Contrib. Mineral. Petrol. 65, 293–299 (1978)

Contributions to
Mineralogy and
Petrology

Fluid Inclusions, Deformation and Recrystallization in Granite Tectonites

Ronald W.T. Wilkins[1] and John P. Barkas[2]

[1] C.S.I.R.O. Division of Mineralogy, P.O. Box 136, North Ryde, N.S.W. 2113, Australia
[2] Department of Geology and Geophysics, University of Sydney, N.S.W. 2006, Australia

Abstract. An investigation has been made of the relationships between tectonic processes and fluid inclusions in quartz from variably deformed and syntectonically recrystallized granitic rocks from the Lachlan Fold Belt, eastern Australia. The quartz contains many fluid inclusions which decorate healed fractures introduced as a result of late-stage brittle deformation. The majority of small inclusions however, are associated with deformation band boundaries and deformation lamellae showing that they have been introduced during or subsequent to ductile deformation. Fluid inclusions disappear from the cores of sub-grains during recovery and before recrystallization, and new inclusions which form along sub-grain boundaries coalesce into stringers. Inclusions are eliminated from both sides of low angle boundaries showing that inclusions leak their contents either through the system of dislocations which accompanies grain interior slip, or by a dissolution-condensation process whereby inclusion contents move by lattice diffusion and condense on the boundaries.

Introduction

Fluid inclusions may be broadly classified into two types: those which are formed at crystal faces during crystal growth (primary inclusions), and those whose origin is associated in some way with deformation (secondary inclusions). The latter group may be subdivided into brittle-deformation inclusions which are formed during the healing of fracture planes, and ductile-deformation inclusions which may be defined as those associated with deformation and recovery features in mineral grains. Brittle-deformation inclusions are typically associated with surfaces that, within each grain, separate areas showing almost no differences in extinction position as observed with the petrological microscope. Such surfaces may be continuous across several grains. Ductile-deformation inclusions, however, have spatial relationships to some deformation lamellae (for example Boehm lamellae), and to features which are associated with lattice rotations resulting in optical extinction contrasts, such as subgrain and deformation band boundaries.

Rocks which have undergone ductile deformation have been regarded generally as uncertain subjects for fluid inclusion research. This is partly because the integrity of inclusions in such rocks is suspect, but also because the inclusions are typically small (<10 μm); indeed most are probably sub-microscopic and therefore unsuitable for heating, freezing and crushing stage studies.

It is well established that the presence of low concentrations of structural "water" significantly promotes deformation, recovery and recrystallization of synthetic quartz (Griggs and Blacic, 1965; Griggs, 1967; Hobbs, 1968). Experiments by the same authors have also shown that the hydrous environment provided by the breakdown of pyrophyllite, kaolinite or talc can significantly weaken and substantially enhance the recrystallization of "dry" natural quartz. Aqueous fluid inclusions are another potential source of hydrogen or hydroxyl ions during deformation, recovery and recrystallization, and although almost every rock contains fluid inclusions, often in abundance, little attention has been given to the possible influence of inclusion fluids on these processes in nature.

In addition to this possible contribution to hydrolytic weakening, inclusions are also of interest in that they are commonly almost entirely eliminated from their host minerals during recrystallization. Recent metallurgical and ceramic studies (Geguzin and Krivoglaz, 1973) have established mechanisms by which solid, liquid and gaseous inclusions can all be

0010-7999/78/0065/0293/$1.40

removed during the growth of new grains, but how inclusions are eliminated from quartz during recrystallization is not well understood.

Recently, Kerrich (1976) recorded a number of significant observations on some effects of tectonic recrystallization on fluid inclusions in vein quartz. Noting that even a small degree of intracrystalline strain may cause inclusion leakage, he concluded that only strain-free grains or strain-free domains within grains contain primary inclusions from which internally consistent homogenization temperatures may be recorded. In general the appearance of optical features resulting from plastic deformation is associated with a decrease in the number of fluid inclusions and an increase in filling temperatures showing that leaking has occurred. During recrystallization, empty cavities resulting from leaking are swept into subgrain walls, leaving the interiors of the subgrains clean.

In the present paper we describe the spatial relations between fluid inclusions and microstructures in quartz from several deformed and partly recrystallized Palaeozoic granites from the Lachlan Fold Belt, eastern Australia, as revealed by optical microscopy. The granites provide a relatively simple system for study, but the features observed are similar to those described in quartz veins by Kerrich, and found in many other quartz-bearing tectonites of diverse origins.

Fluid Inclusions in Deformed Granites

The petrology and tectonic setting of the middle to late Palaeozoic granitic rocks of the Lachlan Fold Belt in New South Wales have been discussed by Vallance (1969) and White et al. (1974). During an investigation of the nature and abundance of fluids trapped as inclusions in the minerals of these rocks (Wilkins and Barkas, 1975, and in prep.), relationships became apparent between the disposition of fluid inclusions and the degree of strain and recrystallization in quartz. For example, the presence of what are apparently fluid inclusions along grain boundaries in recrystallized quartz aggregates and the almost total absence of fluid inclusions from the interiors of recrystallized grains stands in marked contrast to the distribution of inclusions in the quartz grains of undeformed granites. In this paper we illustrate such observations and discuss their implications by reference to specimens from three granite bodies from the Lachlan Fold Belt, each with its own unique characteristics.

Outcropping in an area some 270 km southwest of Sydney, the *Young Granodiorite* is the major component of the extensive, meridionally-trending Burrinjuck-Young Batholith. The Young Granodiorite shows only slight to moderate degrees of deformation; advanced recrystallization of quartz is uncommon except in narrow, linear shear zones. Fluid inclusions are typically arranged along planar or slightly curved surfaces within quartz grains and they are visible as discontinuous streaks separated by inclusion-free areas in thin section (Figs. 1 and 2). Most of these surfaces have one of two dominant orientations. In almost every case the surfaces decorated by the inclusions and separating areas with different extinction positions, are deformation band boundaries.

Situated about 200 km west of Sydney, the *Barry Granodiorite* is an elongate, essentially concordant body approximately 25 km in length (north-south) but with a maximum width of only 4 km. While the northern part of this body consists of relatively massive biotite-hornblende granodiorite, the southern sections are highly deformed, and characterized by a steeply-dipping gneissic foliation. The Barry Granodiorite thus affords the opportunity to study relationships between fluid inclusions and deformation, recovery and recrystallization of quartz in a suite or related specimens showing progressive deformation.

Quartz in the deformed biotite meta-granodiorite is commonly streaked into augen that exhibit total or marginal recrystallization to fine-grained, strain-free, polyhedral aggregates. Larger, relic quartz grains show undulose extinction and varying degrees of internal recovery with the development of a subgrain structure (Fig. 3). The relic quartz, whether strongly or weakly deformed, is crowded with small fluid inclusions, almost invariably < 10 μm in diameter and more or less equidimensional. In the massive granodiorite, fluid inclusions are well dispersed in each quartz grain

Fig. 1. Deformed quartz with numerous small fluid inclusions, visible as black dots, concentrated along deformation band boundaries. Young Granodiorite. USGD 48607[1]. Long edge of figure 0.66 mm ▷

Fig. 2. Deformed quartz with deformation band boundaries decorated with numerous minute fluid inclusions. The deformation band boundaries, visible by extinction contrasts especially in the right hand grain, have three fairly consistent orientations in each grain. Young Granodiorite. USGD 48607. Long edge of figure 2.6 mm

Fig. 3. Deformed biotite-granodiorite showing advanced recovery in relic quartz and extensive recrystallization. Barry Granodiorite. USGD 48317. Long edge of figure 2.4 mm

Fig. 4. Quartz grains deformed into augen in deformed biotite-granodiorite. Fluid inclusions (black dots) are arranged in streaks sub-parallel to the length of the augen. A veil of inclusions (*X*) inclined at low angle to the plane of the section and cutting across the general fabric defines a late-stage healed fracture. Barry Granodiorite. USGD 48317. Long edge of figure 2.6 mm

Fig. 5. Inclusion-free recrystallized quartz grains against relic quartz with abundant fluid inclusions (black dots) of fairly equant shape. Barry Granodiorite. USGD 48317. Long edge of figure 0.26 mm

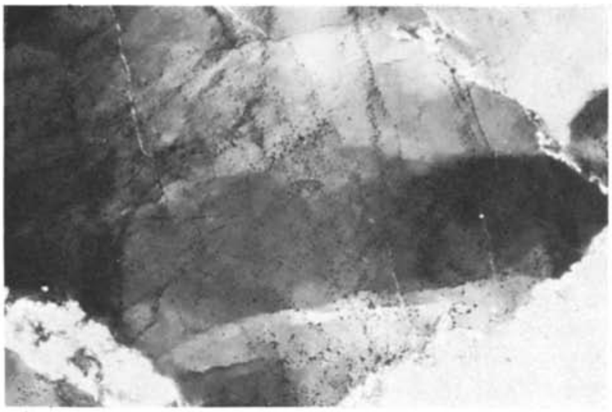
Fig. 6. Subgrains, immediately before an advancing recrystallization front (*R*). Their cores are cleared of inclusions, and boundaries outlined with elongate fluid inclusions which contain vapour bubbles (inset). Barry Granodiorite. USGD 48317. Long edge of figure 0.15 mm

Fig. 7. Etch pits along grain boundaries in recrystallized quartz. Barry Granodiorite. USGD 48317. Thick section. Long edge of figure 0.16 mm

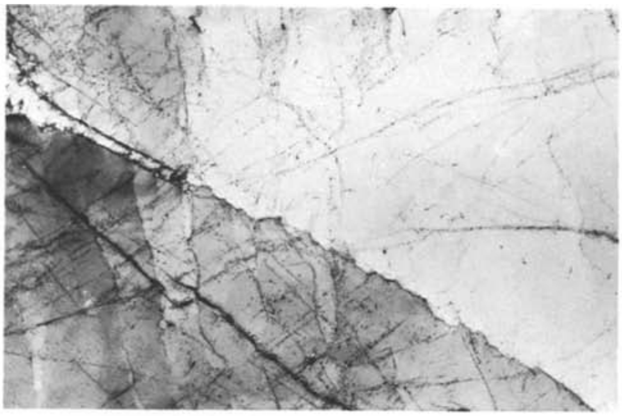
Fig. 8. Zones of depletion of fluid inclusions on both sides of deformation band boundaries. Each black dot is a small fluid inclusion. Erimeran Granite. USGD 48486. Long edge of figure 0.66 mm

---

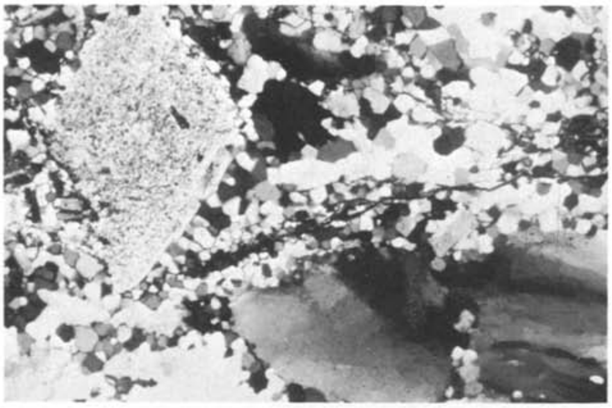
[1] Numbers refer to specimens in the rock collection of the Department of Geology and Geophysics, University of Sydney



1

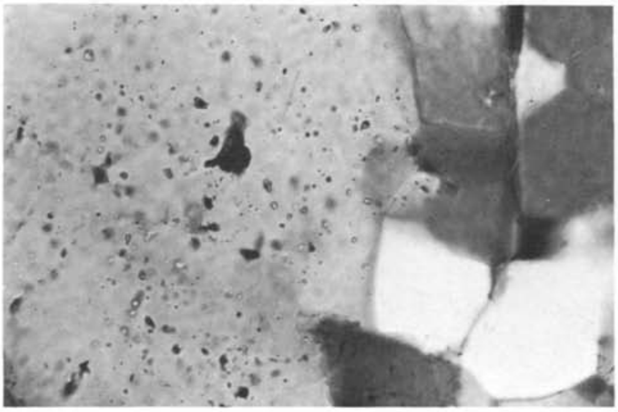


2

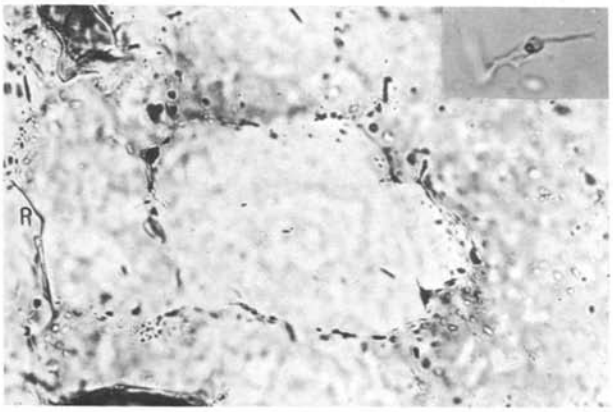


3

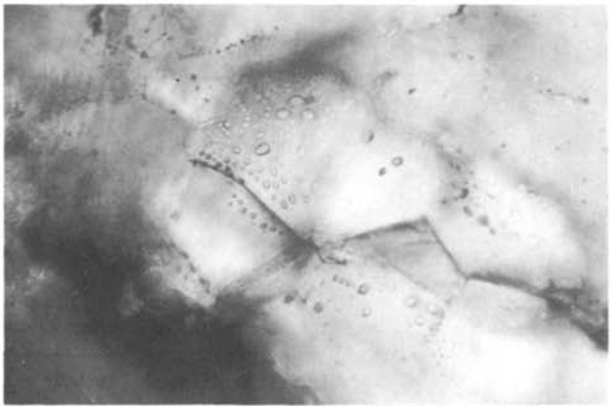
4



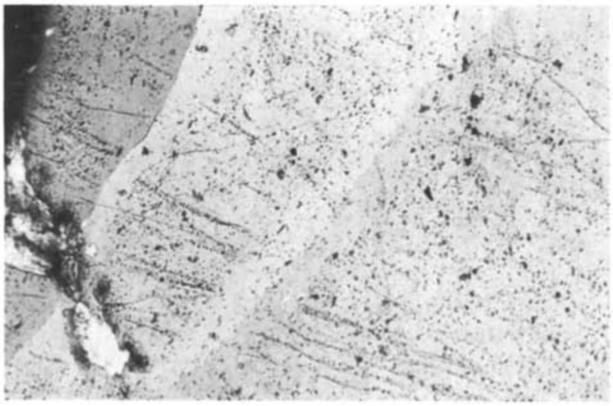
5



6



7



8

with some suggestion of concentration into diffuse patches. In deformed specimens, however, the fluid inclusions are arranged in streaks which are sub-parallel to the elongation of each quartz grain (Fig. 4). Occasional sharp healed fractures of late origin, decorated with fluid inclusions, cut across the general inclusion fabric. Highly saline inclusions containing a halite crystal are not uncommon in the quartz of the massive granodiorite, but most inclusions, especially in the deformed granodiorite are of the two-phase liquid-vapour type. Internally the recrystallized quartz grains are virtually inclusion-free (Fig. 5). Immediately in advance of the recrystallization front, which separates totally recrystallized regions from those showing only advanced recovery, equant fluid inclusions tend to be replaced by discontinuous stringers of elongate aqueous inclusions with vapour bubbles. They are aligned along some but not all sub-grain boundaries (Fig. 6).

The visibility of boundaries between recrystallized grains in plane polarized light is commonly enhanced by the presence of what at first sight appear to be single phase liquid inclusions (Fig. 7). These "inclusions", however, never contain a vapour bubble and show no evidence of freezing at temperatures as low as −100° C. They can, in fact, be shown to be etch pits by allowing a low viscosity fluid to migrate along grain boundaries whereby bubbles of air become trapped in the depressions. Identification of these features as etch pits is further confirmed by the occasional appearance of the distinctive trapezoid form of the $(10\bar{1}0)$ etch figure, but more commonly the pits are triangular or rounded due to irrational nature of the surfaces of the polyhedra. These features are extremely common in recrystallized quartz and care must be taken not to confuse them with single-phase fluid inclusions. Fluid inclusions appear to be rarely, if ever, associated with high angle boundaries in quartz.

The *Erimeran Granite* outcrops in the central part of New South Wales, about 450 km west-northwest of Sydney, and is notable in that parts of it have suffered a pervasive episode of hydrothermal alteration as well as moderate deformation. This has resulted in the virtual elimination of biotite and the growth of muscovite and chlorite. In addition, the quartz grains have attained an almost milky appearance, due primarily to the presence of micron-sized fluid inclusions in concentrations of the order of 10^6 inclusions per cubic millimetre of host quartz.

The hydrothermally altered granite still has an essentially massive appearance both mesoscopically and microscopically. In general, quartz grain boundaries are the original igneous ones, and the most advanced recovery features are deformation bands developing from undulose extinction, a conspicuous feature of each grain. Deformation bands have resulted from at least two periods of ductile deformation. The earlier deformation has resulted in closely spaced deformation bands which are outlined by numerous small fluid inclusions along each deformation band boundary. The later deformation bands are more widely spaced and along their boundaries earlier inclusions have been selectively eliminated (Fig. 8). There is only incipient polygonization in isolated grains and no recrystallization of the quartz. Inclusions have also been eliminated to a distance of approximately 10 µm on both sides of all sub-grain boundaries.

Discussion

Inclusions, individual dislocations and grain boundaries are involved in dynamic interplay during deformation and syntectonic recrystallization. Several types of interaction have been well documented in an extensive metallurgical and ceramic literature.

The sweeping or dragging of solid, liquid and gaseous inclusions by boundaries moving under stress has been noted in such diverse systems as helium bubbles in aluminium (Ells, 1963) and copper (Pati and Maiya, 1971); and liquid GeO_2, B_2O_3, amorphous SiO_2 and crystalline Al_2O_3 inclusions in copper (Ashby and Palmer, 1967; Ashby and Centamore, 1968). In addition the sweeping of voids by migrating boundaries has been demonstrated in studies of polycrystalline MgO (Langdon and Pask, 1971), partially sintered alumina (Coble and Burke, 1963) and copper (Alexander and Baluffi, 1957). There can be little doubt that this process is important in geological materials and it has been invoked by Green and Radcliffe (1975) to explain the accumulation of bubbles on boundaries between recrystallized olivine grains and deformed porphyroclasts in mantle-derived xenoliths. On the other hand Kamb (1972) observed that during syntectonic recrystallization of ice, air bubbles (100–300 µm diameter) in no way interfered with grain boundary migration.

A characteristic of inclusion clearing by this mechanism is an asymmetry of inclusion distribution about the boundary surface. In the granite tectonites we have examined, this sort of distribution of inclusions has not been observed. Where inclusions have clearly eliminated from boundary regions, they have been more or less symmetrically removed. The example in Figure 8 shows two deformation band boundaries crossing closely spaced subparallel fluid inclusion planes at high angle. Many inclusions have clearly been eliminated on *both* sides of each deformation band boundary.

Microscopic evidence, in fact, shows that most inclusions are lost before recrystallization, during the recovery stage. By the time that high angle boundaries are formed and moving, inclusions are almost fully reorganized into low angle boundaries. In syntectonic recrystallization, subgrains as large as 10 µm in size appear to act as nuclei for recrystallization (Hobbs, 1968). But with this mechanism there remains the problem of explaining how small inclusions are eliminated from the cores of newly forming subgrains.

Although fluid inclusions are known to move by self-diffusion in a temperature gradient (Anthony and Cline, 1971, 1972a; Cline and Anthony, 1972) and even drag grain boundaries with them (Anthony and Cline, 1972b; Anthony and Sigsbee, 1971) it is difficult to imagine thermal gradients directed towards subgrain boundaries of quartz in granite, of sufficient magnitude and existing for a sufficient length of time, to induce any significant migration.

It has been proposed that inclusions move by attachment to individual dislocations which are moving under stress (Barnes and Mazey, 1963). Speight and Greenwood (1964) have predicted that beyond a critical dimension, bubbles pin dislocations and prevent them moving. Submicroscopic inclusions (<2000 Å diameter) may therefore respond to changing conditions in entirely different ways to inclusions of a size routinely observed in petrographic studies. Although the experimental evidence is slight, it also seems likely that inclusions can move along stress gradients. The process proposed by Roedder (1971) whereby fluid inclusions lying on more 'soluble' zones could be expected to 'bore' into the mineral and redeposit more perfect material behind it as it moved, is of this type.

Another possibility is that the fluid in the cores of subgrains is leaked to boundary regions. Voids are known to develop along grain boundaries during grain boundary sliding (Greenwood, 1969; Spark and Taplin, 1969) or what has been termed grain boundary cavitation (Dyson et al., 1976). In the latter study, during the deformation of Nimonic 80 alloy, voids were observed to develop at the intersection of slip bands with grain boundaries.

Vacancies essential to bubble growth are generated at grain boundaries and sub-grain boundaries, and when gas bubbles form in metals they are found to be located preferentially at these sites (Cahn, 1966). When voids develop in the subgrain boundaries of quartz undergoing recovery, it is possible that fluid at high pressure in the cores of subgrains will leak into the voids through the system of dislocations which accompanies grain interior slip. Alternatively a dissolution-condensation mechanism could operate whereby inclusion contents would move by lattice diffusion from the cavities and condense on the boundary. A dissolution-condensation process should produce zones located symmetrically on both sides of the boundary (Ashby and Centamore, 1968), similar to those we have noted in the Erimeran granite quartz (Fig. 8). With either mechanism, coalescence of the newly-formed inclusions would lead to the development of stringers of the form commonly observed along sub-grain boundaries (Fig. 6). Plastic flow of quartz into the emptied cavities would remove all visible trace of their former existence within the subgrains.

What is the origin of the ductile-deformation inclusions in these granites? And to what extent are inclusions involved in deformation, recovery and recrystallization processes? When water-rich quartz is heated above 500° C at atmospheric pressure, the structurally bound water is released into fluid inclusions (McLaren and Phakey, 1966; McLaren and Retchford, 1969). Small inclusions are associated with deformation lamellae in experimentally deformed quartz (e.g. Carter et al., 1964; Christie and Ardell, 1974). They are also widely associated with deformation bands, deformation lamellae and subgrains in natural quartz (e.g. White, 1973; White and Treagus, 1975). These small fluid inclusions represent hydrogen rich volumes in the quartz. The fact that inclusions appear on heat treatment, with or without concomitant plastic deformation, shows that hydrogen at least, and possibly OH^- or H_2O, can readily diffuse through the quartz at these temperatures. This is confirmed by the ease with which hydrogen can be replaced by deuterium in silicates in general (Wilkins and Sabine, 1973) and quartz in particular (Kats, 1962). Hobbs (1968) presented evidence that heating pre-treatment homogenizes the hydrogen distribution in synthetic quartz. Bambauer et al. (1969) postulated a dynamic equilibrium dependent upon temperature and pressure between H_2O in inclusions and $\equiv SiOH$ gel-like defects in water-rich quartz. Many of the inclusions found in solution vein quartz are precipitated from water-saturated quartz by release of confining pressure according to White (1973). Experimental evidence of preferential development of deformation bands along water-rich growth bands in synthetic quartz was presented by Hobbs (1968) and Morrison-Smith et al. (1976). In addition Hobbs noted the precipitation of small (1 μm) fluid inclusions in these zones on stress annealing. Kerrich (1976) suggested that the reverse may also occur, namely that during deformation, water 'leaks' from primary inclusions into the structure allowing hydrolytic weakening to occur within that zone.

Experimental evidence on this point is not entirely clear. Balderman (1974), noting that water precipitated as inclusions is no longer directly available to hydrolyse Si-O bonds, showed that a 24-hour temperature pretreatment at 5 kb confining pressure had no appreciable effect on the strength of water-rich quartz. With a heating pretreatment at atmospheric pressure Kekulawala et al. (1977) showed that the strength of quartz at 3 kb confining pressure was greatly increased. This strongly suggests that the gel-like defects which these authors consider to be specifically involved in the process of hydrolytic weakening have decomposed to fluid inclusions. Hydrogen thus removed from the bulk of the structure is unavailable to aid either dislocation propagation or climb (Griggs, 1974; McLaren and Retchford, 1969). There will also be purely mechanical contributions to the strength of the material. It is well established in metals, for example, that the presence of second phase particles, including voids, at interfaces has the important effect of limiting ductility (Greenwood, 1969).

The experimental studies of Balderman (1974) and Kekulawala et al. (1977) suggest that unless confining pressures of the order of 5 kb are achieved, the role of fluid inclusions in promoting plastic deformation of quartz is unlikely to be significant. On the other hand, as Kerrich's (1976) and our own observations have shown, fluid inclusions are certainly mobile or leaking during recovery and it may be supposed that they play a significant role in this process even at modest confining pressures. It also seems likely that the accumulation of fluid at low angle boundaries will effect the rate at which they develop into high angle boundaries.

Conclusion

The fluid inclusions of minerals which have undergone ductile deformation and syntectonic recrystallization have rarely been investigated. The generally-held opinion that such materials are unsuitable for fluid inclusion study is partially justified by the complexity of processes in which the fluid inclusions are involved.

The origin of inclusions associated with ductile deformation features is not known. They could with equal plausibility have resulted from pore fluids of external origin, or from precipitation of structurally-bound water in response to lowering of pressure. Usual assumptions of non-leaking and immobility of inclusions are likely to have been violated in deformed quartz in which recovery is far advanced. Although there is no evidence as yet that fluid inclusions play a significant role during deformation of quartz, it is clear that they can be intimately involved in the process of recovery. The elimination of inclusions during recovery shows that there must be diffusive transfer of hydrogen in one form or another which should be available to promote dislocation propagation and climb.

The small inclusions within quartz grains cannot be dismissed merely as "dust". They are significant entities of distinctive composition and origin and act as markers in tectonic processes as they affect rocks at the microscopic level. Although they are small, sufficient numbers of them are visible at moderate magnification to be used routinely in microstructural studies with the optical microscope.

The effect of composition of the inclusion fluid is unknown. An experimental study of the deformation of quartz samples containing fluid inclusions with a range of composition should be carried out to further investigate whether fluid inclusions play an active or passive role in deformation.

Acknowledgements. We are indebted to B.E. Hobbs, M.S. Patterson, T.G. Vallance and R.H. Vernon for advice and discussion regarding this work.

References

Alexander, B.H., Baluffi, R.W.: Mechanisms of sintering of copper. Acta Met. **5**, 666–677 (1957)

Anthony, T.R., Cline, H.E.: Thermal migration of liquid droplets through solids. J. Appl. Phys. **42**, 3380–3387 (1971)

Anthony, T.R., Cline, H.E.: The thermomigration of biphase vapor-liquid droplets in solids. Acta Met. **20**, 247–255 (1972a)

Anthony, T.R., Cline, H.E.: The interaction of migrating liquid inclusions with grain boundaries in solids. In: The nature and behaviour of grain boundaries (H. Hu, ed.), pp. 185–201. New York: Plenum 1972b

Anthony, T.R., Sigsbee, R.A.: The thermomigration of spherical bubbles through a transparent polycrystalline solid. Acta Met. **19**, 1029–1035 (1971)

Ashby, M.F., Centamore, R.M.A.: The dragging of small oxide particles by migrating grain boundaries in copper. Acta Met. **16**, 1081–1092 (1968)

Ashby, M.F., Palmer, I.G.: The dragging of solid particles through metals by grain boundaries. Acta Met. **15**, 420–423 (1967)

Balderman, M.A.: The effect of strain rate and temperature on the yield-point of hydrolytically weakened synthetic quartz. J. Geophys. Res. **79**, 1647–1652 (1974)

Bambauer, H.U., Brunner, G.O., Laves, F.: Light scattering of heat-treated quartz in relation to hydrogen-containing defects. Am. Mineralogist **54**, 718–724 (1969)

Barnes, R.S., Mazey, D.J.: The migration and coalescence of inert gas bubbles in metals. Proc. Roy. Soc. London, Ser. A **275**, 47–57 (1963)

Cahn, R.W.: Recrystallization mechanisms. In: Recrystallization, grain growth and textures (H. Margolin, co-ordinator), Seminar Am. Soc. Metals, pp. 99–128, 1966

Carter, N.L., Christie, J.M., Griggs, D.T.: Experimental deformation and recrystallization of quartz. J. Geol. **72**, 687–733 (1964)

Christie, J.M., Ardell, A.J.: Substructures of deformation lamellae in quartz. Geology **2**, 405–408 (1974)

Cline, H.E., Anthony, T.R.: The migration of liquid droplets in solids. J. Cryst. Growth **13–14**, 790–794 (1972)

Coble, R.L., Burke, J.E.: Sintering in ceramics. Prog. Ceram. Sci. **3**, 197–251 (1963)

Dyson, B.F., Loveday, M.S., Rodgers, M.J.: Grain boundary cavitation under various states of applied stress. Proc. Roy. Soc. London, Ser. A **349**, 245–259 (1976)

Ells, C.E.: Effect of helium on recrystallization and grain boundary movement in aluminium. Acta Met. **11**, 87–96 (1963)

Geguzin, Ya.E., Krivoglaz, M.A.: Migration of macroscopic inclusions in solids. New York. Consultants Bureau 1973

Green, H.W., Radcliffe, S.V.: Fluid precipitates in rocks from the earth's mantle. Geol. Soc. Am. Bull. **86**, 846–852 (1975)

Greenwood, G.W.: Fracture at interfaces. In: Interfaces Conference, Melbourne (R.C. Grifkins, ed.), pp. 223–236. Melbourne: Australian Institute of Metals, Butterworths 1969

Griggs, D.T.: Hydrolytic weakening of quartz and other silicates. Geophys. J. Roy. Astron. Soc. **14**, 19–31 (1967)

Griggs, D.T.: A model of hydrolytic weakening in quartz. J. Geophys. Res. **79**, 1653–1661 (1974)

Griggs, D.T., Blacic, J.D.: Quartz: Anomalous weakness of synthetic crystals. Science **147**, 292–295 (1965)

Hobbs, B.E.: Recrystallization of single crystals of quartz. Tectonophysics **6**, 353–401 (1968)

Kamb, B.: Experimental recrystallization of ice under stress. Geophys. Monogr. Am. Geophys. Union **16**, 221–241 (1972)

Kats, A.: Hydrogen in α-quartz. Philips Res. Rep. **17**, 133–195, 201–279 (1962)

Kekulawala, K.R.S.S., Paterson, M.S., Boland, J.N.: Hydrolytic weakening in quartz. Tectonophysics. (In press)

Kerrich, R.: Some effects of tectonic recrystallization on fluid inclusions in vein quartz. Contrib. Mineral. Petrol. **59**, 195–202 (1976)

Langdon, T.G., Pask, J.A.: Effect of microstructure on deformation of polycrystalline MgO. J. Am. Ceram. Soc. **54**, 240–246 (1971)

McLaren, A.C., Phakey, P.P.: Transmission electron microscope study of bubbles and dislocations in amethyst and citrine quartz. Aust. J. Phys. **19**, 19–24 (1966)

McLaren, A.C., Retchford, J.A.: Transmission electron microscope study of the dislocations in plastically deformed synthetic quartz. Phys. Stat. Sol. **33**, 657–668 (1969)

Morrison-Smith, D.J., Paterson, M.S., Hobbs, B.E.: An electron microscope study of plastic deformation in single crystals of synthetic quartz. Tectonophysics **33**, 43–79 (1976)

Pati, S.R., Maiya, P.S.: Interaction between helium bubbles and migrating grain boundaries in copper. Acta Met. **19**, 807–813 (1971)

Roeder, E.: Metastability in fluid inclusions. Soc. Mining Geol. Japan, Spec. Issue **3**, 327–334 (1971)

Spark, I.J., Taplin, D.M.R.: Intergranular cavitation of alpha brass. J. Aust. Inst. Met. **14**, 298–305 (1969)

Speight, M.V., Greenwood, G.W.: Grain boundary mobility and its effect in material containing inert gases. Philos. Mag. **9**, 683–689 (1964)

Vallance, T.G.: Plutonic and metamorphic rocks. In: The Geology of New South Wales. J. Geol. Soc. Aust. **16**(1), 180–200 (1969)

Wilkins, R.W.T., Barkas, J.P.: Fluid inclusions in the granitic rocks of the Lachlan Fold Belt. Bull. Aust. Soc. Expl. Geophysicists **7**, 45–46 (1976)

Wilkins, R.W.T., Sabine, W.: Water content of some nominally anhydrous silicates. Am. Mineralogist **58**, 508–516 (1973)

White, A.J.R., Chappell, B.W., Cleary, J.R.: Geologic setting and emplacement of some Australian Paleozoic batholiths and implications for intrusive mechanisms. Pac. Geol. **8**, 159–171 (1974)

White, S.: Dislocations and bubbles in vein quartz. Nature (London), Phys. Sci. **243**, 11–13 (1973)

White, S., Treagus, J.E.: The effects of polyphase deformation on the intracrystalline defect structures of quartz. I. The defect structures.. Neues Jahrb. Mineral. Abhandl. **123**, 237–252 (1975)

Received September 19, 1977 / Accepted November 1, 1977