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Microstructures of the deformed granites of eastern Kuala Lumpur — Implications for mechanisms and temperatures of deformation

NG THAM FATT

Institute for Advanced Studies
University of Malaya
59100 Kuala Lumpur

Abstract: A wide variety of deformed granites, including fault breccia, cataclasite and mylonites have been generated by several episodes of faulting in the eastern part of Kuala Lumpur. The different fault rocks were formed at different ambient conditions. The microstructural variation of the constituent minerals accompanying deformation in these deformed granites are investigated. The fault breccia and cataclasites exhibit mainly brittle microstructures, while brittle and plastic microstructures co-exist in the mylonites. Generally, the minerals responded to deformation by microcracking. Polygonal subgrains were subsequently formed and this was then followed by recrystallization. The microstructural characteristics are used to suggest the mechanisms and temperatures of deformation.

INTRODUCTION

Several major faults have been identified in the Malay peninsula, and two of these cut the eastern part of Kuala Lumpur — the Kuala Lumpur Fault Zone (Stauffer, 1968, 1969; Tjia, 1972) and the Bukit Tinggi Fault Zone (Shu, 1969, 1989; Tjia, 1972). The existence of the major faults, and many other smaller faults and shear zones were recognized by previous workers from studies of aerial photographs, remotely-sensed images, as well as direct field observations. Although numerous faults were drawn on published geological maps of various areas of the Malay peninsula, the nature of the faults, their geometric and genetic relationships, age and conditions of deformation are inadequately known. Faulting has produced a diverse assemblage of fault-rocks, particularly in the granites. In the area of study (see Fig. 1 for location), these include fault breccia, cataclasites and mylonites and they occur in zones ranging from a few millimetres in width to the mylonites in the Bukit Tinggi Fault Zone which is more than 4 km wide in places.

The microstructures of the fault-rocks are important to the understanding of the mechanisms and conditions of deformation. The response of minerals in granitic rocks to deformation has been described for both natural (Eisbacher, 1970; Voll, 1976; Burg and Laurent, 1978; Debat *et al.*, 1978; Lister and Price, 1978; Bèrthe *et al.*, 1979; Hanmer, 1982; Simpson, 1985; Gapais, 1989) and experimental strains (Tullis and Yund, 1977, 1980; Van der Molen and Paterson, 1979). With the changes in the physical conditions (including temperature, confining pressure and fluid pressure), transition of the minerals from completely brittle to fully ductile behavior occurs. However, at the same ambient conditions, different minerals behave differently during deformation — generally quartz and micas behave in a more ductile manner in comparison with the feldspars. The deformation environment of a fault-rock can thus be indicated by the behavior of its constituent minerals which is reflected by their microstructures.

This paper is a result of field and thin section studies of granitic rocks, mainly the Kuala Lumpur Granite and the Bukit Tinggi Granite (Fig. 1), in the eastern part of Kuala Lumpur. Most of the samples, both deformed and undeformed, were collected from granite quarries and road cuts (particularly the Karak Highway). This contribution is intended to show the diverse assemblage of deformed granites generated by faulting. The microstructural modifications of the constituent minerals which accompany the deformation are described and the possible mechanisms and temperatures of deformation are briefly discussed.

GEOLOGY

A greater part of the area east of Kuala Lumpur is underlain by granitic rocks of the Main Range batholith which intruded into folded and regionally metamorphosed clastic and calcareous Paleozoic rocks. The granitic rocks comprises three main bodies: the Kuala Lumpur Granite, the Genting Sempah Microgranite and the Bukit Tinggi Granite (Fig. 1). The Kuala Lumpur Granite is the main granitic body and it is separated from the Genting Sempah Microgranite by a metasedimentary screen at its eastern margin. The Bukit Tinggi Granite

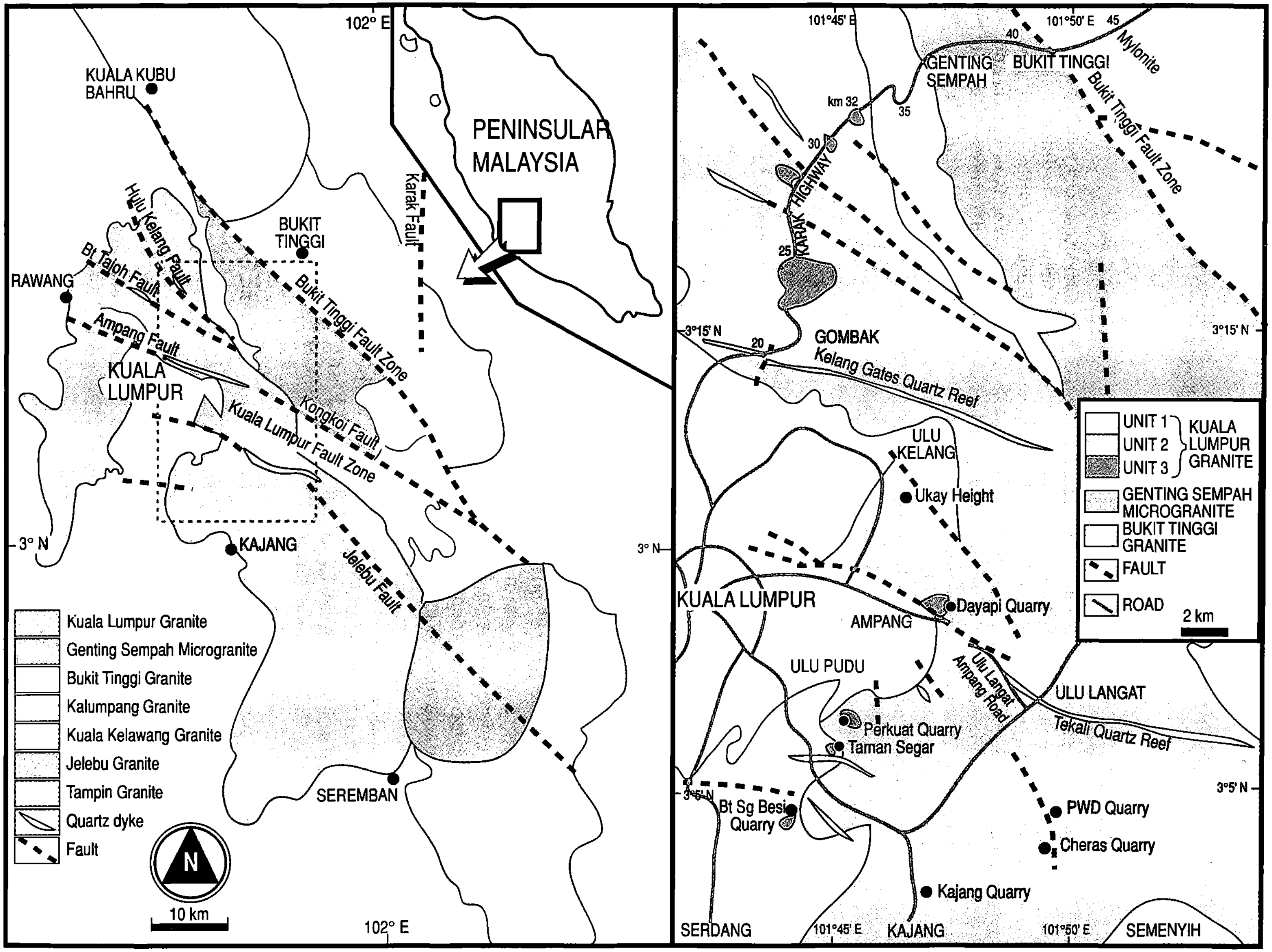


Figure 1. **A)** Sketch map showing the distribution of the granitic bodies and the major faults in the Kuala Lumpur and adjacent areas. **B)** Simplified geological map of the area of study (enclosed by dashed lines in Fig. 1A). Modified after Yin, 1976; Singh, 1985; Cobbing and Mallick, 1986 and Shu, 1989.

occurs as an elongated body which is in contact with the Genting Sempah Microgranite at its western boundary along the Bukit Tinggi Fault Zone (BTFZ), at the northeastern part of the area of study.

The Kuala Lumpur Granite is a large granitic body of irregular shape comprising two lobes. It is predominantly megacrystic consisting of K-feldspar megacrysts set in an allotriomorphic to hypidiomorphic groundmass. The major minerals are K-feldspar, plagioclase and quartz, while biotite, muscovite and tourmaline usually occur in minor amounts, except in the late phase differentiates where these minerals may be dominant. The Kuala Lumpur Granite consists of several textural and mineralogical varieties, and on that basis four main units of granites have been distinguished in the study area (Ng, 1992; Fig. 1B). Unit 1 consists of megacrystic biotite granite, while Unit 2 comprises megacrystic muscovite-biotite granite which represents the typical Kuala Lumpur Granite. Unit 3 is made up of equigranular tourmaline-muscovite granite and Unit 4 comprises of mainly microgranite, aplite and pegmatite. The rocks of Units 1 and 2 are mainly medium to coarse grained, while Units 3 and 4 are mainly fine grained (except the pegmatites). The majority of the samples can be classified as monzogranite (80%), while subordinate syenogranite (15%) occurs in Units 1 and 2, and granodiorite (5%) in Unit 3. Crosscutting relationships indicate that Unit 4 is the youngest. Units 1 and 2 are intruded by Unit 3, and hence they are older than Unit 3; and Unit 1 is very likely to be the oldest.

The Genting Sempah Microgranite is made up of subvolcanic (microgranodiorite) and volcanic rocks (Liew, 1983; Cobbing and Mallick, 1987). The volcanic rocks comprise rhyolitic to dacitic flows, tuffs and tuff breccias. The microgranodiorite contains 20% to 50% of phenocrysts of plagioclase, quartz, K-feldspar, biotite and minor orthopyroxene set in a greenish grey to dark grey, fine grained groundmass with allotriomorphic granular texture. Liew (1983) believes that the Genting Sempah Microgranite represents the coeval eruptive and high level intrusive equivalent of some of the Main Range batholith.

The Bukit Tinggi Granite comprises very coarse grained megacrystic biotite granite. The K-feldspar megacrysts (about 30%) are tabular with rounded edges and up to 5 cm long. The groundmass is made up of grey quartz, plagioclase and biotite clusters. The western part of the Bukit Tinggi Granite is deformed into a broad zone of porphyroclastic mylonites as a result of deformation along the BTFZ.

Geochronological studies by Bignell and Snelling (1977), Liew (1983) and Darbyshire (1988) suggest a Late Triassic age of emplacement for the above granitic rocks. The granites of the Main Range batholith exhibit typical S-type features such as being tin-bearing, and having peraluminous composition, high K_2O/Na_2O ratios, low Fe^{3+}/Total Fe ratios, a restricted compositional range dominated by high SiO_2 granites and high initial $^{87}Sr/^{86}Sr$ ratios (Liew, 1983). On the basis of S-type features and other evidence like absence of associated mafic magmatism, negative ε_{Nd} values and the presence of U-Pb zircon inheritance features, Liew (1983) concluded that the Main Range batholiths are derived from partial melting of underlying old continental crust.

Several episodes of faulting have given rise to various types of deformed granites including fault breccia, cataclasites and mylonites. The mylonites are mainly product of ductile shearing, while the cataclasites and discrete faults are brittle features. The ductile and brittle features are likely to have formed at different ambient conditions, with the ductile ones at greater depths and temperatures.

Both the major fault zones — the Bukit Tinggi Fault Zone (BTFZ) and the Kuala Lumpur Fault Zone (KLFZ) — trend northwesterly (Fig. 1A). The BTFZ appears to be a Late Triassic feature which has probably been reactivated during the Cenozoic (Ng, 1992). The Late Triassic ductile deformation episodes produced a broad zone of S-C mylonites. The S-C mylonites of BTFZ have sub-horizontal to moderately plunging lineations, implying that the BTFZ is a strike-slip fault zone with significant dip-slip components. Field and orientated thin section studies of the S-C fabric and the obliquity of the porphyroclasts indicate a dextral sense of shear. Reactivation of BTFZ during the Cenozoic has produced brittle faults and shear zones with sinistral movements. The KLFZ comprises arrays of discrete faults (i.e. Ampang fault, Kongkoi fault, Bt. Tajoh fault, Hulu Kelang fault, etc.) and a sinistral strike-slip motion is inferred.

The mesoscopic Cenozoic brittle faults and shear zones are steeply dipping and on the basis of their attitudes (strike and dip), three main sets are identified. They are striking at NW-SE, N-S and NE-SW respectively. A less prominent E-W striking set is also present. Analyses of striations on slickensides have shown that the faults are mainly strike-slip faults. However, oblique-slip faults are not uncommon, but dip-slip faults occur subordinately. The sense of shear of the strike-slip faults have been determined using various criteria, including markings on the fault surfaces and the fracture arrays in the brittle shear zones, and it shows that a majority of the NW-SE, N-S and E-W faults are sinistral, though dextral faults also occur.

DEFORMED GRANITES

The descriptive terms used to describe fault-rocks by various workers in the last two decades are far from consistent (e.g. Higgins, 1971; Bell and Etheridge, 1973; Zeck, 1974; Sibson, 1977 and Wise *et al.*, 1984). Almost all the terminology are based on the textures of the fault-rocks. Both incohesive and cohesive fault-related deformed granites are found in the area of study. Incohesive deformed granites are divided using the classification of Sibson (1977) (Fig 2). The cohesive ones are divided using a modified terminology by Wise *et al.* (1984) by incorporating terms from Sibson (1977) (Fig. 2).

Many mylonites in the study area can be classified as S-C mylonites having two sets of penetrative foliations (i.e. C-and S-surfaces). These terms were first used by Bèrthe *et al.* (1979) and later described by Simpson and Schmid (1983), Lister and Snoke (1984), Vauchez (1987) and others. The C-surfaces are internal shear or slip surfaces parallel to, and have the same sense of shear as, the main shear zone. The S-surfaces are related to the accumulation of finite strain and they define the mylonitic foliation.

The Bukit Tinggi Fault has produced the most significant zone of deformed granites in this region. This broad zone comprises largely of porphyroclastic protomylonite and orthomylonite, and subordinate bands of ultramylonite. Well developed S-C fabric is not uncommon in these porphyroclastic mylonites. All the mylonite zones in the Kuala Lumpur Granite are less than 1 m in thickness and consist of fine grained ortho- to ultramylonites, except a band of protomylonite at km 32 of Karak Highway which is about 30 m thick. The cataclasites are relatively more common compared to the other deformed granites. They occur in shear zones up to 10 m in width but are generally less than 3 m. They are observed to cut the mylonites.

INCOHESIVE	**FAULT BRECCIA** (visible fragments > 30% of rock mass)	
	FAULT GOUGE (visible fragments < 30% of rock mass)	
COHESIVE	**CATACLASITE** (non-foliated)	**MYLONITE** (foliated)
	PROTOCATACLASITE *(breccia)* MATRIX < 50%	PROTOMYLONITE MATRIX < 50%
	ORTHOCATACLASITE *(microbreccia)* 50% < MATRIX < 90%	ORTHOMYLONITE 50% < MATRIX < 90%
	ULTRACATACLASITE *(gouge)* MATRIX > 90%	ULTRAMYLONITE MATRIX > 90%

Figure 2. Terminology of fault-rocks. The incohesive fault rocks (fault breccia and fault gouge) after Sibson (1977). The cohesive fault rocks (cataclasite and mylonite) modified after Wise *et al.* (1984) by incorporating the terms protocataclasite, orthocataclasite and ultracataclasite from Sibson (1977) to replace the terms breccia, microbreccia and gouge, respectively.

Fault breccia

The fault breccias are not common. They are observed in a few places, for example, Dayapi Quarry, Cheras Quarry and km 3.4 of the Ulu Langat-Ampang road. The fault breccias are generally 0.1 to 3 m wide. Most of the fault breccia — host granite contacts are sharply marked by near planar faults. The fault breccias are made up of angular granite clasts with subordinate matrix. Clast size ranges from a few millimetres to more than 10 cm but most clasts are of pebble size. Sand to silt size matrix constitutes less than 20% of the total volume of the fault breccia. Most fault breccias are incohesive, uncemented and friable. Quartz cemented fault breccia is found in Dayapi Quarry and Cheras Quarry (Fig. 3A). The quartz cement (about 15%) is clear, forming equant mosaic and prismatic grains in vug-like structures.

Cataclasites

Protocataclasites

Cataclasites differ from the fault breccias in having primary cohesion. They occur as coherent rock bands in contact with the host rock without any macroscopic discontinuity. They commonly anastomose around lenses of protolith. Protocataclasites are the most common cataclastic rock. Some of the fresh and weakly deformed protocataclasites look similar to the undeformed granite, but fractures and fragmental or protoclastic appearance become conspicuous on surfaces etched by weathering, as well as chloritised samples and stained polished slabs.

Most of the fractures (and small-scale faults) are healed. They may be filled by quartz, sericite, chlorite and clay minerals (Fig. 3B). The density and dimension of the fractures vary with the degree of deformation. Fractures in weakly deformed protocataclasites mostly form subparallel arrays which make an acute angle to shear zone boundaries. Cross fractures developed on subsequent deformation. Displacement across the fractures is usually minor. Further strain causes the fractures to coalesce into thorough-going shear fractures and the initiation of microbrecciation.

Granitic textures are still preserved in some of the weakly deformed protocataclasites as revealed under the microscope, but most of them display a fragmental texture, consisting mainly of quartz and feldspar clasts enclosed by very fine matrix. The clasts are usually angular. The clast size is variable and non-uniform. The larger clasts (> 0.1 mm) are highly segmented by microcracks (Fig. 3C). Segments of the parent grains are often displaced along the microcracks. Small individual clasts are often devoid of microcracks. The matrix is very fine-grained, typically less than 20 μm and compositionally variable. The matrix is most commonly made up of minute clasts of quartz and feldspar, and a considerable amount of sericite and opaque minerals.

Orthocataclasites

The orthocataclasites commonly appear to be featureless in the field, though some display a fine fragmental to porphyroclastic texture. However, they display distinct porphyroclastic texture under the microscope, formed by extremely fine matrix surrounding angular to subrounded clasts. The clasts in the orthocataclasites are finer and have lesser microcracks than those in the protocataclasites. Generally, clast size is less than 0.5 mm. Other features of the clasts and the matrix are similar to those in the protocataclasites.

Ultracataclasites

The ultracataclasites form bands up to 5 mm wide in the proto-and orthocataclasites. The transition from ortho- to ultracataclasite may be gradational to fairly sharp (Fig. 3D). The ultracataclasite is composed almost entirely of extremely fine matrix (< 10 μm), with subordinate amounts of porphyroclasts. Most of the individual grains are too fine to be identified reliably under the microscope.

Mylonites

Protomylonites

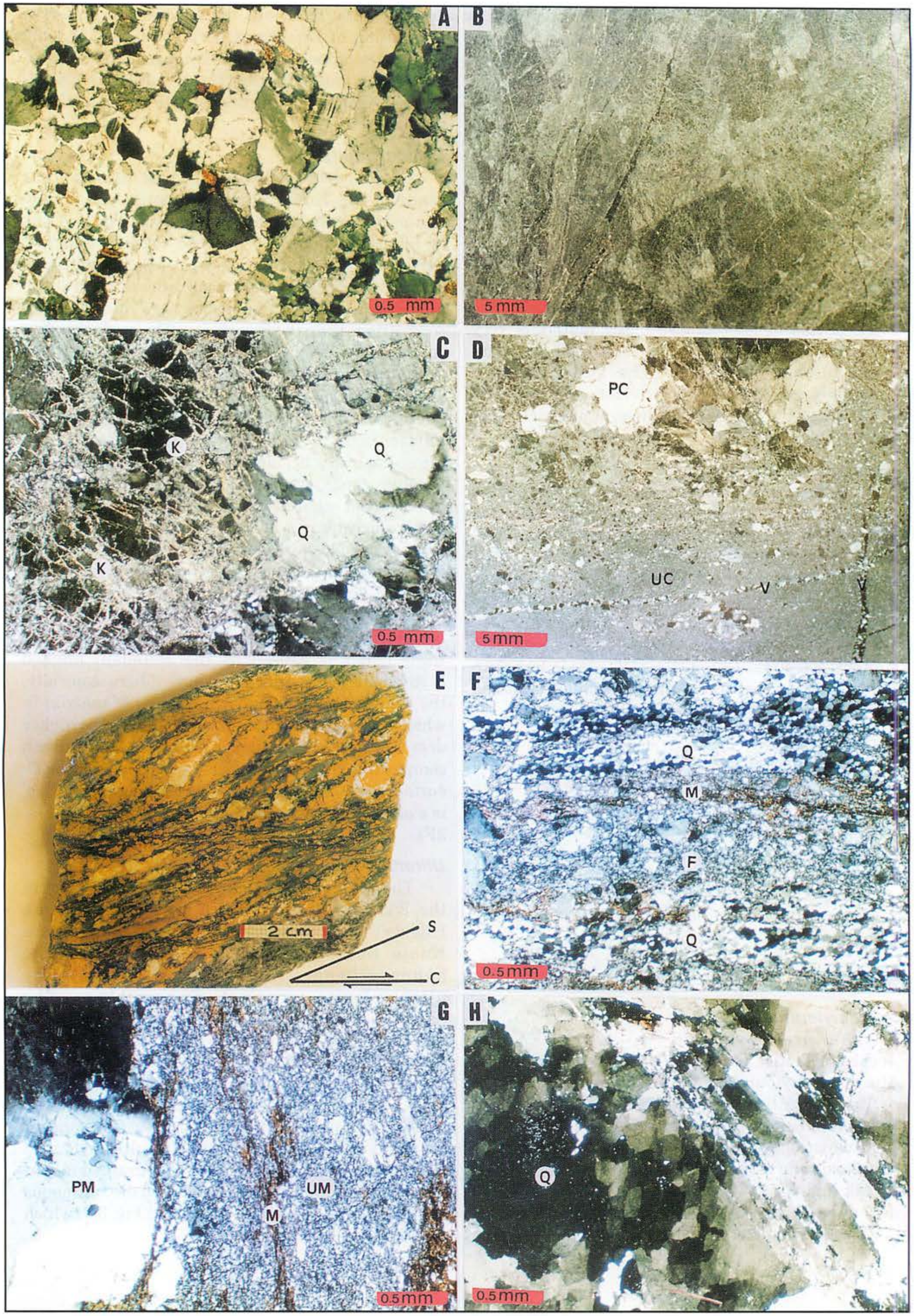
The protomylonites in the BTFZ are porphyroclastic and medium to coarse-grained. Most protomylonites have one set of weak foliation defined either by preferred orientation of tabular to ellipsoidal K-feldspar porphyroclasts and flattened biotite aggregates as in the case of the BTFZ or by flattened quartz and feldspar grains as at km 32, Karak highway. On progressive deformation, two sets of foliations, S- and C-surfaces are formed in the protomylonites of the BTFZ. The S-surfaces are mylonitic foliations demarcated by preferred orientation of K-feldspar porphyroclasts, and the C-surfaces appear as dark-coloured and matrix-rich shear bands cutting the S-surfaces. The S-surfaces make an angle between 45° to 25° to the C-surfaces.

Orthomylonites

Orthomylonites that occur in mesoscopic shear zones in the Kuala Lumpur Granite are mainly non-porphyroclastic and may have one or two sets of foliations. Porphyroclastic texture and S-C surfaces are well developed in orthomylonites of the BTFZ (Fig. 3E), and weak lineations are also observed. The C-surfaces are often more conspicuous than the S-surfaces. The angle between the S- and C-surfaces are smaller (10°–30°) than that of the protomylonites. Mesoscopically, the S-surfaces of the orthomylonites are defined by preferred orientation of elongated clasts, particularly K-feldspar porphyroclasts. Microscopically, besides preferred orientation of the porphyroclasts, the S-surfaces are also demarcated by preferred orientation of elongated parent grains, particularly quartz. The C-surfaces generally form dark-coloured continuous shear bands that cut the S-surfaces, and cause the S-surfaces to curved towards, and become parallel to, the shear bands. The C-surfaces may occasionally form discrete shear bands that offset the S-surfaces. The dark colour of these bands is caused by the abundant aligned biotite lenses and finer grain size. Microscopically, the C-surfaces appear as thin bands of matrix, in which the clasts are finer-grained and have a higher degree of recrystallization. Fine-scale banding (both compositional and grain size banding) along the C-surfaces, which is uncommon in the protomylonites, is clearly discernible in many orthomylonites (Fig. 3F).

Ultramylonites

The ultramylonites occur as narrow bands in the BTFZ (up to tens of cm), at km 32, Karak Highway (2–4 cm) and other shear zones in the Kuala Lumpur Granite (< 10 cm). In the handspecimens individual grains of the ultramylonite are not discernible. The ultramylonites are mainly dark grey to almost black in colour. The foliations are barely visible as very fine laminae. The S-surfaces are usually not as obvious as the C-surfaces. The angle between S- and C-surfaces is very small (less than 20°), and in some ultramylonites, the S- and C-surfaces almost coincide. Under the microscope, the ultramylonites are characterized by extremely fine-grained (about 10 μm) quartzo-feldspatic matrix with discontinuous mica-rich bands (50 μm–1 mm thick; Fig. 3G) which mainly define the C-surfaces.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MICROSTRUCTURAL VARIATION AND DEFORMATION MECHANISMS

Deformation-related microstructures of the deformed granites vary with changing pressure-temperature and other ambient conditions (Tullis *et al.*, 1982). With an increasing P-T condition, microstructural development changes from dominantly brittle to dominantly plastic. Generally, all the minerals show brittle behavior in the fault breccia and cataclasites, while brittle and plastic microstructures co-exist in the mylonites. In the mylonites where the temperature and pressure of deformation were higher, quartz is weaker than feldspar. However, at low temperatures and pressures (i.e. fault breccias and cataclasites) feldspar is observed to be weaker than quartz. The microstructures and the interpreted mechanism of deformation of the major minerals are described below.

Quartz

The first sign of deformation in quartz (as well as other minerals) is microcracking and macrofracturing. These features are conspicuous in the fault breccias and cataclasites. The microcracks may be intragranular or transgranular and may occur in subparallel arrays. Dilation and filling of the transgranular microcracks by fine matrix and vein materials are observed. Macrofracturing and microcracking cause the mechanical breakdown of quartz and other mineral grains in the cataclasites. The larger clasts are usually angular, and roundness increases as the clast size decreases. Rounding of the clasts is caused by the breaking-off of asperities of the clasts which are potential points of stress concentration. Pressure solution at pointed edges of quartz clasts may also have played a role.

In the thin sections, undulatory extinction is observed in all but the recrystallized quartz grains. Recovery of strained quartz is initiated by the formation of polygonal subgrains (polygonization). Polygonization in the cataclasites is generally minor. The subgrains are generally equidimensional to weakly elongated with near rectangular outlines (Fig. 3H). Generally, the size of the subgrains ranges from 20 to 100 μm.

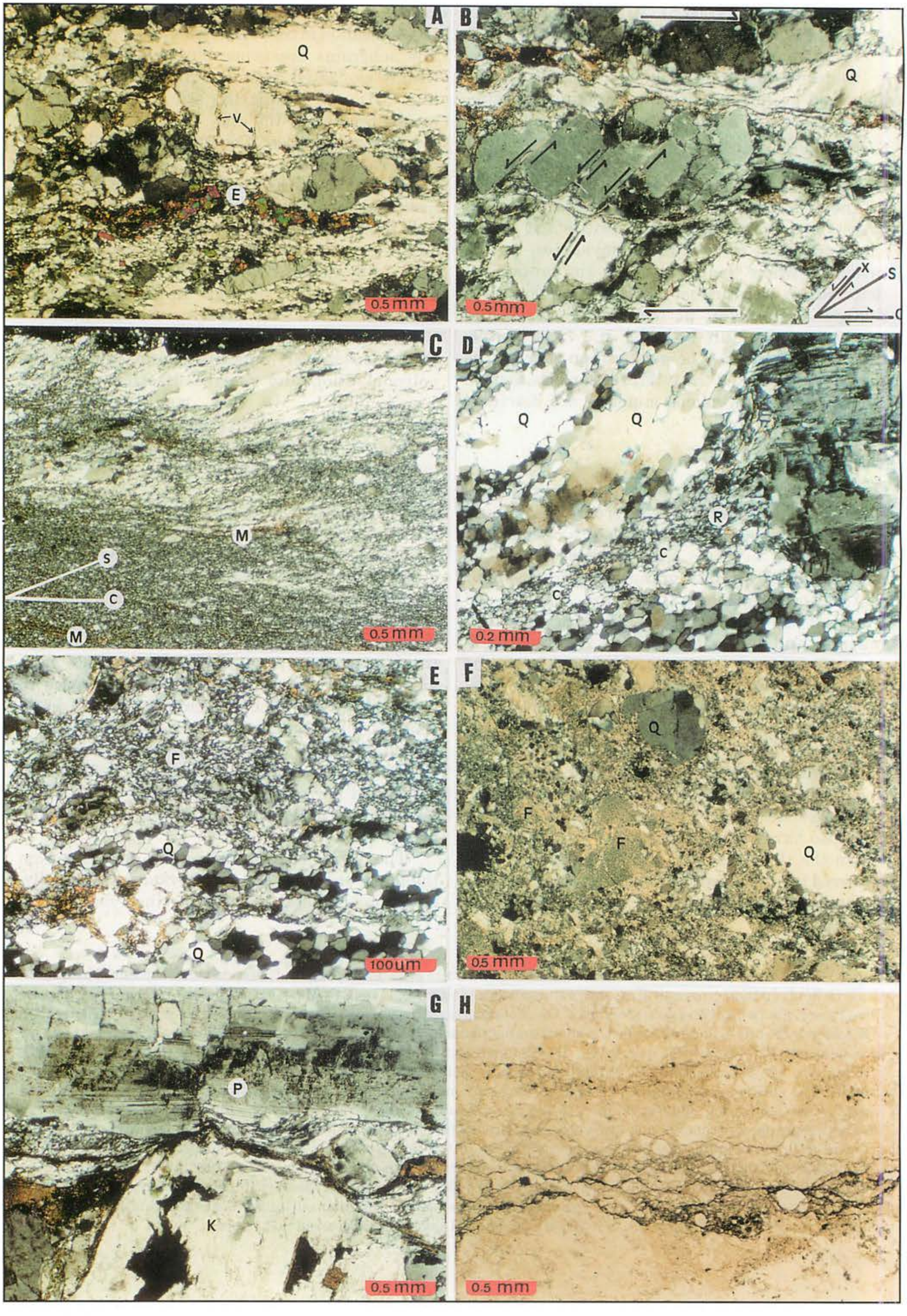
Recrystallization of quartz is not significant in most cataclasites. It occurs along the grain boundaries and microcracks (Fig. 3H). The quartz neocrysts are equant and have similar or finer grain size than the subgrains. Recrystallization also occurs in the extremely fine matrix. In cataclasites affected by fluids, recrystallization is much more common. Some of the new quartz grains might have crystallized from the hydrothermal fluids.

In contrast to the cataclasites, microcracking of quartz is relatively minor in the mylonites, while polygonization and recrystallization are more conspicuous. In the weakly deformed protomylonites, polygonization takes place at grain boundaries and deformation bands. Most of the quartz clasts in the other mylonites are completely polygonised.

The quartz clasts in the mylonites of the BTFZ are stretched into lenses with an aspect ratio of 1.5:1 to 5:1 (Figs. 4A, 4B and 4C). Some of the quartz lenses which form fabric elements defining the C-surfaces are drawn into quartz ribbons with aspect ratios ranging from 5:1 to more than 10:1. With progressive deformation, the aspect ratio of the quartz clasts and ribbons increases. It is accompanied by an increase in the degree of recrystallization. The stretching of quartz clasts was probably accommodated by intracrystalline slip and diffusion. It is indicated by complete polygonization and the presence of deformation bands and microshear bands (Tullis *et al.*, 1982). Solution and mass-transfer might have also taken place.

The degree of recrystallization increases from the proto- to ortho- and ultramylonite. Generally, more than half of the quartz in orthomylonites and

Figure 3. A) Photomicrograph showing angular clasts forming the matrix of a fault breccia being cemented by quartz. **B)** Dark field photomacrograph of an entire thin section of a protocataclasite. Most of the fractures and microcracks are filled by sericite (white) and quartz (black). **C)** Photomicrograph showing part of 3B. Microcracking and sericitisation of K-feldspar (K) occur along cleavages. Some of the microcracks are filled by sericite and fine matrix. Microcracks appear to be denser in K-feldspar than quartz (Q). **D)** Photomacrograph of an entire thin section showing protocataclasite (PC) grading into ultracataclasite (UC) through orthocataclasite. Note the quartz veins (V). **E)** Stained orthomylonite sample. The clasts and aggregates are highly elongated and aligned parallel to the S-surfaces. They are also curved towards the C-surfaces. Quartz is grey, K-feldspar is stained yellow, plagioclase is white and biotite is black. **F)** Photomicrograph of orthomylonite showing C-surfaces defined by compositional and grain size banding. Individual grain in the quartz bands (Q) are coarser than those in the feldspar bands (F) and mica-rich bands (M). **G)** The ultramylonite of the BTFZ comprises extremely fine matrix and discontinuous mica-rich bands (M). Note the sharp contact between ultramylonite (UM) and protomylonite (PM). **H)** Protocataclasite with polygonized quartz clasts but the parent grain is still preserved (Q). The subgrains have near rectangular outlines. Minor recrystallization occurs along the microcracks. Figures 3A, 3C, 3D, 3F, 3G and 3H taken under crossed polarisers.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almost all the quartz in ultramylonites are recrystallized. Recrystallization is usually more intense along the C-surfaces than S-surfaces. Recrystallization usually takes place from the boundaries towards the centre of the clasts (Fig. 4D). There is a gradual progression from subgrain to quartz neocryst. It suggests that subgrain rotation is the dominant mechanism of recrystallization (Vernon *et al.*, 1983; Kruhl, 1986).

The quartz neocrysts usually have straight boundaries. They are slightly elongated (aspect ratio < 1.5:1). They also show dimensional preferred orientation (Fig. 4E), suggesting that they were recrystallized dynamically. However, equant quartz neocrysts are also very common, probably formed by subsequent annealing or subsequent coarsening of dynamically recrystallized grains.

From the study of deformed granites, it is apparent that quartz responded to deformation by microcracking followed by polygonization and ended with recrystallization. But deformational microstructures predominate over recovery in cataclasites, whereas in the mylonites the opposite is true.

K-Feldspar

The K-feldspar clasts in the proto- and orthocataclasites are highly microcracked, often more intense than the quartz (Fig. 3C). A large proportion of the microcracks appear along the cleavages. Larger K-feldspar grains are highly fragmented and the angular fragments are enclosed by fine matrix or alteration products.

The K-feldspar clasts show weak undulatory extinction. Alteration to sericite or clay minerals is conspicuous in many cataclasites. In some ortho- and ultracataclasites, the K-feldspar clasts are almost entirely altered, but faint outlines of the parent clast is preserved (Fig. 4F). Alteration is also frequently accompanied by pressure solution. Generally, polygonization and recrystallization of K-feldspar in the cataclasite are uncommon. Like quartz, these recovery processes are more common where the participation of fluids is evident.

In the mylonites, initially, K-feldspar also responded to deformation by microcracking (Fig. 4B), but the density of microcracks is much lower compared to the cataclasites. Displacement along the microcracks is common. Sliding and rotation of the K-feldspar fragments along microcracks have caused them to form granular aggregates with aspect ratios up to 5:1 (Fig. 4B). Microboudinage of K-feldspar clasts is observed in moderately to highly strained mylonites. These clasts show pinch and swell structures and the microboudins may occasionally be completely separated to form individual clasts.

Quartz and feldspar veinlets occur in some of the K-feldspar clasts (Fig. 4A). These veins are orientated at a high angle to the C-surfaces. They can be formed by filling of dilated microcracks (Debat *et al.*, 1979) or by strain enhanced diffusion (Hanmer, 1981). Both processes may be operative in the mylonites studied. Straight transgranular veins with sharp contacts are suggestive of the first mechanism. Some veins are intragranular, straight to undulating and their contacts are less sharp, probably formed by diffusion.

The K-feldspar porphyroclasts in the mylonites of the BTFZ are oblong in weakly deformed mylonites, and become elliptical with progressive deformation. The largest faces are often aligned to the S-surfaces. This is brought about by rotation, indicated by curved pressure shadows and "tails" (σ_b-type of Passchier and Simpson, 1986) at the sides of the porphyroclasts. The "tails" are made up of minute clasts and neocrysts detached from the porphyroclasts (Fig. 4D) together with biotite, muscovite and quartz neocrysts. The biotite and quartz neocrysts are likely to be physically incorporated into the "tails" from the matrix. But the fine muscovite may also be a product of

Figure 4. **A)** Photomicrograph of orthomylonite of the BTFZ showing highly flattened quartz ribbons (Q). Quartz in the lower portion are fully recrystallized. Note the quartz veinlets (V) in a K-feldspar megaclast and the epidote bands (E). **B)** Photomicrograph of an oriented thin section of orthomylonite showing microcracks and antithetic microfaults in lenticular K-feldspar clasts (centre) with minor recrystallization at clast boundary. Quartz (Q) is stretched into ribbons and partly recrystallized. Arrows indicate sense of shear. **C)** Ultramylonite with S-surfaces defined by the preferred orientation of quartz lenses and the C-surfaces by mica-rich bands (M) and preferred orientation of neocrysts in the matrix. **D)** Quartz clasts (Q) showing progressive transformation into subgrains and neocrysts towards their margins. Note that "tail" of a K-feldspar porphyroclast comprises minute feldspar neocrysts (R) and clasts (C). **E)** Orthomylonite with extremely fine feldspar neocrysts (F) which are elongated with long axes subparallel to the C-surface. Quartz neocrysts (Q) are equant to slightly elongated, and the latter aligned to the S-surface. **F)** Orthocataclasite with corroded quartz clasts (Q) and completely sericitised feldspar clasts (F). **G)** Orthomylonite showing the edge of a K-feldspar clast (K) impinging against a plagioclase clast (P). Recrystallization (near the margins of both clasts) and microcracking (in plagioclase clast) occur at the highly stressed boundaries caused the impingement. **H)** Pressure solution seams in orthocataclasite. Opaque minerals and phyllosilicates are concentrated along the pressure solution seams. Figures 4A, 4B, 4C, 4D, 4E, 4F, and 4G taken under crossed polarisers and 4H under plane polarized light.

recrystallization and alteration of K-feldspar.

Polygonization of K-feldspar is not widespread in the mylonites. Subgrains occur at the clast margins and in highly stressed areas (Fig. 4G). Though recrystallization occurs in moderately strained mylonites, it is only widespread in the ortho- and ultramylonites of the BTFZ with well developed foliation. Recrystallization is also widespread in the protomylonite at the 32nd km of the Karak Highway. In the BTFZ, feldspar neocrysts are elongated (aspect ratio about 2:1, 5–30 μm long) and have sutured boundaries. They are usually finer than the quartz neocrysts in the adjacent lenses, by a factor of about a quarter to a tenth. They form lenticular aggregates extending from the sides of the porphyroclasts to the foliation and also as bands in the matrix. The lenses and bands are about 0.1–0.3 mm wide and up to 1 cm long (aspect ratio > 5:1). Mica (biotite and muscovite) and minor quartz occur in these lenses and bands.

The feldspar neocrysts are aligned, mainly to the C-surfaces (Fig. 4E). This suggests that they were formed by dynamic recrystallization. The occurrence of "tails" of feldspar neocrysts at the sides of porphyroclasts suggests that the neocrysts may have been continuously detached from the parent clasts into the matrix during deformation. Lenses of K-feldspar neocrysts in the matrix probably formed in the same way, or by flattening of recrystallized K-feldspar during and after recrystallization.

The K-feldspar neocrysts in the protomylonite at km 32 of the Karak Highway are mainly equant or slightly elongated and have similar sizes as the quartz neocrysts (about 30 μm). Though recrystallization is often more intense in certain zones which are parallel to the foliation, the neocrysts are not arranged into lenticular aggregates. The neocrysts are probably formed by annealing of highly strained grain boundaries.

Plagioclase

The microstructures of the plagioclase are similar in many respects to those of the K-feldspar. In the protoliths, the plagioclase grains may develop secondary twinning, otherwise they appear to be undeformed. The plagioclase clasts are highly microcracked in the cataclasites. Mechanical polysynthetic twinning is fairly common. It is indicated by relatively thin (tens of μm) twin lamellae which taper towards the interior of the grain and terminate with sharp tips. The twin lamellae may be weakly bent. In general, plagioclase seldom shows evidence of recrystallization in the cataclasites. Plagioclase is susceptible to alteration. The majority of the sericite in the matrix of the cataclasites is probably derived from the alteration of plagioclase clasts.

In the mylonites, the most common microstructures in plagioclase are microcracking, undulatory extinction, mechanical twinning, folding and kink bands. The microcracks in plagioclase are similar to that in the K-feldspar, but less intense. In weakly deformed protomylonites, the plagioclase grains are still intact. Plagioclases in ortho- and ultramylonites are fragmented into angular clasts up to a few millimetres in size. Most of the clasts are arranged as lenticular aggregates in the matrix, with inter-clast spaces occupied by quartz neocrysts.

The frequency of folding of the plagioclase clasts increases with deformation which causes the cleavages and twin lamellae to become curved. The hinge of the fold is usually rounded. Intragranular microcracks may appear at the hinge line, particularly in weakly deformed mylonites. Folding often appears in clasts that are not aligned to the foliation, and it occurs near to the clast edges that curve towards the foliation. Mechanical twinning is very common and microboudinage is also observed.

Compared to K-feldspar, recrystallization of plagioclase is less intense. It is not observed in most weakly strained protomylonites, and is not very common in most mylonites. However, it is conspicuous in the protomylonite at km 32 of the Karak Highway. The plagioclase neocrysts at grain boundaries are equant to slightly elongated (aspect ratio < 2:1, < 200 μm long).

In highly strained ortho- and ultramylonites of the BTFZ, recrystallization of plagioclase clasts occurs at highly stressed boundaries (Fig. 4G). The neocrysts are 5 to 40 μm in size and are slightly elongated (aspect ratio about 1.5:1). They may extend from the clast boundaries into the matrix as thin lenses parallel to the C-surfaces. Usually, when recrystallization of plagioclase occurs, the coexisting quartz lenses are close to complete recrystallization and neocrysts are well developed in K-feldspar.

Biotite and Muscovite

Biotites and muscovites are affected by microcracking, folding and kinking in the cataclasites. In the protocataclasites, microcracking occurs along cleavages, at the hinge of kink bands and across the cleavages. The tightness of the kinks are open to moderate and the hinge line is sharp. Micas are also folded with a broad rounded hinge. Fine muscovite (sericite) is the main mica found in the ortho- and ultracataclasites. Biotites and muscovites are highly diminuted and altered into fine muscovite. Biotite is also altered to chlorite and epidote. The parent mica plates are seldom preserved.

In weakly to moderately deformed mylonites, biotite is altered and kinked or folded. Biotites in highly deformed mylonites are fully recrystallized, drawn into lenticular aggregates or mica fish. The mica fish is an asymmetrical lense, often with the long axes aligned at a small angle to the C-surfaces (Lister and Snoke, 1984). Recrystallization occurs at the mica fish margins and the neocrysts often extend as trails into the matrix marking the C-surfaces.

In the BTFZ, recrystallization of biotite has mainly produced euhedral and elongated biotite neocrysts (< 40 x 100 μm in size), and also aggregates of recrystallized biotite ± muscovite ± chlorite ± epidote. Biotite and muscovite in the other mylonites cutting the Kuala Lumpur Granite are often fully recrystallized into fine aggregates of muscovite ± chlorite ± epidote which are dragged into lenses. The neocrysts are also disseminated in the matrix.

GRAIN SIZE REDUCTION

Deformation of the granites was accompanied by reduction in grain size. Typically, the average grain size of the protoliths is about 3 to 5 mm in the medium to coarse-grained varieties and about 1 mm in the fine grained ones. Their grain size decreases progressively to less than 20 μm in the ultramylonite and ultracataclasite.

Fault breccias and most protocataclasites are cut by extensive macrofracture arrays which divide the rocks into discrete segments. At this stage, there is little or no changes in the grain size within each segment, though segment margins (along macrofracture) are microbrecciated. Macrofracturing grades into microbrecciation and cataclastic flow with progressive deformation.

Though microcracking played a considerable role in the grain size reduction of the mylonites, it is subordinate to crystal-plastic deformation and recovery processes, particularly recrystallization. Microcracking remained the dominant deformation mechanism of K-feldspar and plagioclase until a moderate stage of deformation (i.e. orthomylonite), when it gave way to intracrystalline slip and recrystallization.

Dynamic recrystallization is the main grain size reduction mechanism of quartz and mica in all the mylonites, and feldspars in highly strained mylonites. The sizes of the quartz and feldspar neocrysts are about 30 μm and 10 μm respectively. Grain size of mica neocrysts is rather variable and ranges from a few microns to 100 μm.

THE PRESENCE OF WATER DURING DEFORMATION

The presence of water/fluids during deformation is an important factor that influences the relative ease of operation of the various deformation mechanisms and the microstructures they produce (Tullis *et al.*, 1982). Water is known to decrease the strength of a rock and increase the strain rate for a given stress in both brittle and ducile regime (Tullis and Yund, 1980). Water was available during the deformation of the granites studied as evidenced by (i) alteration, (ii) veinlets (iii) pressure solution indicated by corroded clasts and pressure solution seams (Fig. 4H). The presence of veinlets in the deformed granites suggests that microcracking by hydraulic fracturing (Philips, 1972) and stress corrosion at crack tips (Anderson and Grew, 1977; Atkinson, 1982) might have occurred. In the cataclasites, plastic microstructures usually are more common in samples affected by fluids. Deformational ductility of these cataclasites might have been enhanced by the fluids, as shown by studies by White and White (1983) and Mitra (1984).

DEFORMATION TEMPERATURES

Macro- and microcracking are the dominant deformation mechanism of fault breccia and cataclasites. Though recrystallization of quartz is not uncommon, it is related to the hydrothermal activities. The brittle behaviour of quartz indicates that the temperature of deformation was less than 300°C (Voll, 1976; Kerrich *et al.*, 1977). The depth of generation of the cataclasites is dependent on the local geothermal gradient and the magnitude of shear heating. Sibson (1977) and Scholz (1988) believe that the cataclasites are generated at depth of about 2 to 10 km and the incohesive fault breccias at shallower levels.

Crystal-plastic processes, particularly recrystallization is the dominant deformation mechanism of the mylonites. Recrystallization of quartz and biotite requires a minimum temperature of about 300°C in natural deformation where water is available (Voll, 1976). Feldspars in the mylonites (except the protomylonite at km 32, Karak Highway) exhibit a brittle behaviour which on progressive deformation becomes ductile, indicating deformation across the brittle-plastic transition which is about 450–500°C when water is available (Voll, 1976; White, 1976).

The lack of brittle microstructure in the protomylonite at km 32 of the Karak Highway implies that the temperature of deformation was above 450°C (brittle-plastic transition of feldspar is about 450–500°C). However, recrystallization is not as widespread as expected at such high temperatures. It is probably because the deformation was ephemeral or that the magnitudes of the stress and strain were low. Deformation probably occurred shortly after the emplacement of the granite, before complete cooling, as indicated by the presence of undeformed late magmatic microgranite dikes cutting the protomylonite.

Neocrysts of quartz, K-feldspar, plagioclase, biotite, muscovite, chlorite, epidote and clinozoisite are present in many mylonites. They are suggestive of a greenschist facies condition. Though rare, the presence of actinolite indicates that the deformation might have occurred at the epidote-amphibolite grade. These metamorphic grades are in agreement with studies on naturally deformed granitic rocks by Voll (1976) and Simpson (1985). They show that the onset of feldspar plasticity occurs at the epidote-amphibolite grade.

CONCLUSION

The granitic rocks in the eastern part of Kuala Lumpur experienced several episodes of faulting which have given rise to a diverse assemblage of fault-rocks. These include fault breccia, cataclasites and mylonites. They are formed at different ambient conditions, with the mylonites at greater depths and temperatures.

The cataclasites are the most common fault-rock. They are largely deformed in the brittle domain and microcracking is the dominant deformation mechanism, affected all the minerals. Minor polygonization and recrystallization occur in the quartz clasts, particularly when fluids are present. The fluids also promoted alteration of feldspar and pressure solution of quartz and feldspar. The cataclasites were deformed at temperatures of less than 300°C as indicated by the brittle behaviour of quartz.

Brittle and plastic microstructures co-exist in most mylonites where quartz and mica deformed plastically, while feldspars behaved in a brittle manner which on progressive deformation become ductile. Quartz and mica experienced extensive polygonization and dynamic recrystallization and control the fabric of the mylonites. Feldspars are microcracked, and widespread polygonization and recrystallization occur only in ortho- and ultramylonites. These mylonites probably deformed across the brittle-plastic transition of about 450–500°C.

A zone of protomylonite at km 32 Karak highway exhibits only plastic microstructures, indicating deformation at above 450°C, probably occurred shortly after the emplacement of the granite, before complete cooling.

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