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THE MICROFABRIC OF A CHEMICALLY WEATHERED GRANITE

LA MICROSTRUCTURE D'UN GRANITE ALTÉRÉ CHIMIQUEMENT

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Summary:

A scanning electron microscope has been used to observe the microfabric changes in granite that are brought about by weathering. The initial ingress of weathering agencies occurs along primary cracks and pores and open cleavages and results in decomposition and solution along structurally controlled planes in feldspars, the decomposition and expansion of the biotite lattice, and solution and microfracturing of quartz.

In terms of the fundamental material nature of weathered granite, the initial stages of weathering are dominated by the opening of grain boundaries, microfracturing and the development of an intragranular porosity in feldspars. The later stages of weathering are dominated by the variable nature of the clay weathering product.

Résumé:

Un microscope électronique à balayage a été utilisé pour l'observation des changements de microstructure qui affectent un granite soumis à l'altération météorique. La première avancée de l'altération se produit le long de craquelures et de pores préexistants et de clivages ouverts; elle aboutit à la décomposition et à la dissolution des feldspaths le long de plans correspondant à la structure, à la décomposition et à l'expansion du réseau de la biotite, à la dissolution et à la microfracturation du quartz.

En ce qui concerne la nature fondamentale du granite altéré, les premières phases de l'altération sont dominées par l'ouverture des surfaces de séparation des grains, la microfracturation et le développement d'une porosité intragranulaire dans les feldspaths. Les phases suivantes sont dominées par la nature variable de l'argile d'altération.

Introduction

Loughnan (1969) described the three simultaneous processes that are involved in chemical weathering as:

1. The breakdown of the parent mineral structure with the concomitant release of the constituent elements either as ions or molecules.
2. The removal in solution of some of these "released" constituents.
3. The reconstitution of the residue with components from the atmosphere to form new minerals which are in stable or metastable equilibrium with the environment.

Microscopic examination of the results of these processes is hampered by the very small scale of the products. The advent of the scanning electron microscope (S.E.M.), with its large range of magnification, great depth of field, relative ease of sample preparation (Baynes and Dearman, 1978a) and analytical capabilities (Hearle, Sparrow & Cross 1972) now makes it possible to observe the fine details of weathering which are beyond the capabilities of optical microscopy.

The advent of this tool has led to the description of typical grain-surface textures produced by weathering (Krinsley & Doornkamp 1973, Berner & Holdren 1977) and the form of some decomposition products (Šamalikova 1974) and hence to a greater understanding of the processes involved in weathering.

One practical aspect of such studies is in the field of engineering geology where the effects of weathering on rock conditions is of great importance (Saunders & Fookes 1970, Deere & Patton 1971). To this end, a study of microfabric effects of chemical weathering on granites using a scanning electron microscope was undertaken. Granite was chosen as, in civil engineering schemes, it is commonly encountered weathered to such an extent that the consequences have to be considered in design and construction (Moye 1955, Kiersch & Treasher 1955, Newbery 1970). There is also an extensive literature describing the geomorphological effects (Ruxton & Berry 1957, Ollier 1969), the mineralogical changes (Brock 1943, Loughnan 1969) and the changes in engineering properties (Lumb 1962) due to weathering of granites. Thus the effects are relatively well understood.

The chemical weathering of granite

The chemical reaction involved is between aggressive atmospheric agencies including water, oxygen and carbon dioxide and the quartz, alkali feldspars, plagioclase feldspars and micas which make up granite (the feldspars amounting to 60% by volume). Decomposition products may include clay minerals, insoluble iron oxides and hydroxides, and cations and silica in solution. The nature and relative proportions of the weathering products depends on the rate at which soluble material is flushed out of the system as any particular clay mineral species can only develop if the cations essential to the formation of the mineral are present within the micro-environment. If only small amounts of cations are flushed out of the system, cation-rich species such as montmorillonite and illite can form whereas intense flushing, or continued weathering, results in the complete loss of all but the most insoluble material and kaolinite, and then gibbsite are produced (Loughnan 1969).

Method of study

Samples were taken from exposures of weathered granite on or near Dartmoor which had been previously mapped and interpreted as being caused by Tertiary weathering (Brunsden 1964, Dearman, Baynes & Irfan 1976). The samples were prepared by the air dry-fracture-peel-coat method recommended by Barden & Sides (1971). The instrument was a Cambridge Mark IIA scanning electron microscope fitted with an energy dispersive X-ray fluorescent spectrometer (EDAX) which may be used as a chemical microprobe. This attachment, together with X-ray diffractometry of the samples prior to viewing, allowed at least a tentative identification of most of the weathering products.

The results of this study, based upon hundreds of photographs, reveal some of the fundamental microfabric changes that occur during the weathering of granite.

The mode of ingress of weathering agencies

For weathering to occur, aggressive groundwater must penetrate joint-bounded blocks which often have dimensions in excess of 1 metre. This may occur through a ubiquitous porosity, up to about 1 % by volume, (Birot 1964) which takes the form of equidimensional pores (high aspect ratio cracks or HARCS) or long bluntly terminated cracks (low aspect ratio cracks or LARCS): the division between the two groups of features is arbitrary. It is considered that the equidimensional HARCS may represent the sites of fluid inclusions and that the longer LARCS are partially healed fractures associated with stress relief during cooling or exhumation (Sprunt & Brace 1974). In the case of plagioclase (Montgomery & Brace 1975), partially annealed cleavages or random fractures developed during the early cooling history of the rock are common and this locally higher intragranular porosity (usually twice the average rock porosity) may well contribute to their typically early decomposition during weathering (Goldich 1938).

Similar microfabric features were found in the present study in unweathered granites. An intergranular LARC between two quartz crystals is shown in Fig. 1. The intergranular pore in Fig. 2 is LARC-like in form apart from the wedge shape which suggests divergent crystal growth of the feldspars on either side of the wedge, creating a fluid inclusion rather than a partially healed fracture.

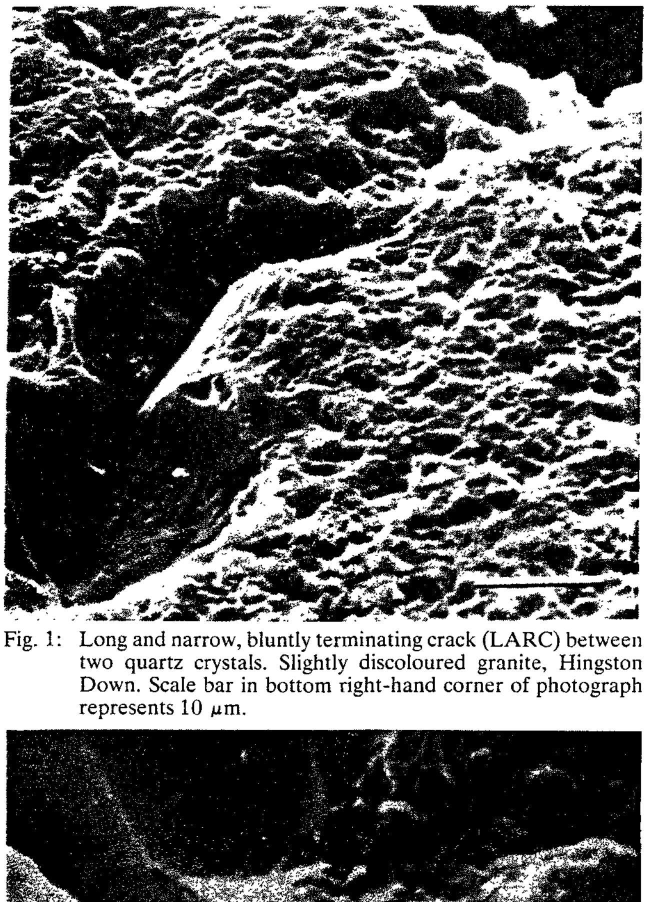

Fig. 1: Long and narrow, bluntly terminating crack (LARC) between two quartz crystals. Slightly discoloured granite, Hingston Down. Scale bar in bottom right-hand corner of photograph represents 10 μm.

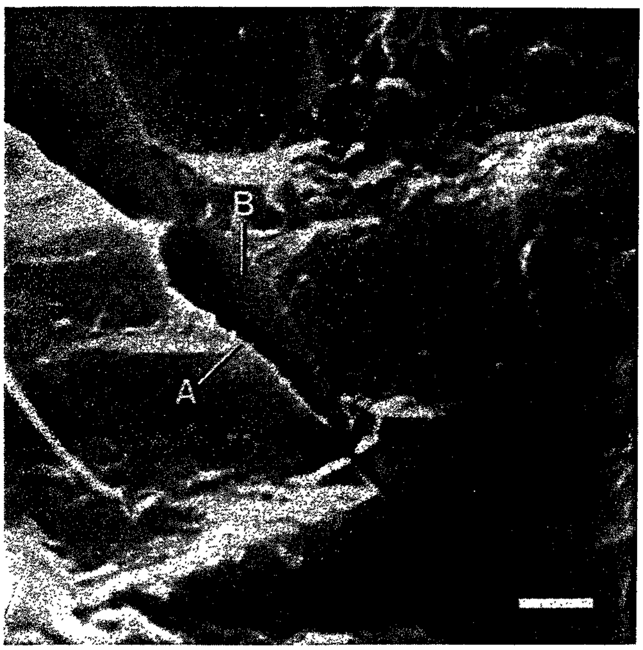

Fig. 2: Void between two potash feldspars. Note bridged portions and differing attitudes of crystal faces A, B. Unweathered granite, Hingston Down. Scale bar 1 μm.

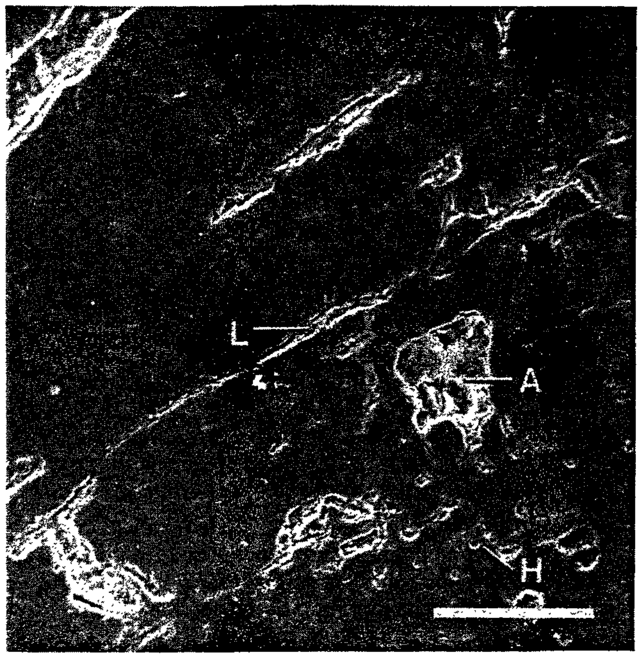

Fig. 3: Long crack like LARCS (L) and equant HARCS (H) in plagioclase. Note slight alteration (A). Unweathered granite, Hingston Down. Scale bar 100 μm.

Numerous LARCS and HARCS were also observed in plagioclase (Fig. 3) and although slight alteration appeared to be associated with them this may merely reflect their capacity to act as channels for aggressive fluids, in this case hydrothermal in origin.

Another possible set of pathways for weathering agencies are microfractures produced by tectonic stressing. Tapponier and Brace (1976) have shown that microfracturing occurs extensively prior to failure in triaxial compression. However no such microcracks were observed in this study and it may be that such features are confined to relatively small volumes of rocks associated with discontinuities.

Some of the grain boundaries appeared tightly welded even when viewed at the highest practical magnification and this raises the question of how well-connected are the observed microvoids? The penetration of large joint-bounded blocks in granite by weathering agencies suggests that the microvoids are interconnecting to a certain extent and the fact that such rocks do have a measurable permeability (Brace, Walsh and Frangos 1973) supports this hypothesis. Further passageways through the rock microfabric may well be provided by the perfect (001) and good (010) cleavage of the feldspars, depending on the degree to which cleavage fractures are developed.

Microfabric changes during the weathering of feldspars

Evidence for the ingress of weathering agencies along feldspar cleavages is afforded by the progressive weathering stages that can be observed. Fresh feldspar contains distinct cleavages and small intragranular HARCS (Fig. 4). The initial stages of weathering of both alkali and plagioclase feldspar appears to be the development of structurally controlled solution features (Figs. 5, 6). These initial features have recently been described by Berner and Holdren (1977) who named them prismatic etch pits (PEP's) and concluded that they occur "primarily at sites of excess energy on the crystal surface (for example dislocations) . . . (and) characteristically develop on (001) with their long axis parallel to (010)". In most of the examples studied the PEP's tend to coalesce as weathering proceeds and become what may be described as prismatic etch trenches (PET's) i.e. elongate, structurally controlled solution features which are developed with remarkable uniformity on the observed surfaces (Fig. 7). In detail (Fig. 8) the PET's can be seen to have opened up the feldspar structure to a remarkable degree, but it is not obvious how deeply this microfabric features extends into the mineral grain. It may well be a surface phenomen developed on crystallographic plane (001). Nonetheless, it was found repeatedly that, in samples chosen for examination because the feldspar appeared to be uniformly transformed to inchoherent particulate matter, this microfabric was displayed rather than a clay microfabric.

Not all feldspars decompose in the same manner; figure 9 illustrates some deep crevasse-like features for which evidence of a solution

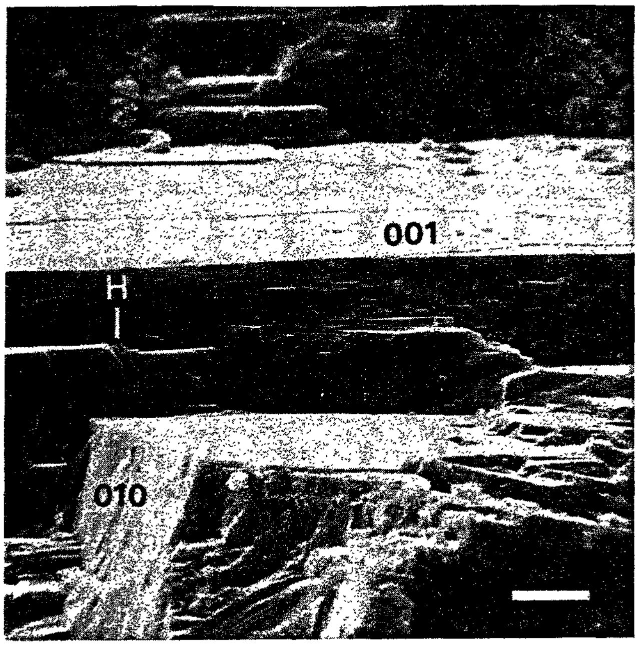

Fig. 4: Fresh potash feldspar. Note HARCS (H), perfect (001) cleavage and good (010) cleavage. Unweathered granite, Hingston Down. Scale bar 10 μm.

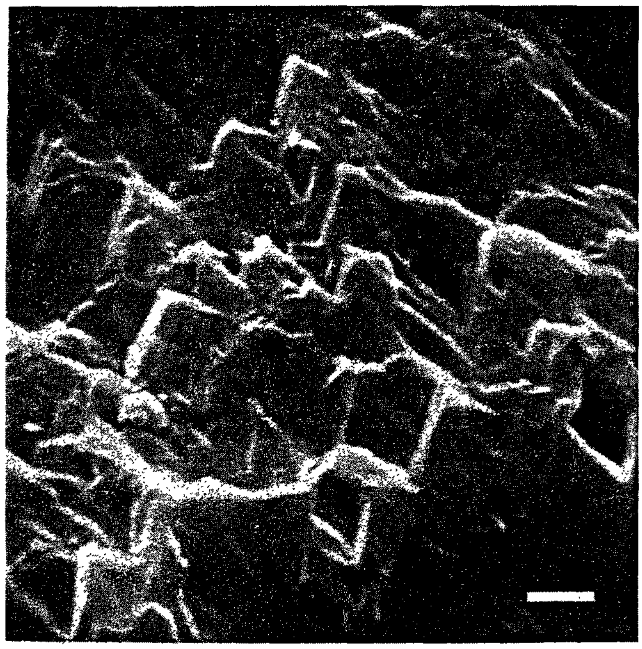

Fig. 6: Prismatic etch pits on a cleavage surface of plagioclase feldspar. Discoloured granite, Hingston Down. Scale bar 1 μm.

Fig. 5: Prismatic etch pits (PEP's) penetrating potash feldspar. Slightly discoloured granite, Hingston Down. Scale bar 10 μm.

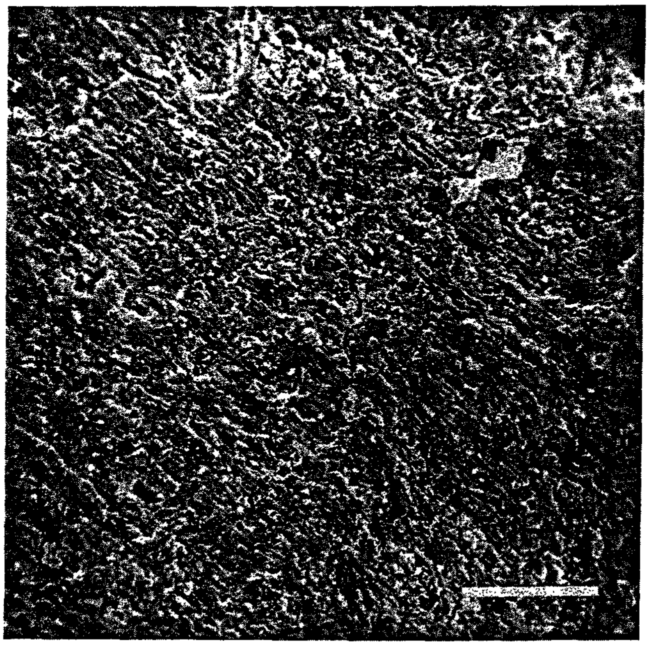

Fig. 7: Prismatic etch trenches (PET's) extending uniformly throughout a potash feldspar. Friable granite, Dartmoor. Scale bar 100 μm.

origin is given by the irregular non-parallel sides and these features can conveniety be termed irregular etch crevasses (IEC's). This is perhaps the initial stage of a decomposition mode that results in a chaotic assemblage of kaolin- and gibbsite-coated feldspar fragments separated by IEC's (Fig. 10).

The consequences and mode of feldspar decomposition

As feldspars make up 60 per cent by volume of granites (Hatch, Wells & Wells 1972) the feldspar microfabric and that of the decomposition products must play an important role in determining engineering properties. The initial stages of decomposition, namely increase in porosity and microfracturing, are reflected in a decrease in compressive strength, Young's modulus and suitability for aggregate which granites show when weathered (Irfan & Dearman, in press, a,b). Unfortunately it is not so easy to define those processes that lead to the development of the microfabric of the decomposition products. This is due to the wide variety of microfabrics that were observed, reflected in the varying grain size and mineralogy of the decomposition product and the proportion of that product developed within any particular decomposing feldspar. It would appear that although all the samples were taken from granite known to have undergone chemical weathering during the Tertiary, variations in microgeomorphological position, initial microfabric and possibly the intensity of jointing and relative positions within a weathering profile have combined to produce a large number of end products. This is because these factors will determine the rate at which released constituents are flushed out of the system and hence the proportion and mineralogy of the decomposition products.

The main decomposition products are kaolinite and gibbsite, although small amounts of illite were detected in some of the samples. This implies that, in general, continued flushing or prolonged weathering occurred. However, the low clay contents and thin development of weathering profiles has been used to argue that only a "sandy type" of weathering profile (Bakker 1967), developed under "meso-humid

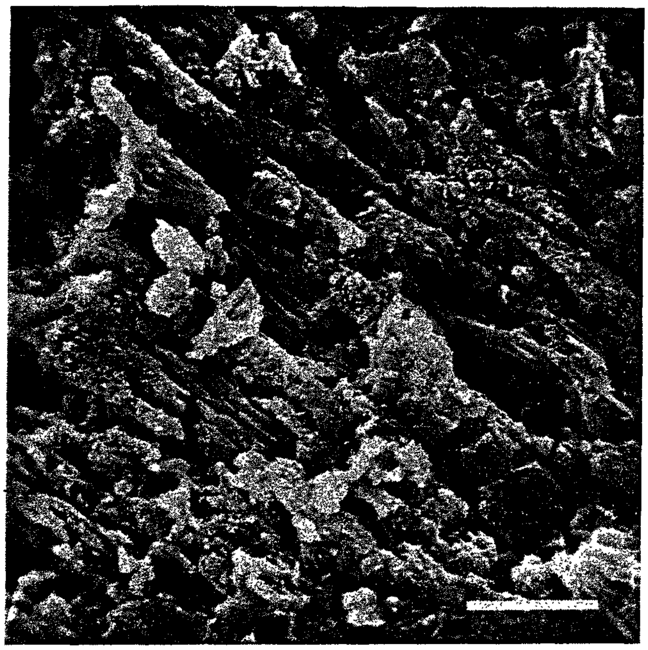

Fig. 8: Detail from Fg. 7. PET's have opened up the feldspar microfabric, decomposition products are irregularly deposited. Friable granite, Dartmoor. Scale bar 10 μm.

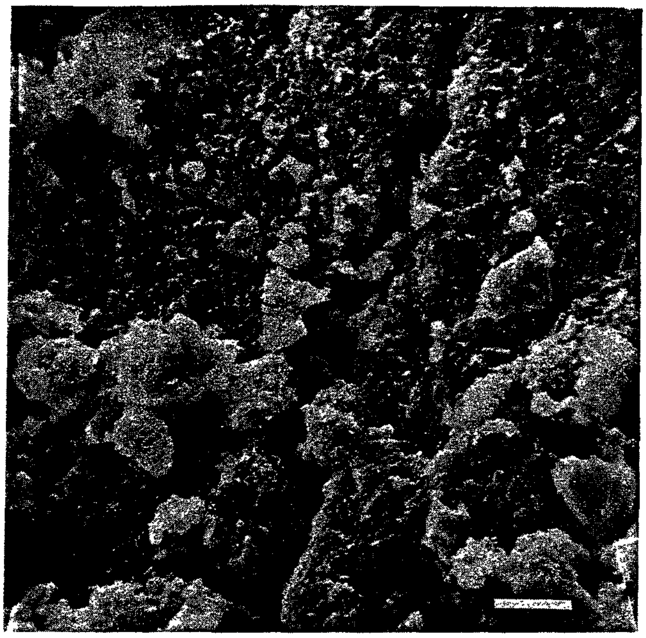

Fig. 9: Irregular etch crevasses (IEC's) developed in potash feldspar. Discoloured weakend granite, Hingston Down. Scale bar 10 μm.

subtropical conditions", is present (Eden and Green 1971). Thus it would appear that many of the microfabrics could be the result of continued flushing. This factor would explain the areas of exposed feldspar and the highly porous fabric in Fig. 8 where most of the released constituents must have been removed. Those areas where larger amounts of decomposition products have been deposited presumably represent slightly more stagnant areas within the microfabric.

Microfabrics of weathering products

The observed clay microfabrics tend to occupy small isolated pockets within a framework of weathered quartz, biotite and feldspars opened up by PEP's, PET's, and IEC's.

The most open clay microfabric consisted of large (3-5μm) kaolin and illite plates occurring either singly or as a few plates forming an

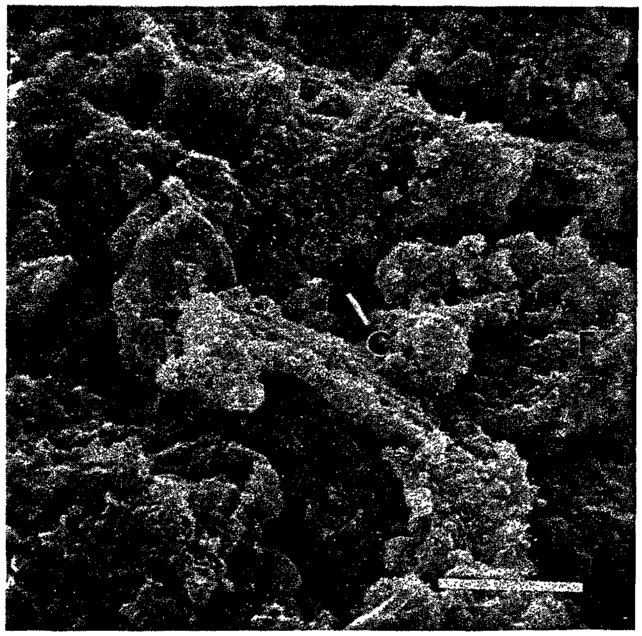

Fig. 10: Kaolin and gibbsite coated feldspar fragments (F) are separated by intragranular IEC's (C). Discoloured and weakened granite, Hingston Down. Scale bar 10 μm.

irregularly edged book: the plates were arranged in an essentially cardhouse or bookhouse form (Collins and McGown 1974) with edge-face (E-F) (Van Olphen 1963) contacts predominating (Fig. 11). A more compact variation on this theme consisted of the same cardhouse/bookhouse form in which the interstices between the cards or books were filled, or partially filled, with aggregations of much finer (<1μm) particles probably consisting principally of gibbsite with some fine-grained kaolinite (Fig. 12). When fine-grained (<1μm) kaolinite dominated the microfabric, it occurred in aggregates of sub-parallel layered plates with a low intra-aggregate porosity with larger interaggregate voids between them (Fig. 13).

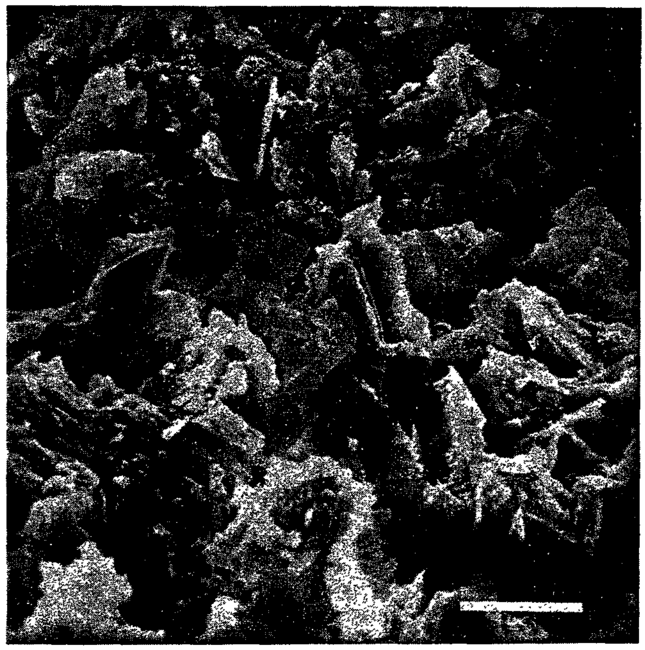

Fig. 11: Large clay plates in a cardhouse/bookhouse arrangement. Friable granite, Dartmoor. Scale bar 10 μm.

The original feldspar from which these microfabrics were derived was identified as orthoclase from the potassium peak given by EDAX. Where a calcium peak was produced, implying a plagioclase origin, microfabrics such as those present in Fig. 14 were observed, consisting of fragments of feldspar set in a matrix of equidimensional kaolin crystals with occasional plates. These are uncommon.

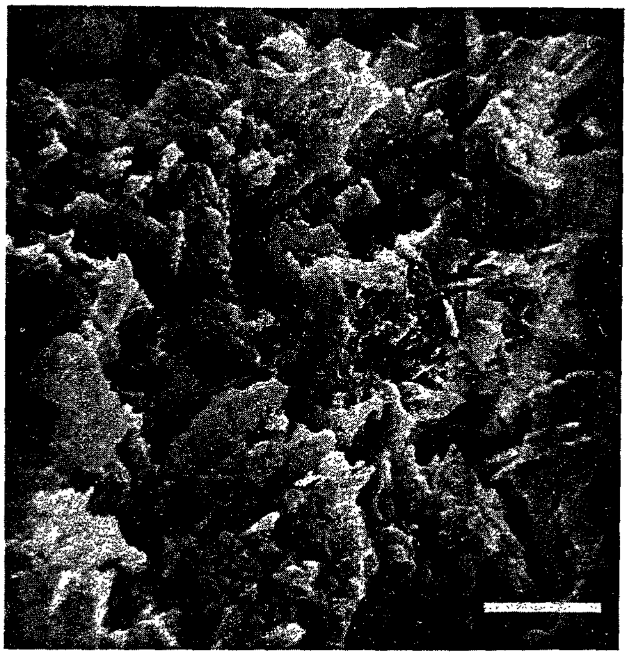

Fig. 12: A cardhouse/bookhouse arrangement with the interstices filled with finer particles. Friable granite, Dartmoor. Scale bar 10 μm.

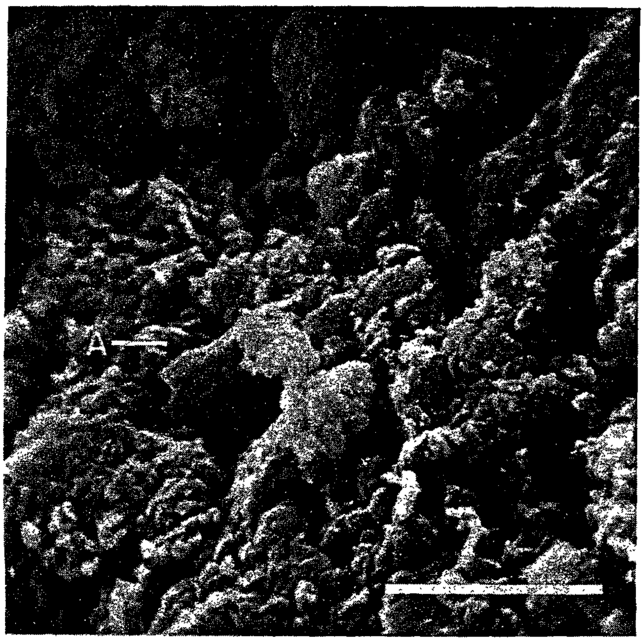

Fig. 13: Kaolin dominated aggregates. Note subparallel layered microfabric at A. Friable granite, Dartmoor. Scale bar 10 μm.

The gibbsite present in most of the specimens possibly originated in one of two ways, both suggesting intense flushing of released constituents. The classic mechanism for the production of gibbsite is by further weathering of kaolinite (Loughnan 1969, Carrol 1970) and this appears to be the case in Fig. 15 where large clay plates, similar to those in Fig. 11 have extremely frayed edges and are covered in fine-grained debris. An alternative mechanism is that feldspars weather directly to gibbsite; this has been reported by Green and Eden (1971) and the results of the process can be seen in Fig. 16 where fine-grained material, positively identified as gibbsite, rests on a cleavage-controlled ridge of feldspar.

One consequence of a weathering microenvironment where intense flushing occurs is the progression from the open PET dominated fabric of Fig. 8, via deposition of small abounts of gibbsite on the open framework of feldspar struts, to an extremely porous network of gibbsite aggregations illustrated in Fig. 17.

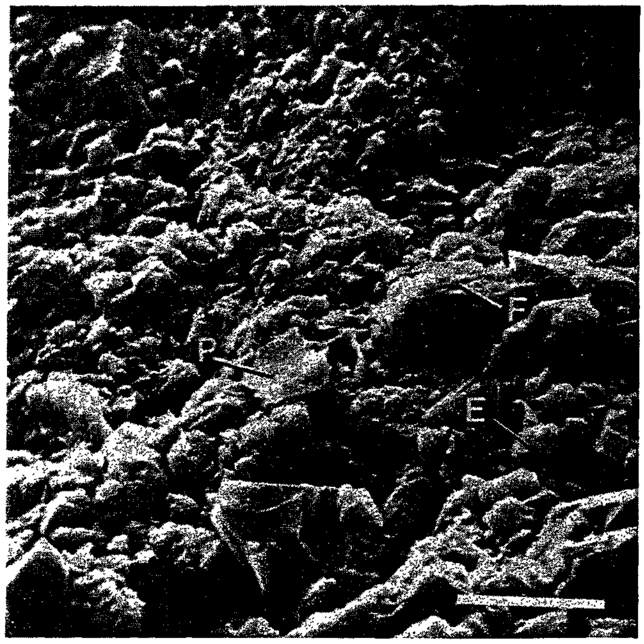

Fig. 14: Fragments of plagioclase (F) in a matrix of equidimensional (E) and platy (P) kaolin particles. Discoloured granite, Hingston Down. Scale bar 10 μm.

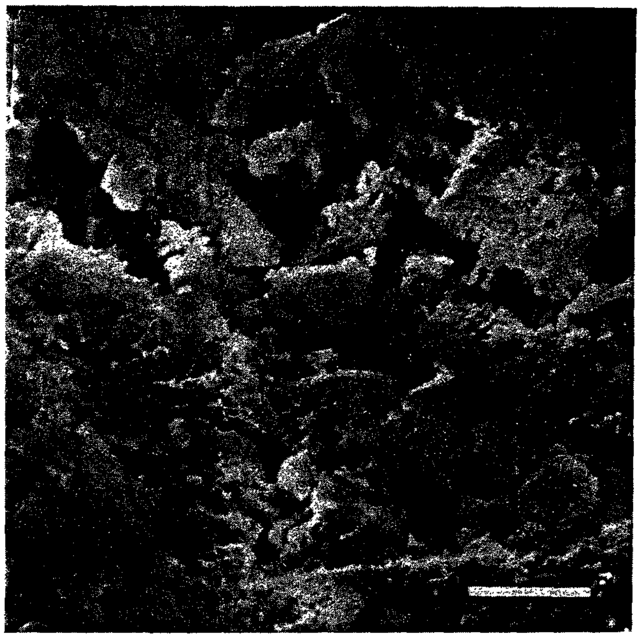

Fig. 15: Large clay plates apparently disintegrating, possibly due to the transformation of kaolinite to gibbsite. Poor quality photograph due to instrument defects. Friable granite, Dartmoor. Scale bar 10 μm.

Whilst some open microfabrics may be due to flushing out of released constituents, the actual eluviation of clay particles from the rock material, as reported by Ruxton and Berry (1957), may increase the porosity. In this respect it is interesting to note that fine-grained white material observed to be deposited in many of the joints in the weathered profile proved upon investigation to be gibbsite, the smallest particles present in the weathered rock (Fig. 18).

These photographs show that the clay microfabric produced by the decomposition of feldspars can vary from dense tightly packed aggregates to cardhouse arrangements and porous networks of aggregated gibbsite. The widely differing microfabrics were in many cases observed in samples taken very close to one another and occasionally in the same sample. They may well reflect variations in the weathering microenvironment producing differing amounts of decomposition products, combined with a certain amount of eluviation of the smallest particles produced.

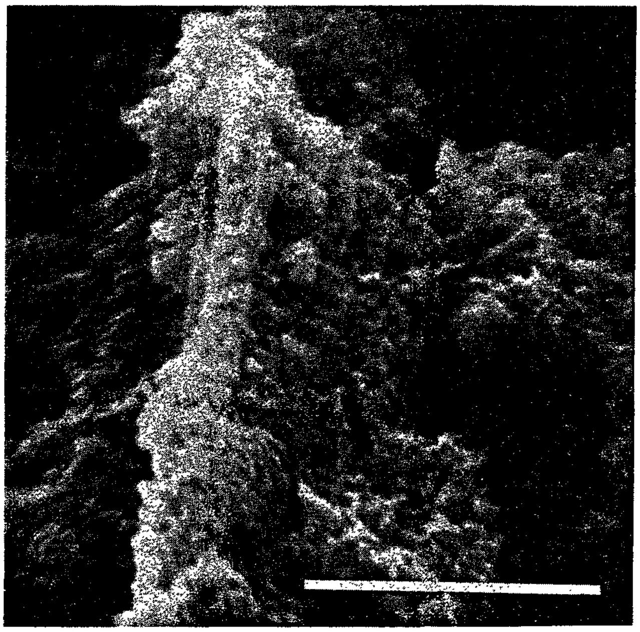

Fig. 16: Gibbsite developing directly from feldspars. Friable granite, Hingston Down. Scale bar 10 μm.

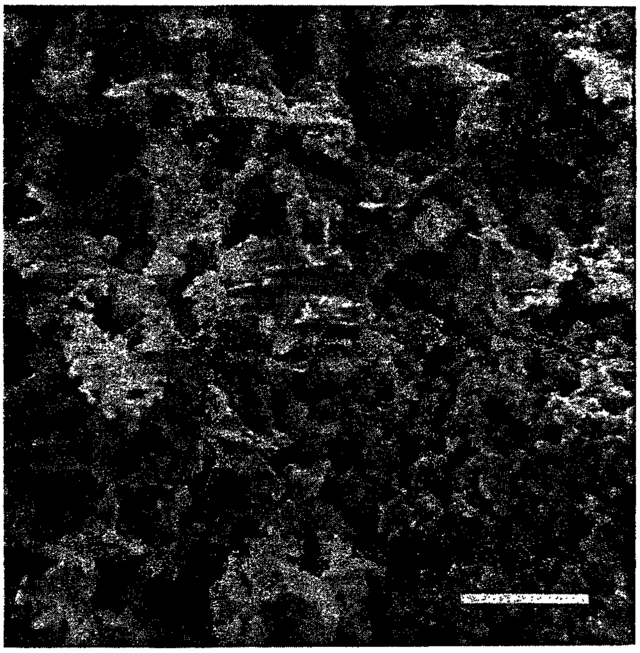

Fig. 17: Porous gibbsite microfabric consisting of a three-dimensional network of aggregated gibbsite particles around large voids. Friable granite, Dartmoor. Scale bar 10 μm.

In this respect it is interesting to note the distinct lack of variation in the published shear strength characteristics of a wide variety of weathered granites (Little 1967, Saunders and Fookes 1970) which all give values of ϕ' of between 28° and 40°, typical values for sands, implying that the clay microfabric produced by weathering does not exert a great deal of control over shear strength characteristics.

Microfabric changes during the weathering of micas

In the granites considered, the mica content consisted mainly of biotite and the successive stages of weathering are shown in Figs. 19, 20 and 21. This mode of decomposition accords with the ideas of Jackson (1963) who suggested that the penetration of cleavages by aggressive agencies (Fig. 20) would allow weathering to proceed whilst maintaining relative crystallographic orientation. The resultant expansion of the lattice due to the increased interlayer spacing of the weathering product can be seen in Fig. 21. This effect has been observed to cause microfracturing during the weathering process

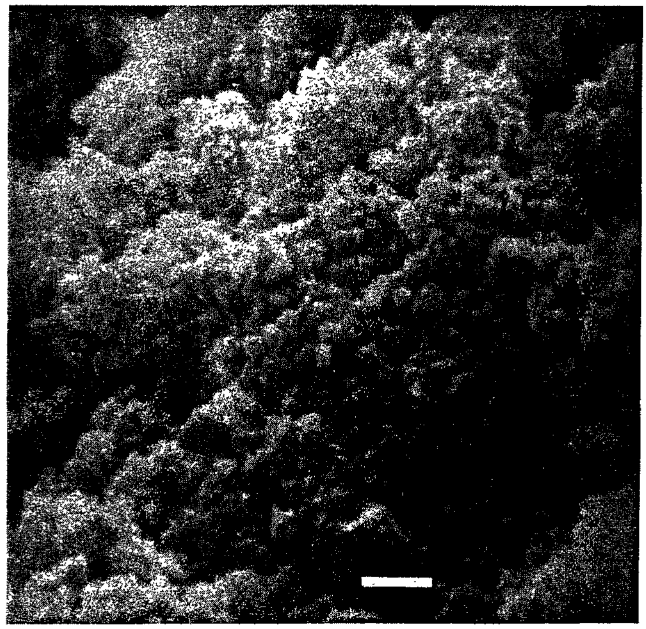

Fig. 18: Fine-grained gibbsite densely aggregated and forming a joint infill. Dartmoor. Scale bar 1 μm.

(Isherwood and Street 1976, Irfan and Dearman 1978) and may be a prime contributor to the disintegration of weathered granite.

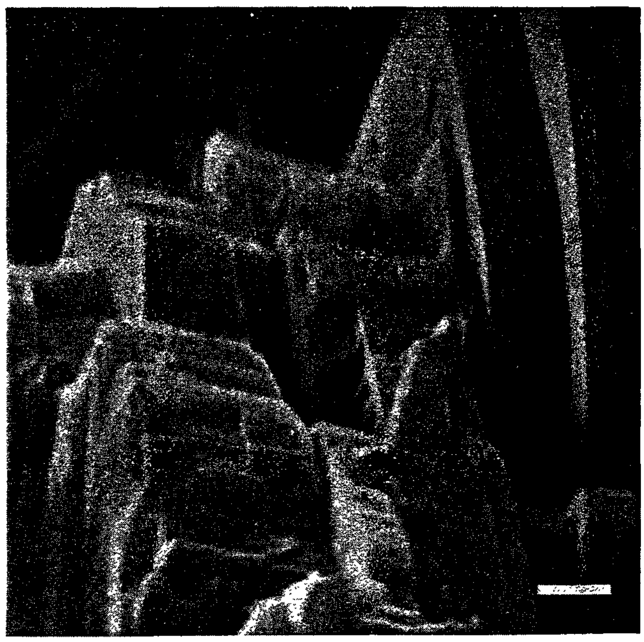

Fig. 19: Fresh biotite. Note the clean uniform cleavages. Slightly discoloured granite, Hingston Down. Scale bar 1 μm.

Microfabric changes in the weathering of quartz

The only form of chemical weathering that quartz undergoes is solution (Loughnan 1969) and generally it is considered to form a resistant coarse-grained residue during the weathering of granites (Lumb 1962b). Nonetheless, as Krinsley and Doornkamp (1973) have shown, wide-spread surface pitting and disintegration are produced by chemical weathering; such features are seen in Fig. 22. The extent of solution shown in Fig. 23 exceeds that which would be expected and may indicate a locally more intense weathering environment.

A feature more typically associated with quartz grains during weathering is that of microfracturing. In fresh granite the quartz crystals display thin, tight, intragranular microcracks (Fig. 24) which on weathering tend to extend, coalesce, widen and become stained with

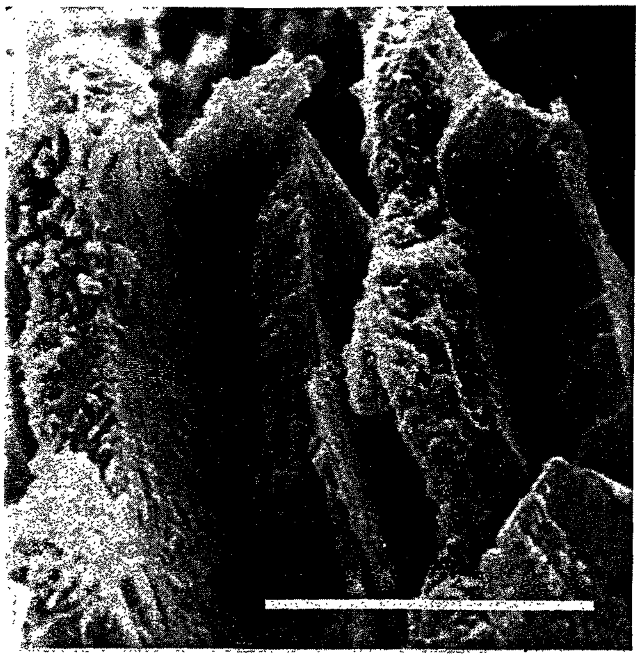

Fig. 20: Slightly weathered biotite. Clay minerals have begun to form on the cleavages and exposed surface of the mineral. Discoloured and weakend granite, Hingston Down. Scale bar 10 μm.

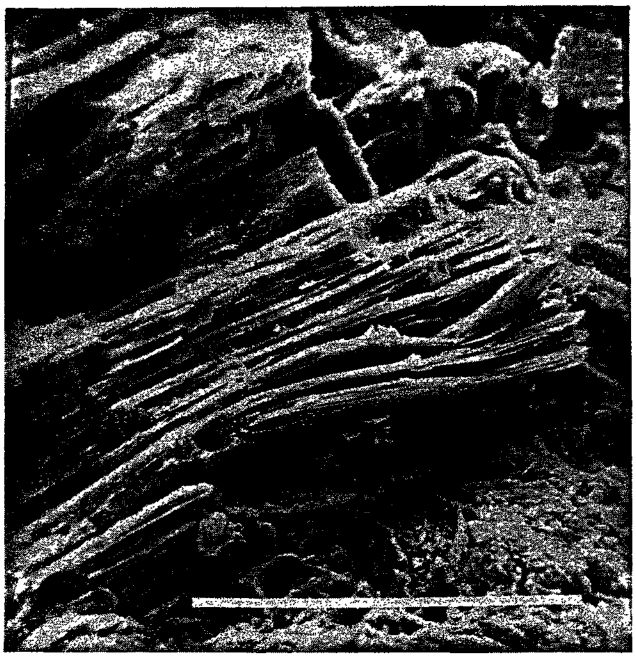

Fig. 21: Weathered biotite. Decomposition has penetrated the cleavages and the mineral grain is expanding. Friable granite, Dartmoor. Scale bar 100 μm.

Fig. 22: Localised irregular etch pits (IEP's) on a quartz grain surface. Granitic soil, Hingston Down. Scale bar 10 μm.

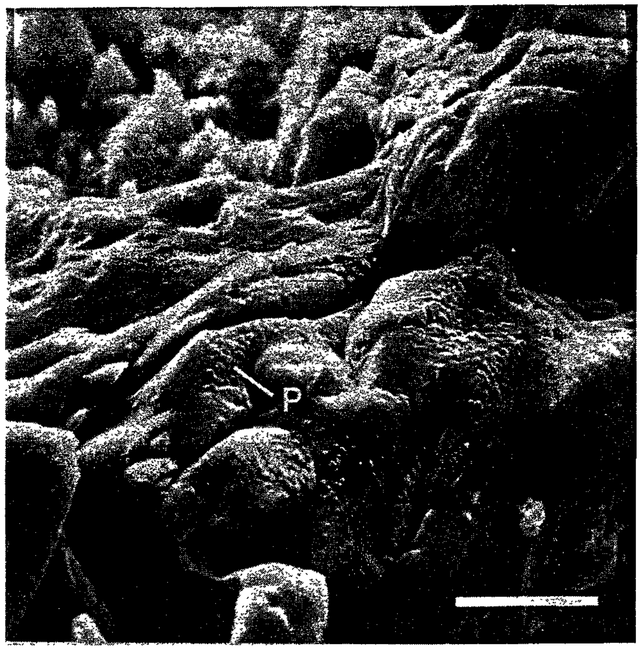

Fig. 23: Quartz showing extensive solution features: smooth rounded outlines, opened fractures. Note also upturned plates (P) indicating period of silica deposition. Friable granite, Dartmoor. Scale bar 10 μm.

iron-rich material (Fig. 25) (Dixon 1969, Irfan and Dearman 1978). Whilst the expansion of biotite, mentioned earlier, may produce microfractures, their intensity and distribution in the granites studied imply that many of them are caused by some other mechanism. Solution effects, as seen in Fig. 23 could extend and widen fractures; as they tend to be straight and parallel sided (Figs. 25, 26) the alternation explanation of a destressing phenomenon seems more likely. Nur and Simmons (1970) have shown theoretically that the effects of cooling and exhumation may be capable of producing microfractures due to the large difference in thermal expansion and compressilibity between quartz and other rock-forming minerals. If some of the stresses that these differences generate are not dispersed by failure, then it is possible that granites at the Earth's surface are in a state of residual stress (Friedman 1972) where potentially recoverable elastic distortions of the constituent crystals are in internal equilibrium and hence "locked in". If weathering processes release the stresses, then locked in strains can relax and microfractures may be opened up. One mechanism which might allow this relates to the processes that occur at grain boundaries during weathering. Sprunt and Brace (1974) comment that grain boundaries are a favoured site for LARCS to occur and consequently also a favoured site for weathering effects. This fact has been confirmed in petrographic studies (Irfan and Dearman 1978). Such a weathered grain boundary can be seen in Fig. 27 to have opened up by weathering. The loosening of grain boundaries throughout the rock coupled with the increase in porosity due to feldspar solution would allow the release of residual stress and the formation of incipient microfractures. The mechanism is analogous to the method of pulse loading used by Price (1966) to create intergranular fracturing and the release of residual stresses.

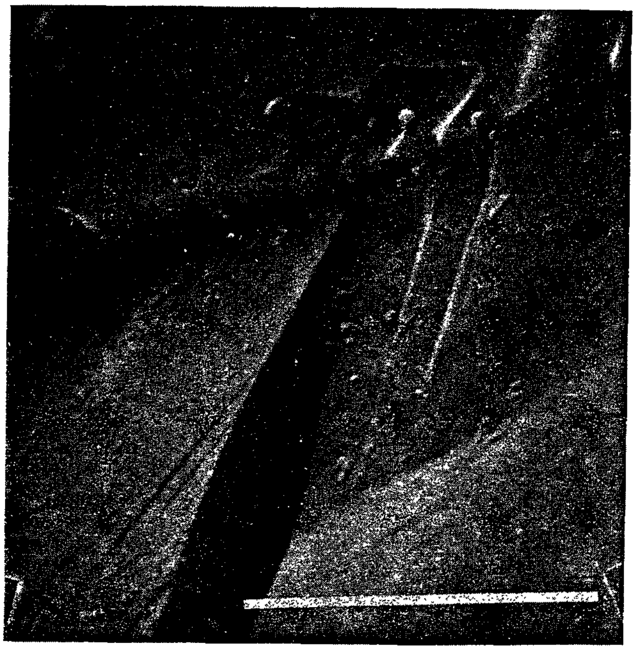

Fig. 24: Clean tight microfractures in fresh quartz. Unweathered granite, Hingston Down. Scale bar 10 μm.

Fig. 26: Open parallel sided intragranular microcrack, probably due to stress relief. Friable granite, Hingston Down. Scale bar 1 μm.

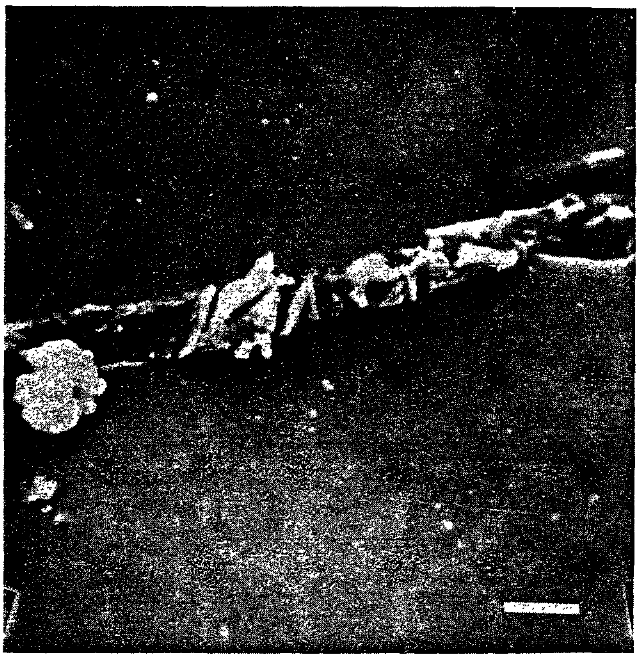

Fig. 25: Parallel sided intragranular microfracture filled with iron rich material. Friable granite, Hingston Down. Scale bar 1 μm.

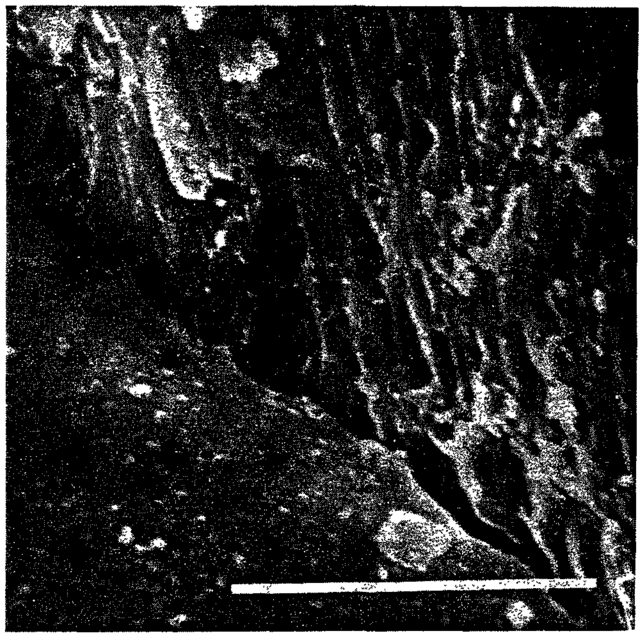

Fig. 27: Open grain boundary between quartz and feldspar due to weathering. Discoloured granite, Hingston Down. Scale bar 10 μm.

Summary and conclusions

The findings of this study may be summarized as follows:

1. Weathering agencies may penetrate the rock material via primary microvoids caused by the cooling and exhumation of the granite and can penetrate feldspar and biotite along the mineral cleavages.
2. The initial stages of weathering produce an increased porosity in the rock material due to the solution of feldspars which generally creates structurally controlled intragranular voids.
3. Weathering may be concentrated at grain boundaries because of the presence of primary microvoids and can lead to the opening up of the grain boundaries.
4. The weathering of quartz by solution locally may be greater than previously thought.
5. The weathering of biotite produces expansion of the mineral lattice which can cause microfracturing.
6. The increased porosity and open grain boundaries caused by weathering could lead to microfracturing by the release of residual stress.
7. Continued weathering may produce extremely open, porous feldspars in which only a framework of thin struts is present. The struts show a tendency to be orientated along the original feldspar cleavage.
8. The microfabric of the final weathering product may vary from dense, tightly packed, clay particles to open cardhouse structures or porous networks of gibbsite aggregates. This probably reflects variations in the intensity of weathering due to widely different microenvironments which may be present within comparatively small areas, combined with a varying amount of eluviation.

Some of the relationships between microfabric features and the engineering properties of weathering granites can be seen in the decrease in compressive strength, Young's modulus and suitability of the weathered granite as aggregate that are manifestations of the increase in porosity and microfracturing caused by weathering. However, the great variations in the final microfabric of the weathering product of feldspars does not seem to be compatible with the observed lack of variation in shear strength characteristic of in situ granitic "soil" which has properties typical of a sandy material. Published results would seem acceptable for friable granite in the early stages of weathering. If 60 per cent by volume of the rock is transformed to a clay matrix with an extremely variable microfabric it would seem reasonable to expect similarly variable shear strength characteristics including Φ' angles normally associated with clayey material. One explanation for this observation may be that as the granite approaches this intensely weathered state the fabric becomes so unstable that it collapses internally due to the high porosity produced by weathering and becomes a true residual soil. Such soils typically have a wide variation in shear strength characteristics and may have Φ' values of 20°, more typical of clayey material.

A further consequence of the microfabric change may well be reflected in the rock mass properties, principally in the form of the weathering profile distribution. Field studies have shown that on well developed weathering profiles the transition from fresh rock to weathered rock is often very sharp and frequently shows a rapid change from strong fresh rock to in situ granitic soil. (Moye 1955, Ruxton and Berry 1957, Vargas 1953). The present study has concluded that the primary rock porosity allows the ingress of weathering agencies and that once weathering starts, intragranular and intergranular porosities increase rapidly, hence leading to accelerated rather than constant rate weathering. It is perhaps the result of this acceleration of weathering that is seen in the rapid transition from soil to rock. Thus, the distribution of the weathering profile may well be controlled by primary microfabric features.

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