with both anatase and rutile reported, though these are usually present in lower concentrations than in pedogenic silcretes (Young, 1985; Taylor and Ruxton, 1987; Webb and Golding, 1998). Clay minerals, alunite and traces of zeolites have also been documented (e.g. Rodas et al., 1994; Bustillo and Bustillo, 2000), while glauconite-illite has been identified within green pan/lacustrine silcretes in the Kalahari (Summerfield, 1982; Nash et al., 2004).

4. Problems and challenges

While the majority of pedogenic and non-pedogenic silcretes exhibit the broad differences described above, there is an emerging literature suggesting that the basic distinction between ‘complex pedogenic’ and ‘simple non-pedogenic’ is not as clear cut as formerly suggested. Indeed, challenges to this bipartite classification arise at a variety of scales.

4.1 Variability in silcrete macromorphology

There are three main complications in distinguishing silcrete types at the profile scale. First, not all pedogenic silcretes display the ‘typical’ profile characteristics described in Section 2; columnar structures, in particular, may be absent or difficult to distinguish. For example, the ‘Pierre de Stonne’ silcretes in northeast France and Luxembourg, of which at least some are attributed to a pedogenic origin (Quesnel et al., 2003), can exhibit more tabular forms. Furthermore, pedogenic silcretes formed in gravelly host materials may develop columnar features at such a large scale (Thiry and Simon-Coinçon, 1996) that they may not be discernible in small exposures, drill core, or displaced boulders. Semi-continuous or lenticular pedogenic silcretes, sometimes associated with channels, have also been described (Callen, 1983; Milnes and Twidale, 1983; Milnes et al., 1991; Benbow

et al., 1995), as have pedogenic silcrete 'skins' (Hutton et al., 1972), discrete nodules (Mišík, 1996) and veins in bedrock (Curlík and Forgác, 1996).

Second, composite profiles may be developed as a result of different silicification mechanisms operating at different times in the same area. For example, pedogenic silcrete profiles may occur superimposed on earlier groundwater silcrete profiles during progressive pedogenesis and concomitant landscape lowering (Milnes and Thiry, 1992; Thiry and Simon-Coinçon, 1996). More commonly, older pedogenic profiles are underlain by younger groundwater silcretes that have formed during later landscape dissection. Well documented examples occur in the Eromanga Basin of Australia (Milnes et al., 1991; Thiry et al., 2006), and the Apt region of southeast France (Basile-Doelsch et al., 2005), where multiple groundwater silcrete layers occur at depths of up to 100m beneath surficial pedogenic silcrete.

Finally, while a number of smaller features discernible at the profile scale are often regarded as diagnostic of pedogenesis, two of the more common – tubular hollows and nodular/concretionary structures – have enigmatic origins. Vertical to sub-vertical tubular hollows are widely documented in the silcrete literature (including in sarsens and puddingstones), and are usually interpreted as rootlet or root holes. While many are undoubtedly root casts, as they retain imprints of root structures (e.g. Carruthers, 1885; Milnes and Twidale, 1983) or contain silicified roots (Clark et al., 1967; Callender, 1978; Lee and Gilkes, 2005), other formative mechanisms may also be responsible (e.g. dissolution, or bioturbation by worms, ants or termites; see Milnes et al., 1991; Benbow et al., 1995; Thiry et al., 1995; Ballesteros et al., 1997). They should not, therefore, be used to infer process. Even if undoubtedly of plant origin, the presence of root casts is only an indication that the silcrete host sediment was deposited in a relatively near-surface setting. Likewise, process should not be inferred from the presence/absence of macroscale nodular/concretionary structures, as these are also common to both pedogenic and non-pedogenic silcrete profiles and may have developed via a range of different formative processes. Instead, attention should focus on the microscale; nodular features in pedogenic silcretes commonly incorporate complex geopetal micromorphological features and occur with a suite of other illuvial features such as laminated caps or 'colloform' structures (Thiry, 1978; Milnes and Thiry, 1992), whereas those in non-pedogenic silcretes are typically large and simple in both form and micromorphology (e.g. Leckie and Cheel, 1990; Shaw and Nash, 1998).

4.2 Variations in silcrete micromorphology

In addition to the problems in interpreting certain macroscale properties of silcrete profiles, a number of complications arise at the microscale. These all involve features that have been long-regarded as indicative of the role of pedogenesis in the silicification process, but which also occur in non-pedogenic silcretes. Foremost are cap structures; silica-cemented conical or cap-like features developed on the top of host sediment clasts. The origin of such structures is not entirely clear, but, particularly where caps are layered, has been suggested to relate to repetitive infiltration events (Thiry and Milnes, 1991). Many reviews of silcrete formation treat cap structures as an exclusive product of pedogenesis. However, as noted above, caps have been described in groundwater silcretes from eastern Australia and the southern UK (e.g. in the Hertfordshire puddingstone) (Fig. 5d), so cannot be considered diagnostic of pedogenic silicification. Instead, Ulliyott et al. (2015) suggest that non-pedogenic silcrete caps may be distinguished from their pedogenic equivalents by their simpler form, which typically lacks laminated colloform features.

Geopetal patches or 'beards' beneath clasts have been documented in both pedogenic (Milnes et al., 1991) and groundwater silcretes (Callender, 1978). Colloform structures, often consisting of alternating laminae of silica and titania, are also described in non-pedogenic silcretes (Taylor and Ruxton, 1987; Webb and Golding, 1998; Ulliyott et al., 2015), although such features appear far less abundant and well developed than in pedogenic silcretes. Finally, microscale glaebules or ped-like structures may also be found in non-pedogenic silcretes. In examples from the Kalahari, these are suggested to result from the silicification of pre-existing pedogenic calcrete (e.g. Nash et al., 1994; Nash et al., 2004), or from silica accumulation at or near the groundwater table resulting in pisolithic textures (Shaw and Nash, 1998) (Fig. 5f).

4.3 Variations in silcrete geochemistry

It was formerly thought that genetic types of silcrete could be distinguished on the basis of geochemistry, in particular by enrichment in titania (e.g. Summerfield and Goudie, 1980; Summerfield, 1983d). Subsequent studies have shown that the geochemistry of silcrete is considerably more complex and reflects the nature of the host material as well as the environment of silicification (e.g. Nash et al., 1994; Webb and Golding, 1998). As noted above, one type of pedogenic silcrete comprises predominantly microquartz and anatase and thus contains elevated levels of titanium (to >1%), with low Fe, Al and K. Rarely, for example in silcrete 'skins', TiO₂ may exceed 20% (Hutton et al., 1972). The second, mainly opaline, pedogenic silcrete type retains clay and iron oxide, so is comparatively rich

in Fe, Al and K but low in Ti (Thiry, 1999). Non-pedogenic silcretes are typically Ti-poor by comparison, although whether or not this is the case appears to depend on the silicified host material. For example, Webb and Golding (1998) describe Ti mobility and enrichment in non-pedogenic silcretes developed in clay-rich host materials and Ti depletion during the silicification of sandy host materials. Such a process could easily explain the variations in Ti content described in UK sarsens and puddingstones (Summerfield, 1979; Summerfield and Goudie, 1980).

5. Conclusions: distinguishing pedogenic from non-pedogenic silcretes

What is clear from the above discussion is that distinguishing between pedogenic and non-pedogenic silcrete can, in many cases, be difficult. To aid identification, we summarise the properties common to each silcrete type in a simple checklist (Table 1), with accompanying observations for the more problematic features noted in Section 4.

The effective use of the checklist requires that – ideally – both macromorphological and detailed micromorphological properties are considered. An understanding of the wider landscape (or palaeolandscape) context of the outcrop is also desirable; this is challenging where the silcrete is in the form of an isolated boulder or lag deposit, or is sampled from drill core, but may still be possible. Furthermore, as Ulliyott et al. (2015) stress, it is not simply the presence/absence of individual indicators that should be taken into account, but rather the combination, abundance and degree of development of features.

For example, an extensive silcrete outcrop that (i) caps a palaeosurface, (ii) exhibits a vertically-differentiated profile with a columnar structure at the macroscale, plus (iii) upward-ripening cements and abundant, well-developed, way-up orientated features (e.g. cusate colloform and laminated cap structures) at the microscale, will almost certainly have formed as a result of pedogenic silicification. A more localised massive outcrop lacking vertical profile differentiation at the macroscale, but with abundant complex way-up micro-features, may also be a pedogenic silcrete. In contrast, a silcrete with a similar simple profile but lacking complex internal structural features is more likely to have formed via non-pedogenic mechanisms. At this stage it would be necessary to assess the geomorphic (or palaeo-geomorphic) context of the outcrop to determine whether it was a groundwater, drainage-line or pan/lacustrine silcrete.

As this review has demonstrated, the silcrete literature has grown to the stage that we now have a good understanding of the external and internal features associated with pedogenic silicification. Much more research is needed, however, into the properties of

non-pedogenic silcretes. While the literature on groundwater and pan/lacustrine silcretes is reasonably abundant, only a handful of studies from southern Africa and Australia have focussed on drainage-line varieties. A better understanding of micro-structures within non-pedogenic silcretes – particularly those such as glaebules/nodules, caps, colloform structures and beard-like features that also occur within pedogenic varieties – will greatly improve our ability to distinguish silcrete types in the landscape and geological record.

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Figure 1: Classification of silcrete (Nash and Ulliyott, 2007).

Figure 2: Typical pedogenic silcrete profiles from (a) Enniskillin, Western Cape, South Africa; (b) Mount Wood Hills, near Tibooburra, New South Wales, Australia; and (c) Montagny-Lencoup, Paris Basin, France. Note the columnar structure of all three profiles and the well-developed 'candle-wax' drip-like macro-structures in image (c).

Figure 3: Examples of non-pedogenic silcrete outcrops: (a) Superposed groundwater silcrete lenses developed within Fontainebleau Sand at Bonnevault Quarry, Paris Basin, France; (b) Groundwater silcrete developed within Red Bluff Sand at Taylor Creek, north of Melbourne, Australia; (c) Drainage-line silcrete in the floor of the Boteti River near Samedupe Drift, Botswana; (d) Pan/lacustrine silcrete exposed at the southern margin of Lake Ngami, Botswana.

Figure 4: Photomicrographs of microscale structures within pedogenic silcretes: (a) Glaebular structure within a pedogenic silcrete from Stuart Creek, South Australia (plain polarised light, scale bar 2 mm, image courtesy of John Webb); (b) Glaebular (top right) and cusped colloform structures (bottom left) within a pedogenic silcrete from Makanna's Kop, Grahamstown, Eastern Cape, South Africa (plain polarised light, scale bar 500 μ m); Cusped colloform structures within pedogenic silcretes from (c) Salcombe Hill, Sidmouth, Devon, UK (plain polarised light, scale bar 1 mm) (d) Stuart Creek, South Australia (plain polarised light, scale bar 2 mm, image courtesy of John Webb), (e and f) north of Albertinia, Western Cape, South Africa (plain polarised light, scale bar 500 μ m).

Figure 5: Photomicrographs of microscale structures within non-pedogenic silcretes: (a) pan/lacustrine silcrete from the southern margin of Lake Ngami, Botswana (cross polarised light, scale bar 500 μm); (b) groundwater silcrete from Roche des Etroits, near Fontainebleau, Paris Basin, France (cross polarised light, scale bar 500 μm); (c) poorly developed cuspate feature (arrowed) within a groundwater silcrete (puddingstone) from Ley Hill, Chesham, UK (plain polarised light, scale bar 200 μm); (d) cap structure within a groundwater silcrete (puddingstone) from Ley Hill, Chesham, UK (plain polarised light, scale bar 1 mm), (e) drainage-line silcrete from Samedupe Drift, Boteti River, Botswana (cross polarised light, scale bar 500 μm); (f) pisolithic structure towards the base of the same drainage-line silcrete as (e) (plain polarised light, scale bar 500 μm).

Table 1: Distinguishing pedogenic from non-pedogenic silcrete varieties.

Pedogenic silcrete	Non-pedogenic silcrete	Observations
Macroscale characteristics		
Complex vertically-differentiated profiles	Simple tabular, lenticular or irregular morphologies	
Profiles laterally extensive	Profiles restricted in lateral extent	Pedogenic profiles may be discontinuous, especially where affected by erosion
Develop on stable palaeosurfaces	Related to landscape depressions, drainage lines, water tables	Non-pedogenic silcretes often form below a land surface
Columnar or systematic vertical jointing present	Columnar structures / vertical jointing absent	Columnar structures may be absent or poorly developed in some pedogenic silcretes
Small- to large-scale nodular or pseudo-nodular structures often present	Where present, nodular or concretionary structures are of a larger scale	See comments below about internal structures within nodules
Microscale characteristics		
Complex fabric with abundant way-up orientated micromorphology	Simple fabric; way-up orientated micromorphology absent or, where present, less well-developed	Complex fabric less well-developed in less mature pedogenic profiles
Abundant cusped colloform structures with titania-rich laminae abundant	Cusped colloform structures absent, or, where present, less well-developed	Cusped colloform structures in pedogenic silcretes that retain Fe and clays are Fe- or Mn-rich
Laminated titaniferous caps on clasts very common	Titaniferous caps may occur but lack laminated structure	
Pendulous, drip- or beard-like geopetal structures frequent	Beard-like geopetal structures absent, or, where present, less well-defined	
Glaebules/micro-nodules with complex internal structures common	Glaebules/micro-nodules rare; pisolithic textures may occur; internal structures are usually simple	Micro-nodular textures must be interpreted with great care
Mineralogy / geochemistry		
Silica cements often show vertical ripening sequences (opaline silica common in lower profile; microquartz/quartz in upper profile)	Ripening sequences in cements very rare	Ripening sequences less clear in pedogenic silcretes retaining Fe and clays
Microquartz-dominant cements typically enriched in titania (>1%); low Fe, Al, K	Levels of titania lower than in microquartz-dominant pedogenic silcretes	Titania may be enriched in non-pedogenic silcretes developed in clay-rich host materials
Opaline-dominant cements typically have low Ti content but higher Fe, Al, K		