THE AMERICAN MINERALOGIST, VOL. 54, JANUARY–FEBRUARY, 1969

ANNEALING OF OLIGOCLASE AT HIGH PRESSURE

HANS-RUDOLF WENK, *Department of Geology and Geophysics, University of California, Berkeley California 54720.*

ABSTRACT

An oligoclase single crystal ($An_{13-5}Ab_{82-4}Or_{4-1}$) with low temperature structural and optical properties was annealed at 5–15 kbar and 800–1000°C in the presence of water vapor and in dry atmosphere. A sharp change in optical properties without intermediate states was observed to occur at 840°C ± 20; above this temperature the optical properties correspond to high-temperature plagioclase, below this temperature they correspond to low-temperature (plutonic) plagioclase. However, the unit-cell dimensions of both the optically high and optically low annealed plagioclases are nearly identical and correspond to a highly disordered structural state.

Large clear crystals of oligoclase twinned after the albite-law from the collection of UCLA (locality Ontario, Canada?)[1] were chosen as starting material for annealing experiments at high pressures (5–15 kbar). Cylinders of 2.5 × 10 mm (axis perpendicular to (001)) were heated in a piston-cylinder apparatus (Griggs, 1967). There exists a considerable temperature gradient (~200°C) between the cooler ends and the hot central part of the specimen.

Thin sections cut perpendicular to (010) and (001) show distinct differences in shape and orientation of the optical indicatrix between the cooler ends and the hot central part (Fig. 1). The remarkably sharp boundary between the two optical states is evidently due to the absence of optically intermediate states. The inversion occurs at 840°C ± 20 which coincides roughly with the breakdown temperature of talc, used as a pressure medium, to enstatite quartz and water.

The experiments were done at various conditions between 5 and 15 kbar for 25–100 hours. To study the influence of water, hydrothermal experiments were done at 1 kbar, dry and with H_2O. Some piston cylinder experiments were done with Alsimag as pressure medium to avoid free water; in others kaolinite or pyrophyllite were used, which break down at lower temperatures than talc. The inversion temperature did not change significantly, however the boundary appears to be more diffuse in dry environments and at lower pressures. No influence of time could be observed.

The orientation of the indicatrix was measured on the U-stage. From measurements of the optical axes, the albite-law twin lamellae and cleavage (001), on four spots in each part, the Euler angles were derived (Table 1).

[1] Possibly the material is identical with the one from Monteagle Township, Ontario, used by Borg and Heard in 1967 for unpublished deformation experiments.

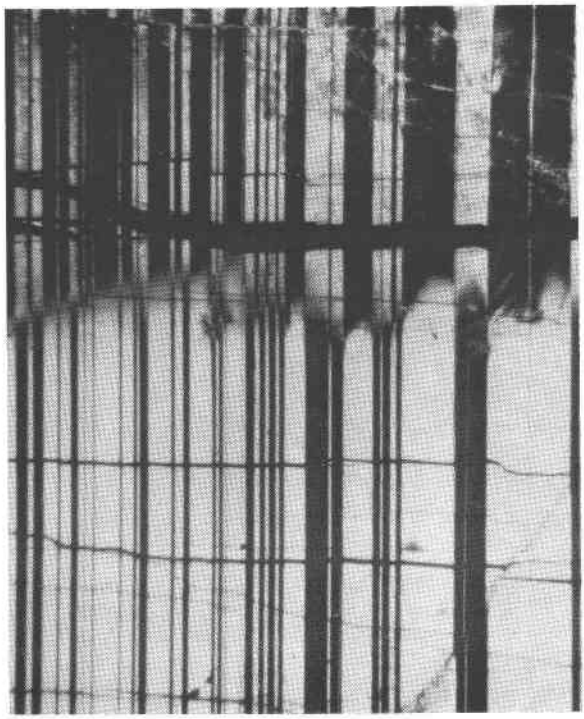

FIG. 1. Specimen DT 472 (annealed for 250h at 5 kbar and 1000°C in the hottest part), oligoclase with albite twinning, upper part inverted to optical high plagioclase.

Euler I angles were measured and constructed, Euler II and III derived analytically. The orientation of the indicatrix in the cooler part was found to be identical with the one of the starting material.

According to Burri, Parker, Wenk (1967) this would correspond to an optically maximum low and maximum high plagioclase of An 14–15 mole percent, respectively (Fig. 3a). This chemical composition was confirmed by microprobe analysis:

CaO	2.85 ± 0.05 wt%	
Na_2O	9.65 ± 0.1	$An_{13.5}Ab_{82.4}Or_{4.1}$ (mole %)
K_2O	0.73 ± 0.02	$An_{14.1}Ab_{81.6}Or_{4.3}$ (by wt)

The orthoclase content is high and makes it difficult to compare the crystal with the Burri-Parker-Wenk curves which are only calibrated for An and Ab. Although the plagioclase lies in the peristerite gap, neither optically, chemically nor by X rays could exsolution be detected, which does not prove, however, that the starting material is not peristeritic. The chemical composition is very homogeneous throughout the low and

TABLE I. ORIENTATION OF THE OPTICAL INDICATRIX

		Cooler end	Central part
Euler I	ϕ	90.7°±1°	95.5°±0.5°
	θ	74.3°±1°	69.2°±0.5°
	ψ	96.3°±0.5°	86.8°±1.5°
Euler II	R	68.5°	104.4°
	I	16.9°	21.0°
	L_α	111.3°	81.6°
	L_A	64.8°	55.9°
	L_B	157.8°	107.4°
Euler III	D	−1.0°	6.6°
	N	96.1°	87.0°
	K_α	164.2°	159.2°
optical axes	$2V_\gamma$	87.0°±1°	128.5°±1°
	A ϕ	222.4°	248.5°
	ρ	74.8°	72.8°
	B ϕ	317.2°	303.0°
	ρ	83.8°	70.0°

high parts and even within lamellae approximately parallel to (001) which developed during annealing (Fig. 2). These lamellae may be inversion-twins after the pericline law as the angle between the rhombic section and the base is very small for high-plagioclase of this chemical composition (Tunell, 1952; Smith, 1958; Starkey, 1967).

Lattice constants for the starting material were derived from powder data (Norelco diffractometer, Cu K_α, monochromator. Si internal standard. Least-squares refinement *cf.* Burnham, 1962):

a	8.161 ± 0.003 Å	a^*	0.13695 ± 0.00005 Å^{-1}
b	12.823 ± 0.003 Å	b^*	0.07817 ± 0.00002 Å^{-1}
c	7.149 ± 0.002 Å	c^*	0.15665 ± 0.00003 Å^{-1}
α	93.91 ± 0.02°	α^*	86.35 ± 0.02°
β	116.52 ± 0.02°	β^*	63.52 ± 0.02°
γ	88.55 ± 0.02°	γ^*	89.67 ± 0.02°
V	667.8 ± 0.4 Å^3	$2\theta_{131} - 2\theta_{\bar{1}31}$	1.30 calc
			1.26° obs.

From these data an An-content of 15 mole percent can be derived according to determination diagrams in standard texts (*e.g.*, Bächtiger, *et al.*, 1967). The deviation is due to the high Or-content as a comparison

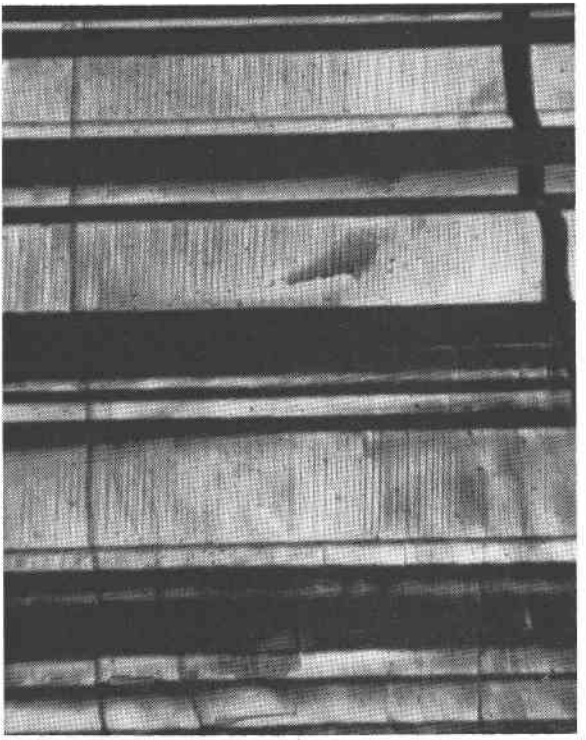

FIG. 2. Pericline inversion-twinning, developed in the high part.

with Orville's (1967) study on alkali-feldspars shows. The Or-content may also be causing the deviations from the optical migration curves. In fact for most single data points with high Or-content in Burri-Parker-Wenk one would derive a too high An-content.

Single crystals from the optically low and high regions were analyzed with the precession method as there was not sufficient material available to do powder studies. Lattice parameters were derived from precession a and c photographs. γ^* is the only parameter that can be measured accurately enough and shows significant deviations between cool and hot parts of the treated specimen and the starting material. The values for both parts of the specimen lie within the field of intermediate to high structures (Fig. 3b): The variations of the reciprocal angle γ^* are

	starting material	cool end	central part
γ^*	$89.67 \pm 0.02°$	$88.40 \pm 0.05°$	$88.04 \pm 0.05°$

In normally exposed precession photographs no b-split reflections could be observed.

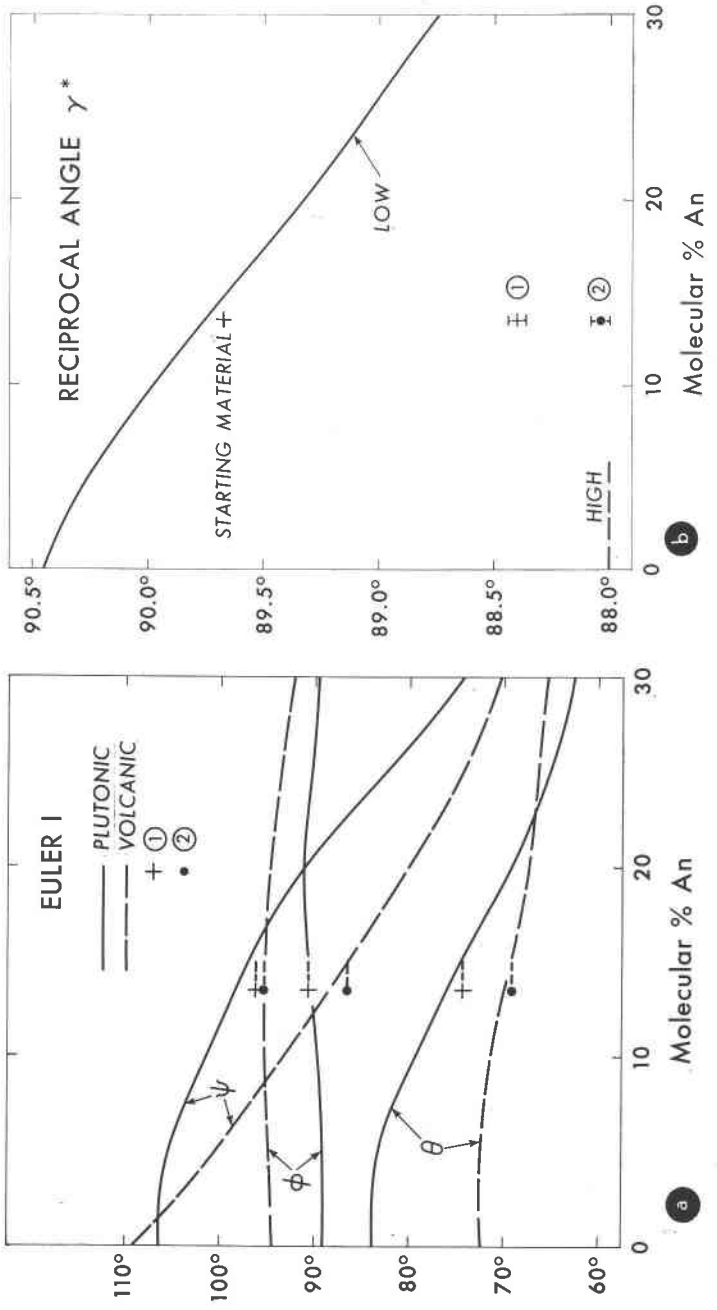

FIG. 3. Optical migration curves (Euler I) after Burri-Parker-Wenk, 1967 (Fig. 3a) and variation of the reciprocal angle γ^* after Bächtiger *et al.*, 1967 (Fig. 3b). The positions of the studied oligoclase specimen are indicated.

An elaborate interpretation of these data is not appropriate at this stage of the work. It is the first time, to our knowledge, that low and high optics are described in the same specimen of identical chemical composition and can be compared directly. Some facts seem to be important enough to be discussed here. In most specimens annealed at high confining pressures there is a definite lack of optical intermediate states. *Optical* intermediate plagioclase may be unstable at any pT-conditions. The reaction goes faster at high pressures (possible H_2O pressures). Similar experiments done by Borg and Heard[1] in vacuo showed only very incomplete optical inversion. There seems to be no direct correlation between the orientation of the optical indicatrix and the unit-cell dimensions (structure, Al/Si order-disorder). We hesitate therefore to interpret the optical migration curves as a direct function of ordering as Marfunin (1958) has done. Conditions that determine the ordering process may, however, also influence the optical properties. Further information should be obtained from experiments on other specimens falling outside the peristerite range of compositions.

Acknowledgments

Thanks are due to D.T. Griggs, J. M. Christie and the NSF project GP 5575 who made it possible to do the experiments in the Institute of Geophysics at U.C.L.A. The help of G. Ernst in hydrothermal experiments, stimulating discussions with I. Borg, microprobe analyses by B. Evans, microphotographs by F. Anderegg, and the support from the computer center at Berkeley are also gratefully acknowledged.

References

Bächtiger, K., H. V., Bambauer, M. Corlett, E. Eberhard, P. H. Ribbe, and K. Visvanathan (1967) Laboratory investigations of plagioclases. *Schweiz. Mineral. Petrogr. Mitt.*, **47**, 303–384.

Burri, C., R. L. Parker, and E. Wenk (1967) *Die optische Orientierung der Plagioklase.* Birkhäuser, Basel.

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

Marfunin, A. S. (1968) Novaja diagramma optičeskoj orientiowki kislych i srednich plagioklasow. *Dokl. Akad. Nauk SSSR*, **118**, 1183–1186.

Orville, P. M. (1967) Unit-cell parameters of the microcline-low albite and the sanidine-high albite solid solution series. *Amer. Mineral.*, **52**, 55–86.

Smith, J. V. (1958) The effect of composition and structural state on the rhombic section and pericline twins of plagioclase feldspars. *Amer. Mineral.*, **43**, 546–551.

Starkey, J. (1967) On the relationship of pericline and albite twinning to the composition and structural state of plagioclase feldspars. *Schweiz. Mineral. Petrogr. Mitt.*, **47**, 257–268.

Tunell, George (1952) The angle between the *a*-axis and the trace of the rhombic section on the {010}-pinacoid in the plagioclases. *Amer. J. Sci.*, Bowen vol., p. 547.

Manuscript received, May 31, 1968; accepted for publication, September 10, 1968.

[1] Borg, I. Y. and H. C. Heard (1967) A.F.C.R.L. Final Report 67-0308.