# SURFACE FEATURES OF QUARTZ SAND GRAINS FROM THE BRASSINGTON FORMATION

by

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## Summary

Quartz grain surface features from the sands of the Tertiary Brassington Formation have been examined with the scanning electron microscope. Two groups of features can be distinguished, those inherited from the parent deposit (Bunter Sandstone) and those associated with the weathering, deposition, and/or diagenesis of these Tertiary sediments. These features are described and discussed and representative photomicrographs shown.

## Introduction

The examination of the surface features occurring on quartz sand grains as an aid to the interpretation of sedimentary environments is now a well-established technique in the geological sciences. Sorby (1880) was the first to systemmatically classify grain surface markings and to relate them to the different kinds of mechanical and chemical changes affecting the grains. This and similar early studies were limited, however, by the resolving power of the optical microscope and it is only within the last ten years with the advent of the scanning electron microscope (SEM) that the surface features of quartz sand grains have been extensively analysed.

The SEM is an ideal instrument by which to study these grain surface features, and has a number of advantages over the formerly used transmission electron microscope (TEM). With the SEM, grain surfaces are observed directly without the need for replication and thus distortions and artifacts are eliminated. The three-dimensional specimen image is displayed on a television screen and a camera attachment enables representative photomicrographs of the surface features to be taken. More detail is observable with the SEM and the wide range of magnifications (20X to 100,000X) has made this a very valuable research instrument in many scientific fields.

During the weathering, transportation, deposition, and compaction of sediments the detrital quartz sand grains may be mechanically abraded and/or chemically altered. The resulting surface features will tend to be preserved unless a subsequent sedimentary episode intervenes during which modification of existing features or the formation of new ones may take place. Consequently much useful information regarding the history of a deposit is carried by the grain surface features. Through careful examination of these surface features it has been found possible to distinguish between grains from several different environments. These are as follows: (i) source material (i.e. bedrock), (ii) diagenetic, (iii) glacial, (iv) subaqueous, (v) glacial and subaqueous combined, (vi) aeolian, and (vii) high-energy chemical environments (i.e. tropical). The most comprehensive work to-date dealing with these environments and their characteristic grain surface features is by Krinsley and Doornkamp (1973). Despite a number of recent advances in this field and numerous post-1973 papers, the publication by Krinsley and Doornkamp is still regarded as the standard reference for all SEM/quartz sand surface analysis.

The quartz grains discussed in this paper come from the sediments of the Tertiary Brassington Formation now found preserved in solution cavities within the Carboniferous Limestone of Derbyshire and Staffordshire.

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1979. pp. 19-30, 2 Tables, Plates 3 - 6

## The Brassington Formation

The name Brassington Formation was formally proposed by Boulter *et al.* (1971) as an alternative to the previously ill-defined term 'pocket-deposits' applied to the bodies of gravel, sand, and clay to be found in limestone solution hollows in the southern Pennines. This new stratgraphical terminology is based on detailed analyses of the sections in the area around Brassington and Friden. Essentially the formation can be divided into three distinct units:

| | | | |
|---|---|---|---|
| BRASSINGTON FORMATION | 3 | KENSLOW MEMBER | - blue-grey clays with plant remains. |
| | 2 | BEES NEST MEMBER | - coloured clays and thin sands, unfossiliferous. |
| | 1 | KIRKHAM MEMBER | - coloured sands and gravels, unfossiliferous. |

The entire succession is regarded as being conformable and on palaeobotanical evidence the formation is of Lower Pliocene - Upper Miocene (Late Tertiary) age (Boulter and Chaloner, 1970; Boulter, 1971). Detailed maps showing the distribution of the Brassington Formation sediments have already been presented by Ford and King (1969), Boulter (1971), and Walsh *et al.* (1972) and for this reason a similar diagram here was thought to be unnecessary.

Several sedimentological studies have been conducted in an attempt to determine the provenance and environment of deposition for the Brassington Formation. Early workers favoured the Millstone Grit and/or Triassic sandstones as the most likely source materials (Howe, 1897; Bemrose, 1906; Scott, 1927; Fearnsides, 1932;Hughes, 1952. More recently detailed work by Ijtaba (1973) has shown that both these rock types did indeed contribute the bulk of the sediments. In particular it was shown that the main source for the Kirkham Member sands and gravels is almost certainly the Bunter Sandstone, the nearest exposure of which is now 9 km. to the south of the Brassington area at Hulland. A fluvial environment of deposition from a retreating Triassic escarpment is envisaged on the basis of current-bedding, shallow channelling, and other sedimentary structures displayed by certain exposures (Ford and King, 1969; Ijtaba, 1973; Thompson, 1977 pers. comm.).

## Aims and Purposes of the Study

Three main aims and purposes for this study of the surface features on quartz grains from the sands of the Brassington Formation can be distinguished:

(i) Other sedimentological evidence has indicated a fluvial environment of deposition. It was hoped therefore to identify surface features of subaqueous origin in order to support this evidence.

(ii) The nearest present-day outcrops of source material suggest that the distance of fluvial transport was relatively short (< 9 km.). Surface features inherited from the parent deposit may not have been totally obliterated and some relic features indicating sand grain provenance may remain.

(iii) Intense chemical weathering of Tertiary age has been widely proven by many workers and the presence of gibbsite in the clays of the Kenslow Member reveals that the Brassington Formation was subjected to such weathering (Boulter, 1971; Boulter *et al.* (1971). Traces of this weathering may be present on the quartz sand grains thus providing additional evidence of a Tertiary age and weathering regime.

## Fieldwork and Laboratory Techniques

Samples of sand were collected from four silica-sand pits in which the sediments of the Brassington Formation are preserved. These were, the Bees Nest Pit (SK 241546), Kirkham's Pit (SK 217540), and the Green Clay Pit (SK 241548), all of which are near Brassington, and the Kenslow Top Pit (SK 182616) near Friden. It was only intended to sample the sand-rich Kirkham Member of the succession and at the three pits near Brassington this was achieved on the basis of comparison of the individual beds with the stratigraphic details of the formation given by Ijtaba (1973). Those samples collected from the Kenslow Top Pit cannot be easily placed in the succession and it is not known whether they represent strata of the Bees Nest or Kirkham Member. At the time of sampling (July 1977) the available exposures were in very poor condition due to a temporary shut-down in sand excavation; consequently much slumping of the sediments had resulted and it was not possible to locate and sample all the Kirkham Member strata. Fragments of Bunter Sandstone from Hulland Quarry (SK 280455) were also collected (Hughes, 1952; Walsh *et al.* 1972; Ijtaba, 1973). This sandstone is now regarded as the main source of the Kirkham Member sediments and the locality represents the nearest present-day outcrop to the Brassington area. Quartz grains from the Bunter Sandstone were examined to determine the changes, if any, between the surface features of grains from the source rock and those of the Kirkham Member. Details of these sites and the material taken for analysis are outlined in Table 1.

TABLE 1. Details of samples analysed with the SEM.

| LOCALITY | SAMPLE CODE. | STRATIGRAPHIC NUMBER (After Ijtaba, 1973). | DESCRIPTION |
|---|---|---|---|
| BEES NEST PIT (SK 241546) | A | 12 | Orange-brown sand with green clay flakes. |
| | B | 8 | Buff sand with orange streaks |
| | C | 7 | Buff sand and pebbles. |
| KIRKHAM'S PIT (SK 217540) | A | 3 | Red, yellow, and buff sand. |
| | B | 1 | Buff sand with orange streaks. |
| GREEN CLAY PIT (SK 241548) | - | 1 (?) | Buff sand with pebbles and orange streaks. At least 5.0 m. thick. |
| KENSLOW TOP PIT | A | ? | White sand and pebbles. At least 0.75 m. thick. |
| | B | ? | Purplish-grey sand with red streaks, 0.22 m. thick. |
| | C | ? | Orange sand with purple streaks. At least 0.5 m. thick. |
| HULLAND QUARRY (SK 280455) | HBS | - | Fragments of Bunter Sandstone. |

In the laboratory the samples were cleaned of adhering materials by a similar method to that described by Krinsley and Doorkamp (1973). This involved boiling the grains in dilute hydrochloric acid solution followed by a thorough washing with distilled water before a further boiling in a stannous chloride solution. A final washing in distilled water was carried out beofre oven drying at 125°C. The isolation of quartz grains from other constituent minerals was achieved using techniques of heavy-liquid separation and the grains were then sieved to the five standard sand size fractions (i.e. 2000 - 1000 - 500 - 250 - 125 - 63 $\mu$m). Ten quartz grains from each size fraction within each sample were selected for SEM analysis. Theoretically this gives a total of 50 grains per sample but the absence of certain size fractions resulted in the examination of 50 grains from two samples, 40 grains from six samples, and 30 grains from one sample. A total of 370 quartz grains have therefore been examined. Individual grains were mounted on small aluminium specimen stubs, using double-sided adhesive tape, and coated with gold in readiness for the SEM work. The fragments of Bunter Sandstone were cleaned in the same way as the individual grains but mounted with Durofix adhesive. Using these small rock particles 'tens' of grains could be examined but it was not possible to accurately determine their size.

Surface feature identification was based on a comparison with previously published photomicrographs of such features and the degree of grain roundness was determined using the Powers' Roundness Scale (Powers, 1953). Basic analysis took the form of recording the presence or absence of 15 diagnostic surface features on each grain and then calculating the percentage frequency occurrence of these features for each grain size fraction (Table 2). This list of features is a modification of that suggested by Margolis and Kennett (1971) and Margolis and Krinsley (1974) and arises from the grouping together of certain features of similar origin and the recent recognition of additional diagnostic features. Categories 1 and 2 refer to the grain's outline, 3-10 are features of mechanical origin, 11-14 are features of chemical origin, and category 15 is a feature of unknown origin although both mechanical and chemical influences may be involved.

## Quartz Grain Surface Features

The surface features observed and their percentage frequency of occurrence in all the Brassington Formation samples analysed are summarized in Table 2.

Most of the quartz grains examined display angular or sub-angular outlines. Rounded and sub-rounded grains are also present but are only found frequently in the Kenslow Top Pit and Kirkham's Pit samples. In many cases it can be seen that the angular grain outline is not necessarily an original characteristic; modification of the detrital grains having taken place through the development of euhedral quartz overgrowths (Plate 3, fig. 1).

Features of chemical origin on these quartz grains comprise crystallographic overgrowths, diagenetic etching, and oriented etch pits. The secondary growths of quartz are very similar to those recorded on grains in the Penrith Sandstone (Waugh, 1970) and Millstone Grit sandstones (Wilson, 1978 *In Press*). Growth stages in the quartz euhedra are clearly visible. Initial oriented crystalline projections marking the first stage of development followed by merging and overlap to produce larger crystal faces are shown in Plate 3, figs. 2 and 3). With continued growth large areas of the detrital grain surface become masked by well-developed prism (*m* and/or rhombohedral (*r* and *z*) faces (Plate 3, fig. 4). Overgrowths are of common occurrence on grains from the Bees Nest, Kirkham's, and Green Clay Pits but are much less frequent in the Kenslow Top Pit samples (Table 2). Grain surface areas lacking in overgrowths tend to be very rough and irregular in appearance and have therefore been referred to as diagenetic etching (Krinsley and Doornkamp, 1973). Such surfaces are visible where overgrowths are absent as shown in Plate 3, figs. 1-4. Subdued relief and a lack of prominent features characterize these surfaces and a solution and/or precipitation cycle in the history of the grains is indicated. A very distinct cycle of quartz solution is displayed by the presence of crystallographically oriented etch pits and two morphological types of pit can be distinguished. Firstly, oriented V-shaped pits on the overgrowth surfaces of grains from the Bees Nest, Kirkham's, and Green Clay Pits (Plate 4, figs. 1 and 2) and secondly, etch pits that form 'zip-like' trails across the surfaces of grains from the Kenslow Top Pit samples (Plate 4, figs. 3 and 4). The length of these trails varies between 8 and 40 $\mu$m with a mean of 18.5 $\mu$m, while their width has a range of from 1 to 7 $\mu$m with a mean of 3 $\mu$m. These two morphologically distinct etch features may be related in that small V-shaped pits can be seen to occur in close proximity to the trails in Plate 4, fig. 3 and 4. The trail patterns may result from the merging of the individual V-shaped pits.

SURFACE FEATURE CATEGORIES

| Grain size | 1 ANGULAR OUTLINE | 2 ROUNDED OUTLINE | 3 BREAKAGE BLOCKS | 4 CONCHOIDAL FRACTURES | 5 STEP-LIKE FRACTURES | 6 ARC-SHAPED STEPS | 7 GROOVES AND SCRATCHES | 8 STRIATIONS | 9 CLEAVAGE PLATES | 10 IMPACT PITS | 11 OVERGROWTHS | 12 DIAGENETIC ETCHING | 13 ETCH PITS | 14 HIGH-ENERGY CHEMICAL | 15 CRACK PATTERNS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **BEES NEST PIT A (12)** | | | | | | | | | | | | | | | |
| 1000 - 500 µm | 100 | 0 | 0 | 10 | 0 | 10 | 0 | 0 | 50 | 0 | 100 | 100 | 30 | 0 | 0 |
| 500 - 250 µm | 100 | 0 | 0 | 10 | 10 | 10 | 0 | 0 | 30 | 0 | 100 | 100 | 30 | 0 | 0 |
| 250 - 125 µm | 100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 30 | 0 | 100 | 100 | 10 | 0 | 0 |
| 125 - 63 µm | 100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 30 | 0 | 100 | 100 | 0 | 0 | 0 |
| **BEES NEST PIT B (8)** | | | | | | | | | | | | | | | |
| 1000 - 500 µm | 100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 10 | 0 | 100 | 100 | 50 | 0 | 0 |
| 500 - 250 µm | 100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 40 | 0 | 100 | 100 | 20 | 0 | 0 |
| 250 - 125 µm | 100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 20 | 0 | 100 | 100 | 0 | 0 | 0 |
| 125 - 63 µm | 80 | 20 | 0 | 0 | 0 | 0 | 0 | 0 | 20 | 0 | 100 | 100 | 10 | 0 | 0 |
| **BEES NEST PIT C (7)** | | | | | | | | | | | | | | | |
| 1000 - 500 µm | 60 | 40 | 0 | 0 | 20 | 0 | 0 | 0 | 40 | 0 | 100 | 100 | 30 | 0 | 0 |
| 500 - 250 µm | 100 | 0 | 0 | 0 | 10 | 10 | 0 | 0 | 40 | 0 | 100 | 100 | 30 | 0 | 0 |
| 250 - 125 µm | 100 | 0 | 0 | 10 | 10 | 0 | 0 | 0 | 10 | 0 | 100 | 100 | 0 | 0 | 0 |
| 125 - 63 µm | 100 | 0 | 0 | 0 | 20 | 0 | 0 | 0 | 40 | 0 | 100 | 100 | 0 | 0 | 0 |
| **KIRKHAM'S PIT A (3)** | | | | | | | | | | | | | | | |
| 500 - 250 µm | 40 | 60 | 0 | 0 | 0 | 0 | 0 | 0 | 30 | 0 | 40 | 100 | 0 | 0 | 60 |
| 250 - 125 µm | 30 | 70 | 0 | 20 | 30 | 0 | 0 | 0 | 90 | 0 | 10 | 100 | 0 | 0 | 50 |
| 125 - 63 µm | 40 | 60 | 0 | 10 | 10 | 0 | 0 | 0 | 70 | 0 | 40 | 100 | 0 | 0 | 60 |
| **KIRKHAM'S PIT B (1)** | | | | | | | | | | | | | | | |
| 1000 - 500 µm | 60 | 40 | 0 | 0 | 0 | 0 | 0 | 0 | 30 | 0 | 10 | 100 | 50 | 0 | 0 |
| 500 - 250 µm | 100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 30 | 0 | 100 | 100 | 20 | 0 | 0 |
| 250 - 125 µm | 80 | 20 | 0 | 10 | 20 | 0 | 0 | 0 | 30 | 0 | 100 | 100 | 0 | 0 | 0 |
| 125 - 63 µm | 100 | 0 | 0 | 0 | 20 | 30 | 0 | 0 | 20 | 0 | 100 | 100 | 20 | 0 | 0 |
| **GREEN CLAY PIT (1?)** | | | | | | | | | | | | | | | |
| 1000 - 500 µm | 100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 30 | 0 | 100 | 100 | 30 | 0 | 0 |
| 500 - 250 µm | 100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 30 | 0 | 100 | 100 | 30 | 0 | 0 |
| 250 - 125 µm | 80 | 20 | 0 | 0 | 0 | 0 | 0 | 0 | 20 | 0 | 100 | 100 | 30 | 0 | 0 |
| 125 - 63 µm | 100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 20 | 0 | 100 | 100 | 0 | 0 | 0 |
| **KENSLOW TOP PIT A (?)** | | | | | | | | | | | | | | | |
| 1000 - 500 µm | 70 | 30 | 0 | 0 | 0 | 0 | 0 | 0 | 40 | 0 | 0 | 100 | 20 | 0 | 0 |
| 500 - 250 µm | 80 | 20 | 0 | 0 | 0 | 0 | 0 | 0 | 50 | 0 | 0 | 100 | 60 | 0 | 0 |
| 250 - 125 µm | 100 | 30 | 0 | 0 | 0 | 0 | 0 | 0 | 30 | 0 | 0 | 100 | 40 | 0 | 0 |
| 125 - 63 µm | 70 | 30 | 0 | 0 | 0 | 0 | 0 | 0 | 30 | 0 | 20 | 100 | 20 | 0 | 0 |
| **KENSLOW TOP PIT B (?)** | | | | | | | | | | | | | | | |
| 2000 - 1000 µm | 70 | 30 | 0 | 0 | 20 | 0 | 0 | 0 | 50 | 0 | 20 | 100 | 50 | 0 | 0 |
| 1000 - 500 µm | 80 | 20 | 0 | 0 | 0 | 0 | 0 | 0 | 30 | 0 | 0 | 100 | 50 | 0 | 0 |
| 500 - 250 µm | 60 | 40 | 0 | 0 | 0 | 0 | 0 | 0 | 50 | 0 | 10 | 100 | 80 | 0 | 0 |
| 250 - 125 µm | 80 | 20 | 0 | 0 | 0 | 0 | 0 | 0 | 20 | 0 | 10 | 100 | 40 | 0 | 0 |
| 125 - 63 µm | 80 | 20 | 0 | 0 | 0 | 0 | 0 | 0 | 40 | 0 | 20 | 100 | 40 | 0 | 0 |
| **KENSLOW TOP PIT C (?)** | | | | | | | | | | | | | | | |
| 2000 - 1000 µm | 90 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 30 | 0 | 0 | 100 | 80 | 0 | 10 |
| 1000 - 500 µm | 60 | 40 | 0 | 0 | 0 | 20 | 0 | 0 | 40 | 0 | 0 | 100 | 60 | 0 | 0 |
| 500 - 250 µm | 80 | 20 | 0 | 10 | 0 | 0 | 0 | 0 | 20 | 0 | 0 | 100 | 30 | 0 | 0 |
| 250 - 125 µm | 70 | 30 | 0 | 0 | 0 | 0 | 0 | 0 | 30 | 0 | 10 | 100 | 20 | 0 | 0 |
| 125 - 63 µm | 60 | 40 | 0 | 0 | 0 | 0 | 0 | 0 | 40 | 0 | 0 | 100 | 40 | 0 | 0 |

TABLE 2 Percentage frequency occurence of selected surface features on quartz sand grains from the Brassington formation. Based on samples of ten grains per grain size fraction.

# Explanation for Plates 3 & 4

## Plate 3

Figure 1 — Angular quartz sand grain. Modification of the original detrital grain caused by overgrowths.
Scale bar = 100 μm

Figure 2 — Initial oriented crystalline projections marking the first stage of overgrowth development.
Scale bar = 4 μm.

Figure 3 — Merging and overlap of overgrowths to produce larger crystal faces.
Scale bar = 40 μm.

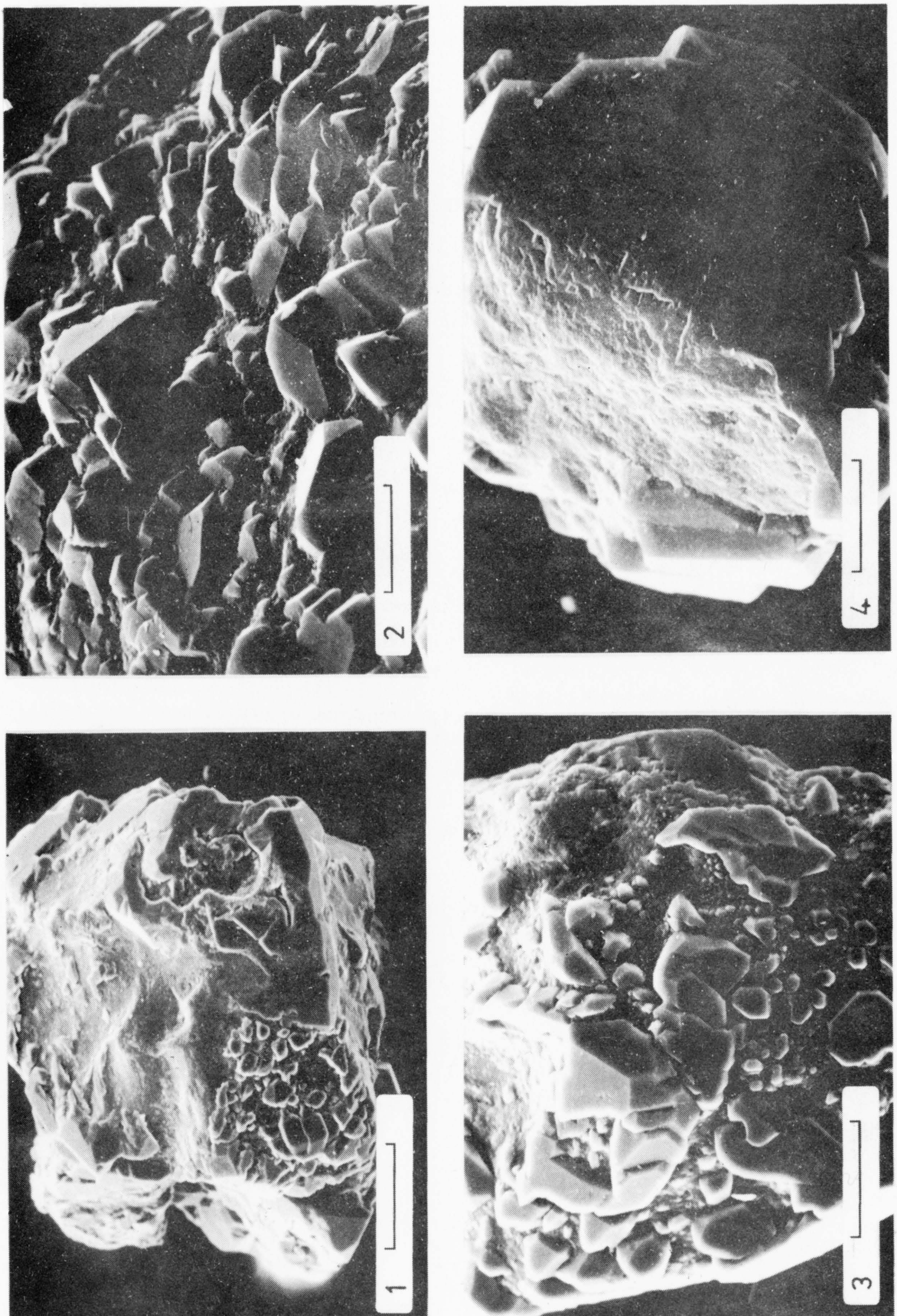
Figure 4 — The result of continued growth of the quartz euhedra. Large areas of the detrital grain are masked by well-developed prism (*m*) and rhombohedral (*r* and *z*) faces. Scale bar = 20 μm.

## Plate 4

Figure 1 — Oriented V-shaped etch pits. Scale bar = 20 μm.

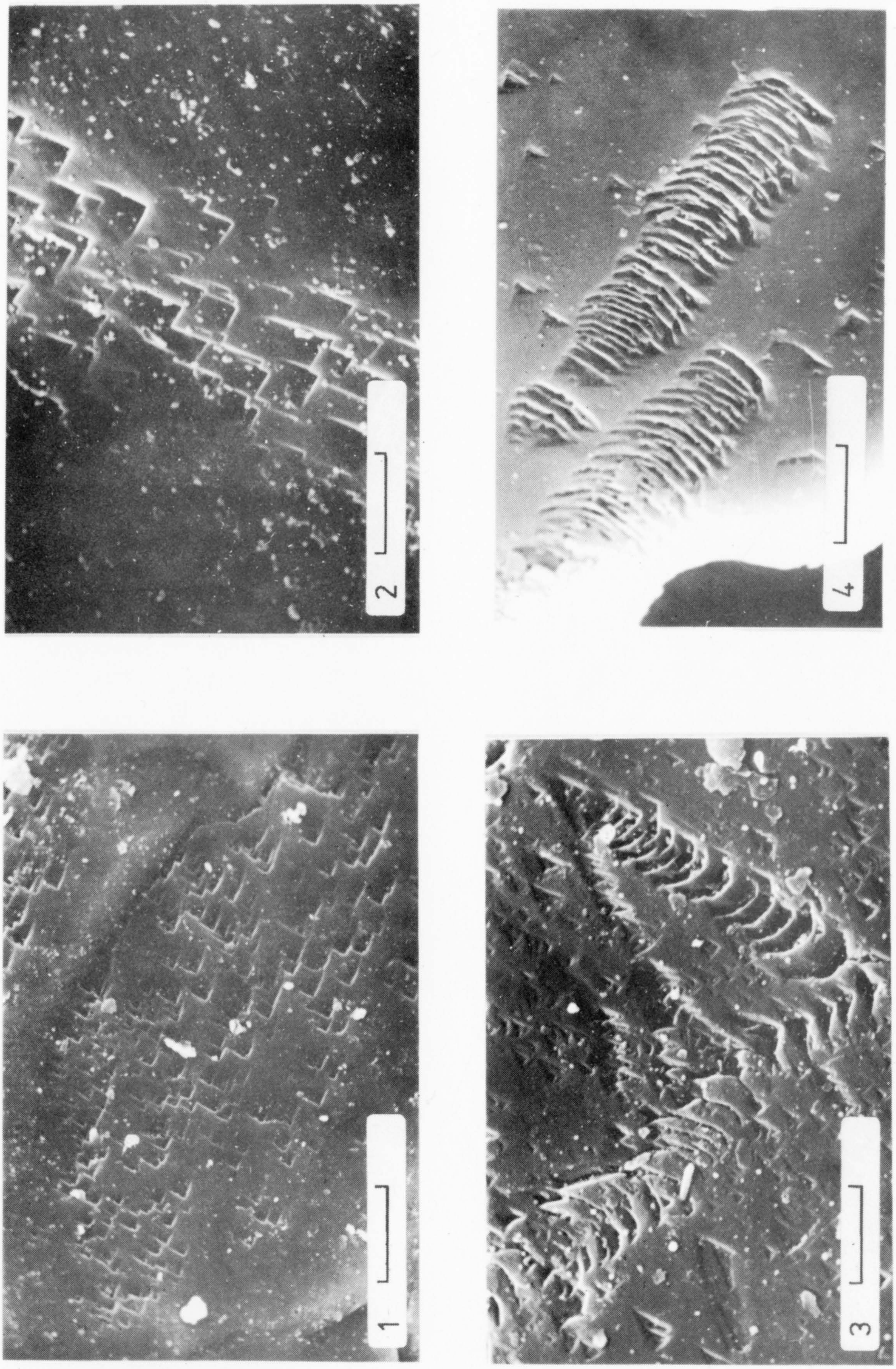
Figure 2 — Oriented V-shaped etch pits. Scale bar = 4 μm.

Figure 3 — 'Zip-like' trails and small oriented V-shaped pits. Note the divergent orientations of the trails.
Scale bar = 4 μm.




P. Wilson - Surface features of quartz sand grains
(For explanation see p. 24.

Plate 4




P. Wilson - Surface features of quartz sand grains
(For explanation see p. 24.

The only mechanically produced surface features observed on these quartz grains are cleavage plates and fracture patterns. Of these the former are the most common although in many cases their presence is related to the degree of overgrowth development. They have only been recorded on those grain surfaces lacking overgrowths. Where overgrowths completely mask the detrital grain cleavage plates have not been observed. Two forms of cleavage are recognized by Krinsley and Doornkamp (1973) and in both cases these features may be described as a series of thin parallel plates, either continuous or discontinuous, running across the grain surface. One type of cleavage may be identified at the grain edges by a stepped or overlapping sequence of plates. These are the grain-edge expression of internal cleavage surfaces. The second type of cleavage is usually observed on those faces unaffected by diagenesis. Here, parallel plates, with depressions between them, oriented at some angle to the grain surface have been termed 'upturned plates'. The cleavage plates observed in this study are of the former type, the 'grain-edge' plates (Plate 5, figs. 1 - 3). A solution/precipitation phase is suggested by the subdued nature of the plates; jagged and sharply irregular plate outlines similar to those produced under experimental conditions have not been found (Margolis and Krinsley, 1974). Although many of the plates are short and discontinuous some can be traced for distances of up to 80 $\mu$m across the grain surface. Mechanical fracture patterns comprise conchoidal fractures, semi-parallel step-like fractures, and arc-shaped steps and are rare throughout all the samples examined. In some samples they have not been recorded at all (Table 2). Where they are present, however, they are clearly defined and sharp and fresh in appearance with no sign of subsequent modification (Plate 5, figs. 4 and 5).

An additional surface feature that has only been observed on grains from Kirkham's Pit and also on one grain from the Kenslow Top Pit, is arcuate, circular or polygonal cracks (Plate 6, figs 1 and 2). The cracks vary in width from between 0.1 and 1.0 $\mu$m with a mean of 0.35 $\mu$m while the maximum dimension of the 'polygons' varies between 13 and 35 $\mu$m with a mean of 20 $\mu$m. These crack patterns have only been recorded on grain surfaces devoid of overgrowths.

The samples of Bunter Sandstone examined for comparative purposes, show quartz grains of angular outline with crystallographic overgrowths and areas of diagenetic etching, some of which display grain-edge cleavage plates (Plate 6, figs 3 and 4).

## Discussion

One of the aims in undertaking this study was to identify surface features of subaqueous origin in order to support a fluvial environment of deposition as proposed by previous workers. But such features have not been observed and this could possibly cast doubt on a subaqueous (fluvial) depositional regime. However, of all the subaqueous environments studied, in terms of their quartz grain surface features, the fluvial environment is the one in which grains are not usually exposed to sufficient abrasion levels to remove pre-existing features (Margolis and Kennett, 1971). These authors have stated that.

> "River sands show few diagnostic features, except that most exhibit rounded outlines, low relief, irregularly finely pitted surfaces, overgrowths and diagenetic etch patterns. Furthermore, large variability in the surface features occurs in sands from different rivers, hence the combining of several samples from different rivers results in a more or less random display of features. This distribution of features is not indicative of events occurring in the river cycle but rather reflects previous transportational and diagenetic history."

Although fluvial sands do not display any characteristic assemblage of surface features, randomly oriented V-shaped impact pits of low density occurrence have been observed on some grains by Margolis and Kennett (1971). This impact pitting is not as prevalent as on beach sands but is an indication of the amount of subaqueous abrasion experienced by a sand grain. The total lack of such subaqueous transport features on quartz grains from the Brassington Formation is suggestive of a short-distance, low-energy fluvial regime. In this respect the evidence for fluvial transport is of an indirect nature.

If the environment of deposition cannot account for the observed surface features on these quartz grains then the features must be regarded as reflecting pre-depositional and/or post-depositional events. It has been shown by Ijtaba (1973) that the sands of the Kirkham Member of the Brassington Formation were derived from the Bunter Sandstone now found to outcrop a short distance to the south of the Brassington area. A comparison of the quartz grains examined from the Brassington Formation with those of the Bunter Sandstone reveals those features of an inherited nature or representing pre-depositional events. These comprise overgrowths, diagenetic surfaces, and cleavage plates. All are present in the sands and the sandstone samples examined. The fact that the overgrowths pre-date the deposition of the Brassington Formation is significant in terms of the short-distance, low-energy fluvial regime suggested. These smooth crystal faces would be ideal sites for the recognition of subaqueous impact features as opposed to the rough irregular diagenetic surfaces. However, no sign of mechanical abrasion has been found on these overgrowths. The arcuate, circular or polygonal cracks seen on grains from Kirkham's Pit and Kenslow Top Pit are also thought to pre-date the deposition of the Brassington Formation. Although they have not been observed on grains examined from the Bunter Sandstone it is considered that the environment under which this sandstone was deposited is more likely to have produced these crack patterns than that associated with the Brassington Formation. Lucchi and Casa (1968), Lucchi (1970), Krinsley and Doornkamp (1973), Baker (1976), and Krinsley *et al.* (1976) consider such cracks patterns to be a principal feature of quartz sand grains from the hot desert environment; an environment associated with Bunter Sandstone formation (Edwards and Trotter, 1954).

The remaining surface features observed on quartz grains from the Brassington Formation, and whose origin has yet to be accounted for, are the mechanical fracture patterns and the crystallographically oriented pits. These features have not been recorded on grains from the Bunter Sandstone and are not considered to be inherited features.

The mechanical fracture patterns may result from the breakdown of the Bunter Sandstone prior to its erosion and deposition as a fluvial sediment or may be due to movement of the grains in the sediment after deposition. It is not thought likely that these fractures are a product of fluvial transport. A fluvial regime incapable of producing V-shaped impact pits is hardly likely to cause grain fracturing. All the observed fractures are sharp and fresh in appearance and do not exhibit signs of subsequent weathering. If these fractures do relate to the breakdown of the Bunter Sandstone then further evidence for short-distance, low-energy fluvial transport maybe implied by the lack of fracture modification through subaqueous abrasion. The possibility that grain fracturing has been induced through movement of the sediment after deposition must also be considered. On the basis of field evidence and laboratory tests a mechanism of solution subsidence has been proposed for the preservation of the Brassington Formation (Walsh *et al.* 1972). It is not known whether a gradual sag of these sediments could have produced the grain fractures but the possibility exists. Although the origin of these fracture patterns is open to question their low frequency of occurrence (Table 2) suggests that their formative mechanism was not of major importance in the history of the deposit.

In the case of the oriented etch pits these features are possibly contemporaneous with sand deposition or may post-date such events. Of the two etch forms recorded, the 'zip-like' trails are probably the more unusual. Pits of the V-shaped variety have been observed by many previous workers but to the author's knowledge etch pits forming 'zip-like' trails across the grain surface have only been recorded on two previous occasions (Bull, 1976, 1977; Friedman *et al.* 1976). Bull (1976, 1977) reported the presence of these trails on the euhedral crystal faces of quartz grains incorporated in cave sediments. The relevant point here for the Brassington Formation is that a fluvial environment was also involved in the deposition of these cave sediments. Whether such trails result from solution by fluvial waters is not known due to a lack of data concerning the chemistry of these streams. If the etch pits are not associated with fluvial quartz dissolution then a post-depositional phase of chemical weathering possibly caused by migrating pore space waters would seem likely.

In addition to the aims of determining the environment of deposition and the source material for the sands of the Brassington Formation it was also hoped to identify surface features associated with chemical weathering under Tertiary climatic conditions; the formation having been shown, on palaeobotanical evidence, to be of Lower Pliocene - Upper Miocene age and gibbsite having been discovered in the clays of the Kenslow Member (Boulter and Chaloner, 1970; Boulter, 1971; Boulter *et al.* 1971). The floristic evidence indicates a warm, oceanic climate whereas the presence of gibbsite suggests extreme tropical weathering. This aspect of the study has been somewhat unfruitful, however, for there is no evidence to support any form of post-depositional high-energy chemical weathering except for the etch pits already described and discussed. Features associated with intense surface disintegration, recorded by Doornkamp and Krinsley (1971), have not been recorded here. Indeed, almost all the grains examined display clear and fresh surface features that are either related to the diagenetic history of the source rock or to the breakdown, deposition, and subsequent modification of these sediments. The lack of intense chemically weathered quartz grain surfaces may be regarded as due to deep burial and therefore protection of the Kirkham Member sands from Tertiary climatic influences. It is only in the uppermost (Kenslow) member of the succession that such weathering has been identified by the presence of gibbsite.

Although these sands display little by way of direct evidence to support the findings of previous researchers they do show some remarkably clear and fresh surface features that testify to a negligible amount of post-depositional diagenetic alteration. Surface features of Tertiary and pre-Tertiary age are well preserved on the majority of the grains examined.

## Conclusions

The application of scanning electron microscopy to quartz grain surface features from the sands of the Brassington Formation has resulted in the formulation of a number of conclusions regarding their derivation, mode of deposition, and post-depositional alteration. These conclusions are listed below:

(i) A number of the observed grain surface features, i.e. overgrowths, diagenetic surfaces, cleavage plates, and crack patterns, are considered to be inherited from the Bunter Sandstone.

(ii) A fluvial environment of deposition has previously been proposed for the sediments of the Brassington Formation. The inherited surface features lack any sign of subaqueous abrasion and a short-distance, low-energy fluvial regime is therefore suggested.

(iii) Surface features not inherited from the Bunter Sandstone reveal phases of mechanical and chemical weathering. The very low frequency occurrence of mechanical fracture patterns indicates that this form of weathering was of very limited extent. The oriented etch pits suggest a more prolonged phase of chemical weathering during which many grains have been affected. These two cycles of weathering are not easily dated in terms of Brassington Formation deposition.

(iv) Despite the proven Tertiary age for the Brassington Formation no evidence of high-energy chemical weathering, to support such an age, has been found on the quartz grains.

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## Explanation for Plates 5 & 6

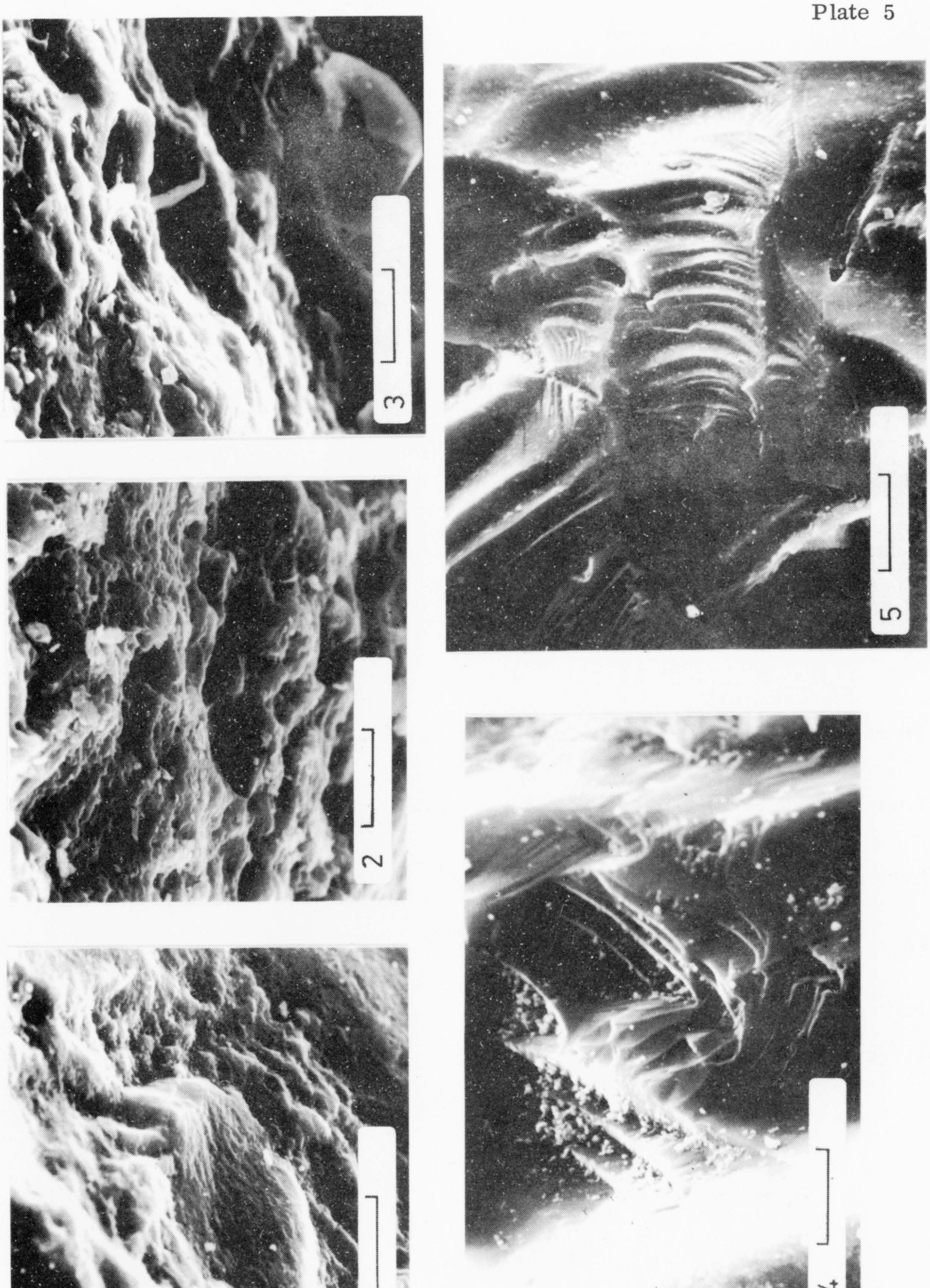
### Plate 5

| | |
|---|---|
| Figure 1 | Grain-edge cleavage plates. Scale bar = 10 μm. |
| Figure 2 | Grain-edge cleavage plates. Scale bar = 10 μm. |
| Figure 3 | Grain-edge cleavage plates. Scale bar = 2 μm. |
| Figure 4 | Conchoidal fracture with semi-parallel step-like patterns. Note the sharp and fresh appearance of the fracture surface. Scale bar = 4 μm. |

### Plate 6

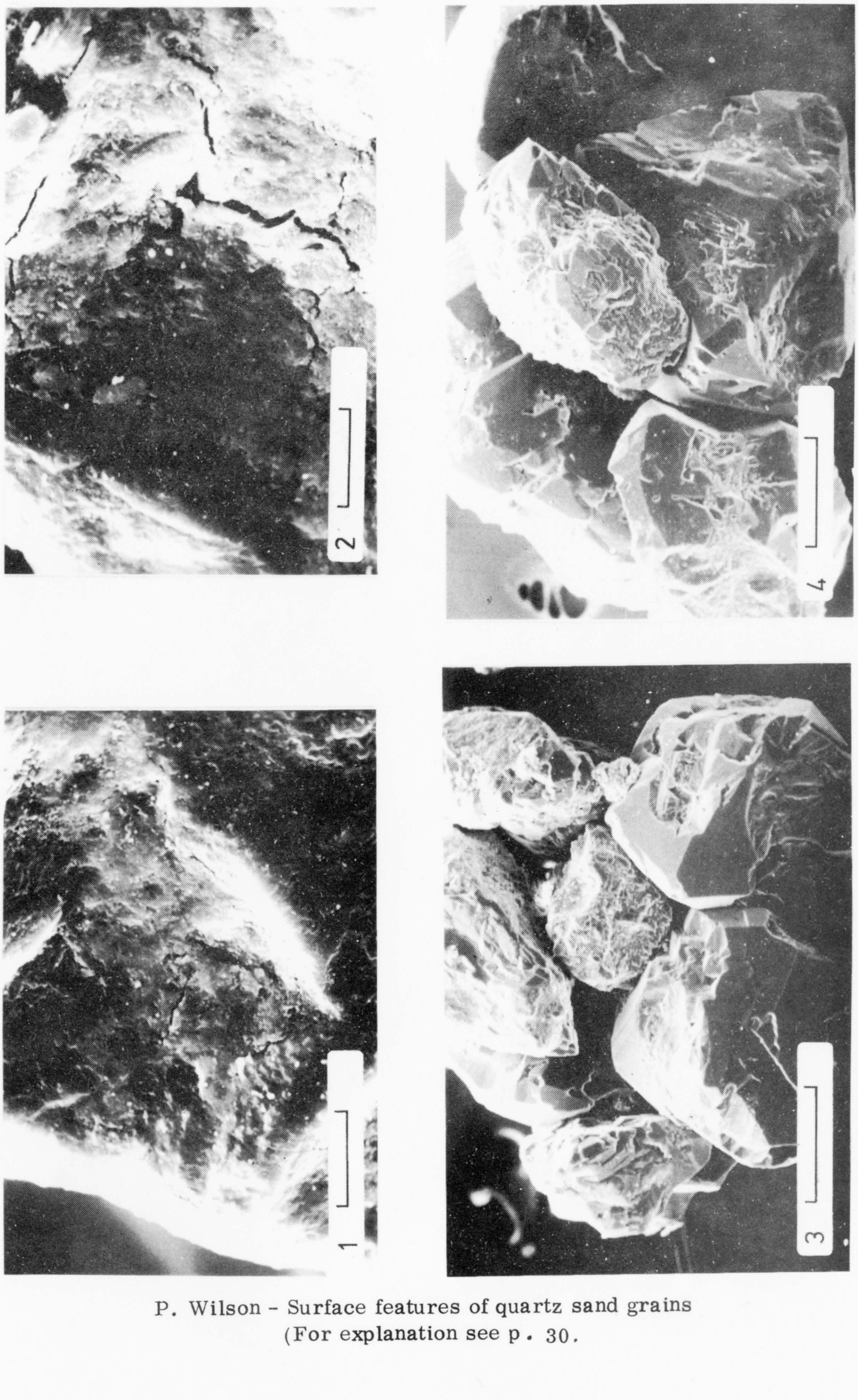
| | |
|---|---|
| Figure 1 | Arcuate, circular or polygonal cracks on grains from Kirkham's Pit Scale bar = 10 μm. |
| Figure 2 | Arcuate, circular or polygonal cracks on grains from Kirkham's Pit. Scale bar = 10 μm. |
| Figure 3 | Bunter Sandstone fragment. Grains display angular outlines, overgrowths, diagenetic surfaces, and cleavage plates. Scale bar = 200 μm. |
| Figure 4 | Bunter Sandstone fragment as above. Scale bar = 200 μm. |

Plate 5



P. Wilson - Surface features of quartz sand grains
(For explanation see p. 30.

Plate 6

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(For explanation see p. 30.