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SHORT NOTE

Cathodoluminescence observations on low-temperature mylonites: potential for detection of solution–precipitation microstructures

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Abstract—This note represents cathodoluminescence (CL) images, obtained using a scanning electron microscope, of a low-temperature granitic mylonite from central Japan. It is argued that CL observations offer a simple but powerful tool for elucidating the importance of solution-transfer processes during mylonitization. Cataclastic deformation such as fracturing of feldspars, accompanied by solution–precipitation processes, were found to be much more clearly observable in CL images than using other techniques. It is also shown that quartz grains precipitated from solution can be distinguished from original quartz grains in the granite, even after being deformed plastically. More detailed CL work on mylonites is needed in the future, since quantitative evaluation of the role of solution–precipitation processes in deep fault zones is essential for constraining the rheological properties of faults at depth.

INTRODUCTION

SINCE solution–precipitation processes can dramatically lower the strength of rocks at slow strain rates (e.g. Rutter 1976, Rutter & Mainprice 1979, Spiers *et al.* 1990), the strength of rocks under geological conditions should depend markedly on the importance of solution-transfer processes in relation to other deformation mechanisms. Recently, *S–C* mylonites and ultramylonites have been proposed to have formed in the transitional regime between the brittle and fully plastic fields where large earthquakes initiate and rock strength approaches a maximum (Shimamoto 1989). Therefore, in order to model the mechanical behaviour of faults and plate boundaries, including the generation of large earthquakes, and to evaluate the strength of the lithosphere, one must know the degree of involvement of solution-transfer processes during mylonitization.

This note demonstrates the usefulness of cathodoluminescence (CL) observations on mylonites for this purpose. CL images have long been used to observe textures within mineral grains and sedimentary rocks to understand mineral growth processes and diagenetic processes in sediments (see comprehensive review by Marshall 1988). CL is generally believed to be associated with defects and/or impurities in crystals, but the exact mechanism for its emission is still poorly understood, particularly in the case of quartz. However, it is well-known in sedimentary petrology that authigenic quartz is much less luminescent and appears much darker than detrital quartz grains which formed at higher temperatures. This type of contrast has motivated the present study, aimed at distinguishing quartz precipitated from solution from original grains in the granite, even after mylonitization.

CL observations have also been used successfully in structural geology to observe patterns of healed microfractures (Sprunt & Nur 1979, Blenkinsop & Rutter 1986, Kanaori 1986). They are shown here to yield rich textural patterns in mylonites as well, which cannot be revealed by other observational techniques.

GEOLOGICAL SETTING

CL observations were made on 17 samples from a mylonite zone in the Ho-oh granite running along the Itoigawa–Shizuoka tectonic line (referred to as the Ito–

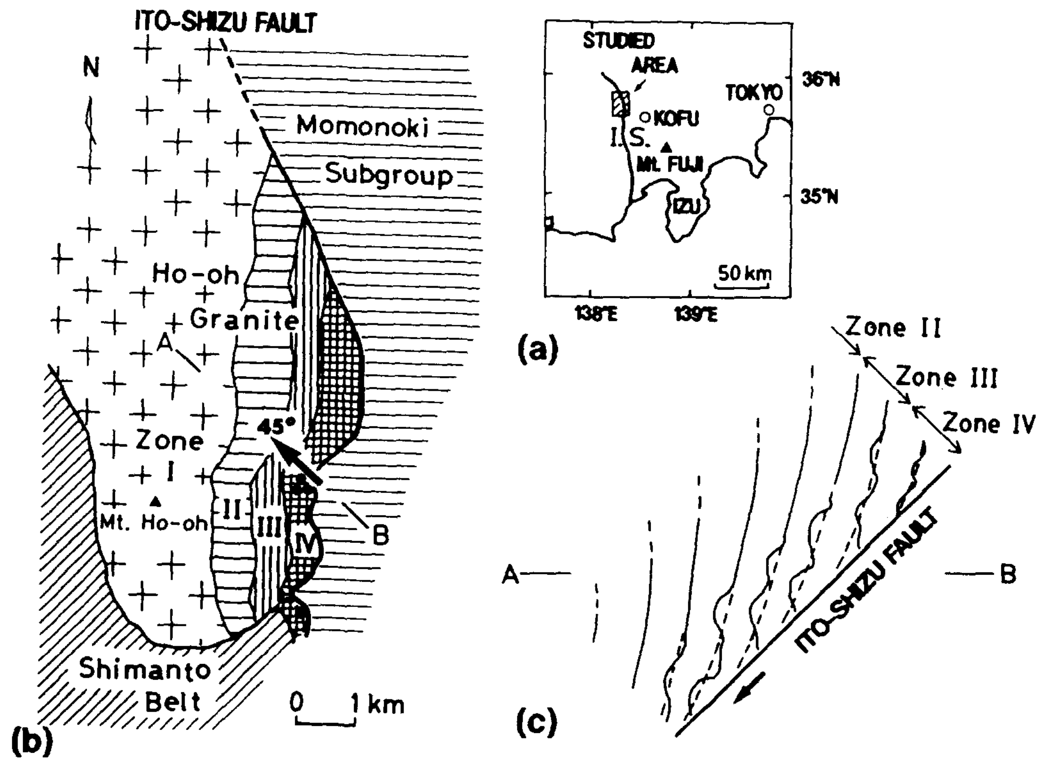

Fig. 1. (a) Locality map of the Ho-oh area in central Japan. (b) Simplified geological map showing Ho-oh granite and its mylonitized zone to the southeastern side along Itoigawa–Shizuoka tectonic line (Ito–Shizu fault). (c) A schematic cross-section across the mylonite zone from A to B in (b) (simplified from Asai 1990). The mylonites have been divided into five zones, I–V, as shown in (b), based on the grain size of deformed quartz and the pattern of mylonite foliation. Dots indicate ultramylonite localities (zone V).

Shizu fault hereafter), central Japan (Fig. 1). The Ho-oh granite is dated at 11.7 Ma and is intruded into the Shimanto belt (Sato *et al.* 1989). Its southeastern margin is mylonitized along the Ito–Shizu fault to a width of 1.5–2 km (Fig. 1b) (Asai 1990). Mylonitic deformation is concentrated in quartz which deformed predominantly plastically and exhibits deformation bands, elongated subgrains or cellular structures, and recrystallized grains. Plagioclase and potassium feldspar are less deformed, in a largely brittle manner. The fractures in the feldspars are filled with quartz, chlorite and a very small amount of greenish biotite. Original biotite is often kinked and sheared, and altered partially into chlorite, whilst epidote is developed very locally. Mylonitization is therefore presumed to have occurred under lower-greenschist facies conditions, not very much later than the K–Ar age cited above.

The relationship between the mylonitic foliation and the Ito–Shizu fault is schematically shown in Fig. 1(c). This, together with the microstructures of the mylonites, indicates essentially reverse-slip motion along the Ito–Shizu fault in the direction of N50° W, with a plunge of 45° NW (the arrow in Fig. 1b)(Asai 1990).

As seen in many other mylonite zones throughout the world, the Ho-oh mylonites exhibit grain-size refinement in the quartz towards the Ito–Shizu fault (Asai 1990). The grain size of the quartz is about 1.0–1.5 mm in the undeformed zone (zone I in Fig. 1b) and decreases progressively to around 0.1 mm within a distance of about 1 km (zone II). The grain size remains at about 0.1 mm on average in zones III and IV, although the mylonitic foliation in zone IV displays more irregular orientation than that in zone III (Fig. 1c). Ultramylonites, much finer grained than the mylonite comprising zone IV, occur sporadically near to the Ito–Shizu fault (zone V, shown as solid circles in Fig. 1b).

CL images of only four representative specimens are shown here. Their localities are given only in terms of the above mentioned zoning; i.e. Sp-1 = zone II, Sp-2 = zone III, Sp-3 = zone IV and Sp-4 = zone V.

CL METHOD

Conventional petrographic thin sections were polished using 1 μm diamond paste and subsequently coated with a 20–40 nm thick film of carbon. The sections were then examined using a scanning electron microscope (SEM Hitachi S-450) operating at an accelerating voltage of 25–30 keV. The near surface CL was detected via an optical fibre attached to a photomultiplier with the detecting wavelength of 400–650 nm. The signal from the photomultiplier was amplified to form black and white CL images on the SEM screen. The images obtained represent the total intensity of CL emitted from each locality exposed to the scanned electron beam. No colour images were constructed.

CL observations were also attempted on the same specimens using a luminoscope (The Nuclide ELM-3, MAAS) attached to an optical microscope. No subtle differences in CL images of different types of quartz grains (see next section) were revealed with this conven-

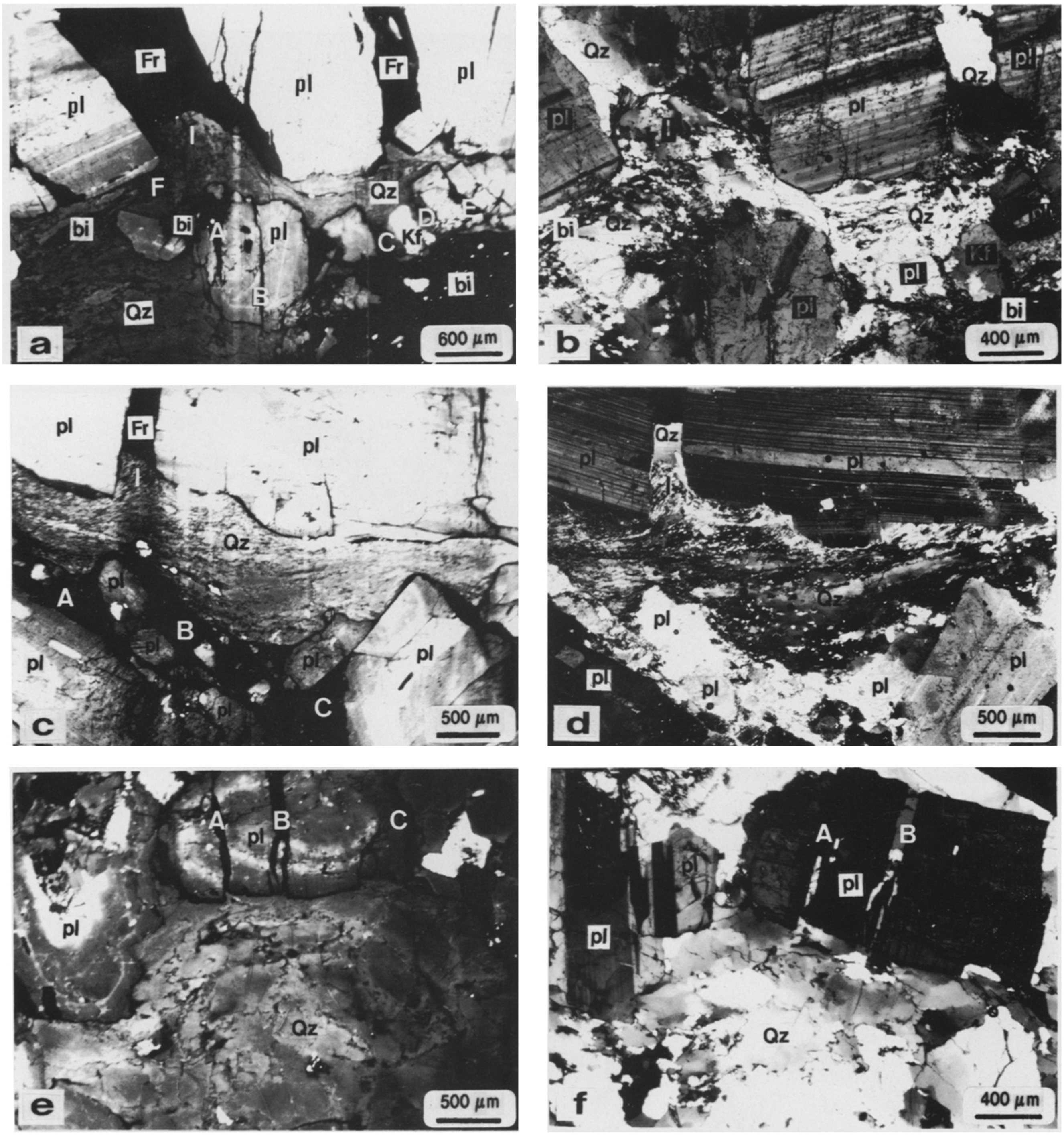

Fig. 2. Cathodoluminescence (CL) images (left) and their corresponding photomicrographs taken in crossed polarized light (right) of the Ho-oh mylonites. Capital letters denote areas referred to in the text. Only conspicuous grains are identified on the photographs using the abbreviations: pl = plagioclase, Qz = quartz, Kf = potassium feldspar and bi = biotite. (a) & (b) (Specimen No. 3, zone IV.) Fractures in plagioclase filled with coarse-grained secondary quartz (non-luminescent and black). (c) & (d) (Specimen No. 2, zone III.) Fractures (Fr in c) in a plagioclase grain filled with non-luminescent quartz: also visible are disrupted and pull-apart plagioclase grains surrounded by secondary quartz, potassium feldspar, epidote, chlorite and plagioclase (A–C in c). Observe in (b) and (d) that the plagioclase deformed primarily by cataclasis, but that deformation of quartz is predominantly plastic. This is characterized by well-developed deformation bands, elongated subgrains or cellular structures and recrystallized grains. (e) & (f) (Specimen No. 1, zone II.) Fractures in plagioclase (A–C) filled with secondary quartz, and quartz with undulatory extinction in slightly deformed granite.

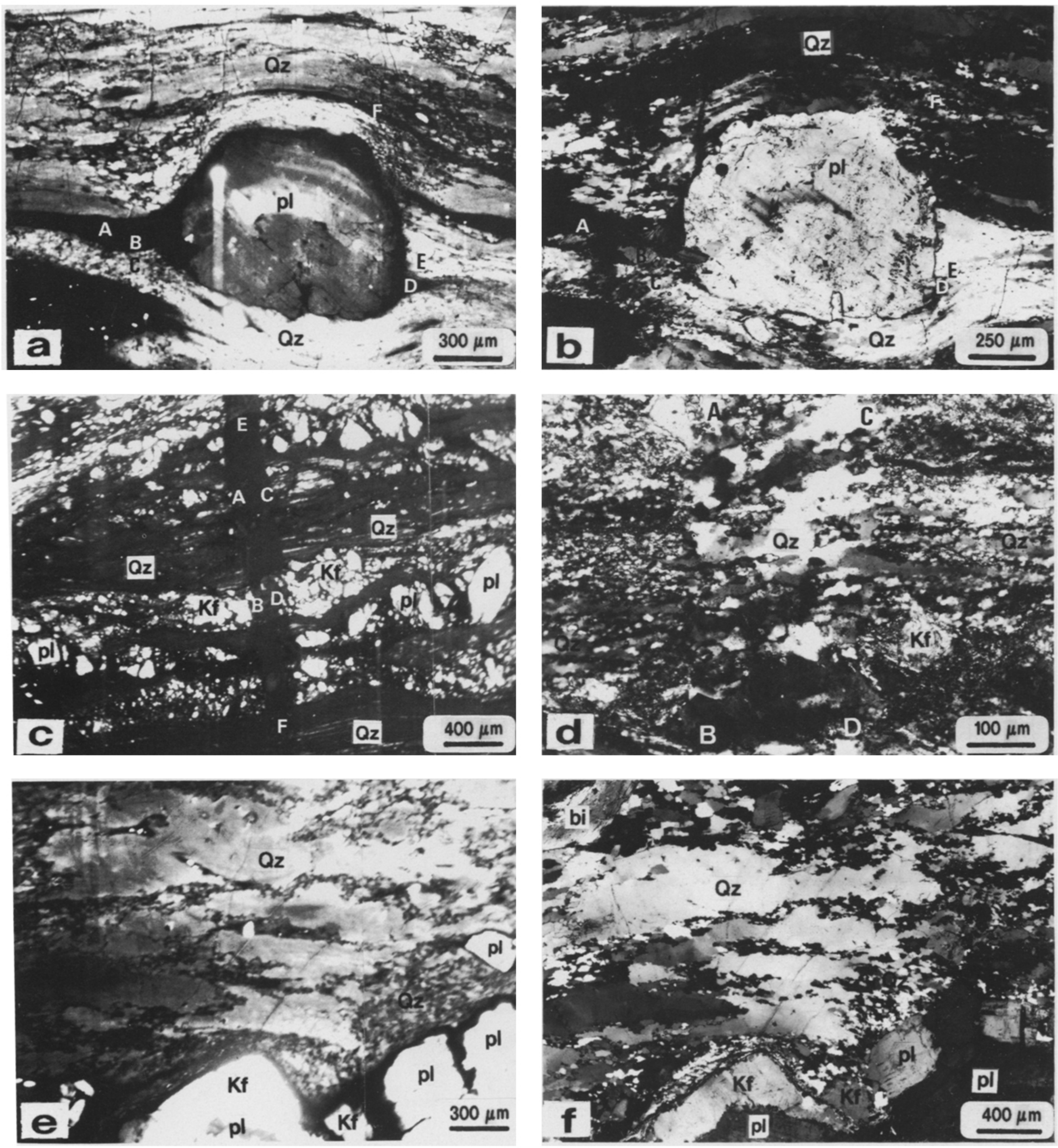

Fig. 3. CL images (left) and their corresponding photomicrographs under crossed polarized light (right) of the Ho-oh mylonites. (a) & (b) (Specimen No. 3, zone IV.) Plagioclase porphyroclast surrounded by plastically deformed quartz. (c) & (d) (Specimen No. 4, zone V.) Quartz vein (E and F in c) in ultramylonite which has deformed plastically during mylonitization. Although the mylonitic foliation is developed uniformly and pervasively across the vein, the quartz vein can still be recognized under CL, even after the mylonitization. (e) & (f) (Specimen No. 3, zone IV.) Plastically deformed and partially recrystallized quartz showing clear CL contrast and thus reflecting the degree of recrystallization. Note in (e) that recrystallized grains are less luminescent than non-recrystallized grains.

tional microscopy with an exposure time of several minutes. An SEM equipped with an image processing device is much more convenient than an optical CL microscope in producing high-contrast images of grains with slightly different CL intensity.

CL OBSERVATIONS AND INTERPRETATION

Typical CL microstructures obtained in the present study are shown in Figs. 2 and 3 (left columns) together with corresponding optical micrographs (right columns). The main minerals in the Ho-oh mylonites were found to show similar CL characteristics to those reported previously (see Marshall 1988). The feldspars luminesce brightly and appear white on the CL images (Fig. 2a). Quartz grains generally show dull-luminescence with grey to dark contrasts, while the mafic minerals in the granite (biotite, hornblende and chlorite) are non-luminescent and hence appear black (Fig. 2).

Plagioclase and potassium feldspar are fractured to various degrees in complex manners. Figures 2(a)–(f) show fractures in plagioclase filled with non-luminescing and hence black quartz (Fr in Figs. 2a & c, and A–C in Fig. 2e). Notice that plastically deformed quartz seems to be partially intruded into the opened-up fractures at point I in Figs. 2(a) & (b). Quartz infill is normally coarser grained than plastically deformed quartz (Fig. 2b), but the distinction can be made much more readily on CL images. In particular, fractures A–E in Fig. 2(a) and A–C in Fig. 2(e) stand out much more clearly in CL than under the polarizing microscope (cf. Figs. 2b & f).

In Fig. 2(c), the dark material between A and C consists of quartz, potassium feldspar, epidote, chlorite and plagioclase. It is well-known from sedimentary petrology that authigenic feldspars and quartz tend not to luminesce, in marked contrast to detrital feldspar and quartz grains (e.g. Marshall 1988). In view of such experience, the textures in Fig. 2(c) can be interpreted as representing fractured and pull-apart grains filled with secondary minerals precipitated from solution. Such contrast can seldom be obtained using other observational techniques (cf. Fig. 2d). Around F in Fig. 2(a), thin and dark seams with anastomosing patterns in plastically deformed quartz are connected to the fracture infill (Fr) and probably represent secondary quartz infilling pull-apart aggregates of plastically deformed quartz. Such contrast cannot be obtained using a polarizing microscope (Fig. 2b).

In Fig. 3(a), the non-luminescent region (A) adjacent to a large porphyroclast consists mainly of deformed biotite and its fine-grained alteration products. The non-luminescent quartz grain denoted by B in Fig. 3(b) seems to have precipitated from solution to fill a pull-apart gap in the biotite grain in a pressure-shadow zone. In marked contrast to the neighbouring plastically deformed quartz, this grain does not luminesce (cf. B and C in Fig. 3a). The non-luminescent zone on the other side of the porphyroclast (D in Figs. 3a & b) consists of quartz which also most likely precipitated from solution in a pressure shadow. Although the quartz grains in the pressure shadow have somewhat different crystallographic orientation from those of the neighbouring grains, the CL contrast between the secondary quartz and the plastically deformed quartz possesses clear advantages over other techniques (cf. D and E in Figs. 3a & b). The non-luminescent upper margin of the plagioclase porphyroclast in Fig. 3(a) probably has a changed composition. However, correlation between the CL signature and chemical composition of feldspars has not yet been attempted. The dark linear zone running nearly horizontally through point F in Fig. 3(a) may indicate secondary quartz filling a pull-apart gap in the plastically deformed quartz (cf. F in Fig. 2a).

An interesting quartz vein was found in an ultramylonite sample, shedding light on the problem of whether quartz grains precipitated from solution can be distinguished from original grains, even after plastic deformation (EF in Fig. 3c). The vein was deformed plastically, more or less contemporaneously with mylonitization. The foliation, defined by the alignment of elongated quartz grains, is developed continuously and pervasively across the vein, although deformed quartz in the vein (ABCD in Fig. 3d) is somewhat coarser grained than those in the surrounding quartz-rich layers. Under CL, the vein appears slightly darker than the surrounding quartz and its margin can be recognized clearly (ABCD in Fig. 3c). Thus the distinction between the two types of quartz seems to be possible even after severe plastic deformation. This is encouraging because solution–precipitation textures even prior to plastic deformation may eventually be identified. However, with our present system of CL observations, unambiguous distinction of such a subtle difference in CL intensity as in the case of Fig. 3(c) is not generally possible.

Plastically deformed quartz grains in the Ho-oh mylonites are frequently characterized by deformation bands, coexisting with recrystallized grains (lighter portions and darker grains, respectively, in Fig. 3f). These recrystallized grains are notably less luminescent than the deformation bands and appear darker in CL images (Fig. 3e). The deformed quartz in the ultramylonite (zone V) is recrystallized more pervasively and is less luminescent than the quartz found in the other zones (cf. Figs. 3c & e). On the other hand, quartz in weakly deformed zones exhibits only undulatory extinction (Fig. 2f) and luminesces more than quartz in more deformed zones, although this difference in CL cannot be recognized in Figs. 2(e) and 3(e) owing to the different setting for the image processing in the SEM used for these CL micrographs. Thus, the general trend is that increasing deformation and recrystallization causes less luminescence.

The origin of this decreasing trend of CL intensity with increasing macroscopic deformation may be related to dislocation density and/or the density of point defects. There are at present no independent data available for point defects. However, for dislocation density, Asai (1990) found decreasing, rather than increasing, dislocation density with grain-size refinement, from zone I to zone V in Fig. 1(b) (cf. Behrmann 1985). A simple interpretation for this is that strongly deformed quartz is more susceptible to recrystallization (either syn- or post-deformational) than less deformed quartz, resulting in decreasing dislocation density with strain (Shimamoto 1989 for more details). If CL emission is associated at least partly with defect content (Marshall 1988), this could explain the observed trend of decreasing CL intensity with increasing strain and is consistent with low CL emission from the recrystallized grains in Fig. 3(e).

Spiers (written communication 1990) has suggested an alternative interpretation that the recrystallized grains in highly deformed material actually grew out of solution (cf. experimental work of den Brok & Spiers 1991), or formed partly by a mechanism of fluid-assisted grain-boundary migration. The former possibility is somewhat unlikely, since the intensity of CL from the recrystallized grains is notably stronger than that from the fracture-filling quartz (Fig. 2) which is definitely a precipitation product. Moreover, the majority, though not all, of the recrystallized grains have a similar crystallographic orientation, typical of subgrains or cellular structures. However, the fluid-assisted grain-boundary migration could have partially altered the texture and this might have contributed to the reduction of CL in the recrystallized grains.

SUMMARY AND CONCLUSIONS

The present work is preliminary, but to our knowledge is amongst the first to demonstrate the potential use of CL observations in the micro-structural analyses of low-temperature mylonites. The major results from the CL observations on Ho-oh mylonites, central Japan, are summarized below.

(1) Cataclastic deformation, in particular fracture patterns, can be clearly revealed using CL, owing to the general lack of luminescence from secondary minerals filling opened fractures (Figs. 2a–f).

(2) CL can clearly image secondary minerals filling the gaps between disrupted and separated grains (Figs. 2a & c, and possibly 3a). These secondary minerals cannot be revealed in a simple and unambiguous manner with other techniques presently available. Likewise, secondary minerals precipitated in pressure shadows stand out clearly under CL (Fig. 3a).

(3) Using CL, quartz precipitated from solution can be distinguished from original igneous quartz even after being deformed plastically during mylonitization. This was demonstrated by means of a deformed quartz vein (Fig. 3c).

(4) In the mylonites studied, recrystallization of quartz becomes more pervasive with increasing strain during mylonitization. This trend is associated with a decrease in dislocation density and emitted CL intensity. The decrease in CL intensity is thought most likely to reflect directly the decreasing defect density, although a possibility that a solution–precipitation process was involved in the recrystallization cannot be excluded definitively. CL observations may provide a crude initial assessment of defect states in specimens.

These results suggest that CL observation is a simple but effective method towards quantitative assessment of the involvement of the solution–precipitation (especially the latter) processes during mylonitization. In particular, result (2) indicates that the involvement of the solution–precipitation processes is more dramatic than implied by healed fractures in feldspars alone. CL observation is particularly important in the strength-peak regimes of the lithosphere, because solution-transfer processes offer an ideal grain scale accommodation process in the semi-brittle and semi-plastic regimes. Closer analyses of deformation mechanisms on the scale of individual grains in combination with CL observation are desirable in future, in order to assess the role of solution–precipitation processes in determining the rheological properties of deep faults and plate boundaries.

The exact source of CL emission from minerals, particularly quartz, is still open to speculation (see Marshall 1988). Results (3) and (4) above are consistent with the idea that CL in the deformed quartz is associated with defects and/or impurities introduced either at the time of formation or during mylonitization. However, the clear distinction of quartz precipitated from solution from the original quartz in the granite is not always possible with our present system of CL observations owing to the subtle difference in CL intensity between the two types of quartz after plastic deformation. This makes it difficult to estimate accurately the strain contribution of solution–precipitation processes in Ho-oh mylonites. More quantitative analysis of CL than that reported herein, including the measurement of CL emission spectrum, may provide clues to delineate mineral grains precipitated from solution even after severe mylonitization. Carefully-designed fundamentally-oriented experiments are needed in the future to establish a standard procedure of CL analyses in mylonites. The present results are encouraging as a first step toward such investigation.

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