Recent advances in silcrete research and their implications for the origin and palaeoenvironmental significance of sarsens

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ULLYOTT, J. S., NASH, D. J. & SHAW, P. A. 1998. Recent advances in silcrete research and their implications for the origin and palaeoenvironmental significance of sarsens. *Proceedings of the Geologists' Association*, **109**, 255–270. Sarsens and puddingstones have long been recognised as varieties of silcrete and were, until recently, considered to have formed under hot sub-tropical or tropical climates in tectonically stable, low relief landscapes during the early Palaeogene. This paper provides a summary of the major advances in silcrete research since the most recent review of sarsen development and focuses upon models of silcrete genesis derived from studies in France, Australia and the Kalahari region of southern Africa. These models include silcretes which formed within soil profiles by pedogenic processes (pedogenic silcretes), those which formed in zones of groundwater outflow or water table fluctuation in association with drainage-lines or in lacustrine settings (groundwater or drainage-line silcretes), and more complex cases where silcretes developed through the interaction of more than one set of processes through time (multiphase and intergrade silcretes). Each of these models is subsequently placed within a landscape context through consideration of a series of case studies. The implications of this recent research for the interpretation of UK sarsens and puddingstones are discussed. The importance of identifying the mode or modes of origin of any silicified remnant materials before drawing any conclusions concerning their age, extent and possible palaeoenvironmental significance is stressed.

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1. INTRODUCTION

There has been a long tradition of interest in sarsens and puddingstones amongst members of the Geologists' Association and this has persisted to the present day (e.g. Robinson, 1994). This paper is partially inspired by a recent article by John Hepworth (1997, *Geologists' Association Circular*, **922**) which resurrected the debate on the relationship between sarsens and puddingstones and other silcretes elsewhere in the world, and their role in landscape evolution in the southern UK. This contribution also reflects continuing silcrete research currently being undertaken by the authors on both sarsens in the UK and silcretes in southern Africa.

The term sarsen is now well established in the UK geological literature, to describe displaced siliceous boulders consisting of silica-cemented sands which occur on the chalklands and on various Cenozoic formations in southern England (Summerfield, 1979). It is generally accepted that puddingstones, consisting of silica-cemented rounded or angular pebbles/cobbles, are the conglomeratic equivalent of sarsens (e.g. Sherlock & Pocock, 1924; Davies & Baines, 1953; Summerfield, 1979; Summerfield & Goudie, 1980). It has been established for some time that sarsens and puddingstones are fragments of silcrete duricrusts and, as such, they are potentially analogous to silcretes occurring elsewhere in the world (Kerr, 1955; Summerfield, 1979; Summerfield & Goudie, 1980). This assumption has formed the basis of the majority of studies and is the premise upon which this paper is founded.

Although the literature on sarsens and puddingstones is plentiful, there is comparatively little detailed work concerning their petrology or micromorphological variability (Whalley & Chartres, 1976). The more influential work has concentrated on their distribution (e.g. Boswell, 1916; Davies & Baines, 1953; Bowen & Smith, 1977); on geomorphological aspects (Clark, Lewin & Small, 1967; Williams, 1968; Small, Clark & Lewin, 1970; Small, 1980) or on reconnaissance sampling from a number of often widely separated sites (e.g. Summerfield & Goudie, 1980; Summerfield & Whalley, 1980). While this gives some idea of what is present, there have been no in-depth studies of the type which has allowed detailed interpretation of the genesis and significance of silcretes in some other parts of the world.

The seminal work of Summerfield & Goudie (1980) assessed silcrete research up to the 1980s and its bearing on the questions of sarsen origin and palaeoenvironmental interpretation. Since then silcrete research has advanced considerably and, although comparatively little has been published on UK sarsens, much work has been done in other parts of the world, particularly the Paris Basin, Australia and southern Africa. This paper aims to provide a brief review of the major advances in silcrete research since Summerfield & Goudie (1980) and assess the possible

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implications for sarsen and puddingstone genesis and interpretation.

2. BACKGROUND

Until recently, the prevailing consensus in the UK literature was that sarsens and puddingstones represented fragments of a former continuous or semi-continuous duricrust 'carapace' (e.g. Kerr, 1955; Clark *et al.*, 1967) which developed under very specific palaeoclimatic and geomorphological conditions; a hot sub-tropical, or tropical, climate was considered essential, as was a tectonically stable landscape of relatively low relief (e.g. Kerr, 1955; Clark *et al.*, 1967; Summerfield & Goudie, 1980; Jones, 1981; Kellaway, 1991; Embledon, 1992). This was based upon the recognition that sarsens and puddingstones were varieties of silcretes which were assumed to form only under such climatic and geomorphological conditions. Sarsen formation was normally attributed to the early Palaeogene as this was considered to be the only time during which these conditions could have been met.

It was also suggested that two varieties of sarsen could be distinguished in the UK. Summerfield (1978, 1983a) reviewed the world silcrete literature up to the early 1980s and, based upon studies in southern Africa, proposed that silcretes could be divided into two major groups. 'Weathering profile silcretes' occurred in direct association with deeply weathered material, were enriched in titanium (TiO_2>2%) and frequently contained micromorphological structures such as glaebules (nodules or concretions) and colloform features (geopetal, cusp-like laminations comprising layered silica, titania and/or iron oxides) (Summerfield, 1983a, d). It was suggested that titanium had been mobile during silcrete development and that formation occurred in a low pH environment probably resulting from high organic productivity under a humid tropical climate (Summerfield, 1981, 1983b,d, 1984, 1986). 'Non-weathering profile silcretes', in contrast, were not directly associated with weathering profiles, lacked glaebules, colloform structures and titanium enrichment. The lack of deep weathering, and high pH regime considered necessary for their formation, together with other factors, indicated that formation had probably occurred under an arid or semi-arid climate (Summerfield, 1982, 1983b,c). Summerfield's model embraced the notion of silica solubility in contrasting pH conditions. Solubility increases significantly above pH 9 and below pH 6 (Beckwith & Reeve, 1964), making it possible for silcrete formation to occur in very different environments. In addition, Summerfield proposed that it might be 'possible to discriminate to a certain extent between silcretes formed in these contrasting environments on chemical and micromorphological grounds' (Summerfield, 1983a, p. 84).

Sarsens were found to include both 'weathering profile' and 'non-weathering profile' varieties, although it was acknowledged that glaebules were absent and colloform features were very scarce in UK silcretes (Summerfield, 1979; Summerfield & Goudie, 1980; Summerfield & Whalley, 1980). Whilst proposing two differing origins for sarsens, Summerfield (1979) and Summerfield & Goudie (1980) still maintained that silicification occurred in a low latitude setting, within a stable landscape of low relief, and therefore concluded that sarsen formation was likely to have occurred prior to the late Miocene.

Research since the early 1980s suggests, however, that many of the prevailing ideas concerning the environment and mode of sarsen formation should be questioned. Studies of ancient landscapes, for example, in Africa and Australia, have indicated that the concept of a single phase of duricrust development is an oversimplification. Furthermore, duricrusts cannot be used reliably to map out vast erosion surfaces as was once believed without recourse to detailed study of the duricrusts themselves (e.g. McFarlane, 1976; Young, 1985; Nash, Shaw & Thomas, 1994a). We also now know that early Alpine tectonic phases were affecting the region from the late Cretaceous onwards (Plint, 1982; Mortimore & Pomerol, 1997) and significant uplift has occurred as late as the Quaternary (Jones, 1999).

Summerfield's conclusions concerning distinctions between 'weathering profile' and 'non-weathering profile' silcretes have also been disputed. For example, silcretes in eastern Australia with similar characteristics to 'non-weathering profile' types were suggested to have formed in low pH conditions in a hot humid palaeoclimate (Young, 1985), as opposed to the high pH, arid or semi-arid palaeoenvironment favoured by Summerfield. In France, Thiry, Bertrand-Ayrault & Grisoni (1988a) suggested that silcrete had formed in a temperate mid-latitude climate and that many silcretes were associated with weathering profiles even though their micromorphology and chemistry was comparable to Summerfield's 'non-weathering profile' type. In the Stuart Creek area of central Australia, silcretes of different origins with differing micromorphology and chemistry occur in the same deeply weathered profiles (e.g. Thiry & Milnes, 1991). Even in the Kalahari, where Summerfield undertook part of his original research, the terminology has proved to be problematic, as Nash, Thomas & Shaw (1994b) identify silcretes which exhibit characteristics typical of Summerfield's 'non-weathering profile' varieties in areas where there is clear evidence of deep weathering from borehole records.

It has also been suggested that titanium content may not be a reliable indicator of mode of origin or palaeoenvironment. Silcretes associated with weathered profiles but which are not titanium enriched are now well documented (e.g. Thiry *et al.*, 1988a; Nash *et al.*, 1994b). Conversely, silcretes without direct relationships to weathering profiles have been found to be enriched in titanium (Young, 1985; Taylor & Ruxton, 1987). There is growing evidence that apparent titanium enrichment may not be entirely due to absolute accumulation, but may be related to original host sediment chemistry (Milnes & Twidale, 1983; Young, 1985; Twidale & Hutton, 1986; Nash *et al.*, 1994b). Titanium accumulation may also not be contemporaneous with silicification but may post-date it (McFarlane, Borger & Twidale, 1992).

3. RECENT MODELS OF SILCRETE FORMATION

On the basis of the above discussion, it would appear that the suggestions made by Summerfield (1979) and Summerfield & Goudie (1980) concerning the origins and palaeoenvironmental interpretation of sarsens may need re-evaluation. Recent silcrete research indicates that the environment of formation of silcretes and their inter-relationships is considerably more varied and complex than previous models had suggested. Whilst silcrete can, and does, form on stable cratons in endoreic basins in hot climates, both arid and monsoonal, it is by no means restricted to such settings. Work in the Paris Basin and South Australia has resulted in a new classification for silcretes, again dividing silcretes into two broad groups but this time on the basis of detailed micromorphological analysis of profiles into pedogenic, or complex, silcretes and groundwater, or simple, silcretes (Milnes & Thiry, 1992). These two categories are used for the following review, with the latter category expanded to include drainage-line silcretes, thereby embracing a range of formational environments, including fluvial and lacustrine settings.

Pedogenic silcretes

Pedogenic silcretes form as part of soil profiles, are often semi-continuous, or lenticular and relate directly to palaeosurfaces. The silcrete commonly retains evidence of its formation by 'downward percolation of soil water in a succession of cycles of leaching and precipitation' (Milnes & Thiry, 1992, p. 357). The most common manifestations of this process are abundant illuviation structures, which often contain alternate lamellae of silica and titania, and are commonly geopetal. These are analogous to the 'colloform' structures described by previous authors (e.g. Summerfield, 1979, 1983a,d). Structures in the host sediment are normally almost completely destroyed and the profile itself is highly organized. The macromorphology and micromorphology are complex and vary consistently throughout profiles (Fig. 1.). According to Milnes & Thiry (1992) a granular or nodular basal facies, characterized by illuvial deposition of silica, is overlain by a columnar facies, the micromorphology of which indicates an interplay of dissolution and percolation, but primarily an infilling of the horizon with materials washed down from above. This columnar part of the profile (Fig. 2a.) is surmounted by a pseudo-brecciated facies principally characterized by micromorphology indicative of dissolution and eluviation. In tandem with the macromorphology and micromorphology, the silica mineralogy also commonly varies consistently throughout the profile (Thiry & Millot, 1987). In mature profiles, more ordered forms of silica, such as quartz, are developed in the older or uppermost part of the profile, whereas in the younger basal parts less ordered forms of silica, such as opal, are predominant. Pedogenic silcrete facies can also be differentiated laterally according to position in the palaeo-landscape and it is clear that there is

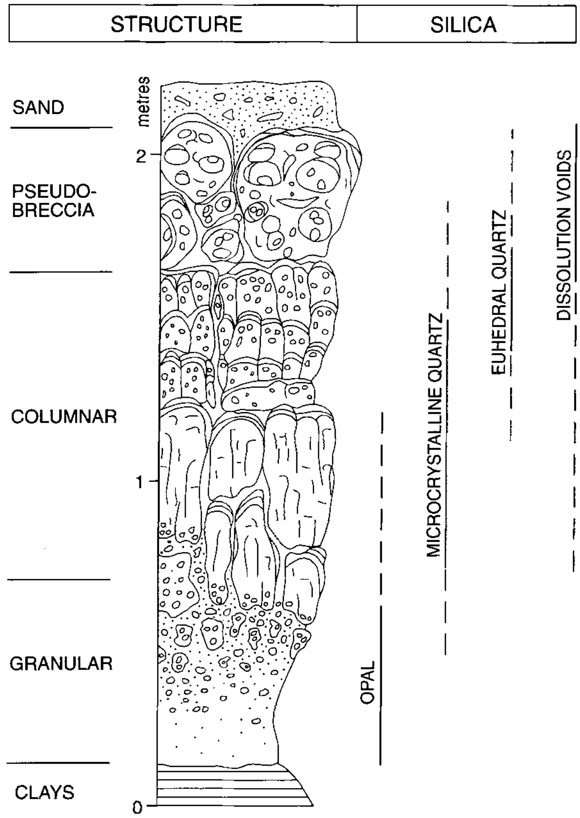


Fig. 1. Generalized section showing the consistent facies variations occurring within pedogenic silcrete profiles in the Paris Basin (after Thiry, 1988, 1989).

a component of lateral transfer of silica as well as downward percolation (e.g. van der Graaff, 1983; Thiry & Millot, 1987; Milnes & Thiry, 1992; Simon-Coinçon, Milnes, Thiry & Wright, 1996). Silica is also formed within the profile by destruction of clays in acid conditions leading to the formation of opal (Thiry & Millot, 1987; Rayot, Self & Thiry, 1992; Dubroeucq & Thiry, 1994).

As pedogenic silcretes form at or near the land surface, profile development would clearly be directly affected by near-surface conditions. Thus, they are much more useful as indicators of palaeoclimate than groundwater or drainage-line silcretes, and their environment of formation is considered to be similar to that previously envisaged for weathering profile silcretes, namely a low latitude setting, with a climate comprising alternating dry and wet phases (Thiry, 1989; Thiry & Milnes, 1991). The geomorphological setting, however, is no longer thought to be restricted to 'landscapes of low relief' as pedogenic silcretes that have developed within scarp foot sediments and on glacis have been identified (Simon-Coinçon *et al.*, 1996). Most pedogenic silcretes appear to be relict, dating from the Palaeogene (e.g. Thiry, 1989; Simon-Coinçon *et*

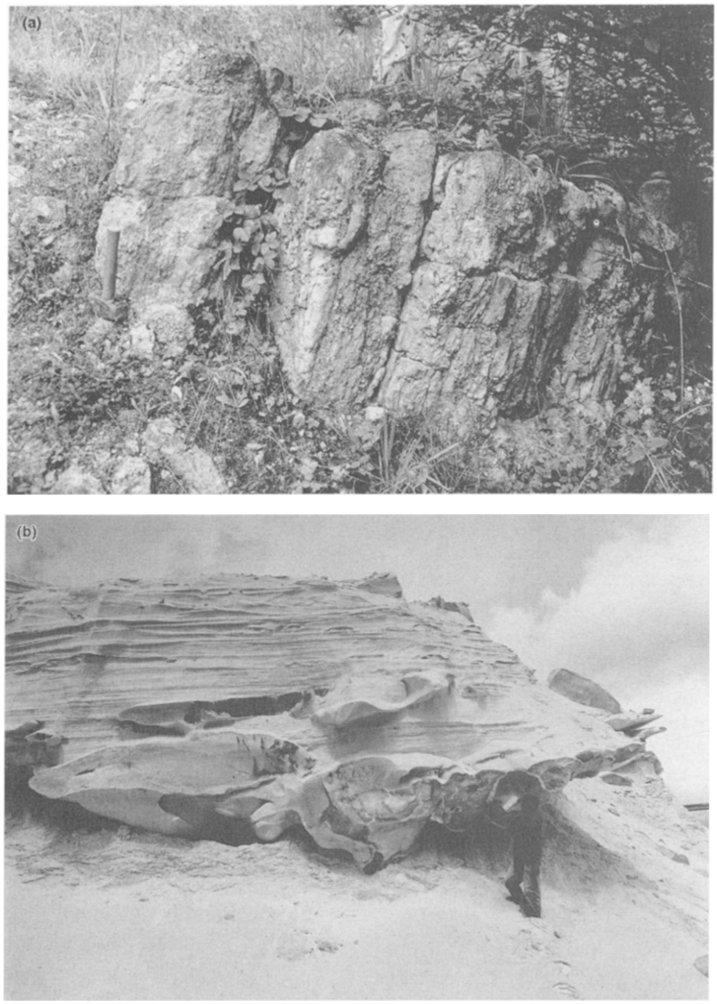


Fig. 2. *In situ* silcretes in the Paris Basin. (**a**) Columnar structures in Eocene pedogenic silcrete at Montigny-Lencoup, Seine-et-Marne (hammer 0.3 m for scale). (**b**) Groundwater silcrete lenses in the Fontainebleau sands at Bonnevault quarry, Larchant, Seine-et-Marne. Irregular lenticular shapes as well as massive tabular lenses are developed at this locality.

al., 1996) or early Neogene (e.g. Milnes & Twidale, 1983; Thiry & Milnes, 1991), although pedogenic silicification in Quaternary volcanic soils is reported by Dubroeucq & Thiry (1994).

Groundwater and drainage-line silcretes

Groundwater and drainage-line silcretes do not usually form in association with soil profiles, but may be found in unweathered or weathered materials, and in weathered profiles. They commonly have a simple structure and consist of silica-cemented sediments situated in or adjacent to drainage features. Silcrete bodies are often relatively localized, occurring as sheets or lenses which may be superposed (Fig. 2b.). They are normally directly related to a present, or former, water table or other groundwater or drainage phenomenon, and thus do not strictly represent a palaeosurface. They may occur at considerably greater depths beneath the surface than pedogenic types. Some form of landscape depression would appear to be the prime determinant in their formation; this could be a basin, pan or valley within an endoreic or exoreic drainage system. Silcrete develops in these settings in association with zones of groundwater outflow (cf. Thiry *et al.*, 1988a) (Fig. 3.), at sites marginal to drainage lines which are subjected to seasonal wetting and drying (cf. McCarthy & Ellery, 1995) or in zones of water table fluctuation (cf. Taylor & Ruxton, 1987; Milnes, Wright & Thiry, 1991). Association with present or past drainage lines is very common and is documented in many areas, particularly in Australia and the

Kalahari (e.g. Barnes & Pitt, 1976; Nash *et al.*, 1994a; Nash, 1997; Nash, Shaw & Ullyott, 1998; Shaw & Nash, 1998). Although groundwater silcretes may parallel the valley or basin for some distance they rarely persist more than a few hundred metres from its edge, and in many cases they now occur in inverted relief and cap sinuous ridges, mesas or buttes (Pain & Ollier, 1995). Silcrete formation may also occur in pan or lacustrine settings (Summerfield, 1982) and in seasonal pools associated with drainage lines (Shaw & Nash, 1998; Nash *et al.*, 1998). In some cases, this is thought to be due to inputs of detrital and dissolved silica brought by annual inflows and subsequent silica fixing by biological activity (Shaw, Cooke & Perry, 1990; McCarthy & Ellery, 1995).

Groundwater and drainage-line silcretes are characteristically devoid of the organized profile structure and the complex micromorphology found in pedogenic types, and exhibit relatively simple fabrics with host sediment structures often preserved. Silica mineralogy in such silcretes is highly variable with one or more of opaline silica, cryptocrystalline quartz, chalcedony, microquartz or quartz overgrowths commonly occurring. They may contain titanium, though usually in lower concentrations than in pedogenic silcretes. Illuviation features or other geopetal structures are less common but may be observed (c.f. Taylor & Ruxton, 1987).

Groundwater or drainage-line silcrete formation is only indirectly dependent upon climate, in that development is normally related to the water table and to groundwater flow within sediments. As such, formation has been attributed to a range of contrasting environments and a range of palaeoenvironments and ages has been suggested. Low pH groundwater conditions are envisaged for some occurrences. This is thought to result from high organic productivity in a tropical humid climate (e.g. Young, 1985; Taylor & Ruxton, 1987) but in other cases it may result from acidification due to weathering and oxidation within the host sediment (e.g. Thiry *et al.* 1988a; Thiry, Bertrand-Ayrault, Grisoni, Menillet & Schmitt, 1988b; Thiry & Milnes, 1991). By contrast, many of the Kalahari silcretes related to drainage-lines are clearly the product of a relatively high pH environment (Summerfield, 1982; Shaw *et al.*, 1990; Nash & Shaw, 1998; Nash *et al.*, 1998). In addition, silica can be derived from either local sources,

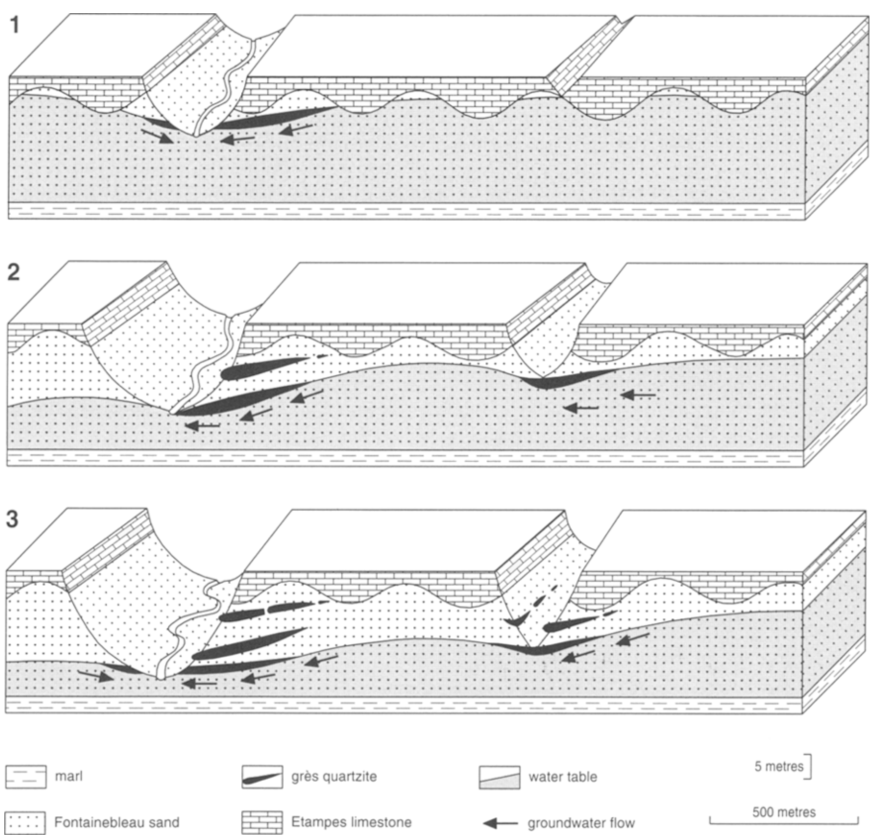


Fig. 3. Block diagram illustrating the formation of groundwater silcretes in the Fontainebleau sands (after Thiry *et al.*, 1988a, b). Silcrete lenses form close to the water table in zones of groundwater outflow (1) and superposed lenses develop (2) with valley deepening due to progressive landscape evolution (3).

such as the profile itself (Taylor & Ruxton, 1987; Thiry *et al.*, 1988a; Thiry & Milnes, 1991; Rayot *et al.*, 1992), or may be transferred by the fluvial system from more distant sources (e.g. McCarthy & Ellery, 1995; Nash *et al.*, 1998).

Multiphase and intergrade duricrusts

Whilst the preceding discussion suggests two relatively simple sets of models for silcrete formation, the situation can, in reality, be considerably more complex. Multiphase silcretes present particular difficulties when attempting to unravel their history of development. As silcretes can be such long-lived features in the landscape they may be subject to a range of different environmental conditions, and thus formative agencies, over time. This may lead to earlier phases of silicification being overprinted by one or more later phases. For example, pedogenic profiles may become superimposed on earlier groundwater silcretes (Milnes & Thiry, 1992; Thiry & Simon-Coinçon, 1996). Similarly, intergrade or hybrid duricrusts which contain other cementing agents in addition to silica may develop, either when changing conditions favour deposition of different solutes or when silcrete is replaced by calcrete or ferricrete, or vice versa (e.g. Summerfield, 1982; Arakel, Jacobsen, Salehi & Hill, 1989; Nash & Shaw, 1998).

4. SILCRETE LANDSCAPE CONTEXTS

Detailed study of silcretes in specific sedimentary basins has revealed the common occurrence of 'multiple silcrete components' within a given landscape. Frequently, different silcrete lenses or profiles, often with widely different origins and ages may occur juxtaposed in the same section or in neighbouring areas. Before it is possible to draw any safe conclusions from the presence of sarsens and pudding-stones in the UK, it is necessary to assess the potential range of materials which could be present and to understand the possible complexity of their inter-relationships in any former landscape. To do this it is useful to consider some examples from areas where silcretes have been studied in some detail.

Example 1: The Paris Basin

In the Paris Basin there is a range of both pedogenic and groundwater silcretes (Fig. 4.). According to Milnes & Thiry (1992) pedogenic silcretes, the *grès lustrés*, mark out a palaeo-pediplain on the southern margins of the Paris Basin and can be constrained by their stratigraphic position to the early Eocene. Close to the basin, silicification occurred in sandy clays and in channel fills of coarse clayey sand, whereas on the southern edge of the pediplain, silcretes (*les poudingues lustrés*) developed in clay with flint pebbles (Thiry, 1988; Milnes & Thiry, 1992). Further south, in the Loire graben, silicification affected flint breccias and profiles over 15 m thick occur where pedogenic silcretes overlie groundwater types (Thiry & Simon-Coinçon, 1996). All these silcretes have formed in kaolinitic host sediments and have highly organized profiles. They are interpreted as forming in hot climates with alternating wet and dry phases.

In northern parts of the Massif Central, a different type of pedogenic silicification is found. Ferruginous kaolinitic palaeosols found on fault scarps and mottled horizons within graben deposits are silicified and form red-brown duricrusts (Thiry & Turland, 1985; Thiry & Millot, 1987; Milnes & Thiry, 1992). In these duricrusts, silicification processes were differentiated in relation to the geomorphology, with illuviation of silica and development of columnar structures in upstream areas whilst platy concretionary structures formed in conjunction with lateral flow in downstream sections (Thiry & Millot, 1987). The presence of potassium and sulphates may indicate an evaporitic environment (Thiry & Turland, 1985).

In addition to these pedogenic silcretes a range of groundwater varieties have formed in neighbouring parts of the Paris Basin and these are much younger (Milnes & Thiry, 1992). There are two principal types; the *grès quartzites*, found in arenaceous formations and the *meulières* which are associated with limestones. *Grès quartzites* are especially well-developed in the Oligocene Fontainebleau sands (Fig. 2b.), where lenses up to 8 m thick can be observed. Detailed studies by Thiry & Bertrand-Ayrault (1988) and Thiry *et al.* (1988a,b) indicate that

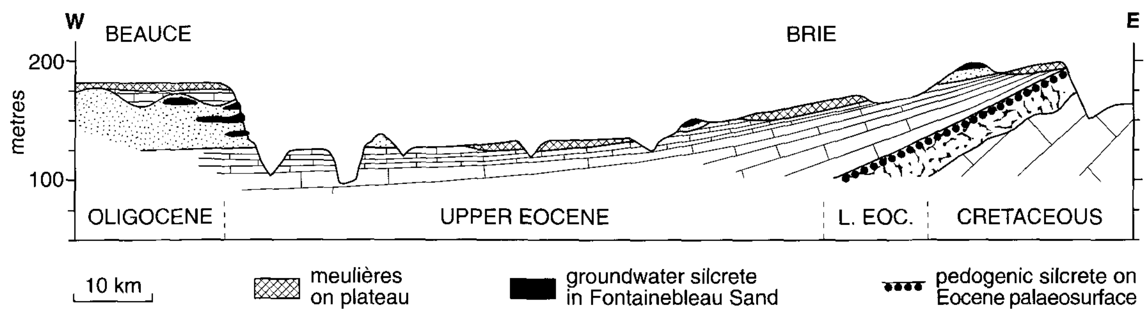


Fig. 4. Schematic representation of the different types of silcrete, their distribution, and relations to Tertiary and Quaternary formations in the Paris Basin (after Milnes & Thiry, 1992).

quartzite formation is related to leaching by low pH groundwaters associated with oxidation of the host sand from a dark facies to a pale bleached facies. Cementation took place close to the water table, leading to the formation of silcrete lenses focused upon zones of groundwater emergence which follow the regional water table gradient (Fig. 3.). In this environment silicification is closely tied to landscape evolution, with periods of landscape dissection leading to the formation of superposed silcrete lenses and, eventually, to relief inversion. The quartzites are cemented by interlocking of quartz overgrowths forming on the original detrital grains. Silica has been redistributed vertically and laterally and the bulk of the silica may be derived from the profile itself. According to Thiry *et al.* (1988a, p. 1283) cementation proceeded relatively rapidly, in the order or 30 000 years for a quartzite lens, and they also envisage that the 'silicification process has no climatic significance but is dependent on the stability of the landscape and on its progressive dissection'. The distribution of the quartzites is clearly related to the present valley systems and thus silicification is likely to have occurred during the evolution of the present landscape in the Plio-Quaternary. Studies of exposed outcrops of Fontainebleau quartzite indicate that the jointing patterns, general macromorphology and even silica mineralogy is different from that observed in recent quarry sections (Thiry & Millot, 1987) indicating the effects of weathering on this silcrete.

Elsewhere in the Paris Basin, similar silcretes are present in other Cenozoic arenaceous formations (of Thanetian to Rupelian age), and it is tentatively suggested that these may have formed by similar processes to those in the Fontainebleau sands (Thiry, Schmitt & Milnes, 1991). Silicification of Eocene and Oligocene lacustrine limestones also occurred related to karst circulation (Ribet & Thiry, 1990) on the Beauce and Brie plateaux. Weathering of this silicified limestone led to the development of cavernous silcretes known as *meulières* which were formerly used as a raw material for millstones. *Meulières* occur on structural and erosional limestone platforms formed during the Quaternary and their silicification is believed to be contemporary with silicification of the Fontainebleau quartzite during the Quaternary (Milnes & Thiry, 1992).

Example 2: Eromanga Basin, South Australia

In the Eromanga (Great Australian) Basin, extensive pedogenic silicification has been identified on plateau surfaces, around the Lake Eyre catchment, and on dissected pediments in the Alice Springs region (Milnes & Twidale, 1983; Twidale & Milnes, 1983). These pedogenic silcrete profiles have a comparable structure, chemistry and micromorphology to those in the Paris Basin (Milnes & Thiry, 1992) and in many cases can be related to a dissected palaeo-pediment (Milnes & Twidale, 1983; Milnes & Thiry, 1992; Simon-Coinçon *et al.*, 1996). Both scarp foot sediments and glacis are silicified, indicating that silcrete development did not occur in a landscape of low relief (Simon-Coinçon *et al.*, 1996). In places pedogenic profiles may show varying facies depending on their position relative to the scarp foot (Milnes & Thiry, 1992). This would imply a significant component of lateral transfer of silica, and it is suggested by Simon-Coinçon *et al.* (1996, p. 474) that 'pedogenic silcretes developed preferentially in areas between the headwaters of streams and the depositional basin'.

Recent studies in the opal mining areas in the southwestern part of the Eromanga Basin, (Milnes *et al.*, 1991; Thiry & Milnes, 1991; Milnes & Thiry, 1992), have revealed the existence of superposed groundwater silcretes at depth beneath the surface pedogenic silcretes. This pattern of distribution is repeated throughout the opal fields on the southwest margin of the Eromanga Basin and extends to the Alice Springs region, in central Australia (Milnes & Thiry, 1992).

In the Stuart Creek opal field, superposed groundwater silcretes occur at depths of 4–10 m beneath the pedogenic profiles and have formed in Cretaceous shales and Tertiary fluviatile sands, developing in the former as amoeboid masses of opalite, and in the latter, as massive or tuberous quartzites (Fig. 5.). Smaller branching or nodular silicified sand masses are also encountered between some of the more massively cemented horizons. Silica mineralogy is highly variable and some lenses are titaniferous (Thiry & Milnes, 1991; Milnes & Thiry, 1992). Similar relationships are observed elsewhere in the opal fields (Milnes *et al.*, 1991). Southeast of Alice Springs, groundwater silcretes again occur underlying pedogenic silcrete, but at depths of 10–30 m. They have developed in clastic sediments as thin lenses 10–30 m long (Milnes & Thiry, 1992). Basinwards, however, pedogenic silcretes are absent and groundwater silcretes are developed in Palaeozoic sandstones and in Tertiary limestones. This distribution of pedogenic silcretes near the basin margin and groundwater silcretes toward the central parts of the basin, again parallels that of silcretes in the Paris Basin.

Similar acidic conditions are envisaged for silcrete formation in this part of Australia as in the Paris Basin (Milnes & Thiry, 1992; Simon-Coinçon *et al.*, 1996). In the case of groundwater silcretes, the silica is at least in part derived from *in situ* dissolution of clay minerals, in the manner identified by Rayot *et al.* (1992). The position of the groundwater silcrete lenses is thought to represent past water table levels and there is evidence of dissolution and re-precipitation suggesting that fluctuation of these levels played a part in silicification (Milnes *et al.*, 1991, p. 145).

It was originally suggested that pedogenic and groundwater silicification may both have been of Neogene age (Thiry & Milnes, 1991; Milnes & Thiry, 1992). However, at least some of the pedogenic silicification is now thought to be older, relating to alternating wet and dry periods in the Late Eocene to Oligocene (Simon-Coinçon *et al.*, 1996). The superposed groundwater silcretes underlying the pedogenic horizons are thought to have formed with progressive down cutting of the landscape, in a manner similar to that proposed in the Paris Basin (Thiry *et al.*, 1988a, b),

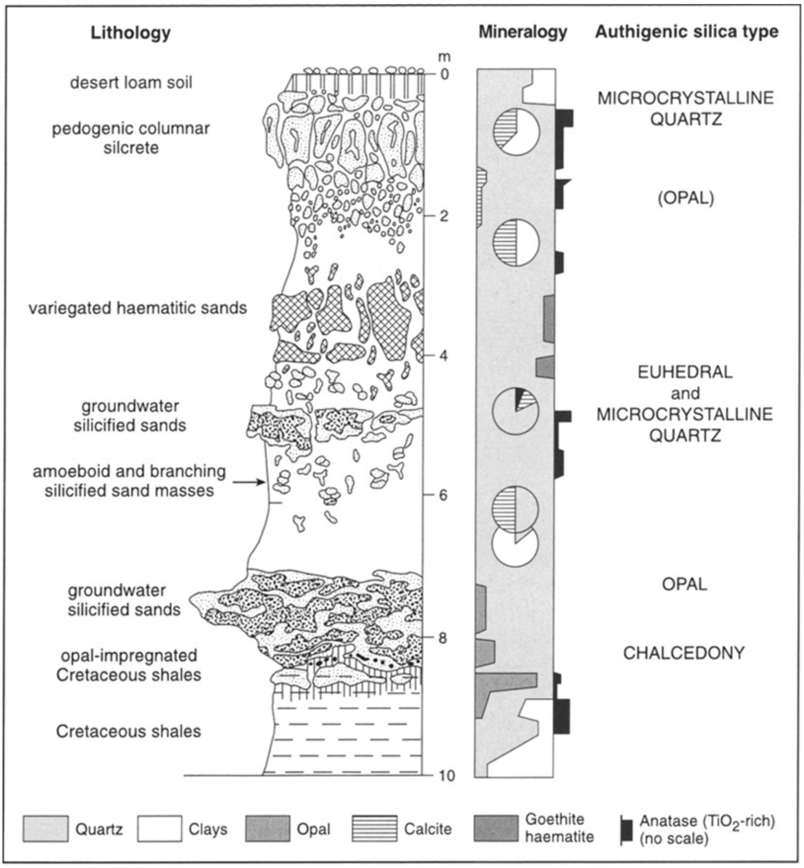


Fig. 5. Schematic section of pedogenic and groundwater silcretes exposed in the Stuart Creek opal field, South Australia. Pedogenic silcretes, exhibiting a columnar structure, are underlain by massive groundwater varieties, developed in Tertiary and Cretaceous host sediments (after Thiry & Milnes, 1991; Milnes & Thiry, 1992; Nash, 1997).

and are thus progressively younger with depth. It is acknowledged, however, that the age relations of silcretes in this region are highly complex, as at some localities pedogenic profiles can be seen to be superimposed on earlier groundwater silcretes, presumably as pedogenic conditions gradually became imposed on subsoil materials during the course of landscape evolution (Milnes *et al.*, 1991; Milnes & Thiry, 1992).

Example 3: Middle Shoalhaven Plain, eastern Australia

In this area silcretes form part of a duricrust catena including ferricretes, bauxites and manganese-rich crusts (Taylor & Ruxton, 1987). The different duricrust types are of varying ages and their distribution is in part determined by the bedrock. The silcretes are predominantly developed in quartzose alluvial gravels and have formed in a range of related settings (Taylor & Ruxton, 1987, fig. 6, p. 398). These include large irregular or lenticular boulders, or discontinuous sheets, in sub-basaltic or inter-basaltic alluvium; skirts marginal to sheets of alluvium on small plateaux where thin discontinuous sheets of silcrete drape the plateau edges; on terraces at various elevations along valley margins; and as drapes on bedrock hillsides, usually in tributary valleys lacking obvious terraces, where they occur as superposed thin or discontinuous sheets. Saprolite on Palaeozoic bedrock is also silicified at some localities.

Silcretes are present at a variety of levels in the landscape and are discontinuous. Furthermore, the palaeo-landscape envisaged during their formation is one of quite considerable relief undergoing progressive dissection (Young, 1978; Taylor & Ruxton, 1987). Quartz overgrowths, microquartz, chalcedony and opal are all recorded as cements. Although silcretes in the Shoalhaven area frequently occur in fluvial sediments overlying deeply weathered profiles (Young, 1978), a number of features suggest that their formation may not simply be related to deep weathering processes. In particular, their field occurrence as skirts and drapes marginal to drainage lines, the simple tabular or lenticular macromorphology with the retention of the sedimentary structures of their host materials, and the predominantly simple micromorphology are all suggestive of groundwater or drainage-line silicification. In this region, in contrast with the Paris Basin and central and southern Australia, a range of titaniferous geopetal and laminated colloform structures are found within them (Taylor & Ruxton, 1987, fig. 7, p. 400). As there is little to indicate pedogenic silicification, Taylor & Ruxton interpret these features as simply indicating an important component of vertical transfer of silica and titania during silcrete formation.

According to Taylor & Ruxton (1987), similarity of macro- and micromorphological features in the silcretes in the Shoalhaven area suggest that the genetic processes which formed them were similar. Silica accumulation is thought to have occurred in a hot and humid climate (Young, 1985) from low pH groundwaters in a zone of water table oscillation (Taylor & Ruxton, 1987). The latter authors also suggest that silica precipitation occurred due to pH changes or by evaporation. As in the case of the Fontainebleau sands, they consider silica to be largely derived from the profile itself, though Young (1978) suggested a significant component of lateral transfer related to flow in the drainage-lines with which the silcretes are predominantly associated. These silcretes are considered to have formed at various times from mid-Tertiary to at least the late Tertiary (Taylor & Ruxton, 1987).

Example 4: Kalahari Desert, Botswana

The Kalahari region contains the greatest areal coverage of silcrete beyond Australia, with a variety of silcrete types ranging in age from at least the early Cenozoic to the present day. There appear to be four principal modes of silcrete occurrence (Summerfield, 1982); cementation of sands, silicified terrace deposits related to a present or former drainage channel, silicification of sediments marginal to pans, and replacement silicification of calcrete (Fig. 6.). Silcretes are found in a variety of landscape settings, but are most common either as escarpment caprocks or in association with landscape depressions such as drainage-lines, lakes and pans (Summerfield, 1982). To date, the latter category have been studied in greatest detail with comparatively little detailed investigation of escarpment exposures (Nash, 1992). Many Kalahari silcretes are presently situated within drainage features and are of groundwater or drainage-line origin. As a result they are spatially limited and do not form an extensive silcrete carapace (Nash *et al.*, 1998). Escarpment silcretes can, however, be relatively extensive, for example in the Serowe area of east-central Botswana. Escarpment silcretes are frequently situated on top of weathered bedrock, particularly basalt, and may be pedogenic in origin. If this is the case, then the Kalahari may reflect the pattern of silcrete distribution previously discussed in France and the Eromanga Basin, with pedogenic silcretes at the margin of the Kalahari basin and groundwater or drainage line silcretes towards the basin centre.

Kalahari silcretes are frequently found in close association with other duricrusts, notably calcrete and occasionally ferricrete (Summerfield, 1982; Shaw & de Vries, 1988; Nash *et al.*, 1994a). These relationships may be laterally gradational (with silcrete merging into other duricrusts along an outcrop; Nash *et al.*, 1994a) or vertically gradational (with silcrete overlying or underlying other types; Watson & Nash, 1997), resulting either from replacement of one type of duricrust by another or by development of complex vertical sequences. Intergrade types such as cal-silcrete, sil-calcrete, or ferro-silcrete may also form when this alteration is highly pervasive (Nash & Shaw, 1998). Superposed silcretes have also been discovered in relation to drainage lines (Shaw & Nash, 1998; Nash *et al.*, 1998) and it is suggested that, in some locations, whilst silcretes are forming in surface pans others may be forming contemporaneously at depth.

Silcretes range from those with very simple mineralogy and structure to those where there are indications of polyphase development (Nash *et al.*, 1994b). Examples of simple silcretes are exposed within the Boteti River at Samedupe Drift (see Shaw & Nash,1998; Nash *et al.*, 1998), whilst the Letlhakeng area of southeast Botswana contains a wide range of simple (Fig. 7a,b.) to polyphase or intergrade silcrete types (Shaw & de Vries, 1988; Nash *et al.*, 1994a; Nash, Thomas & Shaw, 1994c). Both host materials and silica mineralogy are highly variable, but titanium enrichment, glaebules or illuviation features have not been observed (Summerfield, 1982; Nash, 1992). The most common cement type is microquartz but cryptocrystalline silica, chalcedony and opal are all recorded. Glauconite-illite was identified in green pan silcretes (Summerfield, 1982) and this mineral has also been observed in drainage-line silcretes in the Okwa Valley (Nash *et al.*, 1994b) and in superposed groundwater silcretes in outflows of the Okavango Delta (Shaw & Nash, 1998; Nash *et al.* 1998).

Recent studies (Harrison & Shaw, 1995; Shaw *et al.*, 1990; McCarthy & Ellery, 1995; Nash *et al.*, 1998) suggest that biological agencies such as bacteria, as well as certain plant species, may contribute to the process of silicification in surface pans. There is evidence of active silcrete formation at the present day in the Makgadikgadi Basin (Shaw *et al.*, 1990) and in the distal reaches of the Okavango Delta (McCarthy & Ellery, 1995). However, the majority of silcrete exposures are relict. Relatively high pH conditions, in an arid to semi-arid climate appear to be the favoured palaeoenvironment for the formation of silcretes so far studied from this region. It has been proposed, for silcretes related to the Okavango drainage system, that much of the silica cement is largely derived by lateral transfer from the source area in the Angola Highlands (Summerfield, 1982). In this case the climatic and environmental conditions are very different in the source area from those prevalent where silicification occurs. Concentration of silica in annual flood waters by progressive evaporation, followed by precipitation induced by pH changes in groundwater mixing zones, or by further

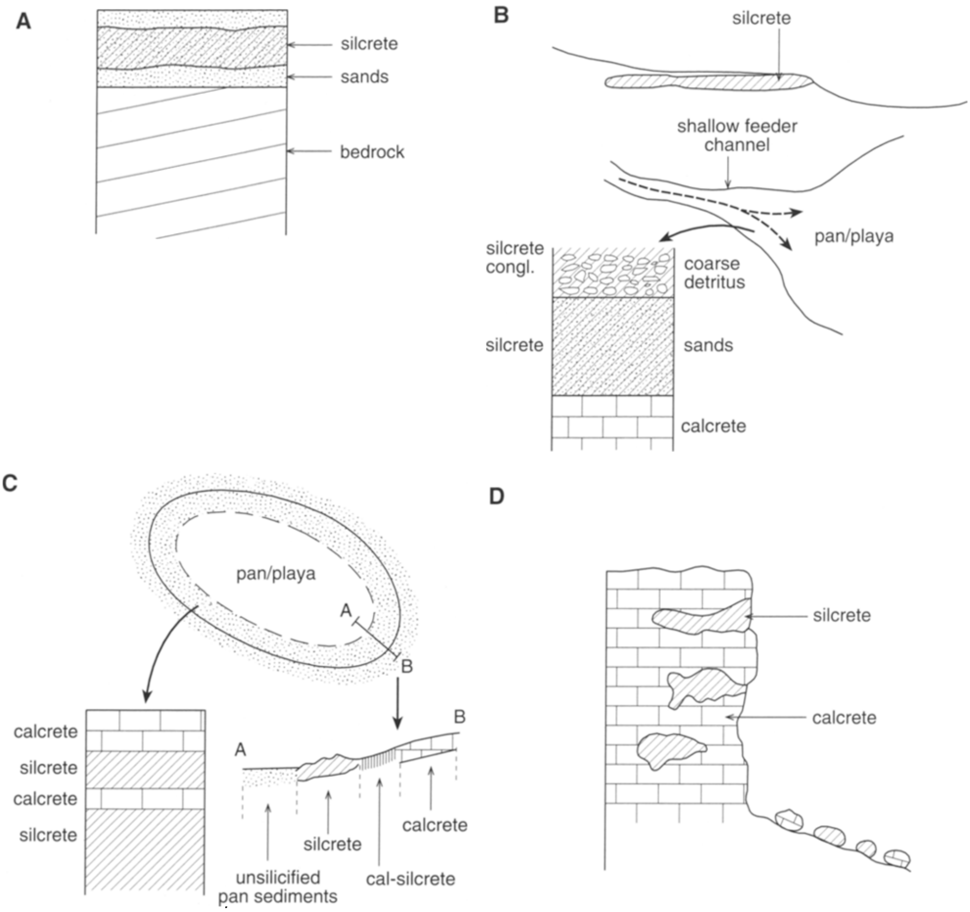


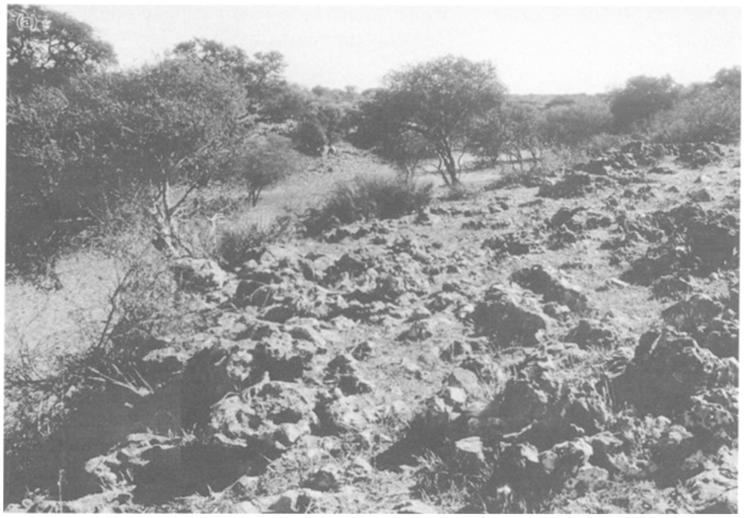
Fig. 6. Diagrammatic representation of some common silcrete occurrences in the Kalahari: (**a**) silicification of sand above bedrock; (**b**) silicification of terrace deposits situated above calcrete in a pan/playa or drainage line setting; (**c**) silicification of pan/playa marginal sediments; and (**d**) silicification of calcrete adjacent to a drainage line (after Summerfield, 1982).

evaporation is considered the most likely mode of formation.

Summary

The above examples illustrate how complex the spatial and temporal relationships between silcrete types can be even within areas of relatively limited extent. In addition, it can be seen that useful comparisons may be drawn between silcretes in different regions, such as the Paris Basin and the Eromanga Basin, and conclusions reached concerning possible modes of formation of silcretes, their age and usefulness as palaeoenvironmental indicators. However, it is also clear that there is no unifying silcrete theory and, as such, any landscape with silcretes would need to be studied in relation to its own particular unique developmental history before useful evidence of landscape evolution or palaeoenvironments could be gleaned with any certainty. Despite these difficulties it is possible to make some generalizations.

1. Two genetic types of silcretes, those forming in pedogenic and groundwater or drainage-line environments, can be distinguished on the grounds of profile characteristics, micromorphology and field relations.
2. Pedogenic silcretes are the most useful palaeoenvironmental indicators as they result from near-surface silicification (Thiry & Milnes, 1991) and are diagnostic of a former landscape surface. Studies up to this time suggest their formation appears restricted to hot climates with wet and dry alternations. Conversely, groundwater or drainage-line silcretes are a poor indicator of palaeoclimate as they can form in a range of climatic conditions, including hot and humid as in eastern Australia, semi arid or arid, as in the Kalahari, or temperate, as in the case of groundwater silcretes in the Paris Basin.



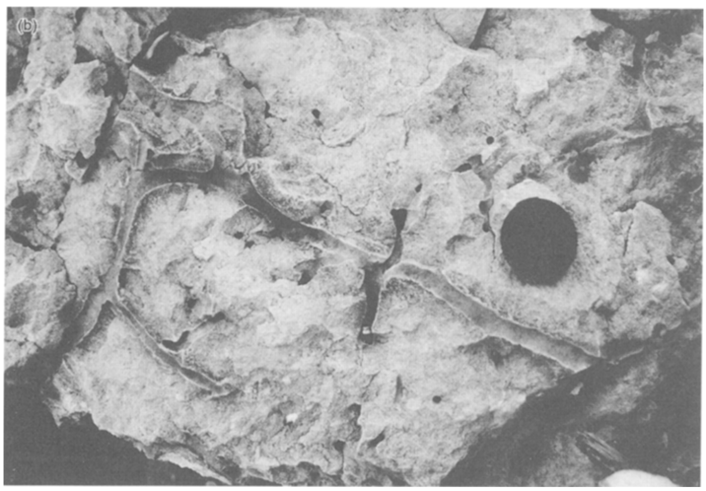


Fig. 7. (**a**) Drainage-line silcrete exposed near the head of the Gaotlhobogwe Valley to the east of Letlhakeng, southeast Botswana, containing (**b**) interconnecting sub-vertical and sub-horizontal tubular structures (lens cap 50 mm for scale).

3. Silcrete genesis is not restricted to landscapes of low relief. The presence of some form of depression would appear to be the most important geomorphological requirement, especially for groundwater silcretes.
4. Whilst pedogenic silicification may take place on former land surfaces, the silcrete produced is often discontinuous. Groundwater or drainage-line silcretes are typically of limited areal extent and may form at different levels in the landscape simultaneously. They are not usually a surface phenomenon and thus do not represent a palaeosurface, but may demarcate palaeodrainage lines.
5. Superposition of silcrete horizons does not necessarily indicate different periods of formation but may reflect different positions of the groundwater table related to seasonal or climatic changes or to progressive landscape dissection (Thiry & Milnes, 1991). Superposition may also reflect the local erosional and depositional history.
6. A silcrete may be the end result of a potentially very complex interplay of environmental factors over an extremely long time span and it may be erroneous to attempt to place a single 'age' or origin on such a feature (Twidale & Hutton, 1986). Silcrete may also replace, or be replaced by, or grade into, other duricrust types.
7. Bulk chemistry of silcretes may not be a reliable indicator either of mode of origin or of palaeoenvironmental conditions during formation.
8. The macromorphology, micromorphology and silica mineralogy of a silcrete may be changed by weathering

processes which postdate and therefore mask evidence of original silicification.
9. Illuviation structures in silcretes indicate an important component of vertical transfer but do not appear necessarily to be diagnostic of pedogenic origins, or of formation within a weathering profile.
10. Silcrete formation may occur in the same landscape by a number of mechanisms in response to different conditions at various stages during the evolution of that landscape.

5. IMPLICATIONS FOR SARSEN GENESIS

Problems of sarsen interpretation

The advances in silcrete research, described above, have been made principally by detailed petrological and micromorphological investigation of *in situ* profiles and their field relations and position in the landscape. Clearly this is not possible when considering the origins and significance of sarsens and puddingstones as there is an apparent lack of any well-exposed profile. To date, only the Hertfordshire puddingstone has been reliably documented *in situ* (e.g. Catt & Moffat, 1980; Robinson, 1994). Previous studies, and any future ones, must therefore be based on loose boulders which have been transported by glacial, periglacial or slope processes, or by human activities, so that even such basic information as original orientation at the time of formation cannot be determined with certainty. It is also possible that micromorphological and mineralogical changes may have occurred due to weathering subsequent to original silicification (cf. Thiry & Millot, 1987).

Despite these problems a number of attempts have already been made to identify the mode of origin and environment of formation for sarsens and puddingstones, both generally (Summerfield, 1979; Summerfield & Goudie, 1980; Summerfield & Whalley, 1980) and in specific areas (Kerr, 1955; Whalley & Chartres, 1976; Isaac, 1979, 1983b). While this existing literature undoubtedly provides a starting point to identify the possible types of silcrete materials that may be present as sarsens and puddingstones, it needs to be re-assessed in the perspective of advances in silcrete research.

Evidence for pedogenic silicification

As can be seen in the examples above, pedogenic silcretes would appear to provide the most unequivocal evidence of former palaeosurfaces and palaeoenvironments. A hot palaeoclimate with alternating wet and dry phases is considered the most favourable environment for their formation. As formation takes place over considerable time spans, a fairly stable landscape would be indicated, but not necessarily one of low relief. Pedogenic silicification would also appear to be frequently associated with pedimentation (Milnes & Thiry, 1992). However, in the existing literature on sarsens and puddingstones, evidence for pedogenic silicification is relatively scant, though this may simply reflect the lack of detailed study, or the specific areas so far sampled.

Silcretes containing abundant titaniferous illuviation features were described by Isaac (1979, 1983b) in the Sidmouth area. The complexity of their micromorphology (Isaac, 1983b, fig. 2, p. 183) is highly suggestive of pedogenic silicification, as is their association with a kaolinitic weathering profile (cf. Dubroeucq & Thiry, 1994). In addition, Isaac (1983a) suggests these silcretes relate to a subaerial Palaeogene surface which is widely recognized in that area (Green, 1985). Early petrological descriptions by Judd (1901), of sarsens near Dorchester, might also be suggestive of complex micromorphology and may suggest that remnants of analogous silcretes could persist further east. The identification of titanium-enriched sarsens, in Berkshire, by Summerfield (1979) could indicate pedogenic silicification still further east. However, it is not clear how strong the micromorphological evidence is to corroborate this; Summerfield (1978, 1979) suggests that illuviation features are absent, or scarce in sarsens and, as previously indicated, titanium content alone may not be a reliable indicator of origin. Westwards, onto the Palaeozoic basement, in north Devon and on the eastern flanks of Dartmoor, displaced boulders and some *in situ* material have been identified as silcretes (Coque-Delhuille, 1987; Bristow, 1993). Bristow (1993) tentatively correlates these with the duricrust materials identified in east Devon by Isaac (1979, 1983b). However, their mode, or modes, of origin are unclear.

Evidence for groundwater silicification

Many authors have suggested that groundwater silicification or, more recently, drainage-line silicification (Nash *et al.*, 1998), was a potentially important, or the predominant, agency of sarsen and puddingstone formation (Williams, 1968; Whalley & Chartres, 1976; Summerfield & Goudie, 1980; Kellaway, 1991). The majority of petrological studies confirm a simple micromorphology (e.g. Boswell, 1916; Kerr, 1955; Howard, 1982) most commonly of grain-supported fabrics with cementation by optically continuous quartz overgrowths, or microquartz (Whalley & Chartres, 1976; Whalley, 1978; Summerfield & Goudie, 1980; Summerfield & Whalley, 1980). This, combined with the predominantly tabular macromorphology, would appear to support a groundwater or drainage-line origin.

Although there is broad agreement concerning the importance of groundwater silicification, there are conflicting views as to the mechanism in detail. Silicification has been envisaged in an acid groundwater environment, such as that associated with podsol development or swampy conditions (e.g. Irving, 1883; Brentnall, 1946). Gallois (1983) also evoked acid groundwater silicification for quartzite boulders, similar to sarsens, which occur in association with bleached sands near Castle Rising in Norfolk. Summerfield (1979), Summerfield & Goudie (1980) and Summerfield & Whalley (1980) on the other hand, attributed the majority of sarsens to the 'non-weathering profile' category and suggested that they were silicified in an alkaline groundwater environment, most probably in an arid or semi-arid environment similar to the present Kalahari desert. Nash *et al.* (1998) also draw parallels with the Kalahari and suggest, on the basis of macromorphological micromorphological, and geomorphological grounds, that sarsen formation could have occurred in alkaline conditions in seasonal pools located along drainage-lines. Similar suggestions have been made previously by Williams (1968) and Kellaway (1991).

Evidence for multiple phases of silicification

It has been proposed that there may have been several phases of sarsen and puddingstone formation, largely on the strength of the age of the assumed host sediments in the UK, or by comparison with the ages of *in situ* sediments silicified in neighbouring parts of Europe (Summerfield & Goudie, 1980). However, as there is no compelling evidence to indicate that silicification was intraformational, this argument must remain very tentative.

More than one period of sarsen or puddingstone formation has been claimed by several authors on the basis of features inherent in the material itself. In the Sidmouth area, Isaac identifies two types of silcrete: a conglomeratic variety, with a very near surface origin, and a quartz arenite type 'which probably formed at greater depth in the profile' (Isaac, 1983b, p. 184). This might be similar to the situation in the Great Australian basin, where pedogenic horizons cap profiles with groundwater silcretes underlying them (Thiry & Milnes, 1991) though such field relations have not been demonstrated at Sidmouth. Two or more phases of silcrete formation are also implicit in Summerfield (1979) and Summerfield & Goudie (1980) as they propose that sarsens formed in two contrasting palaeoclimates within the same geographical area, although there is no evidence of what the temporal or spatial relationships of these silcretes might have been.

Included clasts of earlier silcretes have been claimed in UK silcretes by some authors (e.g. Isaac, 1979, 1983b). The identification of clasts must be viewed with some caution, however (Twidale & Hutton, 1986), as pedogenic silcretes commonly manifest pseudo-conglomeratic fabrics which are actually the result of silicification processes within a single silcrete profile. Similar problems can arise in interpreting patches of differential cementation related to the presence of flint pebbles or cobbles in sarsens and puddingstones, as geopetal orientation of such features can be observed, in some cases indicating that they are likely to have originated as *in situ* features and are not actually silcrete clasts. Such structures are recorded in both pedogenic (van der Graaff, 1983; Thiry, 1988; Thiry & Milnes, 1992) and groundwater silcretes elsewhere in the world (Callender, 1978; Taylor & Ruxton, 1987) and are described both above (van der Graaff, 1983; Taylor & Ruxton, 1987; Thiry, 1988) and below (Callender, 1978) pebbles or detrital grains.

6. DISCUSSION

There is, unfortunately, insufficient evidence to present anything like a complete picture of either the range of materials which might be present as sarsens or puddingstones or make any general palaeoenvironmental or palaeoclimatic interpretation based on their presence, although in some instances conclusions may be drawn for specific areas. The existing literature suggests that there is evidence for pedogenic silicification in the southern UK, but that this may be of restricted occurrence. If pedogenic silcretes did develop then a tropical or sub-tropical palaeoclimate, possibly with alternating wet and dry phases, would be indicated and a relatively stable landscape would also be inferred, though not necessarily one of low relief. The combination of these factors would indeed tend to favour a Palaeogene date for formation, as suggested in previous literature.

At present there would appear to be greater weight of evidence favouring an origin for sarsens and puddingstones by some process of groundwater or drainage-line silicification, although there is insufficient evidence to ascertain the environmental conditions during the phase or phases of cementation. Studies of silcretes elsewhere in the world might suggest a number of possible analogues for sarsen and puddingstone formation. First, silicification may have taken place at or near the surface associated with seasonal pools or pans within drainage lines, as proposed by Nash *et al.* (1998). Silicification would have occurred in high pH conditions, in an arid or semi-arid climate, by progressive evaporation and by fixation by plants and bacteria. Second, silicification may have taken place in low pH conditions, associated with weathering and oxidation within the host sediment (cf. Thiry & Bertrand-Ayrault, 1988; Thiry *et al.*, 1988a,b). Cementation would occur at or near the water table and silcrete lenses form at various levels in the landscape, concomitant with progressive landscape dissection. Third, silicification may have taken place in a low pH environment resulting from high organic productivity in a tropical or sub-tropical wet humid climate (Young, 1985; Taylor & Ruxton, 1987). Under this scenario silicification would occur in zones of groundwater fluctuation and is in part due to evaporation.

These models present a range of prevailing chemical conditions and palaeoclimates which could have been prevalent at the time or times of silicification. In all cases it is the presence of a valley or landscape depression which is the prime determinant in silcrete formation (cf. Nash *et al.* 1998). Furthermore, silcrete formation would be expected at various levels in the landscape, either simultaneously, or with progressive landscape evolution. None of these above models of groundwater or drainage-line silicification would necessarily lead to the development of laterally-extensive duricrusts, though individual silcrete lenses may extend for some distance along the length of valleys or drainage-lines. As groundwater silcrete formation is not restricted to very mature landscapes or to tropical climates then episodes of silicification could have occurred throughout the Cenozoic and possibly even in the Quaternary (cf. Gallois, 1983; Thiry *et al.*, 1988a). It is also conceivable, given this long time-span, that different episodes of silicification may have occurred in quite different palaeoenvironmental conditions.

In terms of the overall setting for Cenozoic silicification in the southern UK, comparisons may be drawn with the neighbouring Paris Basin where pedogenic silicification occurred around the basin margins and on the edges of the basement during the Palaeogene. Progressive groundwater silicification occurred later in response to uplift and dissection of the Tertiary cover in more central parts of the basin (Fig. 4.). Similar spatial and temporal relationships are reported from parts of the Great Australian Basin and may also be present in the Kalahari Basin. This might suggest that pedogenic silcretes are likely to be found close to the basin margins in the southern UK, whereas groundwater types could be more widespread and possibly formed later. At present the evidence for pedogenic silicification would appear to be stronger in the west, close to the area of basement outcrop. However, as previously stated in this paper, the picture is far from complete, and the testing of this hypothesis must therefore await further research.

7. CONCLUSIONS

A variety of different types of silcrete has been recognized, each of which may have a different mode of formation. Until it is more certain which types are represented in UK sarsens and puddingstones, it is difficult to draw any safe conclusions concerning the possible thickness or extent of any former duricrust (or duricrusts), its age, palaeoenvironmental interpretation or significance in landscape evolution. It should be recognized that:

(i) there may have been several silcrete lenses or horizons within a given area;
(ii) there may have been silcrete of different ages and origins present as in other parts of the Anglo-Paris Basin;
(iii) sarsens may have a multiphase origin;
(iv) as neither tectonic stability nor a hot climate is essential for silcrete formation, sarsens may be considerably younger than previously thought;
(v) it is a valid approach to compare other landscapes with silcretes to our own landscape with sarsens to gain a picture of possible former landscapes in the UK, but this must be done with caution to ensure that like is compared with like.

Sarsens and puddingstones should only be used as evidence in models of landscape evolution when their mode or modes of formation can be determined and their possible field relations predicted with accuracy. Inferences concerning palaeoclimate or palaeo-landscape are equally hazardous unless it can be proved that significant numbers of sarsens or puddingstones represent fragments of pedogenic silcretes. The example of silcretes in the Paris Basin forcefully underlines the potential problems of sarsen and puddingstone interpretation. Several types of pedogenic silcrete and groundwater silcrete occur as *in situ* horizons. Fringing these occurrences scattered boulders of all types occur, yet they represent silicification at different times and in different host sediments and palaeoenvironments. It would be foolish indeed to conclude that all represented fragments of a single laterally extensive duricrust.

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