(garnet), 5.9‰ (biotite); (g) has values of $\sin^2\theta_c$, at atmospheric pressure, of 0.2 to 0.32 at 25°C and 0.06 at 90 ± 15°C (new values from Adams, 1971, p. 87–90). Utilization of (e), (f), (g), and Figure 9 indicates that kyanite crystallized near the sillimanite field in a small $P - T$ region near 5 kbar and 545 ± 20°C, in quite good accord with placement of the kyanite-sillimanite boundary by both Newton (1966) and Holdaway (1971, p. 115). Thus we infer that the triple point should lie at a temperature below 545°C along a curve governed by the Clapeyron equation that emanates from $T \sim 545$°C and $P \sim 5$ kbar.

(3) Specimens α39 and AG4 are from the vicinity of the south border of the Gotthard Massif near Lukmanier Pass, Tessin, Switzerland. α39 is from the Triassic Quartenschiefer near the small hamlet of Brönich; and AG4 is from pre-Triassic schist of the Lukmanier-Decke immediately south of Passo del Sole, about 5 km west of Brönich. Specimen α39, a quartz-bearing paragonite schist, (h) shows, by abundant porphyroblasts of kyanite and oligoclase ($\sim An_{18}$), that the reaction leading to production of kyanite was: paragonite + quartz → kyanite + plagioclase + H_2O; (i) indicates, by the relationship of trains of inclusions inside porphyroblasts to their continuation outside, that the porphyroblasts formed late in the last major deformation that accompanied the metamorphism; (j) has some kyanite porphyroblasts that are bent up to 60° and have reaction selvages of sillimanite needles that are also bent, but to a lesser degree, about the same axis (Fig. 11); (k) was located near a paragonite-muscovite schist in which $d_{002\text{ muscovite}}$ = 9.929 Å (Frey, 1969, p. 126). We infer from (i) and (j) that the incomplete reaction kyanite → sillimanite occurred after dehydration reaction (h) that produced the kyanite porphyroblasts and therefore *after* the thermal maximum. If the reaction kyanite → sillimanite had taken place *before* the thermal maximum, dispersed and relatively coarse sillimanite should have been formed by the dehydration reaction instead of kyanite. Inasmuch as this is not the case, we infer that sillimanite formed primarily as a result of unloading and not as a result of rising temperature. Based on Rosenfeld *et al* (1958), we infer that the solid solution between muscovite and paragonite, reflected in basal spacings, indicates the *maximum* temperature of metamorphism. For that association, Rosenfeld (1969, p. 343–344) calibrated $d_{002,\text{ muscovite}}$ against $MgCO_3$ concentrations in calcite of closely juxtaposed dolomitic marbles. This enables use of fact (k) above to select the correct isopleth for $MgCO_3$ solubility in calcite from the experimental work of Goldsmith and Newton (1968), in this case 4.9 percent. Intersection of this isopleth with an isomeke obtained from isogradic specimen AG4 (see metamorphic map of Niggli, 1970, p. 18–19), yields the temperature and pressure of crystallization. Observation shows that isomeke to have a value of $\sin^2\theta_c$ between 0.14 and 0.35 using Figure 9. The intersection (Fig. 10) lies in a small $P - T$ region near 4.3 kbar near 515 ± 25°C.

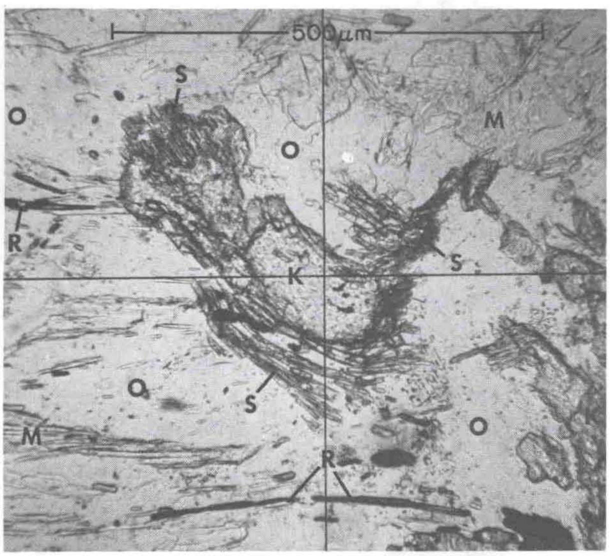

FIG. 11. Bent kyanite porphyroblast surrounded by selvage of sillimanite needles in paragonite schist from vicinity of Brönich in the Lukmanier Pass region, Switzerland. Minerals: K = kyanite; S = sillimanite; O = oligoclase; M = white mica; R = rutile.

(4) The discussion of specimen γ612 from Gap Mountain, New Hampshire, is unchanged from Rosenfeld (1969, p. 340–343) except for recalibration of isomekes. In γ612, which has $\sin^2\theta_c$ between 0.6 and 0.7, there is evidence of the reaction andalusite → sillimanite. This is consistent with the results of Holdaway in that those isomekes intersect his andalusite-sillimanite boundary. The data for γ612 are not so restrictive as the combined results for specimen A57d and the alpine specimens.

In summary, the information from the Alps not only is consistent with location of a pressure and temperature on the kyanite-sillimanite boundary in New England but is probably more restrictive on the temperature of the triple point. What makes the Alpine information of most interest is the above inference that the reaction kyanite → sillimanite took place at or below approximately 515°C. The sillimanite in the southern Gotthard area is 25 km from the nearest point on the sillimanite isograd to the southeast (Niggli, 1970, plate 2). Its occurrence is probably a result of a curious set of circumstances: activation of recrystallization by strain energy of deformation coupled with relatively rapid unloading due to denudation that accompanied the formation of the central Alps as a range of high mountains after the Eocene (Niggli, 1970, p. 18). The rapidity of unloading relative to cooling by thermal conduction apparently maintained temperatures sufficiently high for the reaction to take place when the $P - T$ path of the rock entered the sillimanite field on its way to the lower P and T at the earth's surface.[11] Assuming that there are no problems with metastable crystallization of sillimanite relative to andalusite in the geological time intervals involved, the triple point must lie at $T < (515 \pm 25°C)$. Examination of Figure 10 shows that the experimentally inferred triple points of Newton (1966) and of Holdaway (1971, p. 115) lie within the $P - T$ region below 515°C between temperatures on the isomekes for specimens A57d and AG4 or α39 on the high-P side and specimen γ612 on the low-P side. This is consistent with the above inferences from solid inclusion piezothermometry and geochemistry. The triple point of Richardson, Gilbert, and Bell (1969, p. 266) lies at too high a temperature to be consistent with the above interpretations.

The information from specimens α39 and AG4 in Figure 10 also provides information on the average denudation rate since the thermal maximum in the area. Clark and Jäger (1969, p. 1149) place the thermal maximum in the area at (30 ± 5) m.y., consistent with the work of Steiger (1964). Denudation of ~16 km of material (inferred from the 4.3 kbar pressure of crystallization) during that interval leads to a mean denudation rate of 0.5 ± 0.1 mm/year. This rate is closely comparable with inferred denudation rates of Clark and Jäger (1969, p. 1154) for the area of the Gotthard Tunnel a few kilometers to the west of Passo del Sole along the structural trend. They interpreted a relatively high heat flow there as a transient effect of denudation.

[11] That this phenomenon is not unique in the region is indicated by the textural evidence in a specimen collected 12 km to the south. There, in a specimen of the higher temperature paragonite-muscovite (d_{002} = 9.888 Å) schist near Alp Sponda on Pizzo Forno (collector: J. B. Thompson, Jr.), we have observed in thin section a selvage of sillimanite needles, coarser than those in α39, adjacent to unbent kyanite. This occurrence is in the same area where Keller (1968, p. 41–47) found kyanite and andalusite in lenses ("Knauer") in textural relationships that suggest that the latter recrystallized from the former. He called on a falling P and T path at a T below that of the triple point to explain the sequential relationship. Other possibilities at Pizzo Forno are that the P-T path passed out of the kyanite field into the sillimanite field and then into the andalusite field and that the good expression of these later phases is a consequence of rapid unloading with a broad loop in the P-T path extending to considerably higher temperatures than those of α39. Given the negative dP/dT of the andalusite-sillimanite reaction boundary, a larger P-T loop would give a higher T of entry into the andalusite field, thereby facilitating the crystallization of that mineral. Presumably specimen α39 also passed through the andalusite field, but at too low a temperature for reaction in the available time.

Epilogue

Full application of solid inclusion piezothermometry awaits completion of a high aperture window bomb to complement a heating stage in finding conditions for halo elimination. Using the heating stage and window bomb, it should become possible to cross-check answers obtained totally by solid inclusion piezothermometry against those obtained by other means.

The possibility of plastic deformation around or in an inclusion must be considered. Carstens (1971) has demonstrated creep around inclusions in mantle-derived garnet xenocrysts that must have followed a $P - T$ path which, at high temperature, greatly and rapidly departed from the relevant isomekes (*cf* Rosenfeld and Chase, 1961, p. 538). It remains to be seen whether such plastic deformation is important in regionally metamorphosed crustal rocks that recrystallized at much lower temperatures and that probably followed $P - T$ paths having much lower departures from relevant isomekes over much longer time intervals. It is even possible that quantitative experimental and theoretical analysis of dislocation halos, such as those noted by Carstens, might yield information on original conditions of formation and/or unroofing history.

The work we report here is thus somewhat in the nature of a progress report. Further experimental determinations of isomekes are needed—*e.g.*, sillimanite-garnet, diamond and its inclusions—and some are in progress. Further instrumentation will have to be developed—*e.g.*, the window bomb—and this is also in progress; and further work will be necessary on dislocation creep and the theoretical foundations of solid inclusion piezothermometry.

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