DOI:10.13686/j.cnki.dzyzy.2004.03.001

第 13 卷第 3 期
2004 年 9 月
地 质 与 资 源
GEOLOGY AND RESOURCES
Vol. 13 No. 3
Sep. 2004

· FUNDAMENTAL GEOLOGY ·

Article ID: 1671 - 1947(2004)03 - 0129 - 08 **CLC number:** P588. 12; P578. 968 **Document code**: A

SCANNING OF ESSENTIAL MINERALS IN GRANITE ELECTRON MICROSCOPE STUDY ON THE MICROFRACTURE BEHAVIOR

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Abstract: Granitic samples from Zhejiang Province, Southeast of China, were tested in a uniaxial condition to failure at constant confining pressure. It is found from careful Scanning Electron Microscope (SEM) observations that fractures form the intersection or coalescence of microcavities. Granite consists of three major minerals, Quartz, feldspar (K-feldspar & Plagioclase) and biotite. The cracks in various minerals of the specimen develop differently; this obvious difference in crack patterns is believed to result from the nature of their microstructures. Careful observation shows that quartz display brittle and isotropic crack while feldspar and biotite exhibit anisotropic cracks and the separating of their cleavage planes (cleavage cracks) is the one of the major failure forms of biotite and feldspar. From the tectonic point of view, the granite has been strongly deformed and hydrothermally altered; such hydrothermal fluids may be keep the system open for fluid movement to cause alteration metasomatism of granite.

Key words: granite; microfracture of minerals; scanning electron microscope(SEM)

1 Introduction

There are previous studies have attempted to observe microcracks both optically[1] and with the Scanning Electron Microscope (SEM) [2]. In another research, the authors made thin sections and examined them with the aid of polarized light microscope (petrographic microscope).

But there are several problems with such procedure. First, the production of sections often introduces cracks, making the identification of natural and experimentally stress-induced cracks difficult.

Secondly, the cracks observed are limited in size to about the order of tenths of millimeters or larger and important details are often missed.

The scanning electron microscope (SEM) is ideally suited to the study of cracks in rocks because of its high magnification and three-dimensional resolution. The authors investigated the development of stress-induced microcracks in Zhejiang granite with the SEM, at room temperature and a confining pressure of 51. 6 MPa. The samples we studied are (40 mm × 6 mm × 6 mm) rectangular shape. Microcracks are thought to play an important role in the physical behavior of rocks. The only subsequent surface preparation in stressed rocks was treatment in an ultrasonic cleaner to remove dust particles and the evaporation of a 200 Å layer of 60% gold, 40% palladium alloy onto the specimen surface to provide a conducting layer for SEM operation. Fracture surfaces from granite were examined to study microcrackes and mineral identification such as cleavage, crystal form and fracture behavior.

The engineering properties of a rock mass are a function of the physical properties of the rock. It is important that the mineral composition, texture (grain size and shape) and fabric (arrangement of minerals and voids) are determined accurately because of these properties will control the engineering properties of weathered rocks and their behavior in engineering works [3,4]. On the other hand, microcracks were divided into three types: intracrystalline cracks (lying totally within grain), intercrystalline cracks (extending from a grain boundary

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Received date: 2003 - 09 - 11; **Accepted date:** 2004 - 05 - 18. **Editor:** LI Lan-ying.

Foundation item: This study was supported by the China Scholarship Council (Grant No. 160), National Nature Science Foundation of China(Grant No. 400722006) and the Key Task Project of Science and Technology of Liaoning Province (Grant No. 2001230001). 1

crossing into one or more other grains) and grain boundary cracks (associated and perhaps coincident with the grain boundary). These three types of cracks were observed in Zhejiang granite. Some researchers suggested that the cracks be concentrated in and around quartz[5-7]. For stressed samples, Tapponnier & Brace[8]indicated that, in a sample of Westerly granite stressed almost to failure, K-feldspar and quartz had somewhat higher crack densities than plagioclase. Tullis & Yund[9] found that intragranular cracking in the feldspars exceeded that in quartz in samples of Westerly granite stressed to failure at room temperature. These results indicate somewhat variable responses of quartz and plagioclase to stress, but K-feldspar consistently is highly cracked in stressed samples. Westerly granite and other granitic rocks have a long and complex history of cracking and subsequent sealing and healing processes[10]. Cathodoluminescence studies reveal a much higher density of healed cracks in feldspar than in quartz[10], the open cracks at present study are concentrated in quartz. Many of these early formed cracks may have been healed or sealed as a result of the movement through the granite of the hydrothermal solutions that also affected the plagioclase. According to Wong[11], microcracking in plagioclase in Westerly granites was more closely associated with pores resulting from the hydrothermal alteration than with cleavage planes. He calculated that of the three major minerals in Westerly granite, microcline is the most anisotropic with respect to its elastic properties. Plagioclase also has one perfect and one good cleavage plane, and it should behave similarly to microcline.

2 Methods

In this study granitic rocks of Zhejiang area is medium to coarse grained (1 – 6 mm), altered and composed approximately of 40% plagioclase, 25% K-feldspar 25% quartz, and 10% mafic minerals, mainly mica (biotite and muscovite). Microcracks in Zhejiang granite were observed using an optical microscope. However, under a microscope it was difficult to identify microcracks and, further, to distinguish virgin cracks from secondary cracks produced when the thin sections were made. To solve these problems, scanning electron microscope (SEM) reveals details of cracks and pores with a resolution of about 10^{-6} cm. Shape and location of individual cracks is apparent in the SEM so that a much more detailed characterization of dilatant microcracks should be possible and resolution is extended nearly a hundred times over optical method.

3 Investigation and Discussion

3.1 Quartz

On the fracture surface, the quartz grain is typically characterized by both boundary and transgranular failure. The transgranular failure of quartz grains is often presented themselves as conchoidal breakage pattern, which is a series of irregular shell-like rings. Some of the concentrated deformation bands are accompanied by slip surface, which can be recognized by well-developed striations and grooves (Figs. 1, 2 and 3). This is a typical brittle fracture pattern of quartz. Occurrence of broken quartz minerals in concentric shells is an indication of earlier episodes of cataclasis during deformation in which metasomatism was possible. There are some smooth fractured surfaces without microstructure evidence for quartz grains (Fig. 2), while there are some significant slickensides on the quartz surface, which indicate the stress direction (Fig. 4). A possible explanation may be that in quartz, which is elastically anisotropic, these surfaces are also believed to be formed by transgranular failure. There are some open microcracks are concentrated within and along the edges of quartz crystals (Figs. 1 and 11). Cracks first appear along its boundaries and with the increase of deformations; rapidly develop in the quartz grains (Fig. 1). So the quartz is considered as the valve of failure process in granite.

Also observations reveal that the cracks first open up along the quartz-quartz or quartz-feldspar boundaries in some favorable directions (Figs. 11 and 12) which give an indicate that the quartz boundary is relatively weak in granite and is the most favorable place to crack.

3.2 Feldspar

Microcracking is particularly obvious in feldspar than quartz, fracture in plagioclase has one perfect and one good cleavage plane, and it should behave similarly to K-feldspar (Fig. 5). While the slight concentration of cracking in K-feldspar close to the shear fracture is closely related to the two perfect cleavages in that mineral (K-feldspar, Fig. 6) and is nearly directional and transgranular and follow some parallel planes (Fig. 6). Other cracks develop during tectonic deformation and tend to occur along cleavages (Fig. 7). The existence of cataclasis is likely associated with the cleavage orientations of the K-feldspar (Fig. 7) because these orientations reflect a direction of deformation that initially opened the system of fluid transport. The contact boundary is gradational in K-feldspar-plagioclase boundary (Fig. 8) and seemingly sharp in quartz-biotite or feldspar-biotite boundary (Figs. 12 and 13).

In some K-feldspar grains, the fracture is build from the coalescence of bridges between en echelon group fract ures extended parallel to the load axis (Figs. 9 and 10). It is due to this particular en echelon failure form, the fracture surface of feldspar is more“ undulated ” than that as created by quartz grains. So permanent deformation of feldspars occurs by microcracking, mechanical twinning, creep and grain boundary sliding. The reason of the feeble degree of cracking in between K-feldspar and plagioclase is due to the commonly occurring K-feldspar mantles over plagioclase and the contact between the two minerals will be much stronger than is characteristic for grain boundary (Fig. 11). Some of the large plagioclase crystals in the Westerly granite are mantled by K-feldspar; good example can be seen in the Fig. 11. Similarly mantled feldspars in the Barre granite of Vermont were considered by Chayes[12] to be a late-stage, igneous crystallization process, with the K-feldspar finding a preferred nucleation site on the plagioclase. In detail, thought, at least minor replacement of the plagioclase has occurred along the boundary with the K-feldspar.

Furthermore, plagioclase appears to be more resistant to microcracking than coexisting alkali feldspar, but it has not been demonstrated whether this is related to the bond strength, to the microstructure (e. g., perthite), or both. Mechanical twinning is common in natural plagioclases from deep-seated rocks, but is absent in alkali feldspars. The extensive hydrothermal alteration of some plagioclase crystals may interfere with development of long cleavage cracks, however, because the plagioclase structure will be interrupted in places by replacement minerals that could provide a barrier to crack propagation (Fig. 13).

3.3 Biotite

Biotite can be easily delineated under SEM due to its perfect structure. It is slightly folded and kinked near the borders of quartz and feldspar grains (Figs. 12, and 13). This kinking would be explained by unhomogenity in elastic stiffness at the boundary between biotite (hardness 3 and planer cleavage) and feldspar or quartz (hardness 6 and 7 respectively), which induces large tensile stresses in the stiffer grain . The observations of biotite flakes have indicated that the separating of cleavage planes is the major failure form of biotite (Figs. 14 and 15). Cracks, if any, rarely go through the biotite grain itself and the most mobile boundaries are those between two the outside lattices (Figs. 14 and 15). The cracks are either developed along the boundary or arrested in the biotite grains through some voids that play as a crack prison (Fig. 16). It seems reasonable to treat biotite grains as small“ voids” (Figs. 16) scattered throughout the granite and they act as soft as well as deformable particles with weaker connection to the neighboring mineral grains (Figs. 12, 13, and 14). The specific microstructural nature of biotite, i. e. the perfect cleavage in biotite grains (Figs. 17 and 18), is the dominant factor directly governing the failure form biotite. Compared with quartz and feldspar, biotite is a relatively soft mineral in granite with lower strength and modulus[13] . Furthermore, if weaker minerals such as biotite in a rock surround feldspar and quartz grains it will be cushioned from any applied stress. Finally, the cleavage planes of biotite would have weakened the rock and facilitated local cataclasis, where brittle deformation occurs; the strong replacement of this Na-plagioclase by K-feldspar would favorable.

4 Conclusion

Scanning electron microscope observations reveal the relation of mineralogy with cracks pattern in granite of Zhejiang area. The failure process in granite is possibly more dominated by crack propagation through grains. The orientation of microcracks become evidently more parallel to the loading direction. Most microcracks are following the grain boundaries, cleavage planes within biotite and feldspar, and simple twin planes in plagioclase. Cleavage plane, a weaker crystallographic plane, is an important structural factor to shape the final failure features of feldspar and biotite.

Regarding to failure characteristic the behaviors of quartz and feldspar display a brittle manner, whereas the fracture of biotite exhibit some extent, plastic. Kinking and folding are observed in biotite, principally in grains closed to fracture. Quartz fails in two major forms, boundary cracking and transgranular cracking. Where deformation and shearing was strong, plagioclase crystals whose cleavage planes were aligned parallel to the plane of shearing were the ones which were initially or most often slightly cracked and replaced by K-feldspar. In this way the K-feldspar inherited the lattices of plagioclase crystals all having the same parallel orientation. Deformation that breaks crystal boundary-seals and bends and fractures crystal lattices is essential to produce avenues for fluid migration. So hydrous fluids have existed in fractured rocks to cause nearly isochemical alterations and weathering on a large scale. Quartz is relatively isotropic and feldspar is relatively anisotropic. Grain boundary cracking is strongly associated with mineralogy, and the fracture mechanisms for various types of minerals are obviously different, which are closely related to their native microstructures.

The lesser degree of cracking along K-feldspar-plagioclase boundaries is due in large part to the commonly occurring K-feldspar mantles over plagioclase. Because the K-feldspar overgrowth is in crystallographic continuity with the plagioclase core, the contact between the two minerals will be much stronger than is characteristic for grain boundaries.

ACKNOWLEDGMENTS:

Praise be to God, Lord of the Heavens, Lord of the Earth, and Lord of the all World. The authors wish to thank Prof. Cui-ze Shi, the director of Laboratory Technology Center of China Medical University, Shenyang and Mr. H. J. Wang in the Foreigner Affairs Office in Northeast University, Shenyang for providing the facilities to carryout this work.

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EXPLANATION OF PHOTOGRAPHS:

1 – SEM photomicrograph showing the typical transgranular failure of quartz, which well developed straitions and trenches or pore inside the quartz grain can recognize. The white debris scattered on the surface are cataclastic minerals formed during fractures. Q: Quartz, p: pore.

2 – SEM photomicrograph showing some smooth fractured surfaces of quartz with some micro fracture slickensides, which indicate the stress direction. Q: Quartz.

3, 4 – SEM photomicrographs showing a typical brittle fracture pattern of quartz.

5 – SEM photomicrograph showing the failure of plagioclase, which has one perfect and one good cleavage plane extending in one direction. There is a smooth contact between plagioclase and quartz. PL: Plagioclase, Q: Quartz.

6 – SEM photomicrographs showing the failure of K-feldspar. Their fracture surfaces are closely related to the two perfect cleavages. Note, fracture in feldspars (Plagioclase and K-feldspar) is nearly directional and transgranular and follow some parallel planes compared with quartz. K: K-feldspare.

7 – SEM photomicrograph showing the cataclasis of K-feldspars, which associated with the cleavage orientations of the minerals because these orientations reflect a direction of deformation. There is a contact boundary between the two K-feldspar grains that fail in transgranular form. K: K-feldspar.

8 – SEM photomicrograph showing the gradational contact boundary in K- feldspar-plagioclase grains. PL: Plagioclase, K: K-feldspar.

9, 10 – SEM photomicrograph showing the failure of K-feldspar displayed step-like shape extending parallel to the load axis. It is due to this particular en echelon failure form, the fracture surface of K-feldspar is more "undulated" than that as created by quartz grains. K: K-feldspar.

11 – SEM photomicrographs showing the concentrations of cracking in and around quartz. Cracks in quartz grain usually present themselves as straight and smooth lines. The lesser degree of cracking along K-feldspar-plagioclase boundaries is due in large part to the commonly occurring K-feldspar mantles over plagioclase. A large portion of the fracture surface fails in the form of transgranular cracking, or boundaries cracking, particularly for the fracture of feldspar and these areas always associate with the failure of quartz. PL: Plagioclase, K: K-feldspar.

12, 13 – SEM photomicrograph showing the biotite breaks down and is replaced by plagioclase and quartz. It is slightly folded and kinked near the borders of quartz and plagioclase grains respectively. Bi: Biotite, Q: Quartz, PL: Plagioclase.

14 – SEM photomicrographs showing the contact boundary between biotite and quartz grains. Cleavage plane is obvious in biotite. Bi: Biotite, Q: Quartz.

15 – SEM photomicrographs showing the major failure of biotite and the most mobile boundaries are those between two lattices, which are so oriented. Bi: Biotite.

16 – SEM photomicrograph showing mélange of biotite due to different stresses. Ttransgranular fracture in stressed crystal, folding and kinking in deformed biotite. There are voids inside the biotite. Bi: Biotite ;V: Void.

17, 18 – SEM photomicrograph showing separated cleavage planes of biotite grains. The fractures exhibit distinct propagation across the cleavage planes at which loading took place. Bi: Biotite.

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扫描电子显微镜对花岗岩中主要矿物裂隙作用的研究

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摘　要:微裂隙对于岩石的物理性质有重要影响. 通过光学显微镜对显微裂隙进行的观察, 难以将薄片的制作过程中产生的裂隙同自然裂隙区分 ;其次, 观测的裂隙大小限制在 0. 1 mm 或以上数量级, 一些重要细节观察不到. 扫描电镜的高放大倍数和三维分辨率使其成为适合于裂隙研究的理想工具. 利用扫描电镜观测了浙江花岗岩在室温下由 51. 6 MPa 压力产生的裂隙的发育过程. 观察花岗岩的表面以研究其微裂隙和矿物的解理、晶形及破裂作用. 微裂隙分为 3 种类型 :晶体内裂隙(完全发育在颗粒内部),晶体间裂隙(穿过颗粒边界进入其他颗粒中),颗粒边界裂隙(沿颗粒边界发育或与边界重合). 本研究中的花岗岩为中—粗粒(1 ~ 6 mm),经过蚀变,约含 40% 斜长石,25% 钾长石,25% 石英,10% 镁铁矿物(主要为黑云母和白云母).

(1) 石英　裂隙表面的石英颗粒具有边界破裂和贯穿颗粒破裂. 贯穿石英颗粒的破裂常呈贝壳状断口. 变形集中带与滑动面相伴, 其上发育有擦痕和沟槽, 这是石英典型的脆性破裂类型. 石英矿物的贝壳状破裂产状指示其变形作用早期的碎裂作用, 在变形作用中发生交代作用. 一些平滑的破裂面上没有石英颗粒的微裂隙构造, 但在石英表面却有明显的擦痕面, 可指示应力的方向. 由于石英的各向异性, 这些面也是由贯穿颗粒破裂所形成. 一些开放的裂隙集中于石英晶体之中或沿其边缘发育. 裂隙先在石英边界产生, 随着变形的加剧, 迅速发展到其颗粒内部. 因此石英被认为是花岗岩破裂过程的开端. 观察还显示,破裂首先出现在石英与石英或石英与长石之间的边界上,说明花岗岩中石英边界相对较弱,是破裂最容易发生的地方.

(2) 长石　长石中的微裂隙比石英中更明显. 斜长石具有一组完全解理和一组清楚解理,与钾长石具相似的裂隙特征. 而钾长石中剪切破裂附近的裂隙聚集与这两组解理关系密切, 沿平行面定向排列并穿切矿物颗粒. 其他裂隙由构造变形产生,沿解理面发育. 碎裂作用常沿着钾长石解理的方向,因为它们反映了变形的方向,该变形打开了流体运移系统. 钾长石与斜长石之间为过渡的界线, 而石英与云母或长石与云母之间界线分明. 在有些钾长石颗粒中, 裂隙是由平行于压力轴方

向的雁行裂隙组相连接构成的．由于这种特殊的雁列破裂形式，长石的破裂面比石英颗粒的破裂面更加“起伏”．所以长石的永久变形表现为微裂隙、机械双晶、蠕变和颗粒边界滑动．钾长石与斜长石之间破裂程度较轻，这是因为钾长石常包围在斜长石周围，这种接触关系比颗粒间的边界接触要强得多．深部岩石中的斜长石中常见机械双晶，但缺少钠长石．由于强烈的蚀变作用，产生的交代矿物阻碍了破裂的扩散，影响了斜长石晶体中的长解理裂隙的发育．

(3) 黑云母 在靠近石英和长石的边界处，黑云母发生轻微褶皱和扭折．这种扭折的产生是由于云母与长石或石英间弹性刚度的不同，在刚性颗粒中产生张性应力．解理面破裂是黑云母的主要破裂形式，很少有裂隙穿过黑云母颗粒．裂隙发育在黑云母颗粒的边界或孔洞内的黑云母中．可以将黑云母看作散布于花岗岩中的小“孔洞”，它们为柔软易变形的颗粒，与周围的矿物接触较弱．黑云母的完全解理决定了其破裂形式．与石英和长石相比，花岗岩中的黑云母相对较软，强度较低．而岩石中长石和石英周围的软弱矿物(如黑云母)在受到压力时将起到缓冲垫的作用．黑云母的解理会使岩石变弱，促进局部碎裂作用，产生脆性变形，斜长石被钾长石强烈交代．

关键词：花岗岩；矿物裂隙；扫描电子显微镜(SEM)

图版说明：

1—典型的石英贯穿裂隙，石英颗粒内可见发育的沟槽和孔隙．表面纤维状物为破裂过程中形成的碎裂矿物．Q：石英；P：孔隙．

2—石英平滑的破裂面，具显微裂隙擦痕面，指示应力方向．Q：石英．

3，4—石英的典型脆性破裂形式．

5—斜长石的破裂，具同一方向的一组完全解理和一组清楚解理．斜长石与石英间为平整接触．PL：斜长石；Q：石英．

6—钾长石的破裂．破裂成与两组发育完整的解理关系密切．斜长石和钾长石中的裂隙近定向平行排列，贯穿颗粒．K：钾长石；PL

7—钾长石的碎裂作用，沿矿物解理方向发育，代表变形作用方向．两粒边界接触的钾长石中发育贯穿颗粒裂隙．K：钾长石．

8—钾长石与斜长石之间的过渡接触边界．PL：斜长石；K：钾长石．

9，10—钾长石的阶梯状破裂，平行于载荷方向发育．由于裂隙呈雁列状排列，钾长石的破裂面比石英中更加“起伏”．K：钾长石．

11—石英内部及周围的集中破裂．石英颗粒内的裂隙常呈平直线状．由于钾长石与斜长石的幔核结构，沿它们之间边界的微隙较弱．大部分裂隙面呈贯穿颗粒破裂或边界破裂，尤其对于长石裂隙或有石英裂隙相伴的区域．PL：斜长石；K：钾长石．

12，13—黑云母破裂并被斜长石和石英交代．在靠近石英及斜长石的边界处，黑云母发生轻微褶皱和扭折．Bi：黑云母；Q：石英；PL：斜长石．

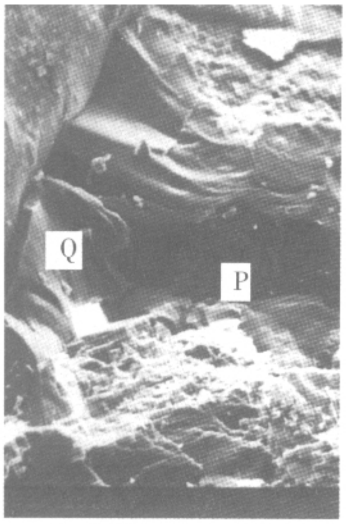
14—黑云母与石英间接触边界．黑云母中可见解理面．Bi：黑云母；Q：石英．

15—黑云母的主要裂隙和最活动边界都产生在两晶格之间，且具方向性．Bi：黑云母．

16—不同应力造成的黑云母混杂排列．受压力晶体发生贯穿颗粒破裂，变形产生褶皱和扭折．黑云母内有孔洞．Bi：黑云母；V：孔洞．

17，18—黑云母颗粒的解理面．在受到载荷处，裂隙扩散穿过解理面．Bi：黑云母．

PLATE Ⅰ (图版Ⅰ)



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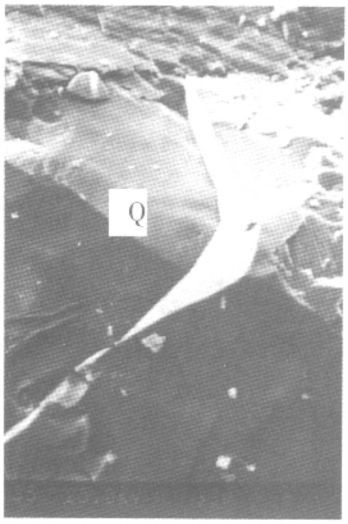

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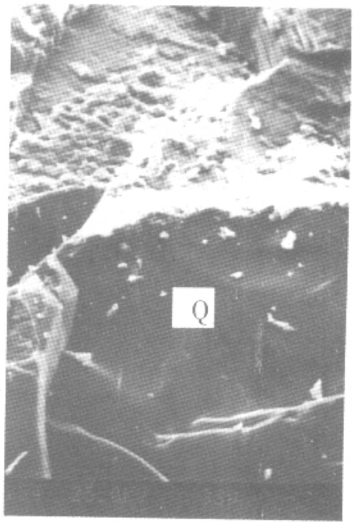

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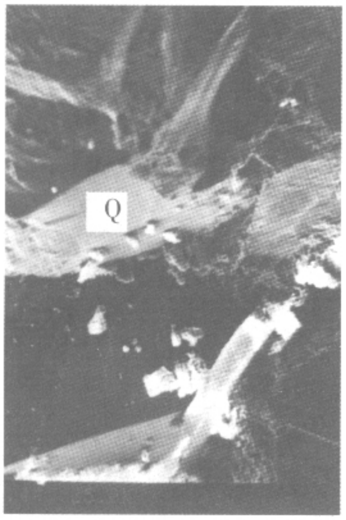

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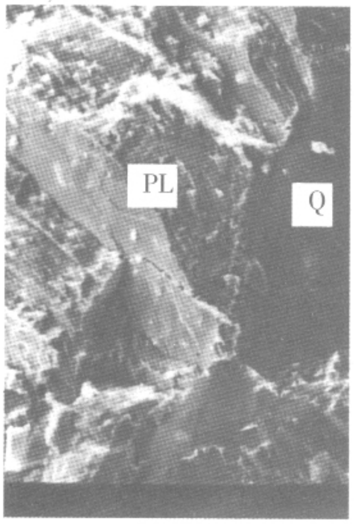

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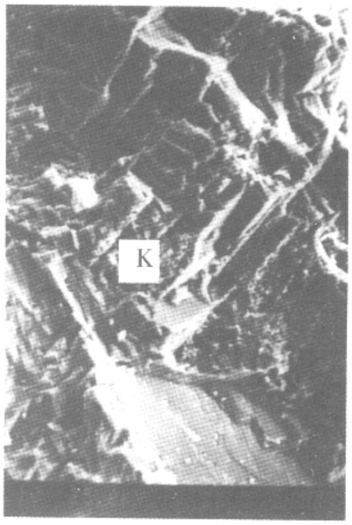

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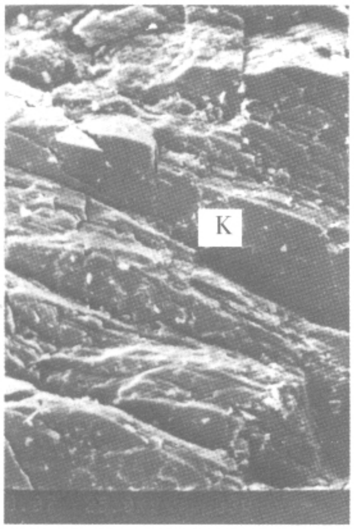

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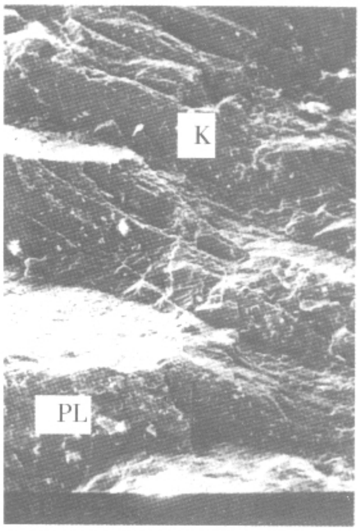

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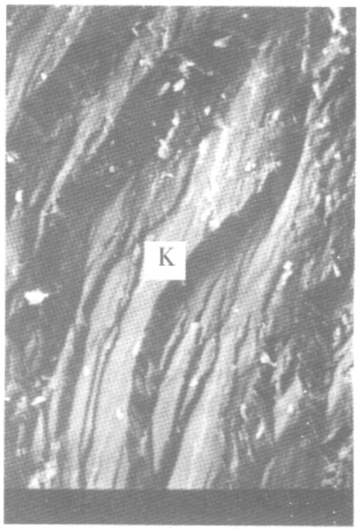

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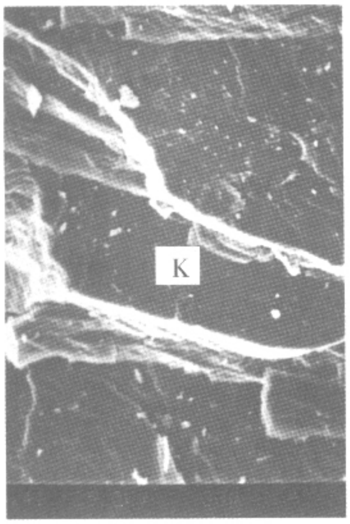
PLATE Ⅱ (图版Ⅱ)



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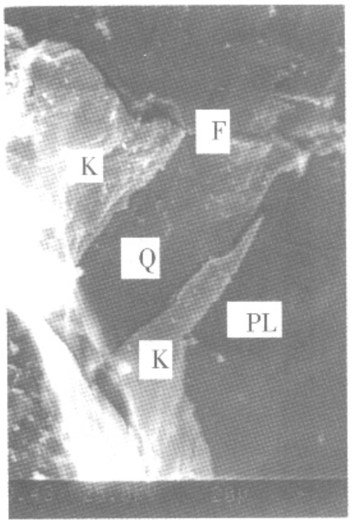

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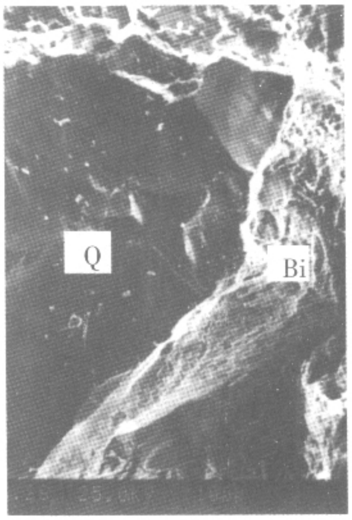

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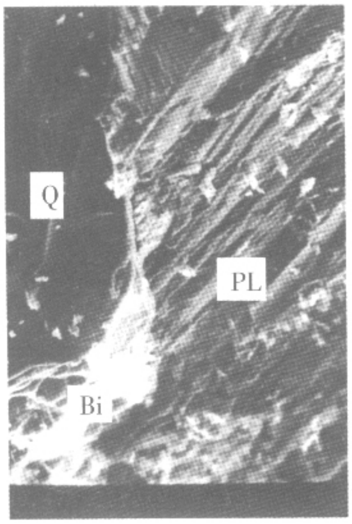

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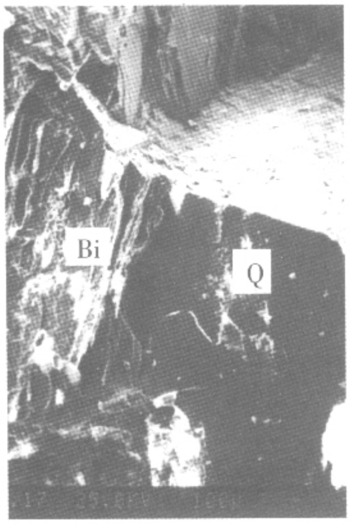

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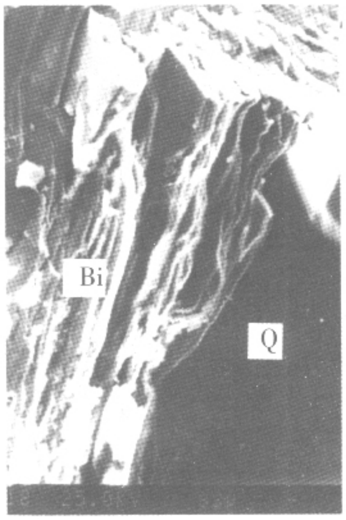

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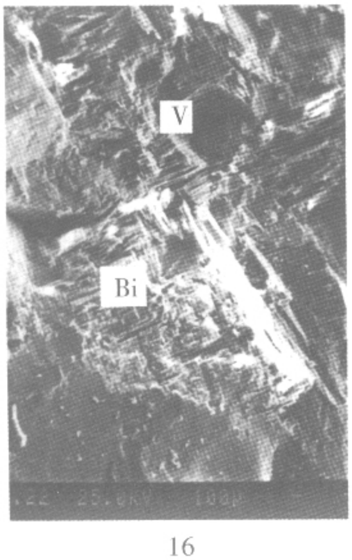

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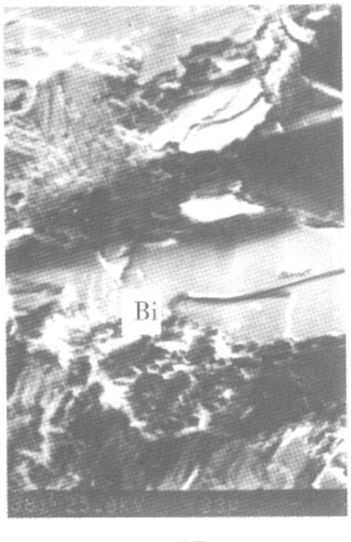

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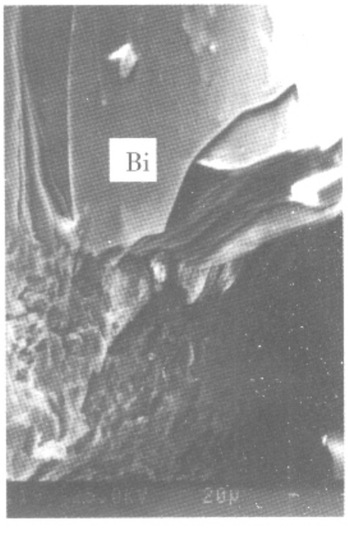

18