SCIENCE

Sanidine: Predicted and Observed Monoclinic-to-Triclinic Reversible Transformations at High Pressure

Abstract. *High sanidine, (K,Na)AlSi$_3$O$_8$, transforms reversibly to a triclinic phase at high pressure. This is analogous to the high-temperature monalbite transformation. Disordered alkali feldspars of various compositions have unit-cell dimensions which are very similar at the transition (a = 8.30 Å, b = 12.97 Å, c = 7.14 Å, and β = 116.2°), indicating that the transformation is structurally controlled. Changes in temperature, pressure, and the sodium/potassium ratio cause similar structural variations: angles between adjacent, rigid tetrahedra vary to accommodate changing effective alkali cation sizes.*

A well-known high-temperature phase transformation is that of disordered monoclinic albite (monalbite, NaAlSi$_3$O$_8$), which becomes triclinic (high albite) at temperatures below ≈1100°C because of collapse of the Al-Si framework about the alkali site (*I*, vol. 1; *2*). The transformation temperature decreases with increasing K/Na ratio, and at room conditions metastable disordered alkali feldspars more potassic than ≈ Or$_{38}$ (*3*) are monoclinic high sanidines (*4*). Mineral crystal structures vary continuously with changes in pressure as well as temperature, and in many silicates the changes during compression to high pressure are similar to changes during cooling from high temperatures (*5*). On this basis it was predicted that high sanidine would transform to the triclinic high-albite structure at elevated pressures, with more potassic sanidines requiring higher pressures. This prediction has now been confirmed, and the monoclinic-to-triclinic transition has been observed in two high sanidines: Or$_{67}$ at 12 ± 1 kbar and Or$_{82}$ at 18 ± 1 kbar.

Single crystals of high sanidine were selected from material described by MacKenzie (*6*). Eifel sanidine from Wehr and Eifel (Or$_{82}$Ab$_{17}$An$_1$) and Mineral Creek sanidine from San Juan, Colora-

do (Larsen 10; Or$_{67}$Ab$_{31}$An$_2$), were the specimens used. Crystals were mounted with a gillespite reference crystal in a miniature diamond pressure cell (*7*), using the Van Valkenburg metal-foil gasketing technique. Index-of-refraction oil was the hydrostatic pressure medium. Unit-cell dimensions were measured at several pressures to 38 kbar using single-crystal x-ray photographic techniques. Pressure was calibrated from the known volume compressibility of alkali feldspar (*I*, vol. 2) and from the 26-kbar red-to-blue gillespite transformation (*8*).

Monoclinic unit-cell parameters vary regularly with increasing pressure; *a*, *b*, and *c* decrease, while β increases slightly (see Fig. 1). At sufficient pressure high-sanidine cell dimensions reach "critical values" of *a* = 8.30 Å, *b* = 12.97 Å, *c* = 7.14 Å, and β = 116.2°. At higher pressures α and γ deviate from 90°, indicating a transition to triclinic symmetry (see Fig. 1). Comparison of critical cell dimensions with those of monalbite at 1100°C [*a* = 8.28 Å, *b* = 12.96 Å, *c* = 7.15 Å, and β = 116.1° (*2*)] and of Or$_{38}$ at room conditions [*a* = 8.32 Å, *b* = 12.96 Å, *c* = 7.15 Å, and β = 116.2° (*I*, vol. 1)] reveals that the monoclinic-to-triclinic transition is struc-

turally controlled, since cell dimensions are nearly constant along the pressure-composition (*P-X*) and temperature-composition (*T-X*) transition curves. The monalbite-to-high albite transition has usually been described as the result of "collapse" of the Al-Si framework about an alkali site which is too small to support a framework with monoclinic symmetry. The size of individual tetrahedra does not change appreciably with temperature or pressure (*9*), but the alkali site may change size in three ways, by changing temperature, pressure, or Na/K ratio. When the effective size of the alkali site falls below the critical level (either by cooling or compression or Na substitution) the monoclinic framework will distort to triclinic symmetry.

Since changes in temperature, pressure, and Na/K ratio seem to cause similar structural responses, it appears reasonable to postulate a transition surface in *P-T-X* space which approximates a surface of constant structure for disordered alkali feldspars (see Fig. 2). The cell dimensions are observed to be constant on the *T-X* and *P-X* faces of Fig. 2, but it should be emphasized that no data are available on the central portion of Fig. 2, and a planar surface has been assumed.

In reversible phase transformations involving a reduction of symmetry twinning may occur. The twin law will be a symmetry element of the higher-symmetry form, and the twin will result from simultaneous nucleation of two different, but symmetrically related, orientations of the low-symmetry form. In the transition from monalbite to high albite (*C*2/ *m* → *C*$\bar{1}$) two types of twins are common: the albite and pericline laws. In Or$_{67}$ no twinning was observed above 12

kbar, but Or₈₂ did twin on the albite law above 18 kbar. It is expected that pericline twins could also occur, and that the types and extent of twinning will depend, in part, on crystal defects and morphology.

The geothermal gradient of the crust averages ≈15°C per kilometer, or 45°C per kilobar, assuming 1 kbar per 3.0 km (*10*). The slope of the transition surface (Fig. 2) in the *P-T* section is somewhat steeper (≈70°C per kilobar). Therefore, some alkali feldspars which are mono-

clinic at surface conditions may have been triclinic at depth, especially if local thermal gradients are low. On the other hand, volcanic sanidines which have not been reburied were probably monoclinic throughout their histories. Since the monoclinic-to-triclinic transition is displacive (and probably second-order) there will be no obvious evidence of triclinic history in disordered monoclinic alkali feldspars. Unlike the slow ordering and exsolution transitions in feldspars, the reversible high-pressure transition is

of no help in determining the thermal or pressure history of a feldspar-bearing rock. However, it is possible that the pressure-induced monoclinic-to-triclinic transition interacts with the order-induced monoclinic-to-triclinic (orthoclase-to-microcline) transition. In this event pressure would enhance the formation of the triclinic ordered form. Furthermore, it is anticipated that partially ordered monoclinic feldspars will transform to triclinic symmetry at lower pressures than disordered feldspars of the same composition.

Perhaps the most intriguing aspect of this work is the evidence of possible isostructural *P-T-X* surfaces, and their close relationships to phase transition surfaces. The stability of many minerals is limited by geometrical packing limits of adjacent groups of polyhedra (such as micas, pyroxenes, amphiboles, and olivines). Since changes in temperature, pressure, and composition may all have the same effect of varying polyhedral size ratios (*9*), the concept of isostructural stability fields in *P-T-X* space does not seem unreasonable for these minerals. Of course, other phase regions will intersect the geometrically limiting surface. Still, the existence of isostructural *P-T-X* surfaces, and their close relationship to phase transition surfaces, may allow prediction of some phase equilibria from basic structural data.

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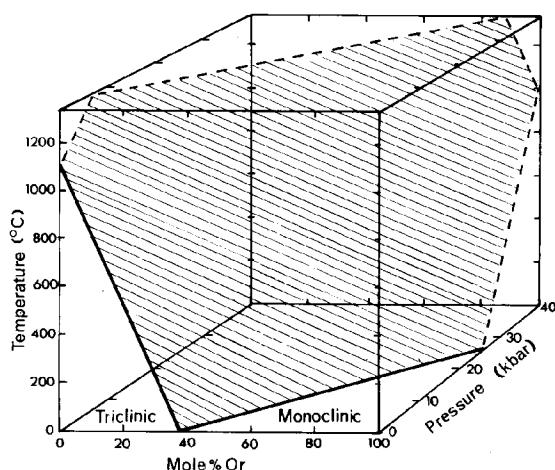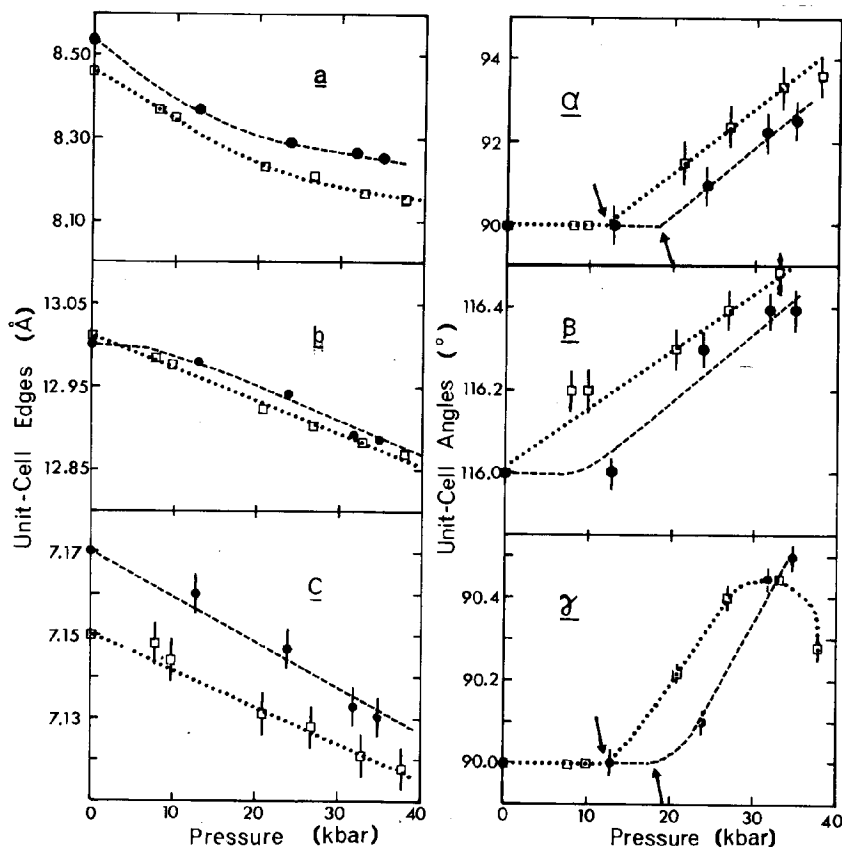Petrology, University of Cambridge,
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Fig. 1 (above). Unit-cell dimensions of high sanidines as a function of pressure. Angles α and γ deviate from 90° at 12 ± 1 kbar for Or₆₇ (squares) and at 18 ± 1 kbar for Or₈₂ (circles), indicating triclinic symmetry. Arrows indicate suggested transition points. Fig. 2 (left). Monoclinic-to-triclinic transition surface for disordered alkali feldspars. Since unit-cell dimensions are constant along the *T-X* and *P-X* curves of this surface, the surface may also represent an isostructural region.