THE AMERICAN MINERALOGIST, VOL 54, MARCH–APRIL, 1969

RELICT PLAGIOCLASE PHENOCRYSTS FROM AMPHIBOLITE GRADE METAVOLCANIC ROCKS

Thomas A. Vogel, *Department of Geology, Michigan State University, East Lansing, Michigan 48823* and William H. Spence, *Department of Geosciences, North Carolina State University, Raleigh, North Carolina 27600.*

Abstract

Relict plagioclase phenocrysts have changed composition and have ordered by solid state diffusion without recrystallization. Original twin planes are preserved, and the orientation of the optical indicatrix with respect to the twin plane has readjusted to reflect the new composition and structural state.

Introduction

Metavolcanic rocks with primary features such as pillow-lavas, agglomeratic textures and relict phenocrysts occur in the Grenville Province near Plevna Lake in southeastern Ontario (Meen, 1944; Smith, 1958). Many of these flows retain recognizable porphyritic textures and the original unrecrystallized plagioclase grains are preserved in a few of these rocks. These metavolcanic rocks are interlayered with metaconglomerate and paragneiss (Smith, *et al.*, 1969).

The relict phenocrysts near Plevna Lake occur in the center of a lense-like metavolcanic flow which has a maximum outcrop width of 1900 feet, and length of 9100 feet. The preservation of these phenocrysts is probably due to their physical size (up to one and one-half inches in length), and lack of deformation; and possibly to a lack of excess volatiles in the center of the flow during metamorphism.

The metamorphic grade of the metasedimentary and metavolcanic sequence is interpreted to be in the lower to middle amphibolite facies, partly on the basis of plagioclase with a composition of An_{20}—An_{40} in the amphibolite; and also on the presence of kyanite in the associated metasedimentary rocks (Smith *et al.*, 1969). Detailed studies of the amphiboles are in progress, and preliminary microprobe analyses indicate that the amphibole is low in Al_2O_3 and high in MgO. X-ray diffraction patterns of the amphiboles are almost identical in detail with actinolite. If the amphibole present in the amphibolite is in the actinolite series, the mineral assemblage would indicate conditions at or near the greenschist-amphibolite facies boundary.

Methods

The compositions of relict plagioclase phenocrysts and secondary groundmass plagioclase grains were studied by means of electron microprobe analyses, the Tsuboi method (Tsuboi, 1923; Vogel, 1967; Morse, 1968) and five-axis universal stage techniques (Emmons, 1943; Noble, 1965). Structural states of the plagioclase were measured by determining, on the five-axis universal stage, orientation of the optical indicatrix ⊥(010). The electron microprobe study was invaluable in studying the relationship between relict phenocrysts and secondary grains and for testing compositional variation within single grains. Three samples were studied in detail, and microprobe analyses were made on nine individual plagioclase phenocrysts and the plagioclases in the groundmass around each phenocryst were analysed.

Results of Investigation

Whole rock chemical analyses for SiO_2, CaO, and K_2O were determined by X-ray fluorescence on the three samples. The analyses fall in the

Table 1. Partial Chemical Analyses of Metavolcanics

	7-3B	7-4A	11-8N	A*	B**
SiO_2	52.8	55.8	58.2	54.3	54.2
CaO	8.85	9.97	8.48	8.30	7.92
K_2O	0.61	0.41	0.51	0.38	1.11

7-3B, 7-4A and 11-8N Plevna Lake, Ontario.
* Quartz diorite, Hawaii (Kuno, *et al*, 1957).
** "Average" andesite (Nockolds, 1954).

general range of quartz diorite to andesite (Table 1), and it is reasonable to assume that volcanics in the general compositional range from basaltic to andesitic were the antecedents to these rocks. According to Williams, Turner, and Gilbert (1954) the average plagioclase composition of andesites is approximately An_{40}, that in basalts is approximately An_{55} and porphyritic plagioclase in most andesites is more calcic than An_{55}. The plagioclase in each of the metavolcanic samples show different ranges of plagioclase composition: An_{24-28}, An_{30-38} and An_{39-41}, and there is no difference in composition between the recrystallized plagioclase of the groundmass and the primary plagioclase phenocrysts.

All three samples may represent disequilibrium assemblages as indicated by relict amphibole phenocrysts which have been partially converted to a secondary amphibole. Sample 7-3B, which has the most sodic plagioclase (An_{24-28}), has more secondary amphibole developed than the other two samples and represents a closer approach to equilibrium. The metavolcanic rocks that contain no relict plagioclase and amphibole phenocrysts (and are therefore completely recrystallized) contain the most sodic plagioclase with a composition of An_{20} to An_{30} and this range may represent the equilibrium composition. Those samples which contain the greatest amount of relict amphibole also contain plagioclase with the highest anorthite content.

The plagioclase phenocrysts are shown to be relict igneous grains by their lath-like euhedral shape, by the type of twinning present (Carlsbad and albite-Carlsbad), and also by re-entrant angles which are sometimes observed (Gorai, 1951; Ross, 1957; Sarbadhikari, 1965; Turner, 1951; Vance, 1961) (Figures 1 and 2). The compositional similarity of the primary plagioclase phenocrysts and the recrystallized plagioclase grains

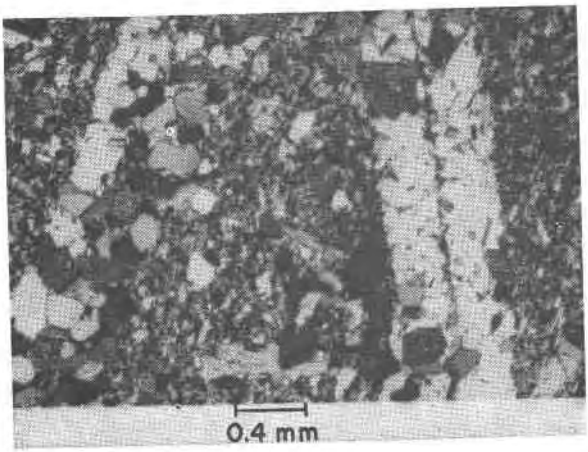

FIG. 1. Photomicrograph of a partly recrystallized plagioclase phenocryst (right side) and a completely recrystallized phenocryst (left side).

demonstrates that these phenocrysts have homogenized and changed composition by solid state diffusion without recrystallization. In this process the original twin planes and re-entrant angles (Fig. 2) were preserved.

Optical examination by five-axis universal stage techniques show that the phenocrysts are in the low structural state, and that any original compositional zoning has been obliterated. The angles from X, Y, and Z to $\perp(010)$ of the primary twin planes and secondary albite deformation twin planes fall on or very near the ordered migration curve (Figure 3). Measurement of the orientation of the optical indicatrix to $\perp(010)$ of adjacent twin lamella show no optical-crystallographic scatter in samples 7-4A and 7-3B. The compositional data obtained by the five-axis method is in agreement with the compositional data obtained in the microprobe and Tsuboi studies. The fact that in some of the phenocrysts, the orientation of the optical indicatrix to $\perp(010)$ plot on the ordered curve without any internal optical-crystallographic scatter would indicate that the twin plane and optical indicatrix have concomitantly reoriented themselves to a new composition and structural state (Vogel, 1964), for the position of the twin plane is controlled by the composition of the crystal as well as the structural state.

A small but consistent internal scatter in sample 11-8N may indicate that the reorientation in this sample is not complete. Zoning is present in a thin area adjacent to the composition planes of primary twins and may be induced by strain near the twin boundary.

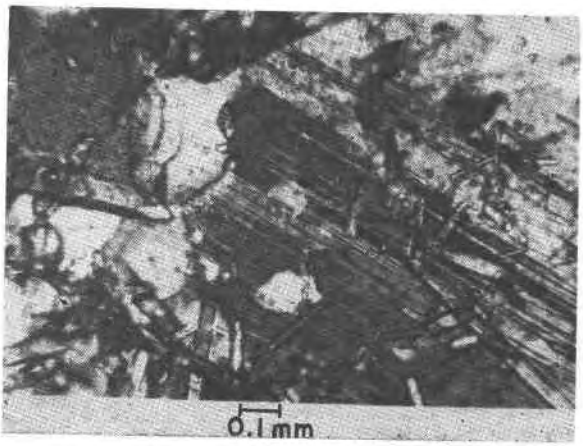

FIG. 2. Relict plagioclase phenocryst with a well-developed re-entrant angle. The small needles are amphibole.

Noble (1966) found relict, calcium-rich, disordered plagioclase phenocrysts preserved in metavolcanic rocks of the greenschist facies. Where the volcanic rocks had been intruded earlier by a granodiorite pluton, the metavolcanics developed mineral assemblages of the hornblende hornfels facies; ordered relict plagioclase, complete with oscillatory zoning are preserved in some of these hornfelsed rocks.

Noble observed that in the regionally metamorphosed rocks that he studied, relict disordered, calcium-bearing, plagioclase phenocrysts were stable up to approximately middle greenschist facies conditions. At this point, they inverted to an ordered structural state while still maintaining the delicate composition zoning. This structural inversion without compositional change by diffusion is in agreement with the work of Goldsmith (1952) who pointed out that local rearrangement of aluminum and silicon atoms will occur much more readily than the long range diffusion of aluminum and silicon (as well as sodium and calcium) needed to change the composition and homogenize the crystal. Noble also showed that the relict phenocrysts apparently acted as closed systems and that no evidence for an isochemical breakdown into two or more phases was noted on a microscopic scale.

At Plevna Lake, the relict phenocrysts have developed a mineral assemblage indicative of the lower amphibolite facies. Under the pres-

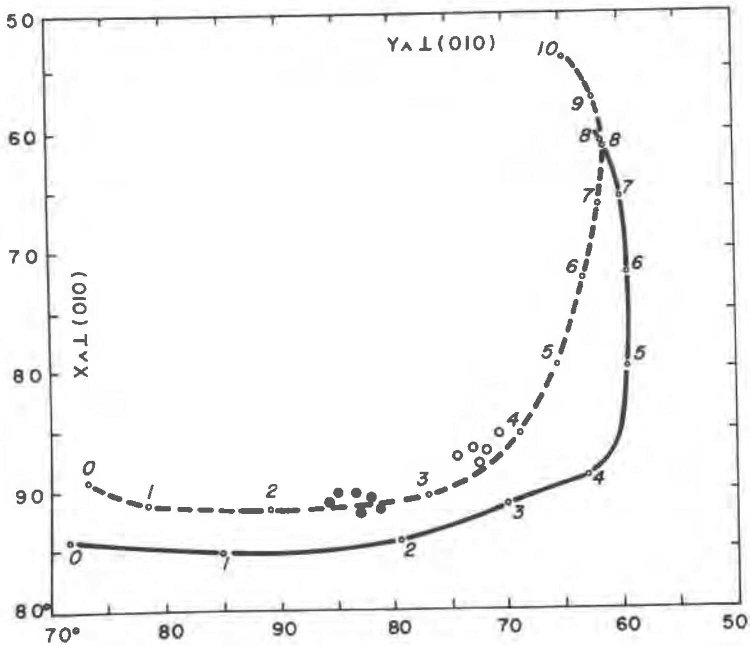

FIG. 3. Plot of X to ⊥ (010) versus Y to ⊥ (010) for ordered (dashed line) and disordered (solid line) plagioclase (after Noble, 1965). Solid circles are 7-3B, open circles are 7-4A that are discussed in the text

sure-temperature conditions at which these minerals formed the phenocrysts have not only inverted to the ordered form, but in addition, they have homogenized compositionally and apparently changed their bulk chemical composition by diffusion in the solid state and reaction with the remainder of the rock. There is no evidence for a breakdown of the plagioclase into two or more phases.

Noble's data show that the disordered plagioclase phenocrysts were metastable up to conditions of the middle greenschist facies, and that inversion takes place isochemically without chemical reaction with the rest of the rock (Noble, 1966, p. 503). At Plevna Lake, the metavolcanics probably passed through the temperature-pressure conditions of the greenschist facies on the way to being metamorphosed to the lower amphibolite facies. While under greenschist facies conditions the phenocrysts may well have existed metastably as compositionally unaltered grains similar to those described by Noble (1966). With continued increase in the intensity of metamorphism, temperature and perhaps water activity reached values where long range diffusion of Si and Al could take place. Possibly slight nonhydrostatic stress aided in this diffusion. Anorthite-bearing plagioclase being a stable phase at these pressure and temperature conditions, only moderate chemical changes were required for the relict phenocrysts to be in equilibrium with the rest of the rock.

Acknowledgments

Part of this study was done while both authors were at Rutgers University, New Brunswick, New Jersey, and the support of Rutgers Research Council is gratefully acknowledged. We wish to express our appreciation to Dr. Louis S. Walter, of the Goddard Space Center, Greenbelt, Maryland, for the microprobe analyses and for his helpful discussion of the problem. We appreciate the critical review and suggestions for improvement of the manuscript by D. C. Noble.

References

Emmons, R. C. (1943) The Universal Stage. *Geol. Soc. Amer. Mem.* **8,** 205 p.

Goldsmith, J. R. (1951) Diffusion in plagioclase feldspar. *J. Geol.*, **60,** 288–291.

Gorai, M. (1951) Petrological studies of plagioclase twins. *Amer. Mineral.*, **36,** 884–901.

Kuno, H., K. Yamasaki, C. Iida, and K. Nagashima (1957) Differentiation of Hawaiian magmas. *Jap. J. Geol. Geog.*, **28,** 179–218.

Meen, V. B. (1944) Geology of the Grimsthorpe-Barrie area. *Ont. Dept. Mines, Ann. Rep.* **51,** (Pt. 4) 1–50.

Morse, S. A. (1968) Revised dispersion method for low plagioclase. *Amer. Mineral.*, **53,** 105–115.

Noble, D. C. (1965) Determination of the composition and structural state of plagioclase with the five-axis universal stage. *Amer. Mineral.*, **50,** 367–381.

——— (1966) Structural state of relict calcium-bearing plagioclases of volcanic origin from metamorphosed and propyliticallyaltered rocks. *Geol. Soc. Amer. Bull.*, **77,** 495–508.

Nockolds, S. R. (1954) Average chemical composition of some igneous rocks. *Geol. Soc. Amer. Bull.*, **65,** 1007–1032.

Ross, J. V. (1957) Combination twinning in plagioclase feldspars. *Amer. J. Sci.*, **255,** 650–655.

Sarbadhikari, T. R. (1965) On the difference in twinning between phenocryst and groundmass plagioclase of basalts. *Amer. Mineral.*, **50,** 1466–1469.

Smith, B. L. (1958) Geology of the Clarendon-Dalhousie area. *Ont. Dept. Mines., Ann. Rept.*, **65,** pt. 7, p. 1–46.

———, Thomas A. Vogel, and William H. Spence (1969). Precambrian metaconglomerate mantling a granite dome in the Grenville province of southeastern Ontario. *Geol. Soc. Amer. Bull.* **80,** 297–302.

Spence, William H. (1968) *Relict Plagioclase Phenocrysts From Metavolcanic Rocks Mantling a Granite Dome and the Petrology of the Associated Rocks in the Grenville Province of Southeastern Ontario.* Ph.D. Thesis, Rutgers Univ.

TSUBOI, SERTARO (1923) A dispersion method of determining plagioclase in cleavage flakes. *Mineral. Mag.*, **20**, 108–122.

TURNER, F. J. (1951) Observations on twinning of plagioclase in metamorphic rocks. *Amer. Mineral.*, **36**, 581–589.

VANCE, J. A. (1961) Polysynthetic twinning in plagioclase. *Amer. Mineral.*, **46**, 1097–1119.

VOGEL, T. A. (1964) Optical-crystallographic scatter in plagioclase. *Amer. Mineral.*, **49**, 614–633.

——— (1968) Tsuboi method of plagioclase determination; an evaluation and comparison (abstr.). *Geol. Soc. Amer., Spec. Pap.* **115**, 299.

WILLIAMS, H., F. J. TURNER, AND C. M. GILBERT (1954) *Petrography: An Introduction to the Study of Rocks in Thin Sections.* W.H. Freeman and Company, San Francisco, 406 p.

Manuscript received August 7, 1968; accepted for publication, December 18, 1968.