

**PETROGRAPHIC INVESTIGATION OF SARSENS
(CENOZOIC SILCRETES) FROM SOUTHERN ENGLAND¹**

M. A. SUMMERFIELD² & W. B. WHALLEY³

ABSTRACT

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The petrography of sarsens (Cenozoic silcretas), which occur extensively as scattered surface deposits over southern England, is investigated through thin-section observations and scanning electron microscopy. Attention is focused on the general characteristics of the various types of sarsen fabric (GS-(grain-supported), F-(floating) and C-(conglomeratic)), and on the nature of quartz-overgrowth development. Evidence for possible host materials is considered and some provisional conclusions are drawn about the diagenesis of these sediments and the environment in which they formed.

INTRODUCTION

Sarsens are highly siliceous (commonly > 95% SiO₂) terrestrial, indurated sediments of Cenozoic age and range from quartz arenites to predominantly fine-grained matrix-dominant rocks and siliceous conglomerates. They represent various types of silcrete (DURY & HABERMANN, 1978; LAMPLUGH, 1902; SUMMERFIELD & GOUDIE, in press) in that they are the product of surface or near-surface silicification; their formation, therefore, is related to local climatic, geomorphological and hydrological conditions.

Sarsens are widely distributed over southern England and they occur as usually rather irregular, tabular boulders (sarsen stones), up to 5 m or more across, resting on the Chalk and on, or within, various unconsolidated Cenozoic deposits. There are no entirely reliable reports of *in situ* occurrences and these may be confined to the localised conglomeratic varieties (Hertfordshire and Bradenham Puddingstones); detailed stratigraphic location is, therefore, impossible.

Host sediments in which sarsens have been reported range

in age from mid-Palaeocene (Thanetian) to Late Eocene (Auversian) and this provides a maximum age for their formation. However, the actual period (or periods) of silicification may have been much later (CLARK ET AL., 1967) and work on the silcretas of continental Europe, especially those of the Paris Basin (meulière) (e.g. CHOLLEY, 1943; THIRY, 1978) and South Limburg (VAN DEN BROEK & VAN DER WAALS, 1967), to which sarsens appear to be petrographically and genetically closely related, suggests a number of phases of formation from the Palaeocene through to at least the Miocene. There is also the possibility that sarsens represent silicified Oligocene and Miocene deposits which are now otherwise absent (Miocene) or poorly represented (Oligocene) in Britain. This would accord with the silicification of Miocene sands reported from South Limburg and adjacent areas (RIEZEBOS, 1974) and the Miocene meulière surfaces of the Paris Basin proposed by CHOLLEY (1943).

Three main types of sarsen can be identified on the basis of macro-scale characteristics. Most common are the 'quartzitic' varieties which consist of quartz grains cemented by optically continuous overgrowths. These tend to fracture around rather than through individual grains. A second type, which frequently exhibits a sub-conchoidal fracture, is composed of a variable skeletal grain component in a fine-grained matrix. The third variety are the conglomerates which consist of rounded (puddingstone), or, more rarely, angular (flint brec-

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² School of Geography, University of Oxford, OXFORD OX1 3TB, England.

³ Department of Geography, Queen's University, BELFAST, Great Britain.

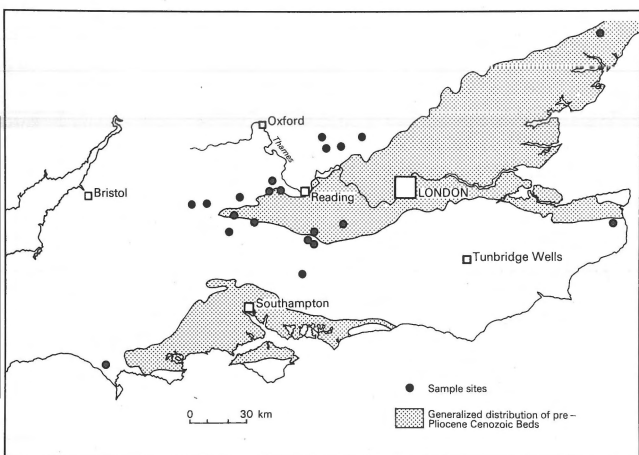


Fig. 1
Map of southern England showing sample locations.

cia), pebbles in a 'matrix' usually of the quartzitic type but more rarely with a significant fine-grained matrix component.

Preliminary petrographic studies of sarsens have been undertaken by KERR (1955), SUMMERFIELD & GOUDIE (in press), WHALLEY (1978-a) and WHALLEY & CHARTRES (1976). Here we present a more detailed description of the wide range of petrographic features encountered in sarsens, employing both thin-section and scanning electron microscope observations. Such a detailed investigation is required in order both to elucidate the likely geochemical conditions prevailing during silicification, in so far as these are reflected in the diagenetic effects observed, and to draw comparisons between sarsens and the much more fully documented petrographic characteristics of silcretes, especially those from southern Africa and Australia (SMALE, 1973; SUMMERFIELD, 1978; WATTS, 1978).

SAMPLE PREPARATION

Samples were collected from a number of sites in southern England (Fig. 1). Sarsens displaying a wide variety of characteristics in hand specimen were sampled. Thin-sections were made from all samples collected.

Fracture surfaces of specimens were prepared for SEM and these were placed uppermost on specimen stubs, being attached with either silver conducting or clear glue. The coating was done either by sputter coating with gold or with a carbon film by radio-frequency deposition. The silver and gold components were not usually employed when energy-dispersive X-ray (EDX) analysis was used. Accelerating voltages from 15 to 25 kV were used on a Cambridge 180 Stereoscan. The voltage is shown by the second figure below each micrograph, and the scale (the distance between each bar at the base of the micrograph) is indicated by the third figure. The micrographs were taken in the normal (secondary-emissive) mode. Impregnation of samples for pore analysis was by

Araldite YD resin with hardner. This was left for 48 hours before the minerals were dissolved by immersion in warm hydrofluoric acid. The skeletons produced were then mounted on stubs and gold sputter coated.

GENERAL FABRIC CHARACTERISTICS

Sarsens in thin-section exhibit GS-(grain-supported), F-(floating) and C-(conglomeratic) fabrics.

GS-Fabric

In the samples examined GS-fabrics are by far the most common and usually consist of predominantly quartz skeletal grains ($> 30 \mu\text{m}$ across) forming a self-supporting and, by virtue of optically continuous overgrowths, interlocking framework. Overgrowths are not usually readily distinguishable from the host grains in thin-section (Fig. 2a) but they are clearly seen in scanning electron micrographs. Figure 2b illustrates a typical example where the quartz overgrowths are generally well-formed. Figure 2c shows stages of overgrowth development comparable to those observed in the Penrith Sandstone by WAUGH (1970-a) but such full sequences are rarely seen in sarsens.

A variety of arrangements of voids are observed in sarsens. The typical GS-fabric with optically continuous overgrowths illustrated in figure 2b gives a resin cast as seen in figure 2d. The voids display high connectivity and there is only limited restriction at void throats. Effective porosity is particularly high where void-filling by overgrowths is incomplete; in such cases euhedral faces on overgrowths are common and the interlocking fabric of competitive overgrowth development is lacking. In figure 2e well-developed euhedral faces on overgrowths can be seen and discrete stages of overgrowth development are indicated by dust coatings on successive crystal faces.

Locally, zones of very small interlocking crystal faces occur in the common GS-fabric samples with optically continuous overgrowths (Fig. 2e) (see also Figs. 2f and 3a). It is unclear whether these zones represent (1) pockets of silt-size quartz grains ($< 30 \mu\text{m}$ across) which have developed optically continuous overgrowths; (2) original or secondary voids within which microcrystalline quartz has been precipitated; or (3) the replacement of a fine-grained precursor in the host material. The SEM evidence is ambiguous in that the abundant euhedral faces seen in such zones are not unequivocally identifiable as optically continuous overgrowths on silt-size quartz grains (Fig. 2f); they may indeed represent the crystal faces of authigenic quartz precipitated in voids or possibly as a replacing mineral. The extremely small, regular and well-formed crystals seen in some samples (Fig. 3a) clearly suggest undisrupted precipitation of authigenic quartz within voids. Because of the difficulty in interpreting these features, and of relating them to features resolvable in conventional thin-

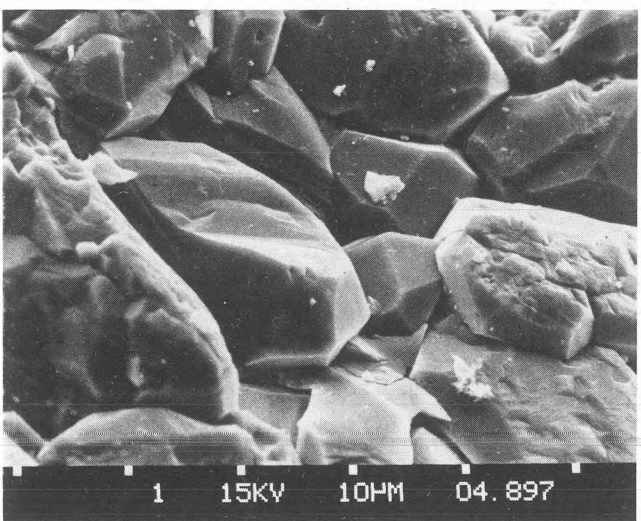
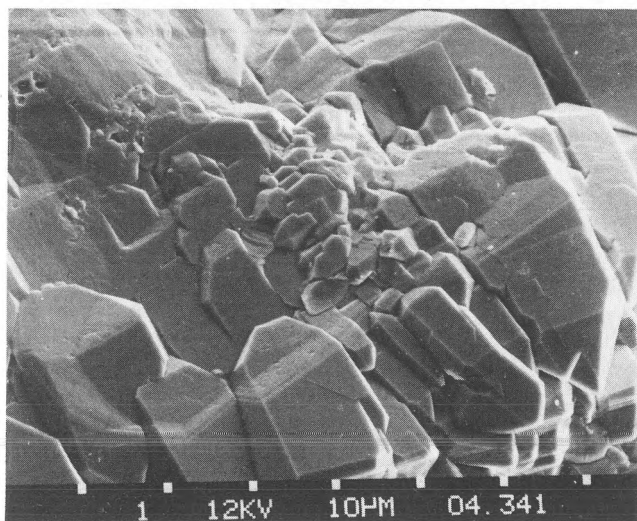
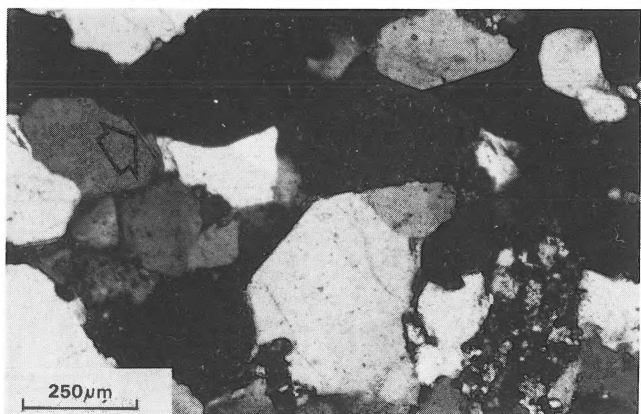
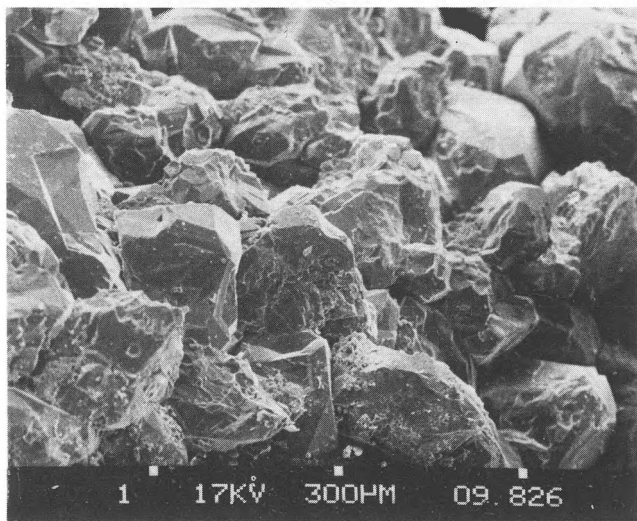
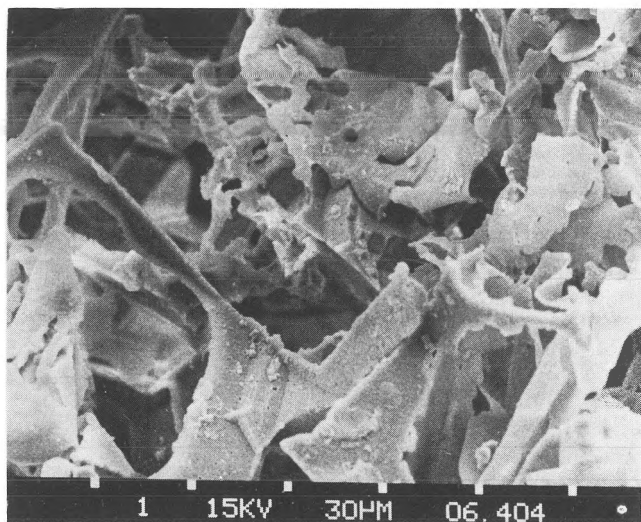
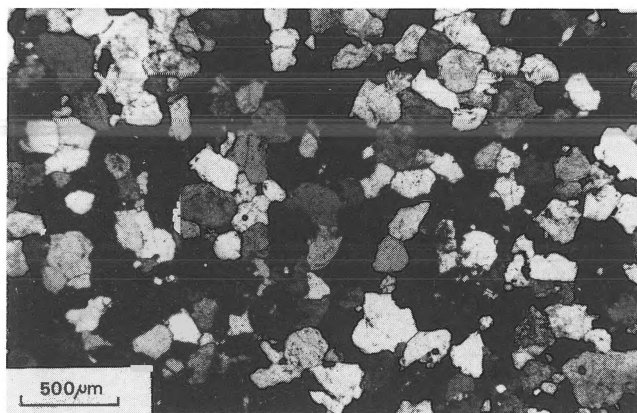


Fig. 2

- (a) Typical GS-fabric sarsen with optically continuous overgrowths (Aston Rowant, Oxfordshire). Crossed polarizers.
 (b) Well-developed optically continuous quartz overgrowths in a GS-fabric sarsen (Walters Ash, High Wycombe, Buckinghamshire).
 (c) Overlapping faces in an incomplete stage of quartz overgrowth formation (Beckhampton, Wiltshire).
 (d) Resin cast of pore spaces in a typical GS-fabric sarsen with optically continuous overgrowths (Walters Ash, High Wycombe, Buckinghamshire).
 (e) GS-fabric sarsen showing dust coatings on successive euhedral overgrowth faces (arrowed) and small zone of microquartz (bottom right corner) (Aston Rowant, Oxfordshire). Crossed polarizers.
 (f) Well-formed crystal faces on silt-size quartz grains in GS-fabric sarsen (Hampstead Marshall, Berkshire).

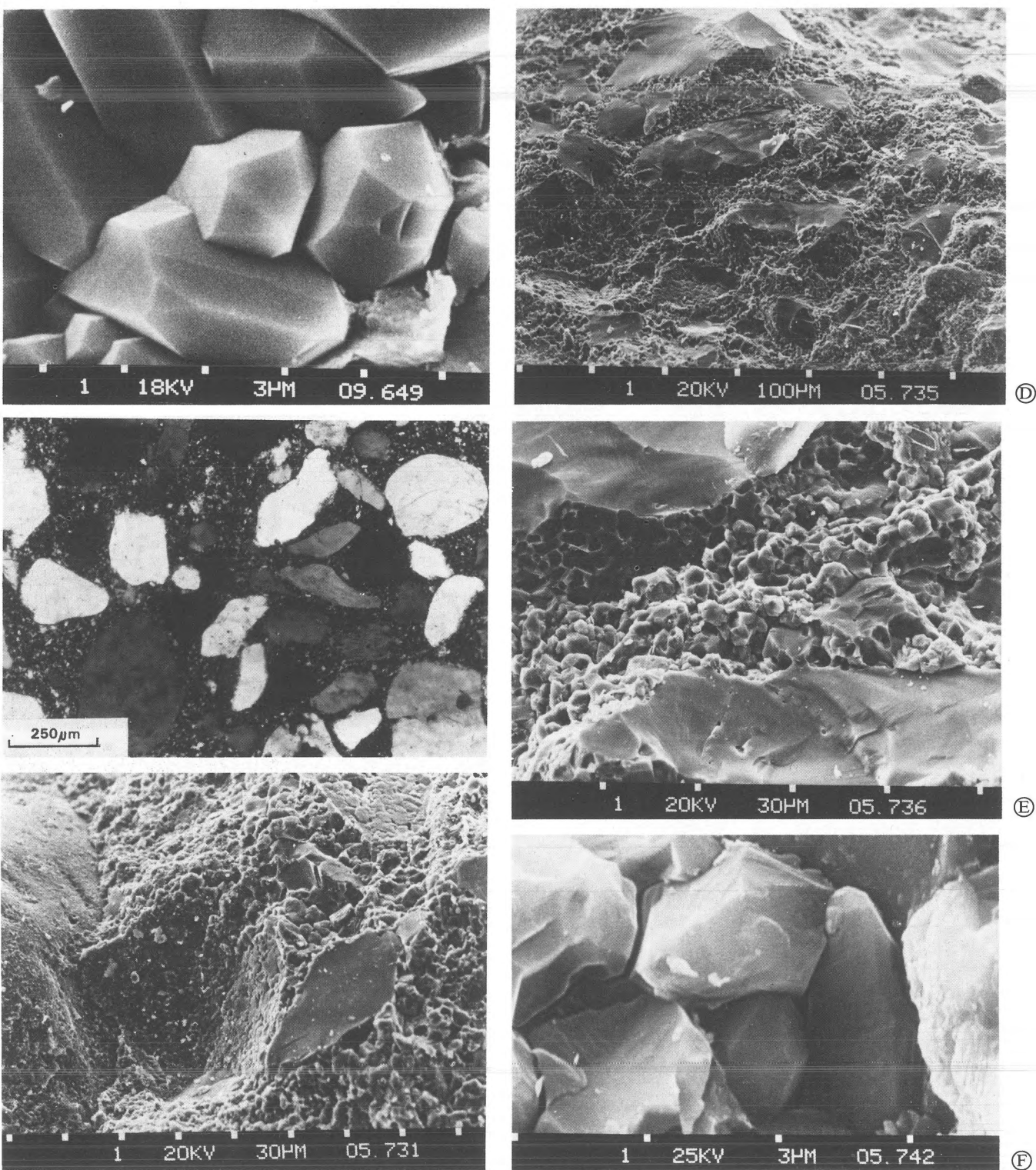


Fig. 3

- (a) Very well-formed crystal faces in microquartz matrix of GS-fabric sarsen (Sandhurst, Surrey).
 (b) Typical GS-fabric with microquartz matrix (Aston Rowant, Oxfordshire). Crossed polarizers.
 (c) Microquartz matrix of GS-fabric sarsen (from Thanet Beds, Sandwich, Kent).
 (d) Skeletal grains and microquartz matrix in same sample as 3c at lower magnification.
 (e) Interlocking microquartz matrix between two skeletal grains (with fracture surfaces) (same sample as 3c).
 (f) Microquartz matrix of same sample as 3c at high magnification. Euhedral faces present but only poorly formed.

section petrography, the term microquartz is applied to this fine-grained material ($< 30 \mu\text{m}$ across).

In some sarsen samples microquartz constitutes the matrix and almost entirely fills the spaces between the skeletal grains, which themselves form a self-supporting framework (Fig. 3b). In such samples optically continuous overgrowths on skeletal grains are usually absent. Figure 3c shows the microquartz matrix between two skeletal grains in one such sample. The grain on the right displays a fracture surface, an artefact of sample preparation, while between it and the large grain on the left is a smooth, slightly rounded cavity left by another grain. The rather flat impress of a small grain is visible towards the top-right of the micrograph, illustrating how precipitation of quartz around the self-supporting skeletal grains has markedly reduced porosity. At a lower magnification on the same sample the fracture surfaces of a number of skeletal grains can be seen with microquartz filling the intergranular spaces (Fig. 3d). In figure 3e the individual crystals within the matrix are seen between two skeletal grains. At a higher magnification the euhedral faces of individual crystals are visible (Fig. 3f). In some cases well-formed crystal faces appear to be absent even at high magnifications (Fig. 4a).

Although in thin-section, and at low magnification under SEM, a microquartz matrix appears to produce a tightly interlocked rock with low porosity, numerous, though very small, voids remain within the matrix (Figs. 2f and 3f). Such micro-porosity would still allow slow percolation of silica-charged solutions for progressive void-filling.

F-fabric

F-fabric sarsens consist of grains floating in a microquartz matrix (Fig. 4b). They are thus distinguished from the GS-fabric varieties in lacking a self-supporting framework of skeletal grains. Quartz is predominant in the skeletal grain fraction but a few grains of feldspar and heavy minerals are present in some samples. The skeletal grain/matrix ratio varies from samples with only a few isolated grains (Fig. 4b) to those with a low matrix content in which a floating fabric is only locally developed. The matrix of the sample illustrated in figure 4b consists of small quartz crystals with some development of euhedral faces and apparent small angular quartz grains with little development of optically continuous overgrowths (Fig. 4c).

C-fabric

C-fabric sarsens consist of cherty (flint) pebbles (5 to 50 mm across) in a GS-fabric 'matrix' of skeletal quartz grains with optically continuous overgrowths (Fig. 4d). However, there is commonly a zone about 2 mm in width around each pebble in which microquartz rather than optically continuous overgrowths is present. In rare cases optically continuous overgrowths are absent and cementation of the skeletal grain component is accomplished entirely by microquartz. Peb-

blematrix contacts are generally very sharp but in a few samples fretting of pebble surfaces has been observed.

OTHER FEATURES

In some samples collections of very small quartz crystals ($< 5 \mu\text{m}$ across) approaching euhedral form are seen attached to skeletal grains (Fig. 4e).

Clays are rare in sarsens. Where present, clay particles are usually seen collecting around void throats (Fig. 4f) or, less frequently, covering sides of crystal faces and filling voids in the matrix (Fig. 5a). The meniscus accumulation of infiltrated clay particles has only been observed once (Fig. 5b). Most of this clay is probably late-stage since void filling is usually associated with proximity to the surface of the sarsen stone.

Surficial late-stage iron oxide staining can be seen on the surfaces of some sarsen stones and this most frequently takes the form of a very thin iron oxide coating. This iron oxide appears to occur as minute particles on crystal or overgrowth faces (Fig. 5c). Occasionally iron is also incorporated into illitic clay overgrowths (Fig. 5d).

The matrix of one F-fabric sarsen examined (Fig. 4b) contains finely disseminated brownish material. Bulk chemical analysis of this sample (SUMMERFIELD, 1978; SUMMERFIELD & GOUDIE, in press), indicates that it is relatively titanium- and iron-rich (2.08% TiO_2 ; 0.8% Fe_2O_3). Titanium and iron-rich zones as colloform features within the matrix of F-fabric sarsens have also been reported (K. Isaac, pers. comm.).

POSSIBLE HOST MATERIALS

Various Cenezoic sediments have been suggested as the host material for the silicification which produced sarsens. (CLARK ET AL., 1967; SUMMERFIELD & GOUDIE, in press). Uncertainty exists because of the lack of evidence for the dating of the phase (or phases) of silicification. Various arenaceous facies, usually presumed to be fluvialite, including the Bagshot Beds, Bracklesham Beds, Barton Beds and Reading Beds, have been proposed as likely host sediments. WHALLEY (1978-a) has described some of the diagenetic features found on uncemented quartz grains from a cavity in a sarsen found at Aston Rowant (Fig. 6). The grains obtained from this pocket (Fig. 5e) are very similar in general characteristics to grains from the Reading Beds, though rather different from those in the Bagshot Beds (Fig. 5f). As only one such pocket has been found and the skeletal grains in many sarsens have overgrowths it is not possible to say whether some sarsens come from existing particular Cenezoic beds or might be derived from strata which have been eroded. Cathodoluminescence techniques and fluid inclusion methods may allow the identification of distinguishing characteristics of the original host grains, and thus improved environmental interpretation and stratigraphic location.

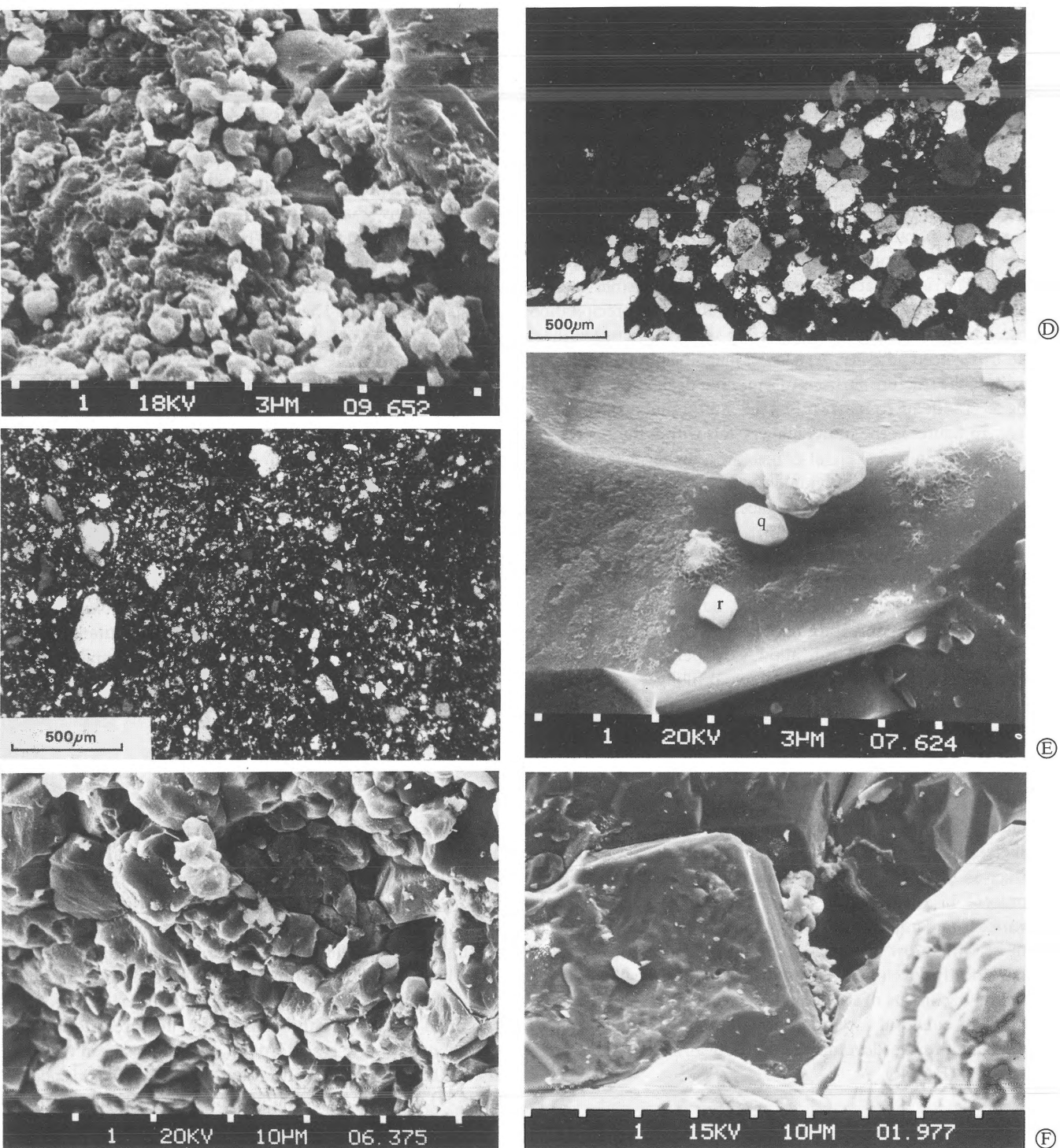


Fig. 4

- (a) Microquartz zone in GS-fabric sarsen (same sample as 2b) with no visible crystal faces on clay-size quartz particles.
 (b) Typical F-fabric sarsen with skeletal grains floating in a titanium- and iron-rich microquartz matrix (Langley Park, Berkshire). Crossed polarizers.
 (c) Microquartz matrix of same sample as 4b. Euhedral faces only moderately developed.
 (d) Boundary zone between flint pebble (top-left) and 'matrix' in C-fabric sarsen. Note presence of microquartz in matrix adjacent to pebble (Bradenham, Buckinghamshire). Crossed polarizers.
 (e) Overgrowth faces on a large skeletal grain with iron and possibly some inwashed clay on the surface. The very small crystals approaching euhedral form are quartz (q) and rutile (r) (Hampstead Marshall, Berkshire).
 (f) Post-diagenetic inwashed clay minerals lodged between overgrowth faces of quartz grains at void throats.

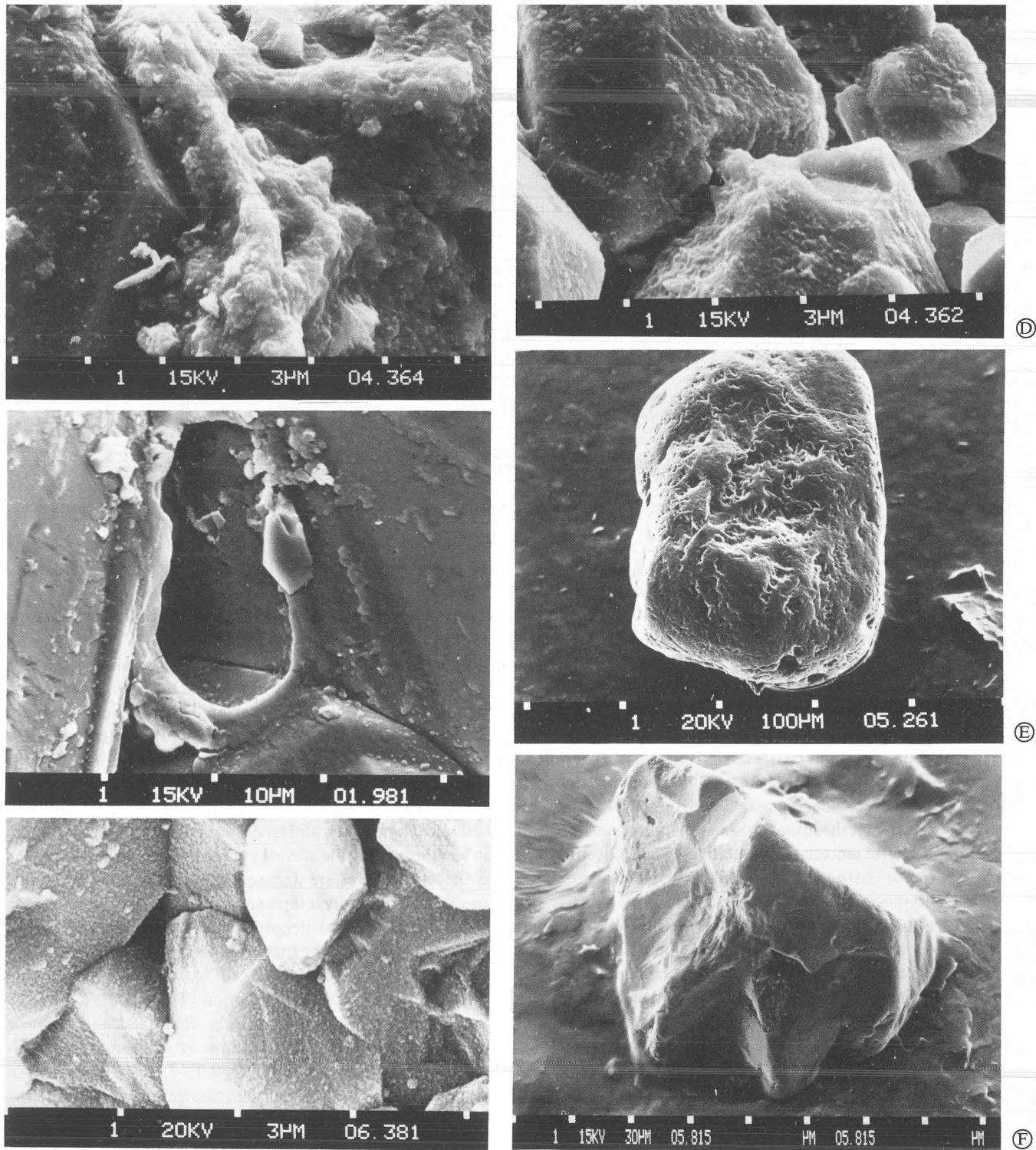


Fig. 5
 (a) Relatively large amounts of inwashed clay covering crystal faces; rarely are distinctive habits of clay minerals seen (Kintbury, Berkshire).
 (b) Clay (probably kaolinite) infilling seen as a meniscus around a pore space (Piggedene, Wiltshire).
 (c) Very small euhedral crystals with iron oxide granules on the surface (Newbury, Berkshire).
 (d) Iron staining in illitic clay overgrowths on euhedral quartz overgrowths (Kintbury, Berkshire).
 (e) Quartz grain from a pocket of sand in a sarsen at Aston Rowant, Oxfordshire. Grain is fairly well-rounded and displays surface texture possibly indicative of fluvial activity.
 (f) Typical grain from the Bagshot Beds (Tadley, Berkshire). Note that grain is much less rounded than that illustrated in 5e.



Fig. 6
Pocket of loose sand in sarsen at Aston Rowant, Oxfordshire, from which the grain shown in 5e was collected.

DISCUSSION

The nature of the host material and characteristics of the circulating solutions responsible for silicification are the key factors in determining sarsen micromorphology. GS-fabric sarsens formed through passive void-filling by authigenic quartz of a quartzose host sediment. The development of optically continuous overgrowths implies a lack of clay within the host sediment (CECIL & HEALD, 1971; HEALD & LAESE, 1974) and circulating solutions characterised by both low concentrations of silica, and of other ions (which could disrupt the orderly growth of macrocrystalline overgrowths) (MILLOT, 1970). Conversely, the initial presence of intergranular clay or other non-quartz material or of relatively high concentrations of silica and/or 'disruptive' ions would give rise to microquartz or even cryptocrystalline silica precipitation.

The surface characteristics of the detrital quartz grains themselves also appear to be of some importance. It seems that only grain surfaces which are clean and highly disturbed prior to cementation provide sufficient nucleation sites to result in the large-scale development of optically continuous overgrowths (RIEZEBOS, 1974).

C-fabric sarsen may be similarly interpreted since these differ from the GS-fabric type only in the size range of their detrital component. F-fabrics can be generated by displacement or partial replacement of skeletal grains, or by replacement of the matrix of an F-fabric host material such as a clayey weathering deposit containing residual floating quartz grains. Matrix replacement is the favoured interpretation for this type of sarsen as evidence of skeletal grain replacement during silica diagenesis is lacking, and displacive growth of authigenic quartz within voids is an improbable explanation for F-fabrics, at least those with a small skeletal grain fraction

(e.g. Fig. 4b), because of the considerable volume increase required.

Work on silcretes in Australia and Africa (LANGFORD-SMITH, 1978; MILLOT, 1970; SUMMERFIELD, 1978), together with geochemical considerations, permits speculation on the environmental conditions which would have led to the formation of the different types of sarsen discussed here. In southern Africa a distinction can be made between silcretes associated with weathering profiles and those that are not (SUMMERFIELD, 1978); this distinction may be of general applicability. GS-fabrics, C-fabrics, optically continuous overgrowths, chalcedonic overgrowths and chalcedony vugh-fills are not found in weathering-profile silcretes while authigenic glaeboles and colloform features are apparently absent in non-weathering profile silcretes, which represent silicification of bedrock or a variety of superficial deposits. There also appears to be a chemical distinction in that weathering-profile silcretes are relatively titanium-rich ($\text{TiO}_2 > 1\%$) while non-weathering profile silcretes are titanium-poor ($\text{TiO}_2 < 0.2\%$) (SUMMERFIELD, 1978). It seems, therefore, that GS- and C-fabric sarsens, which from a limited number of chemical analyses appear to be titanium-poor (TiO_2 0.02 - 0.16%) (SUMMERFIELD & GOUDIE, in press) did not form in association with weathering profiles. However, this petrographic and chemical evidence suggests a weathering profile origin for F-fabric sarsens containing colloform features or which are titanium-rich (Fig. 4b).

On the basis of evidence from silcretes in Australia and Africa, sarsen formation in weathering profiles may have occurred through the downward-migration and subsequent precipitation, probably in association with restricted drainage, of silica released within the weathering profile. Both

titanium mobility and concentration (as exemplified by colloform features) and the mobilisation of aluminium within the probably clayey matrix of the host material, suggests a low pH environment ($\text{pH} < 4$) most likely resulting from high rates of organic activity related to a humid climate (SUMMERFIELD & GOUDIE, in press). Apart from the absence of glaeboles, the silcrete occurrence described by THIRY (1978) in the sandy-clayey sediments of Lower Eocene (Ypresian) age in the Paris Basin would appear to be a possible analogue for titanium-rich F-fabric sarsens.

A wider range of silica sources are possible for the majority of sarsens which are of the non-weathering profile type. Silica may have been supplied from surface waters or atmospheric fall-out and locally concentrated through evaporation and/or an increase in pH above the critical value of approximately 9 (KRAUSKOPF, 1956), precipitation in the latter case occurring through a localised or temporary reduction in pH to below 9. In addition, direct dissolution of quartz grains and enhanced solubility quartz particles produced through grain abrasion (associated with aeolian reworking?) could have produced a local silica source (WAUGH, 1970-b). A capillary-rise mechanism, involving upward silica mobilisation and surface precipitation through evaporation and associated with a seasonally dry climate has been suggested for sarsens (CLARK ET AL., 1967), but only thin surface crusts could form in this way as initial surficial silica precipitation would inhibit, and eventually prevent, the further upward movement of solutions to the surface. Moreover, experimental work synthesising this process (PARAGUASSU, 1972; WHALLEY, 1978-b) indicates that, presumably due to the rapidity of precipitation, amorphous silica is formed, rather than the well-ordered macrocrystalline structures observed in sarsens. However, compared with this process, a comparatively slow rate of precipitation appears likely for the development of the optically continuous overgrowths found in many sarsens. Since most surface and near-surface waters are moderately supersaturated with respect to quartz, silica may have simply precipitated as overgrowths from slowly migrating solutions relatively depleted in other reactive ions and sarsen formation may have occurred several metres below the surface.

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