THE FELDSPAR GEOLOGIC THERMOMETERS

by

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A rock is the result of a series of completed processes. Whatever rock present is far removed from the conditions under which it was formed. Any record of temperature will for these completed processes be obtained by inspection of the cold rock. We have to look for some properties indicative of former conditions, indicative of the temperatures that have existed long ago.

The minerals of the rock are the geologic temperature recorders. For granites and gneisses, and generally for quartzo-feldspathic rocks, quartz may be used as a geologic thermometer. For in principle it is possible to find out whether a quartz crystal was formed above or below the $\alpha-\beta$ inversion point (around 600 °C).

If one wants more accurate temperature determinations—ideally we want a geological thermometer capable of indicating any temperature—the feldspars have to be developed into a thermometer, indeed, for these kinds of rock one has the choice between using a feldspar geologic thermometer, or no thermometer at all. Fortunately the feldspar assemblages can be used as excellent geologic thermometers reflecting continuous temperature changes, just like ordinary thermometers. The important prerequisite is that chemical equilibrium at a definite temperature was established in the rock.

Which temperature do we actually measure with a geological thermometer? The rock at the time of the measurement is cold, and its minerals are no more in mutual equilibrium. The geologic thermometer measures a temperature that has existed, but not necessarily the maximum of the many pre-existing temperatures.

Thus the temperatures recorded by the thermometer could be much lower than the highest temperature to which the rock material was

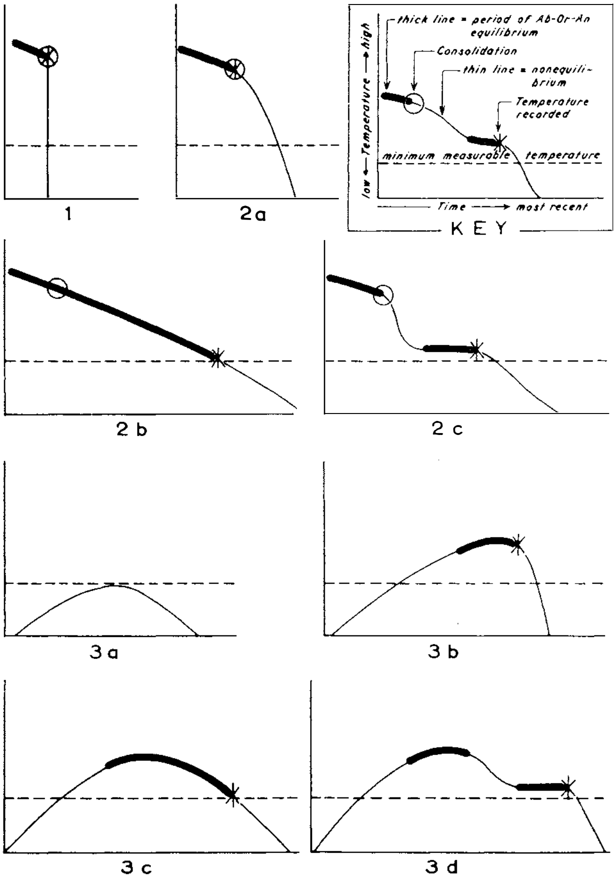

Figure 1. Generalized possible thermal history curves for: 1. extruded or intruded-into-"cold"-rocks magma, 2a. intruded-into-"cool"-rocks magma, 2b. very slowly cooled magma, 2c. erratically slowly cooled magma, 3a. low grade metamorphism, 3b. higher grade metamorphism with slow cooling during waning stages, 3c. higher grade metamorphism with very slow cooling during waning stages, 3d. higher grade metamorphism with erratic coolings—even diaphtoresis—in post-highest temperature metamorphism period. (After Dietrich (1960)).

exposed. Various possibilities are graphically shown in Figure 1. This is very simple, but it has to be mentioned, for so many irrelevant objections have been raised to the use of the feldspar thermometers.

The two-feldspar thermometer: There are three chief molecules constituting the natural rockmaking feldspars. Ab, Or, An, (i.e.) sodium, potassium, calcium feldspar).

Albite (or sodium feldspar) is soluble in both orthoclase and anorthite. During the crystallization of a rock, albite will distribute itself between potassium feldspar and calcium feldspar, thus two feldspar phases are formed: alkali feldspar and plagioclase. Let x_1 be the concentration of Na in alkali feldspar, and x_2 the concentration of Na in plagioclase, P = pressure, T = temperature. At equilibrium any of the variables can be represented as a function of the other three; therefore there exists a characteristic relation that may be expressed as follows:

$$f(x_1, x_2, P, T) = 0 \, .$$

It was assumed by Barth (1956) that the effect of pressure is of less importance than is that of temperature and composition, and will therefore, in this first approximation be neglected. It was furthermore shown that in rocks carrying sodic plagioclases (in the composition range An_5–An_{40}) there is a tendency of constant ratio of distribution of Na between alkali feldspar and plagioclase. Thus the following relation is approximately correct:

$$\Phi = (x_1/x_2, T) = 0 \; \ldots\ldots \quad (1)$$

In petrology one has to work with approximations. As distinct from mathematics or theoretical physics natural phenomena cannot be treated with schematic accuracy. All schematic equations are to be regarded as idealized cases that approximately correspond to the physical facts.

A consequence of equation (1) is:

$$\frac{\text{mole fraction of Ab in alkali feldspar}}{\text{mole fraction of Ab in plagioclase}} = \frac{x_1}{x_2} = k_T$$

where k_T, the coefficient of distribution, is constant at constant temperature. However, as explained in a previous publication (1956) there is no talk about these rather concentrated solid solutions following the distribution law of Nernst. Nevertheless, there is within a limited range of composition a tendency to approach this law. See Figure 2 A: at each temperature the tie lines are parallel (on a logarithmic scale and within the range An_5–An_{40}).

Figure 2 B shows how Na is distributed between alkali feldspar and

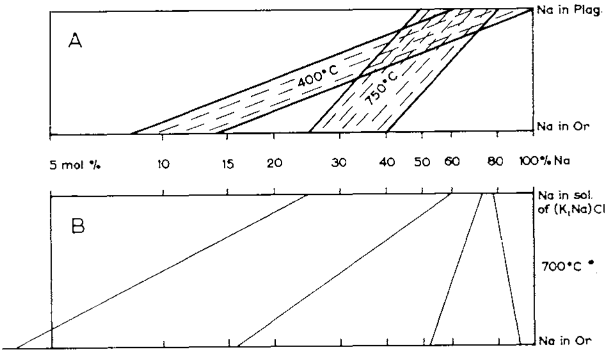

Figure 2A. Distribution of Na (in terms of Ab molecules) between an orthoclase lattice and a coexisting plagioclase lattice at 400 °C and at 750 °C. (See Barth (1956)).

Figure 2B. Distribution af Na between an orthoclase lattice and a 2-molecular solution of NaCl + KCl at 700 °C. (Redrawn from Orville (1959)).

an aqueous solution of alkali chloride at 700 °C. In this case the solute consists of sodium ions dissolved in a liquid and in a solid. This is quite different from a solute of albite molecules that dissolve differentially in two dissimilar feldspar lattices. Even so, the tie lines begin to parallelize for aqueous solutions containing less than about 50 mol % Na^+/total alkali ions again indicating that, within this composition range, the coefficient of distribution approaches a constant value.

Figure 2A shows furthermore that the coefficient of distribution is different at different temperatures.

The theoretical variation of the coefficient with absolute temperature, T, is given by the equation

$$k_T = k_0 e^{-\frac{\Delta E}{RT}}$$

or

$$ln k_T = -\frac{1}{T}\frac{\Delta E}{R} + ln k_0$$

where ΔE is the difference in lattice energy between one mole of albite dissolved in alkali feldspar and dissolved in plagioclase; k_0 is the coefficient in a notional standard state. Plotting this equation as a function of $-1/T$ says that the result should be a straight line whose slope is proportional to ΔE. How well this is fulfilled is shown by the curve in Figure 3. This curve approaches that of a straight line; it gives us the relation between temperature and the composition of

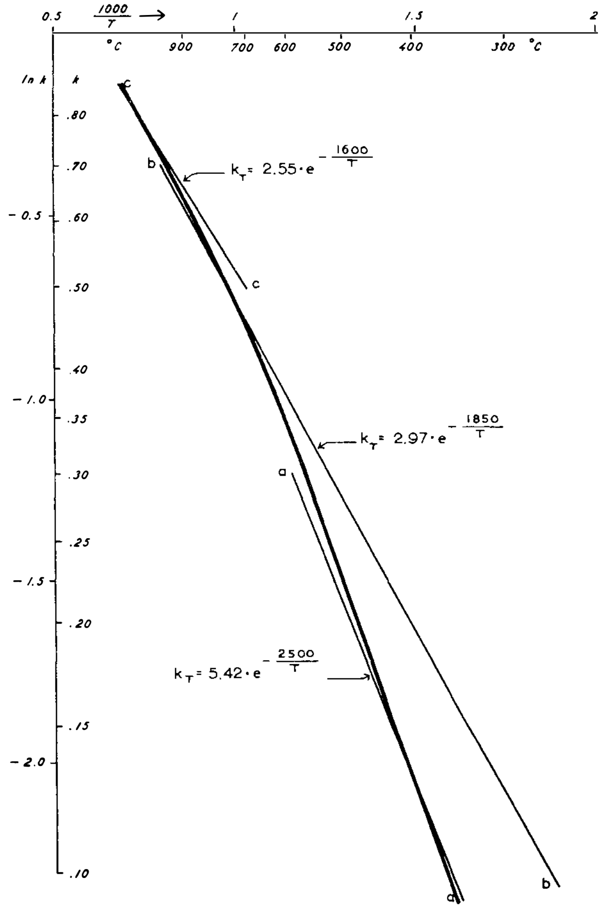

Figure 3. Relation between temperature and the ratio of distribution of albite between K-feldspar and plagioclase. Abscissa: the inverse of the absolute temperature. Ordinate: natural logarithms to the ratio of distribution. The line is not straight but has a slightly variable slope, corresponding to changes in ΔE.

the two feldspar phases in a rock; it is a geological thermometer of great importance for granites and gneisses. In Figure 4 it is redrawn to a diagram directly indicating the stable associations of alkali feldspar and plagioclase. For further discussions, see Barth 1956.

A test of the reliability of the thermometer can be given: More than hundred pairs of analyzed coexisting feldspars have been compiled and arranged according to increasing temperatures. Some of them are

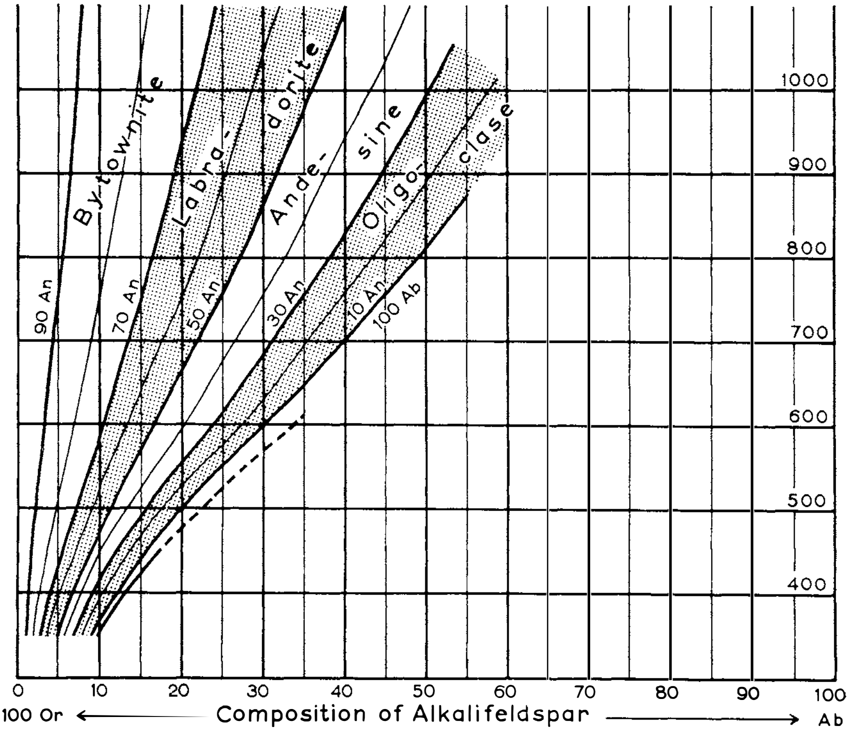

Figure 4. The co-existence of alkali feldspar and plagioclase. Abscissa gives the composition of alkali feldspars in terms of Or and Ab. Ordinate gives the temperature in centigrades. The curves indicate the equilibrium relation between the composition of the plagioclases (in terms of An) and the composition of the alkali feldspars at various temperatures.

projected onto the composition-temperature diagram of Figure 5. Of particular interest are the plots marked by crosses. In these analyses the plagioclase phase is almost pure albite, i.e. there is no Ca present, and the plots belong to the binary system Or–Ab; it is of considerable interest to note therefore that these plots very accurately lie on the solvus curve in the system Or–Ab. This is taken as a proof that the temperature determinations are correct, for only then is this particular distribution of the plots explainable.

A series of rocks may thus reliably be arranged according to increasing (or decreasing) temperatures. Such arrangements are highly important; for thus is it possible to investigate into certain fundamental

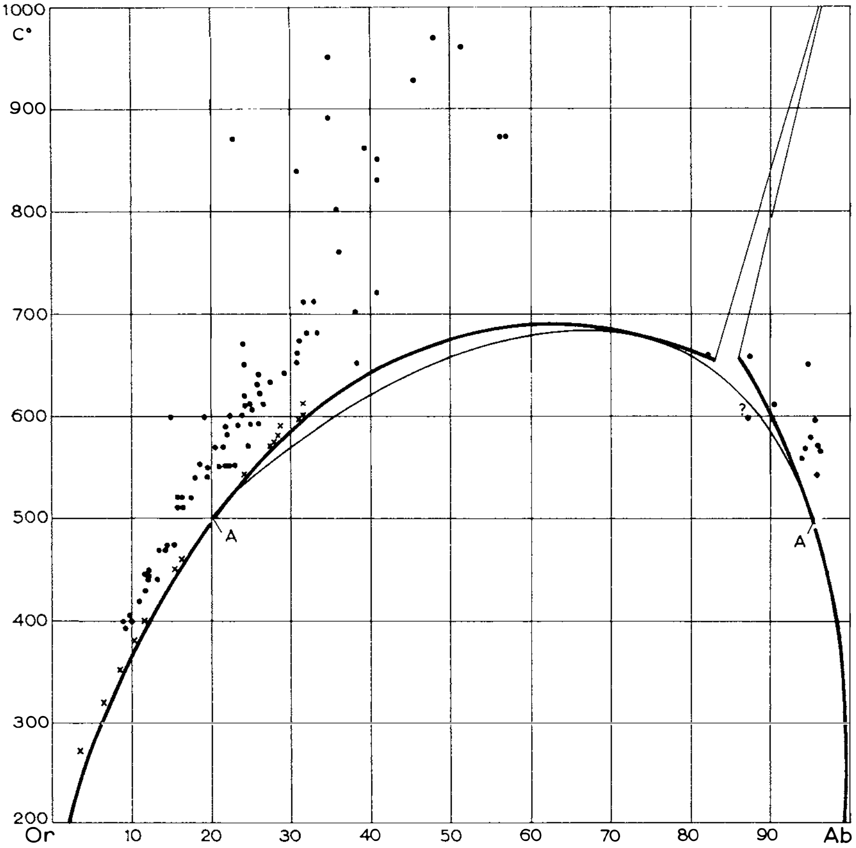

Figure 5. Heavy line indicates the solvus in the system of the alkali feldspars as determined with the two-feldspar thermometer. The thin line A–A represents the solvus of synthetic alkali feldspars after Orville (1963). (See Barth (1962)).

crystallo-chemical and geochemical relations of the natural feldspars.

For example, in this way were obtained quantitative data on the distribution of Ba and Sr between alkali feldspar and plagioclase. There was much discussion in the geochemical literature as to which feldspar is preferred by these elements. Recently Barth (1961) demonstrated that the coefficient of distribution depends on temperature, and that, within the pertinent temperature range, the coefficient for Ba ranges from 1 to 100, and for Sr from 0.1 to 10; i.e. both Ba and Sr prefer the alkali feldspar lattice at elevated temperatures, but the lower the temperature, the more is the plagioclase lattice preferred.

The order/disorder transitions in feldspars represent another thermometer which, however, is not yet definitely developed. The transitions are gradual and are in principle able to record continuous changes in the temperature. The degree of disorder is here reflected in the difference in interplanar spacing of $(1\bar{3}1)$ and (131). For plagioclases Smith (1956) first indicated the quantitative relation between this difference and the temperature. Based on his work and on the work of MacKenzie (1957), Christie (1962) constructed a diagram for the difference $(1\bar{3}1)$–(131) versus temperature. See Figure 6. This diagram may be used as a geologic thermometer.

There is much more work to do in testing this thermometer. But the results so far indicate that the temperatures measured may be different from those measured by the two-feldspar thermometer.

Table 1 shows a remarkable regularity: When the coexisting feldspar phases are homogeneous, the plagioclase disorder thermometer registers a higher temperature, but if one or both of the feldspar

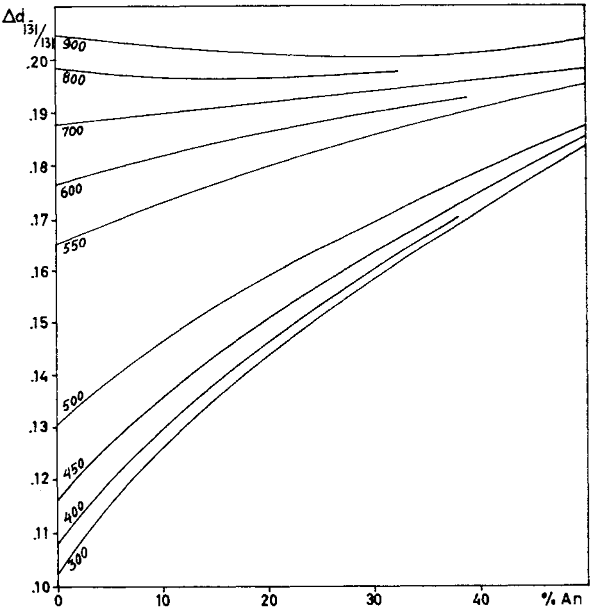

Figure 6. Tentative diagram for the difference $(1\bar{3}1)$–(131) versus temperatures (after O. H. J. Christie (1962)).

Table 1. Apparent Temperatures According to the Two-feldspar Thermometer and the Plagioclase Disorder Thermometer. [1]

Nos.	Two-feldsp. °C	Plg. °C	
1	400	440	All feldspars homogeneous
2	475	525	
3	500	510	
4	500	430	Alk-f.randomly disordered[1] plgs. homogeneous
5	550	440	
6	520	350/300	All feldspars randomly disordered
7	605	450/430	

[1] For further data and explanations, see article by Christie, this volume p. 383

phases are randomly disordered, the plagioclase disorder thermometer registers a lower temperature than does the two-feldspar thermometer.

As an example the relations of the two feldspars of rock no. 1 will be discussed, and an explanation of these apparent temperatures will be attempted. No. 1 is a granitized migmatite from near Kristiansand, southern Norway (Aukland RR tunnel. Torridal) exhibiting a granitic composition with sub-parallel bands or surfaces enriched in biotite. The alkali feldspar forms irregular patches in the ground mass; it is evidently late and without crystal forms insinuating itself between all other mineral grains; it is homogeneous, non-perthitic and of monoclinic symmetry. It contains less than 1 % Na_2O and according to the two-feldspar thermometer it grew at 400 °C. Evidently this feldspar was never eposed to higher temperatures. For if so, it would have taken more soda in solid solution that would then have exsolved as perthite at 400 °C. The monoclinic symmetry (corresponding to a disordered state of the lattice) comes of the low thermal energy that at 400° was insufficient to organize the growth of an ordered lattice, but resulted in a disordered crystal of the adularia type. The coexisting plagioclase shows rather well developed euhedral crystals, often twinned according to the albite law, the composition is 24 An. The state of the disorder of the lattice corresponds to a temperature of 440°.

This suggests that the migmatite during the peak of the regional metamorphism reached temperatures of 440° and possibly above. At this temperature the plagioclases assumed their proper degree of disorder which was preserved, or only slightly changed, during the subsequent stages of lower-temperature granitization and introduction of alkali feldspar at around 400 °C.

The combined use of two different thermometers may thus under fortunate circumstances reveal interesting details in the complicated history of rocks: plagioclase existed before granitization when the metamorphism was slightly higher, the granitization took place at a somewhat lower temperature with introduction of adularia-like orthoclases, and with the earlier minerals only partly adjusting themselves to the new temperature conditions.

Discussion

Schuiling (Utrecht)

I should like to put in a word in defense of a structural, non-mineralogical thermometer, i.e. the anatexitic structure (nebulites, agmatites etc). I think you will nearly all agree that these structures simply indicate that the rock was partly molten. Then it will be sufficient to take a sample of these rocks, put it in a bomb under sufficient water-pressure and observe the onset of melting. This procedure, incidentally, gives us temperatures of the order of 650 °C which is somewhat higher than found with feldspar geothermometry for the same rocks.

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