

Polytype transformations in experimentally deformed wollastonite

STEPHEN GUGGENHEIM

Department of Geological Sciences, University of Illinois at Chicago
Chicago, Illinois 60680

Abstract

Two deformation experiments involving cores and one involving powder from a single crystal of parawollastonite are described. Directed stress (at a recorded temperature of 1000°C, confining pressure of 10 kbar, and a constant strain rate of 10^{-5} sec⁻¹) parallel to the silicate chain axis produced kinking of the parawollastonite and, consequently, a rotation of domains approaching polygonization. Under similar experimental conditions, the other core of parawollastonite, oriented with the maximum resolved shear stress on the (100) and [010] down-dip within the shear plane, developed a disordered structure. The suggestion by Wenk (1969) that disordering may occur when there is significant resolved shear stress on (010) is confirmed. Syntectonic recrystallization of powder (at a recorded temperature of 1100°C, confining pressure of 10 kbar, and a constant strain rate of 10^{-6} sec⁻¹ for 23 hours) produced ordered wollastonite-1Tc crystals.

Introduction

As early as 1950 Ito suggested that the parawollastonite structure is similar to the wollastonite-1Tc structure but with each successive pseudomonoclinic cell shifted to produce an overall monoclinic symmetry. Subsequently, several authors (Jeffery, 1953; Dornberger-Schiff *et al.*, 1955; Prewitt and Buerger, 1963; Peacor and Prewitt, 1963; Trojer, 1968) have described the parawollastonite structure as one derived from the wollastonite-1Tc structure (or the pseudomonoclinic cell). The formation of other polytypic modifications was suggested by Wenk (1969), using precession photographs of wollastonite from regional-metamorphic rocks of the western United States and the Lepontine Zone of the southern Alps as evidence. Furthermore, he proposed that the different polytypes could be explained genetically by variations in deformational history.

Further investigation of wollastonite polytypes was done by Jefferson and Bown (1973), in which they considered the effect of the different stacking arrangements on the diffraction pattern. Later, Wenk *et al.* (1976) used transmission electron microscopy (TEM) to study partial ordering and also reinterpreted the parawollastonite structure. Most recently, Hutchison and McLaren (1976, 1977) re-investigated wollastonite polytypes by electron microscopy.

The available indirect data by electron microscopy

and the crystal-chemical data from structural studies both indicate that $b/2$ translations on (100) appear to be the best mechanism for polytype transformation. This paper describes two deformation experiments using single-crystal sections (obtained from a single specimen) in a Griggs-type apparatus to provide direct data on the effect of crystal orientation and deformation on polytype formation. In addition, powdered material from the specimen was used in a deformation experiment to produce a polytype change.

Experimental

Difficulty in obtaining cores, even by ultrasonic drilling, due to brittleness of the material limited the number of total experiments. However, two cores were obtained from a homogeneous ordered parawollastonite crystal from Crestmore, California. In both cases, the core lengths were extended by carbide packing to achieve an overall starting length of 1.905 cm for placement in a large Griggs-type solid-pressure (talc) medium, constant strain rate apparatus (Griggs, 1967). It is assumed that the effect of the carbide packing and smaller sample size was to increase the axial temperature gradient from that given by Carter and Ave' Lallemand (1970).

Core A The core was permanently deformed by 12 percent shortening of the original starting length of

0.906 cm. The core was cut so that the Y axis of the crystal was parallel to the core length. The recorded temperature of $1000^{\circ}\text{C} \pm 15^{\circ}\text{C}$ is not the actual temperature of the inside of the core, which is believed to be about 100°C higher, based on calibration curves by S. H. Kirby (Carter and Ave' Lallemand, 1970). Other experimental conditions were a confining pressure of 10 kbar and a constant strain rate of 10^{-5} sec^{-1} . The stress *vs.* strain curve, the strain *vs.* time curve, and a sketch of the core cross-section are presented in Figure 1.

Core B Core B was cut so that (100) was the maximum shearing plane with [010] down-dip within the shear plane. The starting length was 1.008 cm and it was permanently deformed by 18 percent shortening under similar conditions as Core A. Figure 2 presents the stress *vs.* strain curve, the strain *vs.* time curve, and a core cross-section sketch.

Core C Powder from the Crestmore crystal was ground to less than $37 \mu\text{m}$ and compressed into a core 1.905 cm long. After 21-1/2 hours at a recorded temperature of 1100°C , a confining pressure of 10

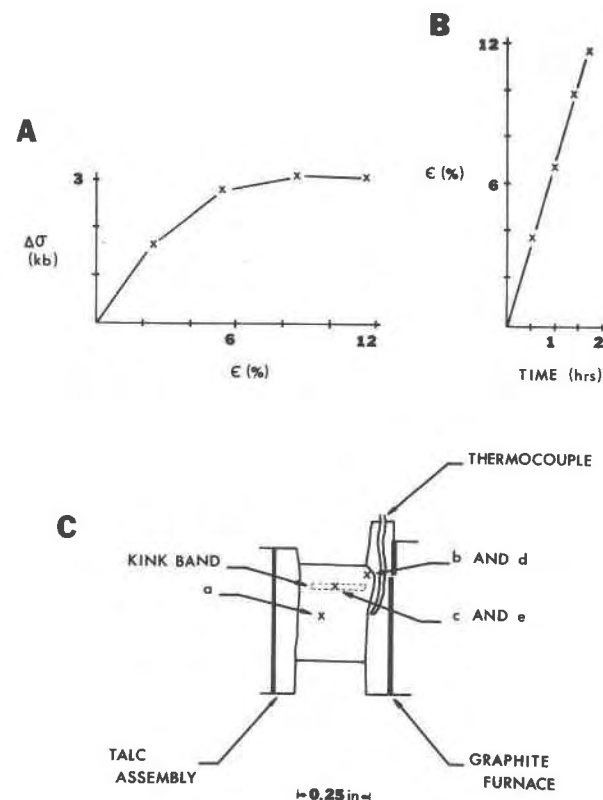


Fig. 1. Results of deforming Core A with Y parallel to the core length. Part (A) shows the stress *vs.* strain curve, part (B) the strain *vs.* time curve and part (C) a sketch indicating where the crystal sections were taken for X-ray work.

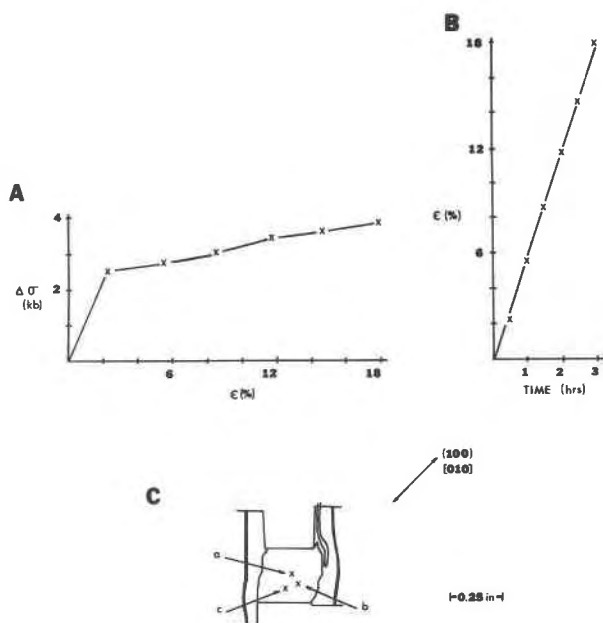


Fig. 2. Results of deforming Core B with (100) as the maximum shearing plane and [010] down-dip as shown in part (C). Parts (A) and (B) show the stress *vs.* strain plot and strain *vs.* time curve, respectively.

kbar, and a constant strain rate of 10^{-6} sec^{-1} , recrystallization was observed. A stress *vs.* strain curve is not meaningful for this core because the curve would be, in part, a function of the core's initial compaction.

Crystal sections taken at different locations from an undeformed core section indicated that coring and sawing had no effect on X-ray single-crystal patterns.

Results

Highly localized deformation resulting in a kink was observed in Core A, with varying degrees of undulatory extinction throughout the petrographic section made after deformation (see Fig. 3). Buerger $hk0$ precession photographs of crystal sections near the kink band show a discontinuous arc of moderately diffuse reflections emanating from only one side of each normal wollastonite reflection (see Fig. 4). The arc is not along the X^* direction but rather along regions of equal $\sin \theta/\lambda$ values. In contrast, the differences associated with disordering occur along X^* on the $hk0$ net for $k \neq 2n$ reflections. No significant streaking of this type was found for Core A. In this case, diffuse streaking may be attributed predominantly to a rotation of domains with some accompanying bending. Comparison to precession photographs from a parawollastonite crystal section taken

from a natural kink band showed similar, although less diffuse, reflections on the $0kl$ net.

A thin section cut longitudinally along the length of Core B indicated that simple shear had occurred to varying degrees. Precession photographs of crystal sections taken near the core center where shear was greatest show diffuseness along X^* on the $hk0$ net for $k \neq 2n$ reflections. This diffuseness is quite pronounced and no maxima were observed within the streaks. Hence crystal sections from the core center had been disordered, whereas crystal sections taken elsewhere show little or no disordering.

The recrystallization experiment produced very small (<0.1 mm) crystals with crystal lengths aligned approximately perpendicular to the σ_3 axis. Two crystals were characterized, and both were wollastonite-1Tc. One of these crystals showed twinning of the wollastonite-1Tc structure.

Discussion

Disordering will occur when there is significant resolved shear stress on (100) in the [010] direction. These results are consistent with crystallographic data, based on refinements of the wollastonite structures in which the silicate chains running parallel to the Y axis are periodically translated by $b/2$. No Si-O bonds are broken. Since a disordered structure may

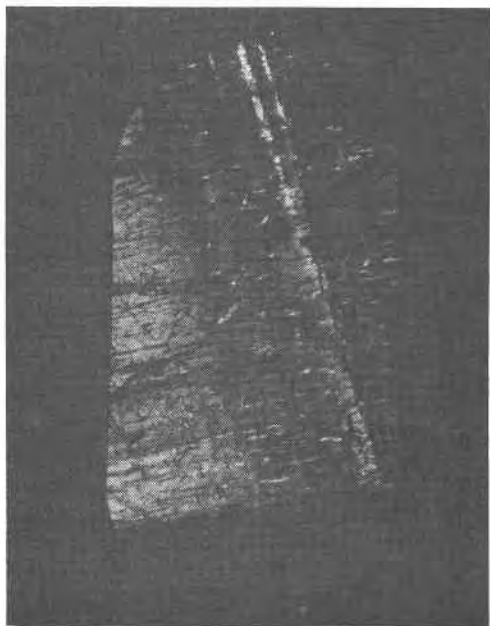


Fig. 3. A photomicrograph taken with crossed polarizers showing the kink band of Core A. The experimentally deformed section is mounted on a transmission electron microscope mask; the sample width is 1.0 mm.

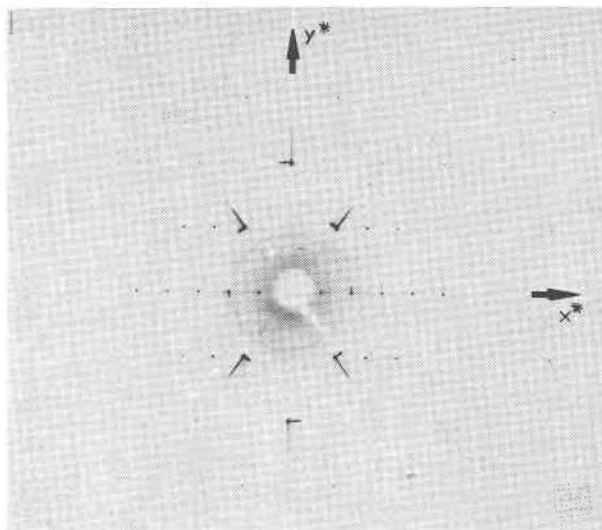


Fig. 4. The $hk0$ net of a small wollastonite fragment from the kink band from Core A. Because of the crystal size, $k \neq 2n$ reflections are quite weak and are not clearly reproduced. However, the effect of the deformation (the arcs along equal $\sin \theta / \lambda$ values) is apparent on the stronger reflections. Their discontinuous nature is quite subtle and may not be readily apparent in the photographic reproduction.

be considered in the strictest sense a polytype, although not a regular one, these results also confirm Wenk's (1969) suggestion that wollastonite polytypes and disordering may result from deformation-induced (100) faults which separate units consisting of one or more pseudomonoclinic cells. However, these experiments do not eliminate the possibility, also suggested by Wenk, that other processes may be responsible for regular polytype development. In particular, other processes or a combination of several processes may be necessary to produce the periodic faulting that yield polytypes with a repeat unit along [100] greater than one.

The significance of the syntectonic recrystallization experiment (Core C) is less clear. Neither these data nor the abundance of naturally-occurring parawollastonite can be used as evidence to deduce the existence of a stability field for this polytype. However, the experiment does lend credit to the idea that deformational history may be important to polytype formation. Further work is needed to describe that relationship. In addition, an experimental determination of the activation energy required for initiating the disordering process would be useful as a minimum stress indicator. These results as well as those of Wenk (1969) are potentially useful as deformational indicators. However, stress is usually not homoge-

neously transmitted through an inhomogeneous rock mass, and care must be taken in using the orientation effect as a regional stress-direction indicator.

Acknowledgments

I thank Drs. C. T. Prewitt and N. Carter, both of SUNY at Stony Brook, New York, for use of their laboratory facilities, and Dr. J. Arem and the Smithsonian Institution for providing the wollastonite specimen (NMNH 93137).

References

- Carter, N. L. and H. G. Ave' Lallemand (1970) High temperature flow of dunite and peridotite. *Geol. Soc. Am. Bull.*, 81, 2181-2202.
- Dornberger-Schiff, K., F. Liebau and E. Thilo (1955) Zur Struktur des β -Wollastonites, des Maddrellschen Salzes und des Natrium Polyarsenats. *Acta Crystallogr.*, 8, 752-754.
- Griggs, D. T. (1967) Hydrolytic weakening of quartz and other silicates. *Roy. Astron. Soc. Geophys. J.*, 14, 19-31.
- Hutchison, J. S. and A. C. McLaren (1976) Two dimensional lattice images of stacking disorder in wollastonite. *Contrib. Mineral. Petrol.*, 55, 303-309.
- (1977) Stacking disorder in wollastonite and its relationship to twinning and the structure of parawollastonite. *Contrib. Mineral. Petrol.*, 61, 11-13.
- Ito, T. (1950) *X-ray Studies on Polymorphism*. Maruzen, Tokyo.
- Jefferson, D. A. and M. G. Bown (1973) Polytypism and stacking disorder in wollastonite. *Nature*, 245, 43-44.
- Jeffery, J. W. (1953) Unusual X-ray diffraction effects from a crystal of wollastonite. *Acta Crystallogr.*, 6, 821-825.
- Peacor, D. R. and C. T. Prewitt (1963) Comparison of the crystal structures of bustamite and wollastonite. *Am. Mineral.*, 48, 1527-1542.
- Prewitt, C. T. and M. J. Buerger (1963) Comparison of the crystal structures of wollastonite and pectolite. *Mineral. Soc. Am. Spec. Pap.*, 1, 293-302.
- Trojer, F. J. (1968) Crystal structure of parawollastonite. *Z. Kristallogr.*, 127, 291-308.
- Wenk, H.-R. (1969) Polymorphism of wollastonite. *Contrib. Mineral. Petrol.*, 22, 238-247.
- , W. F. Müller, N. A. Liddell and P. P. Phakey (1976) Polytypism in wollastonite. In H.-R. Wenk, Ed., *Electron Microscopy in Mineralogy*, p. 324-331. Springer-Verlag, New York.

Manuscript received, September 1, 1977; accepted for publication, April 6, 1978.