The American Mineralogist, Volume 60, pages 884–888, 1975

Deformation and Recrystallization of a Plagioclase Grain

R. H. VERNON

School of Earth Sciences, Macquarie University, Sydney, 2113, Australia

Abstract

A large deformed grain of plagioclase (An_{40}) contains numerous deformation (kink) bands and fewer broader kink-like zones that may have involved fracturing. The plagioclase has been recrystallized along narrow zones of relatively high strain. The orientations of the new grains are close to that of the original grain, implying crystallographic control in the recrystallization process. Small, consistent chemical differences exist between old and new grains, suggesting that small chemical changes provided some of the driving force for nucleation. The grain shows evidence that subgrain nucleation, bulge nucleation, and sintering of fragments have contributed to the production of the recrystallized aggregates.

Introduction

This paper discusses optical and chemical aspects of recrystallization in a large, deformed grain of relatively ordered plagioclase (An_{40}) occurring in the Giles Complex, central Australia. The plagioclase has been variably deformed and partly recrystallized in a deformation zone under conditions of the granulite facies of metamorphism (Moore, 1973).

The grain was chosen for detailed study because it contains new recrystallized grains adjacent to remnants of the original grain. Consequently, it is ideal for evaluating two hypotheses that have emerged from recent work on the intragranular recrystallization of silicates, namely (1) that the orientations of new grains are systematically related to, and controlled by the orientation of the original grain (Hobbs, 1968; Ave'Lallemant and Carter, 1970; Ransom, 1971), and (2) that small chemical changes typically accompany silicate recrystallization and may even be necessary for recrystallization to occur (Etheridge, 1971; Etheridge and Hobbs, 1974).

Deformation

The deformed plagioclase shows many planar to lenticular kink-like structures of two types.

(1) Relatively broad, well-separated, strongly misoriented zones trend obliquely to (001), as shown in the center and top-middle parts of Figure 1. Examination at high magnification shows that their boundaries consist of aggregates of small subgrains that may have been former fragments. If so, brittle deformation may have been involved in the formation of these structures, which may not be true kink bands as defined by Christie, Griggs, and Carter (1964).

(2) More numerous, narrower, more continuous deformation bands occur throughout much of the plagioclase, as shown in the left part of Figure 1. They appear to be true kink bands in the sense of Christie *et al* (1964). The deformation bands vary from 0.02 to 0.2 mm across, and range from relatively uniform (Fig. 2) to variable in width and lenticular (Fig. 1). Their boundaries vary from smooth to irregular, they trend from 0 to 10° to the trace of (001), and the misorientation across their boundaries generally varies from 1 to 7°. These bands appear to have been formed by plastic deformation, and their misorientations are similar to those produced experimentally by (010) slip (Borg and Heard, 1971).

The deformation bands generally are more regular than those described by Seifert (1965, Fig. 1) for natural albite (An_7). Moreover, the maximum misorientation is much less than the 45° found by Seifert. This large misorientation may be due to optically observed fracturing along the band boundaries in the albite (Seifert, 1965, Fig. 3), whereas optical evidence of fracturing is absent from the deformation bands described herein.

Numerous small inclusions (inferred to be apatite from qualitative microprobe measurements) are elongate parallel to (010) in the original plagioclase (Figs. 2, 5), and a banding caused by variation in their size and concentration (Figs. 1, 2) trends up to about 10° to (001). The deformation bands generally

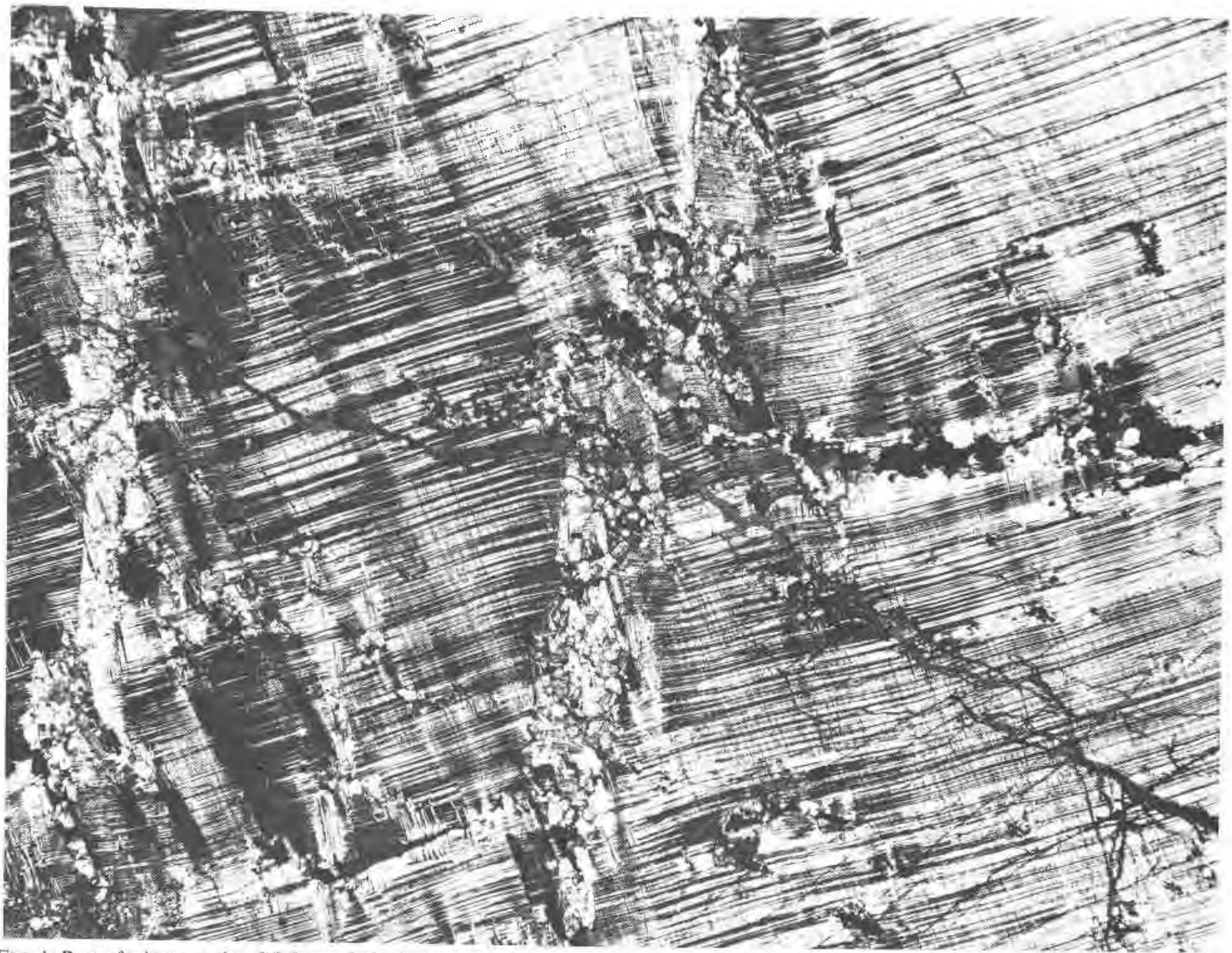

FIG. 1. Part of a large grain of deformed plagioclase showing recrystallization to finer-grained polygonal aggregates in elongate zones and patches. The *a* axis of the main grain is roughly normal to the plane of the paper, and the trace of (010) is parallel to the prominent (albite-law) twins. Local grains and small aggregates of hornblende (black) and clinopyroxene (high relief) occur in some recrystallized areas (*e.g.*, to right). Crossed polars. Base of photo 23 mm.

are parallel to these trails of inclusions, but some are transgressive. Variation in the size and concentration of the larger inclusions generally coincides with deformation band boundaries, which mostly are free of inclusions (Fig. 2).

The concentration of mechanical albite twins commonly varies from one deformation band to the next (Figs. 1, 4), so that the twinning appears to have post-dated the formation of the deformation bands. Slip on (010) occurs in grains unfavorably oriented for (010) twin gliding in experimentally deformed plagioclase (Borg and Heard, 1971, p. 397). The stress system probably changed after the production of the deformation bands, so as to permit (010) twinning in areas of former (010) slip. Judging from the common occurrence of deformation twins in the recrystallized grains (Fig. 1), the main twinning episode may have post-dated the recrystallization also, but several twinning episodes are not excluded by the evidence.

Recovery

Two microstructural features are ascribed to recovery of strained plagioclase, either during or after the deformation, namely: (1) the migration (bulging) of deformation band boundaries and (2) the formation of subgrains.

(1) As described above, planar deformation band boundaries generally are free of the minute inclusions. However, some irregular boundaries do not coincide with inclusion-free zones, suggesting that they have migrated into adjacent bands, leaving their clear zones behind (Fig. 2). Local migration of this

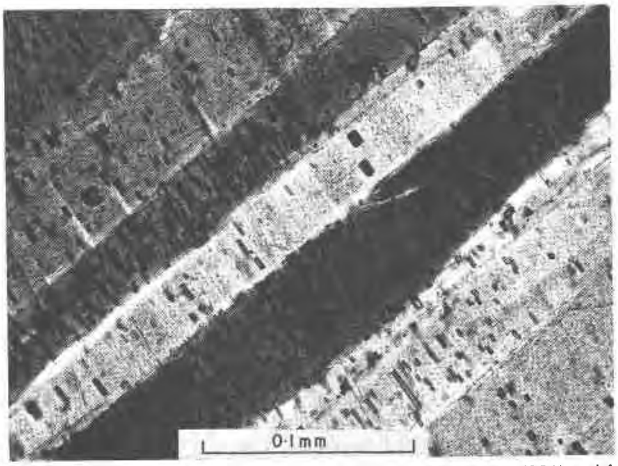

FIG. 2. Elongate deformation bands parallel to (001) with relatively small misorientations and irregular to smooth boundaries. Thin deformation twins, normal to the band boundaries, occur in some bands. Most deformation band boundaries are free of the minute inclusions. An exception is the lower boundary of the large dark band, which appears to have migrated into the adjacent band, leaving its clear zone behind. Crossed polars.

FIG. 4. Recrystallized zone running parallel to deformation bands. The zone contains both equant (polygonal) grains (right) and very elongate grains (left), the shapes of which appear to have been controlled by the deformation bands, and some of which pass into elongate, diffuse subgrains. Inclusions are much less abundant in the recrystallized zone. Crossed polars.

kind may account for much of the variation in width shown by the deformation bands (Figs. 2, 3, 4).

Other evidence of the migration of deformation band boundaries includes small local bulges with a small crystallographic misorientation relative to the host band (Fig. 3), and the repeated bulging of thin deformation bands, owing to pinning of the boundaries by small grains of another mineral. Furthermore, a small degree of rotation of large parts of deformation bands occurs in places. This is accompanied by increasing sharpness of the band boundaries and decreasing concentration of minute inclusions (Figs. 3, 4), resulting in new grains markedly elongate parallel to the bands (Fig. 4).

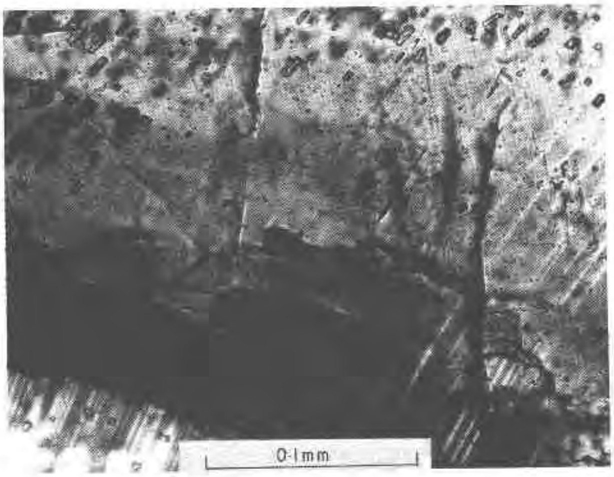

FIG. 3. Small bulge, which may be a potential grain nucleus, in an irregular (migrated) deformation band boundary. Note the general paucity of inclusions in the area of movement of deformation band boundaries. Crossed polars.

Bands in which migration appears to have occurred have sharper, optically distinct boundaries, variable misorientations of up to 13°, and variable trends of up to 16° from (001). In the third dimension, most deformation bands dip exactly or approximately parallel (0 to 5°) to (001), but rarely a band that shows evidence of migration dips at up to 25° away from (001).

(2) Subgrains occur as local lenticular to elongate individuals at deformation band boundaries, as local polygonal aggregates in deformation bands (Fig. 4), and as small aggregates where a deformation band either splits into two or "steps" across to become another band. The subgrains have small relative misorientations and less distinct boundaries than those of true grains in the recrystallized aggregates.

Recrystallization

Recrystallization is confined to narrow elongate zones and patches, most of which appear to occupy zones of relatively large strain in the host plagioclase grain (Fig. 1). The new, recrystallized grains are polygonal in shape with planar or, more commonly, smoothly curved boundaries (Figs. 1, 5), as is typical of experimentally recrystallized metals, ceramics, and minerals (*e.g.*, Carter *et al*, 1964; Hobbs, 1968; Ave'Lallemant and Carter, 1970). The grains average about 0.1 mm across. Adjacent to the

FIG. 5. Recrystallized grains and aggregates of plagioclase (clear of minute inclusions) generally surrounded by a zone of host grain containing minute inclusions, surrounded in turn by unaffected plagioclase containing larger inclusions. The apatite occurring as grains and inclusions in the recrystallized plagioclase aggregates is much coarser-grained than the inclusions in the surrounding plagioclase. Plane-polarized light.

recrystallized aggregates, the host plagioclase generally is devoid of the larger apatite inclusions, containing swarms of extremely small inclusions instead (Fig. 5). The new plagioclase aggregates are free of these, but contain a few much larger apatite grains with curved boundaries, either as polygonal to lenticular grains along plagioclase grain boundaries, or as roughly spherical to ellipsoidal inclusions in the plagioclase (Fig. 5). Their shapes indicate a close approach to microstructural equilibrium between the plagioclase and apatite (Kretz, 1966; Vernon, 1968). The material for the apatite probably was derived from the extremely small inclusions, and accumulated into fewer larger grains by diffusion enhanced by progressive movement of grain boundaries through the inclusion-swarms during recrystallization of the plagioclase.

Many new grains are larger than the width of the deformation bands (Fig. 1), but some have the same width and are elongate parallel to the bands (Fig. 4), and some aggregates are confined to a single bandwidth (Fig. 4). Rarely, fine-grained aggregates of new grains with similar orientation are separated from adjacent aggregates with slightly different orientation in such a way as to preserve vaguely the outlines of former deformation bands. These observations suggest a close relationship between some recrystallized aggregates and deformation bands.

The principal optical vibration directions of recrystallized grains, measured with a universal stage, tend to cluster around those of their *adjacent* host. The angles between specific vibration directions in new grains and their adjacent host grain (Table 1) have broad maxima of 10–30°, although this is less obvious for Z. All but 15 percent of the angles are in the range: 0–40°; this suggests that the orientation of the deformed host grain exerts a strong control on the orientations of new grains formed by recrystallization within it, as shown for the intragranular recrystallization of quartz (Hobbs, 1968; Ransom, 1971) and olivine (Ave'Lallemant and Carter, 1970). About 50 percent of the grains measured have misorientations for each indicatrix axis within 10° of each other, and about 75 percent are within 15°, which suggests that the recrystallization process involves progressive misorientation of all three crystallographic axes.

Chemical analyses of recrystallized grains and *adjacent* host, from different parts of the same thin section, have been made with an energy-dispersive electron probe microanalyzer, following a procedure based on the methods of Reed and Ware (1973). Analyses are available from the author, on request. The new grains have lower An and higher Ab contents than the immediately adjacent host grain, the variation in Or content being non-systematic. New grains appear to have gained Si, Mg, Na, and K, and lost Al and Ca, relative to the host (Table 2). The chemical differences are small but consistent, and could affect the nucleation of the new grains, especially if a spinodal decomposition mechanism is involved (Etheridge and Hobbs, 1974).

Discussion

Recent metallurgical work on mechanisms of nucleation of recrystallization has been reviewed with respect to quartz by Hobbs (1968) and to mica by Etheridge (1971) and Etheridge and Hobbs (1974). In the absence of transmission electron microscopy, mechanisms of nucleation and growth in the

TABLE 1. Angular Differences Between Optical Vibration Directions of Host and New Grains

Difference angle (degrees)	X	Y	Z
80 - 90	-	1	2
70 - 79	-	1	-
60 - 69	-	2	2
50 - 59	4	1	2
40 - 49	2	-	3
30 - 39	6	4	10
20 - 29	9	18	9
10 - 19	13	12	9
0 - 9	7	2	4

TABLE 2. Average Cation Differences Between Recrystallized and Host Plagioclase

Si	+ 0.047
Al	- 0.071
Mg	+ 0.010
Ca	- 0.054
Na	+ 0.053
K	+ 0.006

* Cation differences expressed as gains (+) and losses (-) of new grains with respect to composition of adjacent host areas. Number of cations per formula unit calculated on the basis of 32 oxygen ions.

plagioclase recrystallization process are poorly understood. However, bulge nucleation (Cahn, 1966) is suggested by the local migrations of deformation band boundaries described above. Moreover, the plagioclase shows no optical evidence of growth of new grains from small nuclei, but only the occurrence of relatively large subgrains. This suggests that preformed (subgrain) nucleation was more important than classical nucleation in the recrystallization process. Release of chemical free energy also may have assisted nucleation, as suggested by the small chemical differences between new and old grains; this process has been suggested for the intragranular recrystallization of biotite (Etheridge, 1971; Etheridge and Hobbs, 1974) and pyroxene (M. A. Etheridge, Monash University, personal communication, 1973).

Some spatial correlation exists between deformation bands and recrystallized aggregates. However, the main recrystallized zones broadly trend obliquely to the deformation bands in kink-like zones of relatively high strain, possibly fracture-zones (Fig. 1). Therefore, recrystallization by sintering of fine fragmental aggregates formed by cataclasis along fractures may account for many of the recrystallized zones.

Acknowledgments

I wish to thank S. J. B. Reed and N. G. Ware for assistance with electron microprobe techniques, and The Australian National University, Canberra, for providing access to its microprobe analyzer. The work has benefited from discussions with M. A. Etheridge, R. H. Flood, B. E. Hobbs, and P. F. Williams. A. Goode kindly provided the speciment of plagioclase, S. Dobos made the photograph for Figure 1, and research expenses were paid by Macquarie University.

References

AVE'LALLEMANT, H. G., AND N. L. CARTER (1970) Syntectonic recrystallization of olivine and modes of flow in the upper mantle. *Bull. Geol. Soc. Am.* **81,** 2203–2220.

BORG, I. Y., AND H. C. HEARD (1971) Experimental deformation of plagioclases. In, P. Paulitsch, Ed., *Experimental and Natural Rock Deformation.* Springer-Verlag, Berlin.

CAHN, R. W. (1966) Recrystallization mechanisms. In, H. Margolin, Ed., *Recrystallization, Grain Growth and Textures.* Am. Soc. Metals, p. 99–127.

CARTER, N. L., J. M. CHRISTIE, AND D. T. GRIGGS (1964) Experimental deformation and recrystallization of quartz. *J. Geol.* **72,** 687–733.

CHRISTIE, J. M., D. T. GRIGGS, AND N. L. CARTER (1964) Experimental evidence of basal slip in quartz. *J. Geol.* **72,** 734–756.

ETHERIDGE, M. A. (1971) *Experimental Investigations of the Mechanisms of Mica Preferred Orientation in Foliated Rocks.* Ph.D. Thesis, Australian National University, Canberra, Australia.

———, AND B. E. HOBBS (1974) Chemical and deformational controls on recrystallization of mica. *Contrib. Mineral. Petrol.* **43,** 111–124.

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

KRETZ, R. (1966) Interpretation of the shape of mineral grains in metamorphic rocks. *J. Petrol.* **7,** 68–94.

MOORE, A. C. (1973) Studies of igneous and tectonic textures and layering in the rocks of the Gosse Pile intrusion, Central Australia. *J. Petrol.* **14,** 49–80.

RANSOM, D. M. (1971) Host control of recrystallized quartz grains. *Mineral. Mag.* **38,** 83–88.

REED, S. B. J., AND N. G. WARE (1973) Quantitative electron microprobe analysis using a lithium drifted silicon detector. *X-Ray Spectrom.* **3,** 69–74.

SEIFERT, K. E. (1965) Deformation bands in albite. *Am. Mineral.* **50,** 1469–1472.

VERNON, R. H. (1968) Microstructures of high-grade metamorphic rocks at Broken Hill, Australia. *J. Petrol.* **9,** 1–22.

Manuscript received, March 17, 1975; accepted for publication, May 13, 1975.