Drainage-line silcretes of the Middle Kalahari: an analogue for Cenozoic sarsen trains?

David J. Nash*, Paul A. Shaw† and J. Stewart Ullyott*

NASH, D. J., SHAW, P. A. & ULLYOTT, J. S. 1998. Drainage-line silcretes of the Middle Kalahari: an analogue for Cenozoic sarsen trains? *Proceedings of the Geologists' Association*, **109**, 241–254. This paper describes models put forward to explain the development of silcretes within drainage lines at the distal end of the Okavango Delta system in the Middle Kalahari of Botswana, and proposes that they provide an analogue for the formation of sarsen stones within sarsen trains. The models describe silcrete formation in shallow pans situated within river valleys, with silicification resulting from the accumulation of fluvial inputs of clastic material, silica from groundwater and additions of silica phytoliths from aquatic vegetation in seasonal pools. It is suggested, on the basis of macro- and micromorphological comparisons, that sarsens in the Clatford Bottom area of Wiltshire formed by this mechanism. The sarsens would have originally formed a spatially-limited linear silcrete body and would have then accumulated within contemporary valleys during the course of landscape evolution. The implications of this model for the environmental conditions associated with sarsen formation and the likely timing of silicification are subsequently discussed. It is concluded that the geomorphological setting of sarsen formation may have been more important than climatic conditions at the time(s) of silicification.

* *Earth and Environmental Science Research Unit, University of Brighton, Cockcroft Building, Lewes Road, Brighton BN2 4GJ.*
† *Department of Environmental Science, University of Luton, Park Square, Luton LU1 3JU.*

1. INTRODUCTION

Cenozoic silicified deposits are widespread across southern England and have been the subject of much interest in this journal (e.g. Robinson, 1994). Such materials are termed **sarsens** (or **sarsen stones** if found individually), **puddingstones**, or **flint breccias** and are distributed over an area broadly coincident with the outcrop of Chalk and pre-Pliocene Cenozoic beds. In contrast to neighbouring northwest France, there are very few well-documented *in situ* exposures of Cenozoic silicified material in the UK. The best documented sarsen localities are the large concentrations of stones occupying valley floors (commonly referred to as **sarsen trains**) the most prominent examples of which are found in tributaries of the River Kennet in Wiltshire (e.g. Clark, Lewin & Small, 1967; Williams, 1968; Small, Clark & Lewin, 1970) and the 'Valley of the Stones' near Portesham in Dorset (Strahan, 1898). A comprehensive bibliography of work on UK Cenozoic silicified deposits can be found in Summerfield & Goudie (1980).

The majority of occurrences of silicified deposits are found south of a line joining Lowestoft and the Bristol Channel (Summerfield & Goudie, 1980). There is, however, considerable evidence for relocation of many blocks of silicified material as a result of human activity (e.g. Brentnall, 1946; Williams, 1968; Bowen & Smith, 1977; Howard, 1982; Green, 1997) so that present distribution may not accurately reflect original patterns. Greatest numbers of sarsens are found in Wiltshire, Berkshire and Dorset with smaller concentrations in Devon, Essex, Suffolk, Kent, Hampshire and Sussex (e.g. Whitaker, 1862; Adams, 1873; Strahan, 1898; Ussher, 1906; White, 1906, 1907, 1912, 1923; Boswell, 1916; Richardson, 1933; Brentnall, 1946; Davies & Baines, 1953; Kerr, 1955; Bowen & Smith, 1977; Summerfield, 1979; Summerfield & Goudie, 1980; Summerfield & Whalley, 1980; Isaac, 1981, 1983a). Puddingstones and flint breccias occur mainly in Hertfordshire and Buckinghamshire (e.g. Hopkinson, 1884; Whitaker, 1889; Green, 1890; Hopkinson & Whitaker, 1892; Hopkinson & Kidner, 1907; Sherlock, 1922; Davies & Baines, 1953; Ward, 1975; Catt & Moffat, 1980; Summerfield & Goudie, 1980; Robinson, 1994), as well as in Hampshire and Sussex (e.g. Codrington, 1870; White, 1910, 1924, 1926; Bury, 1922; Summerfield & Goudie, 1980).

Much of our understanding of the genesis and palaeoenvironmental significance of sarsens has been drawn from comparative studies of morphologically similar tropical and sub-tropical siliceous duricrusts. Sarsens are recognised as a variety of silcrete (Lamplugh, 1902, 1907; Kerr, 1955) and widely regarded as:

> 'remnants of surface and near-surface silicification developed on tectonically stable land surfaces of minimal local relief... under a semi-arid or arid climate although there is evidence of development in a relatively humid environment for some occurrences' (Summerfield, 1979 p. 137).

Despite a flurry of interest in the late 1970s and early 1980s, where general similarities between sarsens and silcretes from a variety of environments were drawn (e.g.

Isaac, 1979, 1983b; Summerfield, 1979; Summerfield & Goudie, 1980), there has been little recent detailed work undertaken on UK silcretes. There have, however, been major advances in our understanding of silcretes since this time, most notably through studies in France (e.g. Thiry, Bertrand-Ayrault & Grisoni, 1988a; Thiry, Bertrand-Ayrault, Grisoni, Menillet & Schmitt, 1988b; Thiry, 1989; Milnes & Thiry, 1992; Thiry & Simon-Coinçon, 1996), Australia (e.g. Thiry & Milnes, 1991; Milnes & Thiry, 1992; Simon-Coinçon, Milnes, Thiry & Wright, 1996) and southern Africa (Shaw & de Vries, 1988; Shaw, Cooke & Perry, 1991; Nash, Shaw & Thomas, 1994a; Nash, Thomas & Shaw, 1994b). These studies have identified a variety of types of silcrete which can form by a number of mechanisms in a range of different geomorphological settings. Thus, earlier models of the formation and environmental significance of sarsens and sarsen trains need review.

Here we assess the possible origins of UK sarsen trains in the light of recent models describing the genesis of drainage-line or 'fluvial' silcretes at sites near the distal end of the Okavango Delta system in northern Botswana (Shaw & Nash, 1998). A broadly 'fluvial' origin for some sarsens has been suggested previously by Brentnall (1946, p. 431) and Summerfield & Goudie (1980, p. 89) but, to date, no detailed model of formation has been put forward. Sarsen trains in the vicinity of Clatford Bottom, Wiltshire, are used as a case study as they are part of the best documented UK sarsen locality. Whilst not necessarily reflecting precise environmental conditions at the time of sarsen development, the models for Kalahari drainage-line silcrete formation described here may provide an analogue for the formation of sarsen trains and further the debate concerning the palaeoenvironmental significance of silicified remnant materials.

2. CHARACTERISTICS OF WILTSHIRE SARSEN TRAINS

Sarsen stones and sarsen trains from the Marlborough Downs of Wiltshire have been described in a number of studies (e.g. Clark *et al.*, 1967; Williams, 1968; Small *et al.*, 1970), particularly those in the Clatford Bottom area (Fig.

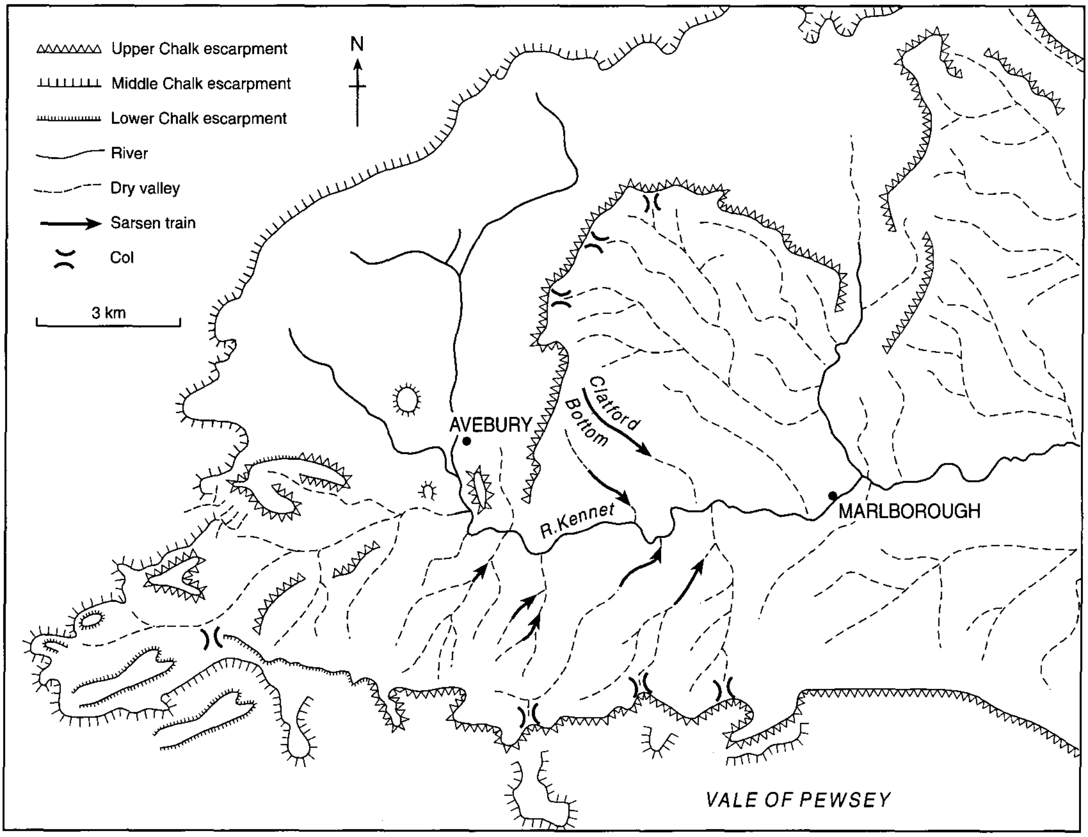

Fig. 1. The geomorphology of the area around Marlborough and Avebury, showing the location of major sarsen trains (after Clark *et al.*, 1967).

1). The geomorphology of this area has been described in great depth by Clark *et al.* (1967) and, as such, will only be considered briefly here with most attention given to the characteristics of the sarsen stones.

Sarsens at Clatford Bottom (Fig. 2a) occur upon the floor and, to a lesser extent, the flanks of a shallow asymmetric valley incised between 30 and 50 m below the level of nearby Overton Down and Clatford Down. Clark *et al.* (1967, p. 20) estimate that between 8000 and 10 000 individual sarsen stones occupy the valley with further concentrations of stones in tributaries which enter Clatford Bottom from the north. Valley asymmetry has been attributed to differential erosion due to periglacial activity (Clark *et al.*, 1967; Williams, 1968). Both Williams (1968) and Small *et al.* (1970) suggest that the sarsens along the valley axis represent a periglacial rock stream. There were originally more stones in the area as many have been removed for use as building stones (Brentnall, 1946; Williams, 1968). This may explain why there are very few blocks resting in contact with adjacent stones, as might be

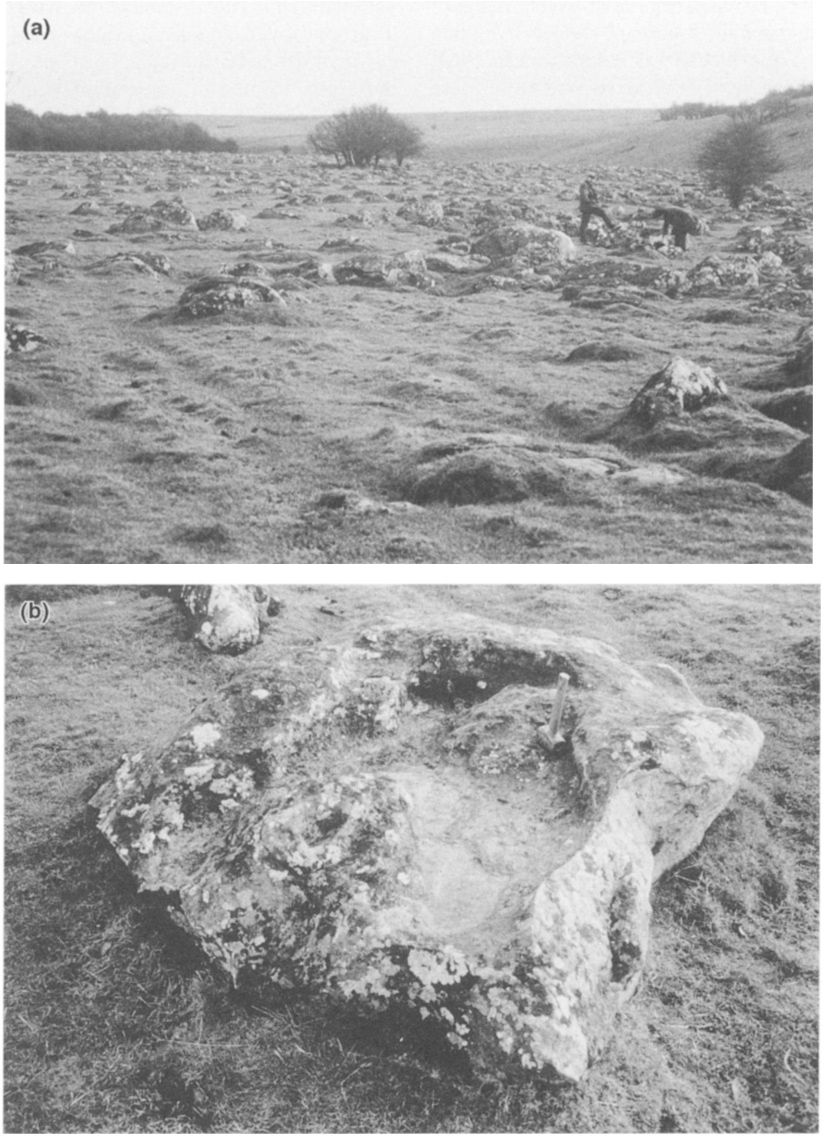

Fig. 2. (**a**) The sarsen train at Clatford Bottom. (**b**) Surface morphology of a sarsen block from Clatford Bottom (hammer for scale is 20 cm length).

expected in a rock stream. However, the form of the sarsen train and the density of stones within it suggest that the material has not been horizontally transported over a great distance.

Sarsens at Clatford Bottom occur as individual tabular blocks of up to several metres in length, although the precise shape and size is frequently difficult to distinguish owing to the partial burial of many blocks. They exhibit highly variable surface morphologies with a range of features including channels up to 100 mm deep and basins of variable dimensions. Tubular hollows of up to 30 mm diameter (Fig. 2b) are common and have previously been interpreted as root casts. There appear to be two distinct types, the thinner being orientated parallel to the c-axis of blocks and the larger forming branching systems running through the length of the blocks (cf. Clark *et al.*, 1967, p. 34). Similar root casts have been described from these and other Wiltshire localities (White, 1925). One example was tentatively attributed to a type of palm (Carruthers, 1885) and another to a variety of swamp cypress (Brentnall, 1946). This latter identification led Brentnall (1946, p. 431) to hint at a fluviatile origin for sarsens. Grey surface patinas with evidence of spalling occur on most blocks, with a smooth brown surface occasionally present on vertical faces.

The stones appear lithologically similar throughout the Clatford Bottom site. In hand specimen the rock is very pale grey to buff coloured with minor patches of dark brown staining. The lithology is moderate- to well-cemented homogeneous fine- to medium-grained quartz sandstone with a saccharoidal texture and slightly crumbly fracture. Occasional coarse quartz grains are present with some white clasts, most probably weathered chert or flint, also discernible.

The majority of samples are very well cemented with little or no void spaces present. The sarsens exhibit a grain-supported or GS-fabric (see Summerfield, 1983a for a definition) with predominantly quartz grains cemented by an interlocking mosaic of optically continuous quartz overgrowths (Fig. 3a and b). Some euhedral overgrowths are present although the majority of overgrowth contacts are irregular. In addition, there are occasional areas of microquartz or cryptocrystalline silica present within the matrix together with minor void fills comprising macroquartz with an undulose extinction. In general, the outline of the original host sediment is not readily identifiable due to the overgrowth cement, but some original grains are visible due to the presence of dust rings (probably Fe_2O_3) around quartz particles. Where grains are visible they are invariably well to very well rounded.

3. MODELS OF KALAHARI DRAINAGE-LINE SILCRETE FORMATION

The association of siliceous duricrusts with extant or fossil drainage features has been recognized in a number of locations, including central and eastern Australia (e.g. Stephens, 1964, 1971; Barnes & Pitt, 1976; Twidale & Milnes 1983; Arakel, 1986; Ollier & Pain, 1995; Pain & Ollier, 1995), the Fontainebleau region of France (e.g. Thiry & Millot, 1987; Thiry *et al.*, 1988a,b) and various parts of the Kalahari (Summerfield, 1982, 1983a,b; Shaw & de Vries, 1988; Nash *et al.*, 1994a; McCarthy & Ellery, 1995; Nash, 1997; Watson & Nash, 1997; Shaw & Nash, 1998). In general terms, duricrust accumulation in riverine or valley settings may involve deposition within channel or floodplain alluvium, deposition from floods, and/or the lateral seepage of groundwater at the channel margin (Goudie, 1983). In these cases, the fluvial system primarily acts as a transfer mechanism for silica-bearing water. Additionally, the river valley may provide a suitable site for silicification at zones of groundwater emergence, as has been described by Thiry *et al.* (1988a,b) and Nash *et al.* (1994a). Indurated duricrusts formed in association with drainage lines may ultimately lead to the development of inverted relief (Pain & Ollier, 1995) or, in areas where there has been limited landscape incision (Nash, 1997), be preserved within valley floors. However, until the publication of recent work on silcretes developed within the distributaries and outflows of the Okavango Delta system of the Middle Kalahari, the processes by which silcretes form within drainage lines has not been clearly understood.

Silica accumulation in the Okavango Delta

The first study to address the early stages of silica accumulation in a fluvial setting was that of McCarthy & Ellery (1995), through an analysis of diagenetic alteration of sandy floodplain sediments adjacent to the Boro Channel in the lower Okavango Delta (Fig. 4). The Okavango Delta is an anastomosing delta-fan system (Nanson & Knighton, 1996) of permanent and seasonal swamps with an area of over 20 000 km^2 (Thomas & Shaw, 1991). It has a complex hydrology which varies in response to annual flooding between February and August as a result of rain falling over the Angolan Highlands (Shaw & Thomas, 1993). Evaporation leads to the loss of up to 96% of the water within the Delta (Wilson & Dincer, 1976) and causes increased groundwater salinity within the floodplain sediments. Solute levels are low (< 30 ppm) at the head of the Delta but increase in concentration towards the distal margins and outflows as a result of evapotranspiration (Hutton & Dincer, 1976; Summerfield, 1982; McCarthy, McIver & Cairncross, 1986; McCarthy & Metcalfe, 1990; Sawula & Martins, 1991). Thus the dry sediments at the distal end of the delta system receive an annual influx of silica-saturated water as a result of the passage of the annual flood. This, in turn, promotes the precipitation of amorphous silica as surface floodwater permeates to the water table (McCarthy & Metcalfe, 1990). Trees and sedges further control groundwater salinity levels (McCarthy, McIver & Verhagen, 1991) and precipitate silica through the production of silica phytoliths by absorption of silica into plant tissue. McCarthy & Ellery (1995) consider that the primary mechanisms of silcrete formation are the

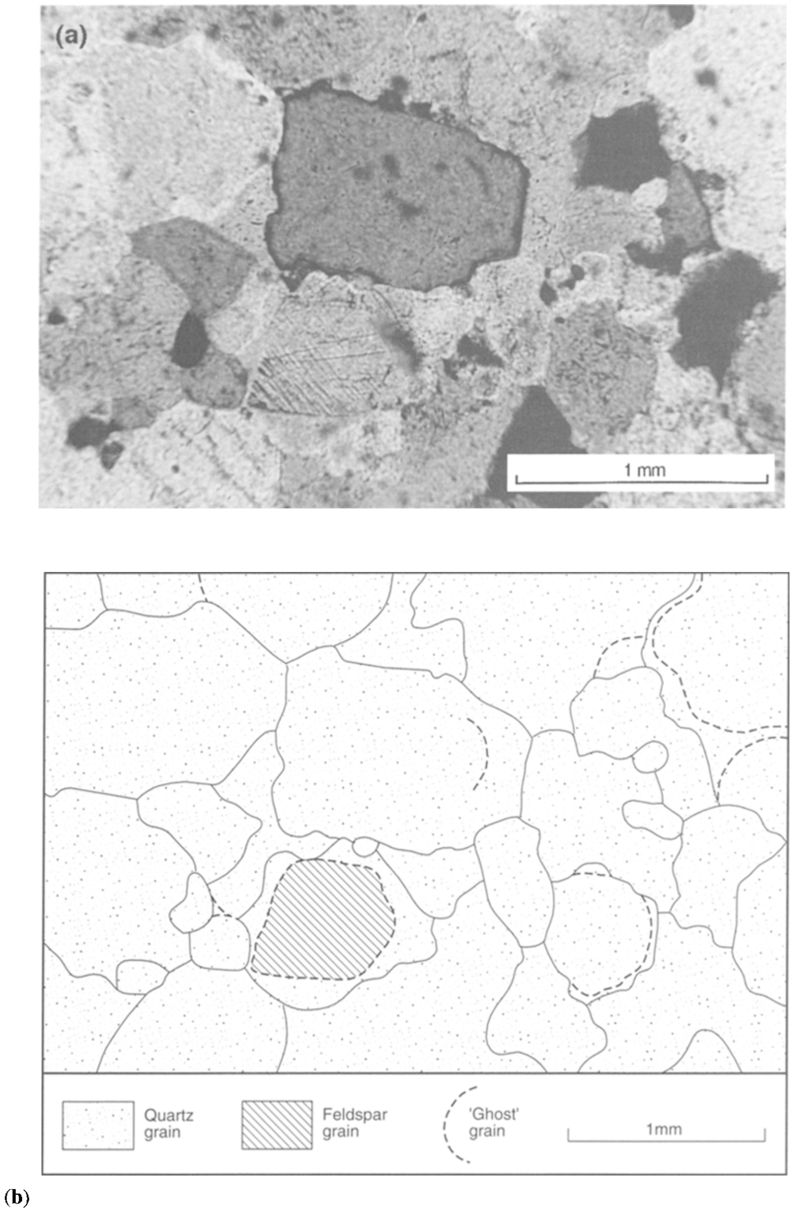

Fig. 3. Micromorphology of a typical sarsen sample from Clatford Bottom.

progressive dissolution and illuviation of phytolithic silica into the sediment profile and the precipitation of silica from groundwater.

Whilst there are no exposures of fully indurated silcrete within the Okavango Delta (Snowy Mountains Engineering Corporation [SMEC], 1989) and floodplain sediments are often only partly consolidated, the model suggested by McCarthy & Ellery (1995) may provide an explanation for the first stages of the generation of duricrusts in floodplain environments. More massive silcretes occur in the outflows of the Okavango system, most notably at the bifurcation of the Thamalakane–Boteti/Nchabe rivers and within the Boteti River at Samedupe Drift (Shaw & Nash, 1998). Of these two sites, the exposures within the Boteti River are most analogous to the sarsen trains at Clatford Bottom and will be described in more detail.

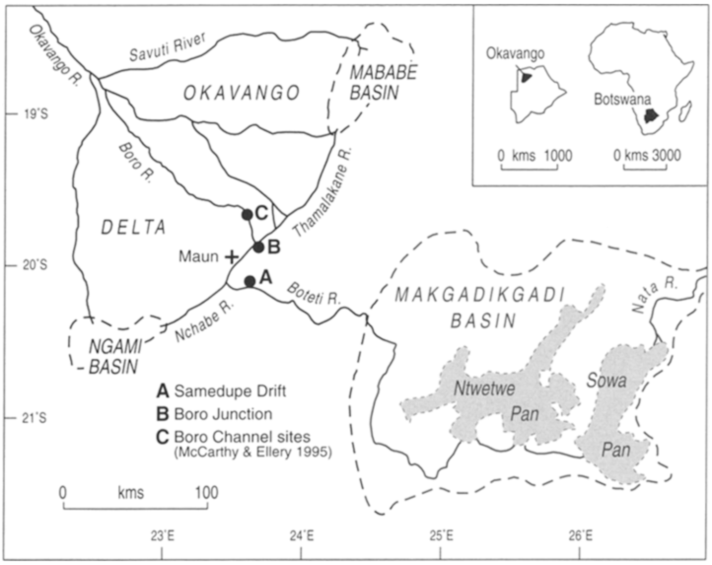

Fig. 4. The major distributaries and outflows of the Okavango Delta system, showing the location of drainage-line silcrete sites mentioned in the text.

Drainage-line silcretes in the Boteti River

The largest silcrete exposure within the floor of the Boteti River occurs at Samedupe Drift (Fig. 4), where blocks of silcrete occupy the full 180 m width of the channel (Shaw & Nash, 1998). Silcrete is exposed over a distance of some 400 m of river bed and has the appearance of a continuous sheet underlying the bed with eroded blocks scattered across the surface (Fig. 5a). The river channel at this point is bordered by a narrow floodplain with terrace sediments rising to 8 m above the river bed. The silcrete blocks are mostly tabular in shape but are highly variable in terms of their surface morphology. Common surface features include hollows and basins, interconnecting tubular structures of variable orientation with diameters from 18 to 45 mm, and a prominent case-hardened weathering rind (Fig. 5b). The surface of all exposures appears relatively fresh with little or no vegetation present.

The silcretes vary in colour from pale brown to buff or grey in hand specimen, with minor patches of iron oxide staining. The silcrete is extremely well-indurated and has a saccharoidal texture, conchoidal fracture and vitreous lustre. Surface exposures allow detailed examination of the well-developed weathering rind which is up to 12 mm thick and bounded by a 3 mm thick zone of iron oxide staining. The rind is characterized by a slight decrease in the amount of cement producing a more friable texture. In thin section (Fig. 6a and b), the silcretes are extremely well cemented with a skeletal grain component consisting of moderate- to well-rounded quartz grains up to 0.75 mm diameter. They exhibit a predominantly grain-supported (GS-) fabric, with minor floating (F-) fabric components arising from the infilling of voids within a quartzose host material. There are trace quantities of microcline feldspar and heavy minerals in addition to the quartz component. The host sediments are cemented within a disordered length-fast chalcedony and cryptocrystalline silica matrix with less than 0.5% void space. The contact between the chalcedonic matrix and the skeletal grain material is invariably sharp with only localized quartz overgrowths.

Two cores were extracted from the floor of the Boteti channel at Samedupe Drift (Fig. 7) which allow the sub-surface characteristics of the silcrete exposure to be examined. Core 4101 (depth 16 m) was taken from the centre of the floodplain and penetrated a succession of massive and pisolithic silcrete layers and green-white sand- and clay-sized sediments. The uppermost metre of the core contained the brown coloured surface silcrete described in hand specimen but the sub-surface silcrete layers were a pale green colour due to the presence of glauconite (shown by XRD analysis). Core 4102 (depth 20 m) was extracted from the floodplain to the north of the channel and shows a similar sequence of materials. Sand was encountered in the first 4 m overlying an 80 cm thick layer of massive green silcrete. Beneath this layer sandy sediment was dominant with thin layers or lenses of pisolithic and massive silcrete at 16 m and 17 m depth. Similar silcrete pisoliths, sampled from a further core (4103) taken at the Boro Junction on the floodplain of the Thamalakane River (Figs 4 & 7), have been analysed in hand specimen and by orientated thin section. The pisoliths are grey to green in colour and have a spherical to columnar shape with individual pisoliths

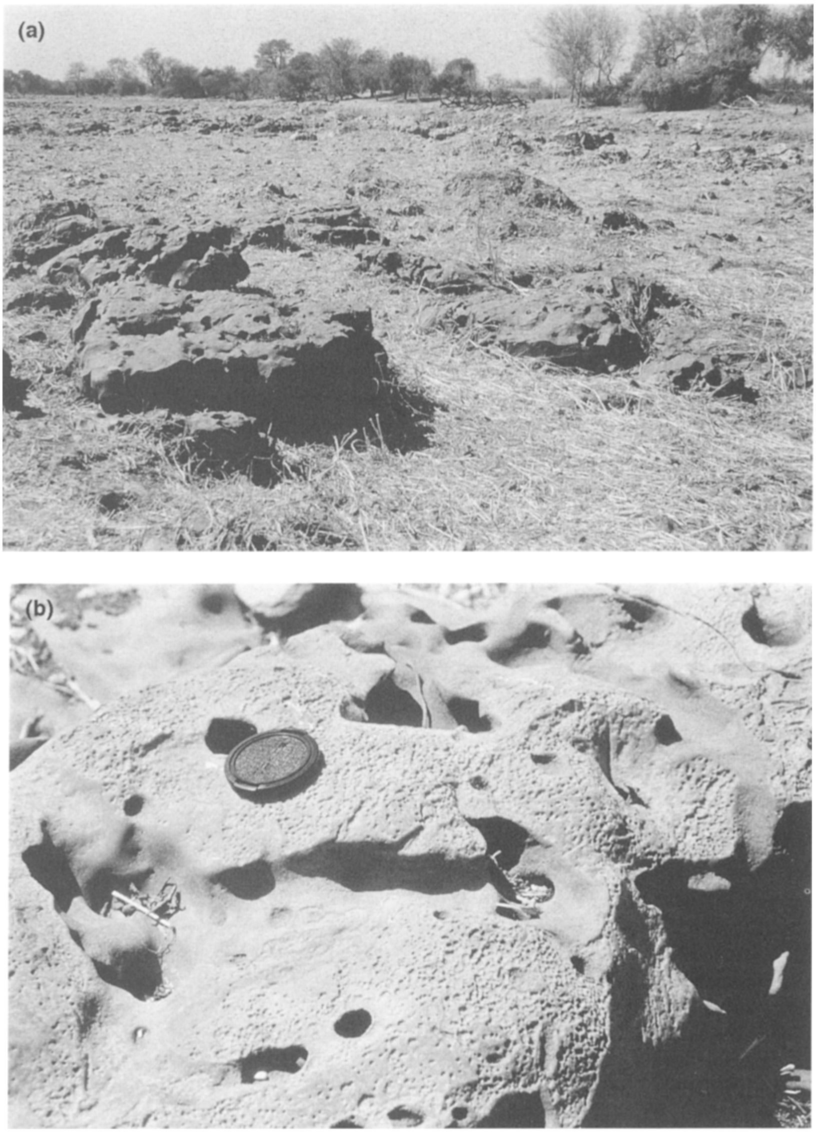

Fig. 5. (**a**) The drainage-line silcrete body at Samedupe Drift. (**b**) Surface morphology of a silcrete block from Samedupe Drift (lens cap for scale is 5 cm diameter).

cemented by red-brown silica. A concentric structure is revealed in thin section with alternating phases of silica and calcium carbonate present.

On the basis of the core and surface samples, Shaw & Nash (1998) have proposed two distinctly different silicification mechanisms for the surface and sub-surface materials. The surface silcretes are representative of simple cementation of quartz sands in a near surface environment and are likely to have formed in the way suggested by McCarthy & Ellery (1995). Water commonly persists in pools in the bed of the Boteti River between floods and supports aquatic vegetation such as reed beds. This sort of environment promotes silica accumulation, as pools are provided with an annual supply of clastic sediment and silica phytoliths in addition to experiencing pH fluctuations and evaporation. As such, apart from the obvious dissimilarity in terms of field shape and setting, drainage-line silcretes in the Boteti are broadly analogous to pan silcretes described by Summerfield (1982). Sub-surface silcretes are more likely to have formed as a result of silicification associated with groundwater recharge due to the passage of the annual flood. The development of

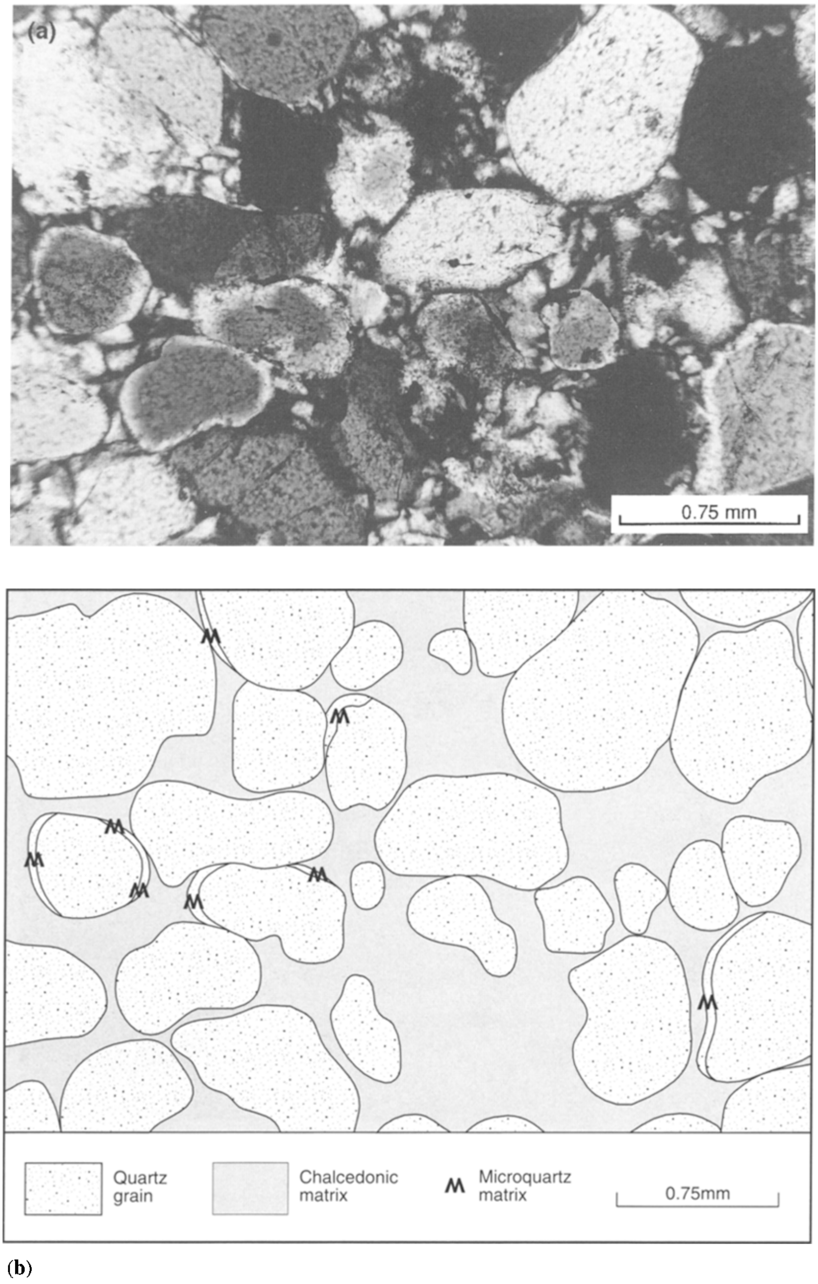

Fig. 6. Micromorphology of a typical surface silcrete sample from Samedupe Drift.

pisoliths is closely associated with the position of the water table which fluctuates markedly during the passage of the annual flood (SMEC, 1987) resulting in alternating aerobic and anaerobic conditions and seasonal changes in salinity levels, both of which influence silica precipitation (Shaw & Nash, 1998).

4. COMPARISON OF SARSENS AT CLATFORD BOTTOM AND SILCRETES AT SAMEDUPE DRIFT

The model of early phase silicification proposed by McCarthy & Ellery (1995) and that put forward by Shaw &

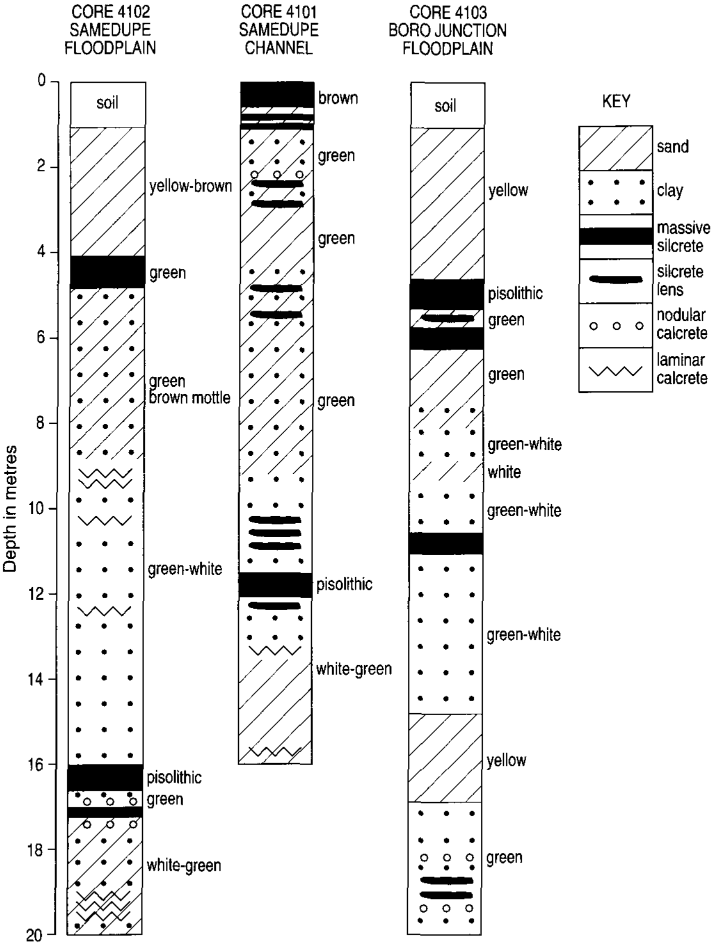

Fig. 7. Lithological logs of cores from Samedupe Drift and the Boro Junction floodplain.

Nash (1998) to describe the origin of the surface silcretes at Samedupe Drift provide useful analogues for the formation of sarsens at Clatford Bottom. The applicability of these models as an explanation of sarsen train occurrences is best addressed by considering similarities and differences between the UK and Kalahari sites at a variety of scales.

The most immediate similarity between the two sites is in terms of their overall appearance. The silcrete body at Samedupe is a discrete linear sheet-like feature occupying a limited section of a valley floor. The sarsen train at Clatford has a similar setting although the individual sarsen stones are not *in situ* and have been relocated from their original site of formation during the course of landscape evolution. The great numbers of sarsen stones found at sites like Clatford Bottom may be an indication of a pre-existing spatially limited silcrete body which has been substantially disrupted and eroded, with the remnants moved over relatively short distances to their present valley floor position.

It is, however, the macro- and micro-morphological characteristics of Clatford Bottom sarsens and Samedupe surface silcretes which are more directly comparable (Table 1). Individual blocks show the greatest similarity in terms of overall morphology and surface features. Both sites are dominated by tabular blocks with tubular structures which are most likely to have developed during the formational process if, as suggested by Clark *et al.* (1967) amongst others, tube-like structures represent root casts. The presence of tubular structures in the Samedupe silcretes is almost certainly attributable to silcrete formation in association with reed beds or other similar vegetation types, although Summerfield (1978, p. 37) suggests that they are 'of a rather unusual morphology for this origin'. The basin structures may either be original features, as seen in freshly exhumed silcrete lenses developed within the Fontainebleau

Table 1. Comparisons between Clatford Bottom sarsens and Samedupe silcretes

Feature	Clatford sarsens	Samedupe silcretes
Micromorphological features		
Microquartz matrix	Rare	Common
Chalcedonic matrix	Absent	Common
Optically continuous overgrowths	Common	Absent
Opaline overgrowths	Absent	Rare
Glaebules	Absent	Absent
Colloform features	Absent	Absent
Void-fill features	Rare	Rare
Length-slow chalcedony void fills	Absent	Absent
Length-fast chalcedony void fills	Absent	Rare
Macromorphological features		
Tabular block morphology	Yes	Yes
Weathering rind	Present	Present
Basin structures	Present	Present
Tubular structures	Present	Present
Surface dissolution	Present	Present

Sand Formation (Thiry *et al.*, 1988a,b), or may be a product of post-formational weathering.

The main difference between the Kalahari silcretes and Clatford Bottom sarsens is in terms of their micromorphology. The silica matrix in the silcretes from Samedupe is dominated by chalcedony and microquartz with minor opaline grain overgrowths and chalcedonic void fills, whilst optically continuous quartz overgrowths and minor quantities of microquartz occur in sarsen samples from Clatford Bottom. This variation in matrix material may, however, be of minor importance, as it could be simply attributed to differences in the quality of the original host sediment prior to silicification or to maturation of the matrix cement. The development of optically continuous overgrowths in the sarsen implies that there was no clay present at the time of silicification (Heald & Larese, 1974) and that the cementing solutions contained low concentrations of silica and a lack of other ions which would prevent the growth of quartz crystals (Summerfield, 1979). Alternatively, it is possible that the matrix of the sarsens has 'matured' or 'ripened' (Landmesser, 1995) through a series of silica phase transformations from amorphous silica to opaline silica to chalcedony to quartz (Williams, Parks & Crerar, 1985).

In other respects, the micromorphological properties of the two materials are extremely similar, as has been noted from previous general comparisons of sarsens and Kalahari silcretes (Summerfield, 1979; Summerfield & Goudie, 1980). Both are formed by the cementation of well-rounded quartz grains and have a grain-supported fabric. More importantly in terms of their palaeoenvironmental significance, neither type of silcrete contains glaebular or centripetal colloform structures which are common in many silcretes on the southern coast of Cape Province in South Africa (Summerfield, 1983b). Colloform structures, in particular, are an indication of illuviation of silica-rich cements through a profile and are most commonly identified in silcretes formed by pedogenic processes (Thiry & Simon-Coinçon, 1996). Whilst the absence of such features does not preclude the possibility that sarsens at Clatford Bottom developed within a pedogenic setting, the overall micromorphology is closer to non-pedogenic silcretes described by Summerfield (1982), Thiry *et al.* (1988a) and Milnes & Thiry (1992). Thus, the sarsens at Clatford Bottom are broadly similar to 'non-weathering profile' silcretes described by Summerfield (1979), although the use of such a term for Kalahari silcretes has recently been disputed (Nash *et al.*, 1994b). Sarsens containing illuviation features have been described by Isaac (1979), Summerfield (1979) and Summerfield & Goudie (1980), but not from the Clatford Bottom area.

5. DISCUSSION AND IMPLICATIONS

If the sarsens within sarsen trains in Wiltshire developed in former drainage lines this has a number of potential implications for the palaeoenvironmental interpretation of these deposits. These implications are, perhaps, best considered with reference to the work of Clark *et al.* (1967), Summerfield (1979) and Summerfield & Goudie (1980) who discuss the environment of sarsen formation in greatest detail. These previous studies all recognize the potential macroscale climatic controls of silcrete development, and Summerfield (1979) and Summerfield & Goudie (1980) further stress the importance of geochemical conditions and micromorphological properties, but none fully address the potential significance of the geomorphological setting of silcrete formation beyond mentioning the possible models of formation and the general concensus of a need for a relatively flat land surface.

Development within a drainage line would partly negate the idea inferred in previous studies that sarsens represent the remnants of a former widespread planar sheet of silcrete developed upon a flat landscape in a region with heavy seasonal rainfall and high evaporation rates. Whilst recognizing that the contemporary Kalahari landscape is extremely flat and experiences high evaporational water losses, the most significant factor concerning the origin of the surface silcretes at Samedupe Drift is that formation has taken place in a pan-like environment situated within a river valley. This geomorphological setting acts in combination with evaporational water loss to provide a context for silcrete formation, but the fact that silicification takes place within a landscape depression is of greater significance than the climatic setting.

A similar argument has been put forward by Thiry *et al.* (1988a,b) with reference to the formation of silcretes within the Oligocene Fontainebleau Sands in the Trappes–Étampes–Fontainebleau region of the Paris Basin. Silcretes have developed during the Plio-Quaternary due to the percolation of water containing silica derived from bleached sands. Silicification occurred at the vadose/phreatic interface, with the development of lenses of silcrete which mirror the slope of the regional water table, dip towards the valley axis and are focused upon zones of groundwater emergence in the valley floor. Silicification is closely related to the evolution of the present landscape, with episodes of landscape dissection leading to the development of superposed silcrete lenses and ultimately to landscape inversion with the formation of silcrete-capped mesas and buttes. The geomorphological setting, particularly the presence of valleys, is considered by Thiry *et al.* (1988a) to be the primary determinant of silcrete formation, with silicification processes operating independently of climatic conditions. The Fontainebleau groundwater silcretes are distinct from the drainage-line silcretes described in this paper as they outcrop for considerable distances along valley flanks and have formed by different processes. On the basis of the shape and dimensions of the sarsen train at Clatford Bottom it would appear that the sarsens originally formed a body more closely analogous to that at Samedupe Drift than the present Fontainebleau silcrete outcrop.

There is still much debate surrounding the timing of silicification and the likely host materials within which sarsen formation took place. The difficulties largely arise due to the absence of convincing evidence for the *in situ* occurrence of sarsens in the UK, although Clark *et al.* (1967), Catt & Moffat (1980) and Small (1980) include reference to a number of instances where sarsens and puddingstones are closely associated with a range of Palaeogene sediments. It has, however, yet to be proved conclusively whether particular sarsen occurrences developed within specific host sediments or are merely found in their area of outcrop at the present day. There are two main schools of thought concerning the timing of silicification. The first sees at least three periods of silica cementation during the Palaeogene and early Neogene (specifically the late Paleocene, the middle to late Eocene and the middle Oligocene to early Miocene; Summerfield & Goudie, 1980), on the basis of four lines of evidence. These are:

(a) the ages of the various Tertiary deposits from which sarsens are assumed to have formed
(b) the likely variation in climate in southern Britain during the Tertiary (with either warm/wet or arid conditions generally suggested as a requirement for silcrete formation)
(c) the timing of the establishment of a sufficiently flat landscape upon which a silcrete sheet could develop,
(d) comparison with the timing of formation of silcretes within the more complete stratigraphic sequences of northwestern Europe (van den Broek & van der Waals, 1967; Small, 1980; Summerfield & Goudie, 1980; Wopfner, 1983).

The second view is that whilst sarsen formation may have occurred within Palaeogene sediments of three different ages, there was only one major period of silicification during the late Palaeogene and early Neogene (Clark *et al.*, 1967; Small, 1980). The presence of supposed sarsen 'pennystones' in the Eocene Blackheath Beds (Dewey, Bromehead, Chatwin & Dines, 1924) may, however, be at odds with this.

The concept that sarsen formation may have taken place within drainage lines does not necessarily help in the evaluation of these sets of arguments and, if anything, may serve to complicate the issue. If, as in the case of the silcretes at Samedupe Drift, sarsen formation were less reliant upon climate and more dependent upon geomorphological setting, then the presence of a valley containing seasonal pools within a semi-arid or arid setting may have been the primary requirement for sarsen development. This would remove the need for an extensive planar surface as a prerequisite for sarsen formation and therefore place less restriction upon the timing of silicification and more emphasis upon the combination of landscape evolution and climatic development. It would, however, require the presence of a former valley system (or systems) containing pan-type environments within which silcrete formation took place. Despite the size of the Okavango system any former drainage system would not necessarily need to have an extensive catchment. The identification of such a system would necessitate detailed reassessment of the various theories concerning the landscape evolution of southern England (e.g. Jones, 1980; Small, 1980), particularly the age of the Chalk drainage, and is, as such, beyond the scope of this paper.

Finally, a drainage-line model of sarsen train formation may allow further elucidation of the time needed for a fully indurated tabular silcrete body to form. Whilst it is not possible to postulate how long the surface silcrete at Samedupe has taken to form (largely due to the complex and, for the most part, undefined stratigraphy of the Kalahari Group sediments) there are other silcrete bodies, such as the Fontainebleau silcretes described above, which exist within tightly defined stratigraphic frameworks. Detailed studies of these silcretes suggest that silicification in a valley setting may be relatively rapid, taking as little as 30 000 years for lenses of silcrete in excess of 3 m thickness to form (Thiry *et al.*, 1988a). The silcretes are suggested to have formed during the Plio-Quaternary (Thiry *et al.*, 1988b) and are therefore considerably younger than any previously suggested age for sarsens. The fact that multiple silcrete horizons occur at Fontainebleau is also of potential interest as it raises the possibility that several sarsen horizons may have been superimposed during the course of landscape evolution. This may eventually also happen at Samedupe Drift given the vertical separation of silcrete horizons beneath the valley floor.

6. CONCLUSION

This paper has described the macro- and micromorphological characteristics of sarsen stones within the Clatford Bottom area and has compared them to silcretes within the Boteti River in the Middle Kalahari of Botswana. On the basis of morphological and petrographic similarities it is suggested that the model of silcrete formation put forward by Shaw & Nash (1998) to explain the origin of silcretes at Samedupe Drift on the Boteti may be a useful analogue for the formation of sarsen stones now forming parts of sarsen trains. This model, in part based upon the work of McCarthy & Ellery (1995), envisages silcrete formation occurring within a river valley in a semi-arid or arid environment with silica accumulating as a result of direct fluvial inputs of clastic material and solutes, inputs of dissolved silica from groundwater and indirect additions of silica phytoliths derived from aquatic vegetation in seasonal pools. Sarsens formed in this way would have originally been part of a spatially-limited linear silcrete body associated with a pan-type setting in a valley environment and would have then accumulated within contemporary valleys during the course of landscape evolution. On the basis of this model, it may be necessary to reassess some of the traditional ideas surrounding sarsen development, not least the notion that sarsens once formed a much more extensive sheet of material and the assumed requirements of a flat landscape setting and relatively high precipitation inputs on a seasonal basis for sarsen formation. It is not implied that all sarsens formed by this mechanism, nor that all sarsen trains originated in this way as there is clear evidence from the work of Summerfield (1979), Summerfield & Goudie (1980) and Isaac (1983a) that many sarsen stones in other areas may be more closely related to pedogenic silcretes developed by illuviation of silica through weathered materials. Nonetheless, the model described may provide a useful indication of the types of environmental conditions associated with sarsen formation.

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