and makes electrical contact with the metal coating on the base via conductive paint.

Description of "Opposed Rods" Dilatometer. To eliminate some of the difficulties associated with the "J" dilatometer, a variant, the "opposed rods" dilatometer (Fig. 2) was developed. The longitudinal 90° groove in the "opposed rods" dilatometer is through-going and is easily ground with a shaped grinding wheel. This permitted construction of narrower but simultaneously less fragile fiducial ridges for the rods by using an Airbrasive® tool and masking technique. Narrowness of fiducial ridges (≈ 100 μm) contributes to precision, but this improvement is partly offset by error associated with the presence of the fiducial ridge for the second rod. The electrical circuit is similar to that of the "J" device.

This device also has the virtue of utilizing more readily available smaller pieces of mineral for both the rods and the base. Although vacuum-deposited conductive coatings are still necessary on the tops and contacting parts of rods, this design eliminates dependence on conductive paint, at best a somewhat unreliable component of electrical circuitry. A roller bearing is kept near each fiducial ridge so as to maintain high frictional resistance to sliding between rod and fiducial ridge but low frictional resistance at the free end.

Experimental Procedure. An isomeke is determined for a particular setting of the gap by noting the set of $P-T$ points for which a voltage source just causes a detectable current to pass through the device (that is, the switch is closed). Normally an isomeke is determined with this type of device by slowly changing, say, temperature until the circuit is just closed, then *immediately* reversing the sense of temperature change so as to break the circuit before force builds up at the electrical contact and causes a rod to reset by sliding at the clamped support(s). The pressure is then changed and the previous operation repeated to locate another point on the isomeke, and so on. Figure 3 is part of a strip chart record that shows a typical example of isomeke determination.

Distinction is made between data points obtained on the P-T path going away from starting conditions and those obtained on the return path. Reproducibility is necessary for a run to be accepted. This test was applied to all dilatometers described here.

For this kind of dilatometer, the quality of coating and its adhesion to mineral surfaces is critical. For example, experimental data for "make contact" and "break contact" had to be treated separately until improved coating techniques rendered the distinction unnecessary.

The dilatometer is reset to determine a new isomeke by changing the gap width γ between the free end of the rod (r) and the corresponding part of the base (b) in the "J" device, or between the free

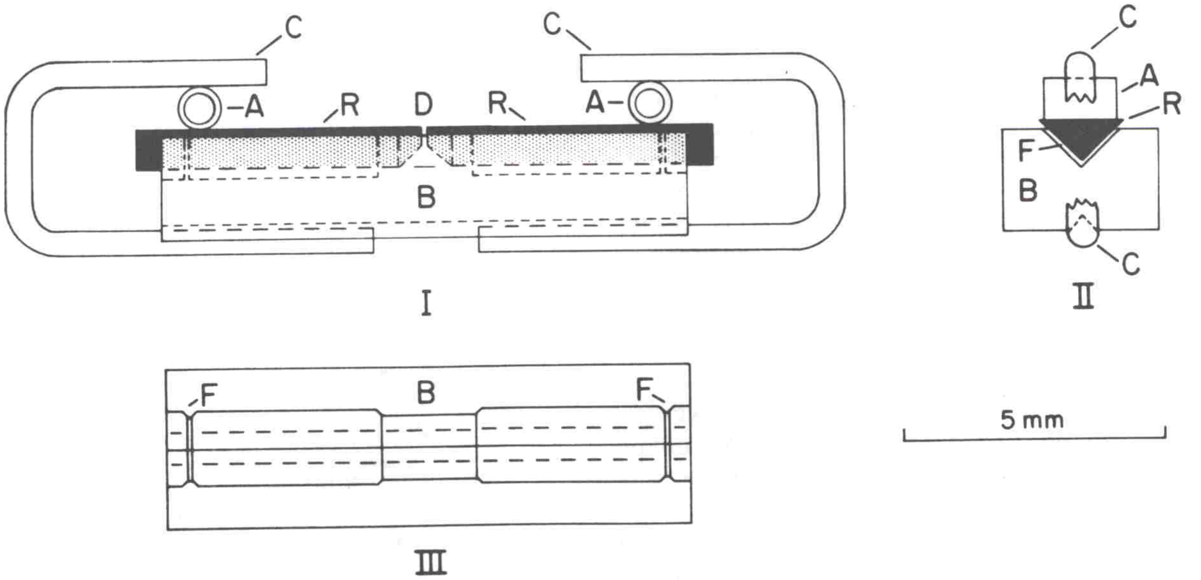

FIG. 2. Scale drawing of "opposed rods" dilatometer. I. Side view. Two insulated electrical leads, not shown, are attached to clamps (C). II. End view. III. View from top showing base (B) only. Letters designate the following components: A, roller bearings that are in electrical contact with metallic coatings atop rods; B, base, one of minerals being investigated; C, tungsten wires that clamp rods to fiducial ridges in base; D, electrical contact, formed between coatings at ends of rods; F, fiducial ridges; R, rods, other mineral being investigated. Thermocouple (not shown) is placed near dilatometer during experiment.

ends of the rods in the "opposed rods" device. This adjustment of the position of the rod(s) is normally done under a microscope at room conditions (designated by subscript o). γ is estimated from

$$\gamma \equiv l_{\mathrm{bo}} - l_{\mathrm{ro}} \approx [(\beta_{\mathrm{bo}} - \beta_{\mathrm{ro}})(P_i - P_o) - (\alpha_{\mathrm{bo}} - \alpha_{\mathrm{ro}})(T_i - T_o)]l_{\mathrm{bo}} \quad (1)$$

where l_{bo} and l_{ro} are the lengths of mineral being compared, α is the linear coefficient of thermal expansion, β is the linear coefficient of compressibility, and P_i and T_i are the P and T at which one desires to intercept the new isomeke.

It is evident from the nature of devices of this type, their convenient adjustment at ambient conditions, and the necessity that $\gamma \geq 0$ (compare Equation 1 above) that they permit determination of isomekes only in that part of P-T space on one side of the isomeke passing through ambient P and T. Isomekes in the other part of P-T space are attainable by construction of a congruent device in which the oriented material of rod(s) and base are interchanged.

Accuracy. As a check on accuracy of this type of dilatometer, a "J" device was made of quartz with the base oriented $\|$ c and the rod $\perp$ c. This combination was selected because of the existence of accurate data on α and β for quartz (McSkimin *et al,* 1965). Figure 4 shows data for runs projecting to the temperature axis at 31°C and 65°C.

The points for both runs conform rather closely to straight lines having a slope of 0.0360°C/bar below approximately 3 kbar. Using equation (7-II),[3] this slope almost exactly equals the 0.03605°C/bar calculated for 25°C and 1 bar using data for quartz from McSkimin *et al* (1965). Lines bracketing the calculated slope in Figure 4 represent a standard deviation of 0.0076°C/bar, calculated from analysis of error propagation (Bevington, 1969, p. 56–65) assuming conservatively estimated standard deviations $\sigma_\beta = 10^{-9}$ bar^{-1} and $\sigma_\alpha = 10^{-7}$ °C^{-1}. An estimate of the precision with which thermal expansion or compressibility in one direction, say $\|$ c, could be determined is obtained by combining the above estimate of standard deviation in slope with the same conservative assumptions for $\sigma_{\beta\perp c}$ and $\sigma_{\alpha\perp c}$. We obtain $\sigma_{\alpha\|c} = 0.18 \times 10^{-6}$ °C^{-1} and $\sigma_{\beta\|c} = 0.0074 \times 10^{-6}$ bar^{-1}.

Critique. These devices have the great advantage of simplicity of design; and some excellent data, such as those in Figure 3, have been obtained with them. Their designs do not make strong demands on precision of machining. Unlike the design of Bridgman (1949, p. 194) and in common with our other dilatometers, possibility of hysteresis and other error due to "stick-slip" of sliding parts is reduced essentially to nonexistence. There are also difficulties. Construction of the base of the "J" dilatometer requires a rather large homogeneous crystal—a major objection when dealing with natural materials in which zoning and inclusions are commonly present.

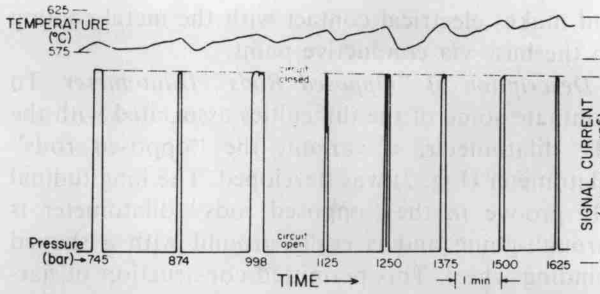

FIG. 3. Part of 2-pen strip chart record for determination of an isomeke between quartz (48° from c) and almandine using the "J" dilatometer. Corrected for offset of pens.

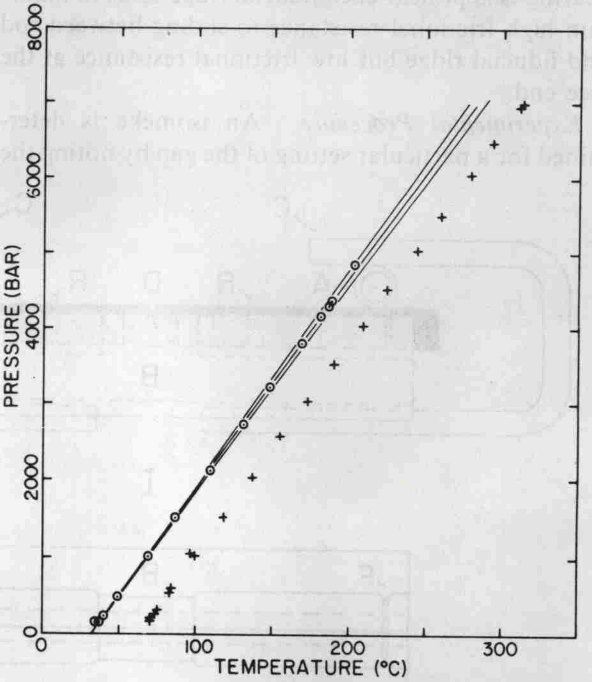

FIG. 4. Data points obtained with "J" dilatometer for determination of two isomekes between quartz $\perp$ c and quartz $\|$ c. The intermediate straight line associated with the set of experimental points denoted by circles was determined using Equation (7-II) and data at 25°C and atmospheric pressure from McSkimin *et al* (1965). Straddling lines indicate standard deviation of slope based on estimated standard deviations of properties used in Equation (7-II).

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[3] Equations so labeled are from Part II of this series (Adams *et al,* 1975).