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Solid Inclusion Piezothermometry II: Geometric Basis, Calibration for the Association Quartz—Garnet, and Application to Some Pelitic Schists

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Abstract

A procedure that enables determination of a pressure-temperature curve containing the pressure and temperature of incorporation of one mineral into a crystallizing host mineral consists of two steps. One step is determination of any experimentally-determined pressure and temperature for which a piezobirefringent halo in the host around the inclusion just vanishes. The second step uses a set of pressure-temperature curves, each of which indicates constant difference in natural strain between the two minerals as obtained by comparison dilatometry (Part I of this series). Barring complications, especially plastic creep, the curve that passes through the pressure and temperature at which the halo vanishes contains the pressure and temperature of incorporation. The intersection of two independently-determined curves of this type is the pressure and temperature of incorporation.

We report calibration of the association, quartz in three different orientations and garnet having a variety of compositions, to 7 kbar between 25°C and just below the low-high quartz transition. Extreme compositional variation within the solid solution $(Fe^{2+}, Mg, Ca, Mn^{2+})_3Al_2Si_3O_{12}$ has little effect on calibration. An implication of our work is that the linear coefficient of thermal expansion of almandine-type garnet near standard conditions is $\sim 7.58 \times 10^{-6}\ {}^\circ C^{-1}$, considerably higher than previously accepted.

Tight pressure-temperature restrictions on the Al_2SiO_5 triple point, consistent with the determinations of Newton and of Holdaway, result from applications of solid inclusion piezothermometry and other petrological information to occurrences in New England and an Alpine occurrence. The inferred denudation rate of 0.5 ± 0.1 mm/year at the Alpine occurrence lies within the range of values obtained by Clark and Jäger from data on heat flow and geochronology at the nearly Gotthard Tunnel.

Introduction

Some years ago Rosenfeld and Chase (1961, p. 528–535) and Rosenfeld (1969, p. 320–331, 345–347) discussed application of comparison dilatometry to solid inclusion piezothermometry, a procedure for determination of the pressure and temperature at which a mineral inclusion was incorporated into a host mineral. In the previous paper of this series (Adams, Cohen, and Rosenfeld, 1975; hereafter referred to as Part I), we have detailed techniques of comparison dilatometry that were petrologically motivated.

In this paper we pursue further petrological goals by (1) elaboration of the general qualitative

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geometric basis for solid inclusion piezothermometry, previously treated extensively and quantitatively for the special case of the host-inclusion pair, almandine-quartz (Rosenfeld, 1969, p. 320–328); (2) presentation of results of comparison dilatometry between garnet of various compositions and quartz in three orientations, extending the work of Adams *et al* (1970) to higher pressures; (3) correction, based upon experiments, of precalibration petrological inferences of Rosenfeld (1969, p. 335–345); and (4) addition of new observations on metamorphic rocks in western New England and the central Alps. We also briefly call attention to the discordance of our comparison dilatometry with previous X-ray diffraction work on synthetic almandine (Skinner, 1956).

Basis for Solid Inclusion Piezothermometry

Relationship of Geometry to Method

Assumptions of our model are that: (1) at the condition of envelopment (designated by subscript f) by the host, the inclusion is

(a) congruent to its cavity in the host;
(b) at the same temperature (T_f) as that of the host;
(c) at the same pressure (P_f) as that of the host; and that pressure is, for all practical purposes, hydrostatic;

and (2) after envelopment,

(d) host and inclusion are of such strength and stability that, within the lifetime of the combination and the conditions affecting it, all strains are solely elastic and thus not the consequence of plastic flow, phase transition, or radioactive damage;
(e) no tensile stress is maintainable across the interface between inclusion and host; and
(f) the inclusion does not shift irreversibly to a new position in the cavity.

The outline of the inclusion at P_f and T_f is the reference state for subsequently developed strains of inclusion and host.

For the purposes of analysis of ensuing strains and their implications, conceive the inclusion to be removed from the host without rotation and its outline to be superposed on the outline of the cavity in the host. Further, let host and inclusion, considered in this way, undergo identical changes in homogeneously distributed temperature and hydrostatic pressure.

If this assemblage, as imagined above, is subjected to a sufficiently wide range of pressure-temperature conditions, two regions in P-T space will logically arise if host and inclusion have different equations of state. Region *I* will be characterized by the presence of at least one direction in the inclusion for which its strain (≡ fractional change in length) is greater than the strain of the cavity in the same direction. Region *II* will be characterized by the absence of any direction for which the strain of the inclusion is as great as that of the cavity in the same direction. These two regions will be separated by a boundary along which, at each point, (1) there will be at least one direction in the inclusion for which the strain in the inclusion is equal to that in the host in the same direction; and (2) there will be no other direction for which the strain in the inclusion exceeds that of the host. That boundary will, of course, include P_f and T_f if the stated restrictions apply.

Now consider the inclusion within the host. By some procedure, permit access of a pressure medium of low viscosity to the host-inclusion interface. There will be a region of the P-T diagram within which the strains of both inclusion and host are governed by the second-rank tensor properties, thermal expansion and compressibility, which relate strain to the scalars, respectively temperature and hydrostatic pressure (Nye, 1957, p. 290). This region is characterized by those conditions for which all strains in the inclusion are less than those in the host in the same directions (*i.e.,* region *II*). This would not necessarily have been so if the pressure medium had not been permitted access to the host-inclusion interface.[3] Within region *I*, on the contrary, the situation is more complicated. There the strains of both inclusion and adjacent host are governed by second-rank thermal expansion tensors and fourth-rank compliance tensors, relating strain to nonhydrostatic stress. Accommodation of an inclusion, which in the model has at least one direction in which strain of the inclusion exceeds that of the host in the same direction, results in a halo of inhomogeneously distributed nonhydrostatic stress in the host around the inclusion.

In the absence of relaxational phenomena within or around the *in situ* inclusion, the boundary between regions *I* and *II* must pass through P_f and T_f. Further, *that boundary can be located because nonhydrostatic stress in the host around the inclusion in*

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[3] The preceding sentences of this paragraph state the essential "trick" that allows avoidance of difficult problems in elasticity and permits use of hydrostatic pressure apparatus in our system of piezothermometry.