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PERITECTIC REACTIONS IN THE SYSTEM An–Ab–Or–Qz–H_2O

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Abstract

At low pressures, there are two possible types of peritectic reaction in the ternary feldspar system, corresponding to two types of liquid paths followed during fractional crystallization: (1) The liquid moves across the two-feldspar liquidus boundary from the plagioclase field to the alkali feldspar field (plagioclase + liquid → alkali feldspar); (2) the liquid moves across the two-feldspar boundary from the alkali feldspar field to the plagioclase field (alkali feldspar + liquid → plagioclase). Limitations are established for the range of P, T, a(Qz), $a(H_2O)$ that favor each type of peritectic reaction. It has been proposed that rapakivi texture (alkali feldspar mantled by plagioclase) and anti-rapakivi texture (plagioclase mantled by alkali feldspar) may be the result of isobaric fractional crystallization involving the peritectic portion of the two-feldspar liquidus boundary (Tuttle & Bowen 1958, Stewart & Roseboom 1962). Examples of anti-rapakivi texture are shown to be consistent with isobaric fractional crystallization, but the same explanation does not seem applicable to the origin of rapakivi textures.

Sommaire

Aux basses pressions, deux types de réaction péritectique sont possibles dans le système ternaire des feldspaths; ils correspondent aux deux parcours des liquides au cours d'une cristallisation fractionnée: (1) le liquide atteint la limite entre le champ de stabilité des deux feldspaths sur le liquidus en se déplaçant du domaine du plagioclase vers celui du feldspath alcalin (plagioclase + liquide → feldspath alcalin); (2) le liquide franchit cette limite en allant du champ du feldspath alcalin vers celui du plagioclase (feldspath alcalin + liquide → plagioclase). Des limites sont imposées à la variation des paramètres P, T, a(Q) et $a(H_2O)$ qui favorise chaque type de réaction péritectique. Tuttle & Bowen (1958) et Stewart & Roseboom (1962) ont tenté d'expliquer les textures rapakivi (feldspath alcalin enrobé de plagioclase) et anti-rapakivi (l'inverse) par cristallisation fractionnée isobare impliquant une réaction péritectique le long de la limite du champ des deux feldspaths sur le liquidus. Cette hypothèse se vérifie sur certains exemples de texture anti-rapakivi, mais elle est incompatible avec plusieurs exemples connus de texture rapakivi.

(Traduit par la Rédaction)

Introduction

Understanding the crystallization history of feldspar-bearing igneous rocks requires an understanding of the phase relationships in the ternary feldspar system. This paper undertakes a detailed examination of these phase relationships under various conditions of P, $a(H_2O)$ and a(Qz), the activities of the components H_2O and SiO_2 in the liquid phase. The paper serves to shed some light on the origin of rapakivi and anti-rapakivi textures. Here, rapakivi texture refers to the rimming of alkali feldspar phenocrysts by plagioclase. Anti-rapakivi refers to the reverse textural relationship in which plagioclases are rimmed by alkali feldspar. It has been suggested that these textures may have originated during isobaric crystallization as the result of a peritectic reaction relationship involving the silicate liquid, plagioclase and alkali feldspar (Tuttle & Bowen 1958, Stewart & Roseboom 1962). Depending on the conditions of P, $a(H_2O)$ and a(Qz) the peritectic reaction proceeds in one of two ways: 1) liquid + alkali feldspar → plagioclase; 2) liquid + plagioclase → alkali feldspar. During fractional crystallization, the first reaction may result in the rapakivi texture. whereas the second reaction may produce the anti-rapakivi texture.

General Considerations

It is fairly well accepted that a portion of the two-feldspar liquidus boundary in the system An–Ab–Or (An: $CaAl_2Si_2O_8$; Ab: $NaAlSi_3O_8$; Or, $KAlSi_3O_8$) must be odd (peritectic) rather than even (cotectic) at low pressures (Tuttle & Bowen 1958, Stewart & Roseboom 1962). The odd-even terminology of Ricci (1951) is used throughout much of this paper. The term *peritectic* and *cotectic* are used synonymously with odd and even, respectively). Such peritectic behavior is to be expected, in general, whenever the two-feldspar boundary terminates at a *critical*

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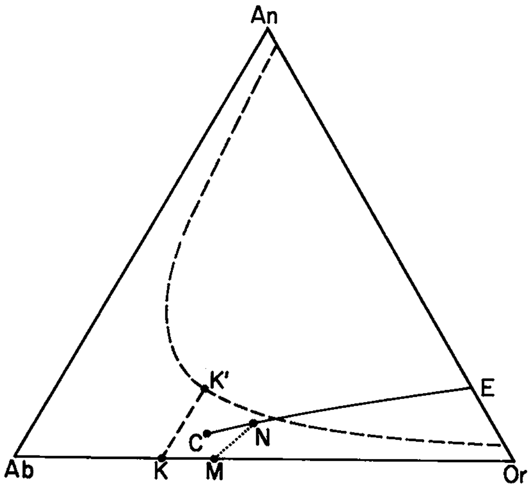

FIG. 1. Schematic representation of the ternary feldspar liquidus at low pressures. *C* is the critical end-point, *N* the neutral point, *E* the eutectic on An–Or join, *M* the liquidus minimum, *K* the critical point on Ab–Or join; *K'* the critical point on solidus. *CNE* is the two-feldspar liquidus boundary, *NM* the special line, *KK'* the critical line.

end-point (C in Fig. 1) having a ternary composition. The critical end-point marks the liquid composition coexisting with the critical feldspar *K'* (Fig. 1).

The highest temperature on the two-feldspar boundary is the eutectic point *E* (Fig. 1) on the An–Or join. There is no indication that the point E and consequently the high-temperature portion of the two-feldspar boundary are ever odd (peritectic) regardless of the conditions of P, $a(H_2O)$ or a(Qz). It follows that when the low-temperature portion of the two-feldspar boundary is odd, there has to be a point on the boundary which is neither odd nor even. This point will be referred to as the *neutral point* (N in Fig. 1).

During ideal fractional crystallization, a liquid cooling on the even portion of the two-feldspar boundary (EN) will leave the boundary at the neutral point (N) and change composition toward the liquidus minimum *M* along a unique path which will be referred to as the *special line NM*. Figure 1 has been drawn for the case where the special line is on the alkali feldspar side of the two-feldspar boundary. A liquid that reaches the odd portion of the two-feldspar boundary *(NC)* by fractional crystallization of plagioclase will move into the alkali feldspar field at lower temperatures.

The special line may move from the alkali feldspar field to the plagioclase field under changing conditions of P, $a(H_2O)$ or a(Qz) (Stewart & Roseboom 1962). During such changes the special line moves closer to the two-feldspar boundary as the neutral point moves closer to the critical end-point (Fig. 2). Ultimately the neutral point and the critical end-point become coincident. When this happens, the two-feldspar boundary is even (cotectic) along its entire length. Hence, the tangent to the two-feldspar boundary at the critical end-point must pass through the critical point *(K')* on the projected ternary solidus (Fig. 2b). Under any other circumstances a portion of the two-feldspar boundary must be odd. The special line

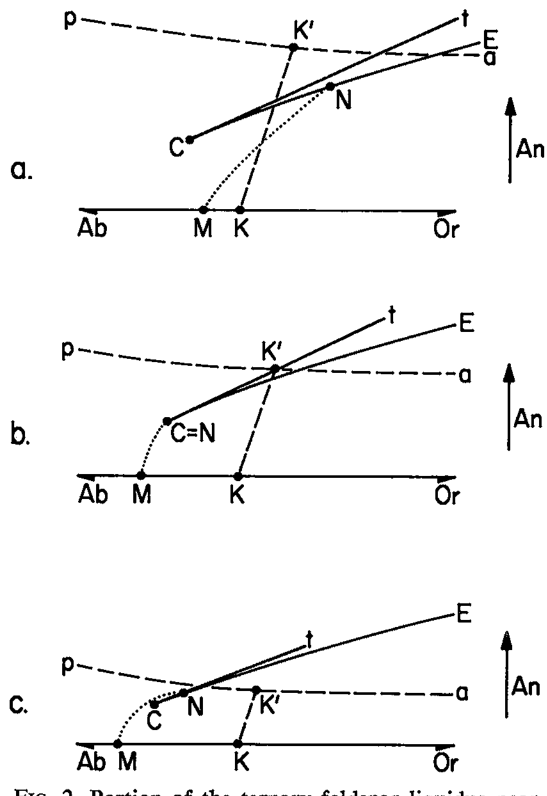

FIG. 2. Portion of the ternary feldspar liquidus near the critical end-point *C*. The sequence of diagrams (a,b,c) shows schematically the movement of the special line (*NM*) from the alkali feldspar field (diagram a) to the plagioclase field (diagram c). Note the transitional state (diagram b) where the neutral point *N* is coincident with the critical end-point *C*. In the transitional state the tangent to the two-feldspar boundary at the critical end-point (*Ct*) passes through the critical point *K'* on the two-feldspar portion of the solidus (*pK'a*). *KK'* is the critical line, *M* the minimum.

moves into the plagioclase field (Fig. 2c) by the same process in reverse. When the special line is in the plagioclase field, a liquid that reaches the odd portion of the two-feldspar boundary by fractional crystallization of alkali feldspar will move into the plagioclase field at lower temperatures.

On the Ab–Or join, the composition of the critical phase on the alkali feldspar solvus is about $Ab_{67}Or_{33}$ (Waldbaum & Thompson 1969). The composition is essentially independent of pressure. At low pressures in the ternary feldspar projection, the lowest temperature on the two-feldspar portion of the solidus is the critical point K'. As the two-feldspar portion of the solidus expands with increasing pressure, the critical point on the solidus (K') changes composition toward the Ab–Or join. When $a(Qz)=a(H_2O)=1$, the critical point on the ternary solidus becomes coincident with the critical point on the Ab-Or join ($K=K'$) at 2300 bars (Stewart & Roseboom 1962). At higher pressures in the Qz– and H_2O–saturated system critical phases are not encountered.

The locus of critical points (KK' in Fig. 1) is referred to as the *critical line*. Tuttle & Bowen (1958, p. 135) placed the critical line parallel to the Ab–An join at Or_{33} for a wide variety of volcanic rock compositions. For samples of shoshonite and phonolite Carmichael *et al.* (1974) showed that compositional zoning in coexisting phenocrysts of alkali feldspar and plagioclase defined a portion of the two-feldspar solidus. The rim compositions indicate that the critical phases are less potassic than about Or_{33}. The orientation suggested by Tuttle & Bowen (1958) seems to be one of the limiting cases.

The orientation of the critical line KK' depends only on the solvus in the system An–Ab–Or, hence is unaffected by non-feldspar components. The orientation should also be relatively independent of pressure by analogy with the behavior of the critical point K in the system Ab–Or. Consequently, even though Carmichael *et al.* (1974) used volcanic rocks that were undersaturated with respect to Qz, the limitations on the orientation of the critical line are still applicable to systems that are saturated with respect to Qz, H_2O or both. In the following discussion, the critical line KK' is assumed to be parallel to the An–Ab join at Or_{33}.

When the special line is in the alkali feldspar field (Fig. 2a) the critical point on the solidus (K') and the critical point on the Ab–Or join (K) must lie on opposite sides of the tangent to the two-feldspar boundary at the critical end-point. When the special line is in the plagioclase field (Fig. 2c) K and K' lie on the same side of the tangent to the two-feldspar boundary at the critical end-point. As the special line moves from the alkali feldspar field to the plagioclase field, the critical point on the solidus passes across the tangent to the two-feldspar boundary. This can only happen when the critical end-point is less potassic than the critical line KK' (Or_{33}), provided of course that the odd portion of the two-feldspar boundary lies outside the two-feldspar portion of the solidus. Under any other circumstances the liquidus minimum would have a ternary composition rather than on the Ab–Or join. It should be noted that when the tangent to the two-feldspar boundary at the critical end-point passes through the critical point on the solidus (Fig. 2b), the special line is in neither liquidus field but leaves the two-feldspar boundary at the critical end-point.

In the limit that the two-feldspar boundary just touches the Ab–Or join, the critical end-point must always lie between the liquidus minimum and the critical point on the Ab–Or join. Hence, when the special line is in the plagioclase field the minimum must be more sodic than the critical point on the Ab–Or join ($Ab_{67}Or_{33}$). Also, when a portion of the two-feldspar boundary is odd and the minimum is less sodic than the critical point on the Ab–Or join the special line has to be in the alkali feldspar field.

The following discussion establishes the physical conditions of T, P, $a(Qz)$ and $a(H_2O)$ under which the special line moves from one side of the two-feldspar liquidus boundary to the other. The discussion focuses on regions of the system An–Ab–Or–Qz–H_2O where liquids are undersaturated with respect to Qz, H_2O or both. In these undersaturated regions it is important to clarify what is meant by the term "minimum" (or "liquidus minimum"), especially when applied to the ternary feldspar projection. Here the minimum or liquidus minimum is simply defined as the lowest temperature on the liquidus at fixed values for P, $a(Qz)$ and $a(H_2O)$. According to this definition the term "minimum" is not necessarily synonymous with "minimum melting point" inasmuch as there is no constraint that the minimum be terminal to the liquid phase. In the ternary feldspar projection, the minimum is terminal to the liquid phase under four circumstances: 1) when the liquidus is saturated with respect to Qz [$a(Qz)=1$] and H_2O [$a(H_2O)=1$]; 2) when the liquidus is in the Qz–saturated [$a(Qz)=1$] subsystem An–Ab–Or–Qz [$a(H_2O)=0$]; 3) when the liquidus is in the H_2O–saturated subsystem An–Ab–Or–H_2O (no normative Qz), and 4) when the liquidus is in the subsystem

An–Ab–Or [$a(H_2O)=0$ and no normative Qz]. Between these four extremes the liquidus minimum in the ternary feldspar projection is non-terminal to the liquid phase. Here the minimum simply represents the lowest temperature on the ternary feldspar liquidus projection for a given pressure and degree of undersaturation with respect to Qz, H_2O or both.

H_2O–Saturated Systems

In the Qz– and H_2O–saturated ternary feldspar projection the temperature of the minimum decreases with increasing pressure. Figure 3 shows the P–T locus of minima *(yz)* as determined experimentally by Tuttle & Bowen (1958, p. 83). Also shown is the univariant line for the critical point on the Ab–Or join *(pc)*. The formulation for the univariant line for the Ab–Or critical point is from Waldbaum & Thompson (1969): T (°K) = 921.23 + 13.460 P (Kbar).

At a given pressure below 2300 bars the two-feldspar boundary terminates at a critical end-point having a higher temperature than the minimum. There is no experimental or petrological reason to suspect that the lowest temperature on the two-feldspar boundary is not at the critical end-point. Hence, the neutral point can safely be assumed to have a higher temperature than the critical end-point. The highest temperature on the two-feldspar boundary is of course the eutectic point on the An–Or join.

The temperature of the minimum is about 960°C at 1 bar (Tuttle & Bowen 1958) and the temperature of the eutectic on the An–Or join is reported as 950±30°C (Schairer & Bowen

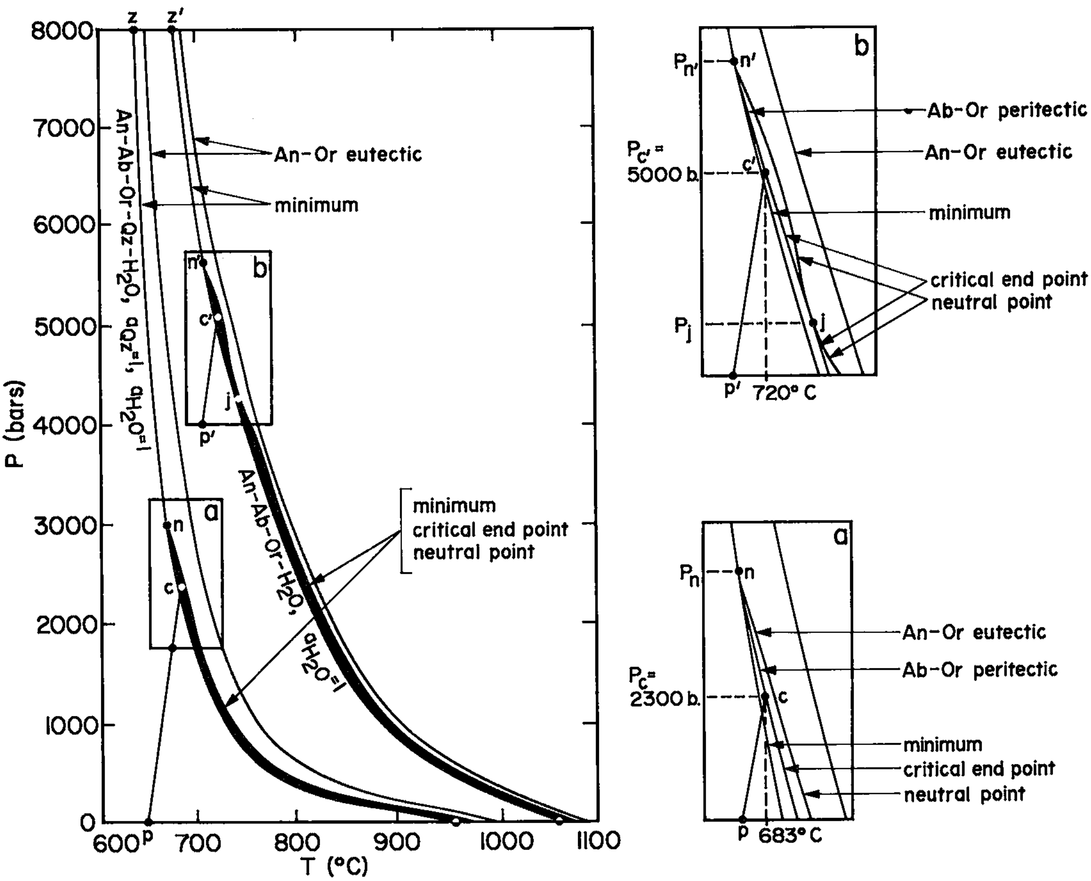

Fig. 3. Selected P–T relationships in the ternary feldspar portion of the liquidus in the system An–Ab–Or–Qz–H_2O [$a(Qz)=1$; $a(H_2O)=1$] and An–Ab–Or–H_2O [$a(H_2O)=1$]. In each case the locus of minima, *yz* and *y'z'* respectively, are taken from Tuttle & Bowen (1958); *n*, *n'* = terminal neutral point; *c*, *c'* = terminal critical end-point; *j* = neutral-critical end-point; *pc*, *p'c'* = univariant line for the critical point on the Ab–Or join.

1947). There is little reason for believing that the eutectic on the An–Or join is lower than 960°C. Hence, the temperature at the critical end-point and neutral point must be between 960°C and at most 980°C. At 1000 bars the critical end-point and neutral point must be between 725°C (minimum) and about 775°C (An–Or eutectic) (James & Hamilton 1969). This indicates that the locus of critical end-points and the locus of neutral points must be less than 50°C above the minimum at 1000 bars. At 2300 bars the locus of critical end-points terminates at the univariant line for the Ab–Or critical point. This point (*c* in Fig. 3) will be referred to as the *terminal critical end-point*. At this pressure the critical point on the Ab–Or join just touches the Ab–Or solidus. This happens at a slightly higher temperature than the minimum because the point of first contact (Ab_{67}) does not coincide with the minimum (Ab_{62}). The temperature difference cannot be more than 3 or 4°C. This is indicated by the low degree of curvature of the solidus in the vicinity of the minimum on the Ab–Or join (Stewart & Roseboom 1962). At 2300 bars, a portion of the two-feldspar boundary remains odd. At some unknown pressure P_n above 2300 bars but below 4000 bars (Steiner *et al.* 1975), the locus of neutral points terminates at the locus of minima. The point of termination (*n*) will be referred to as the *terminal neutral point*. Between 2300 bars and P_n the two-feldspar boundary terminates on the Ab–Or join but a portion of the boundary remains odd. The locus of the lowest temperature on the two-feldspar boundary meets the locus of liquidus minima at the same point (*n*) as the locus of neutral points. This must be so because at P_n the neutral point is the lowest temperature on the two-feldspar boundary. The two-feldspar boundary is even (cotectic) along its entire length above P_n up to at least 10000 bars (Luth *et al.* 1964).

The two-feldspar boundary terminates at a critical end-point from 1 bar to 2300 bars in such a way that the low-temperature portion of the boundary is odd. Over this range of pressure the liquidus minimum is less sodic than the critical point on the Ab–Or solvus (Tuttle & Bowen 1958). This indicates that on the ternary liquidus projection the special line has to be in the alkali feldspar field. From 2300 bars to P_n, the two-feldspar boundary terminates on the Ab–Or join, but a portion remains odd with the special line in the alkali feldspar field. Above P_n, the two feldspar boundary is even along its entire length.

Figure 4 shows schematically the various invariant, univariant and divariant phase relationships near the terminal neutral point (*n*) and terminal critical end-point (*c*) in the Qz– and H_2O–saturated system.

In the absence of normative Qz, the relationships in the H_2O–saturated ternary feldspar projection (Fig. 3) are generally similar to those just described for the Qz–saturated system. The locus of minima (*y′z′*) is at a higher temperature than in the Qz–saturated system. Below about 500 bars, the liquidus minimum is less sodic than the critical point on the Ab–Or solvus (Tuttle & Bowen 1958). Hence in the ternary liquidus projection, a portion of the two-feldspar boundary must be odd such that the special line is in the alkali feldspar field. Below 500 bars, the four loci, one each for the minima, critical end-points, neutral points and An–Or eutectics, must have the same relative positions as in the Qz–saturated case. At 5000 bars Yoder *et al.* (1957) demonstrated a peritectic relationship on the Ab–Or join. The univariant line for the Ab–Or critical point intersects the locus of minima at about this same pressure. However, the peritectic relationship is the reverse of that described for the Qz–saturated system, such that on the ternary liquidus projection, the special line is in the plagioclase field. This indicates that at some pressure P_j (Fig. 3) between 500 bars and 5000 bars, the special line must move from the alkali feldspar field to the plagioclase field. At P_j the neutral point coincides with the critical end-point. Hence, the locus of critical end-points and locus of neutral points must touch at some point *j*. The point *j* in Figure 3 will be referred to as the *neutral-critical end-point*. The neutral-critical end-point *j* was arbitrarily placed at a high pressure in the range from 500 bars to 5000 bars. There are insufficient data to locate *j* more precisely. Above P_j at about 5000 bars, the locus of critical end-points terminates at the univariant line for the Ab–Or critical point. At higher pressures, the lowest temperature on the two-feldspar boundary is on the Ab–Or join but a portion of the boundary remains odd until the locus of the lowest temperature on the two-feldspar boundary and the locus of neutral points meet on the locus of minima at some high pressure $P_{n'}$. At still higher pressures above $P_{n'}$, the two-feldspar boundary is even along its entire length.

Five "unique" points have been established, two in the Qz– and H_2O–saturated ternary feldspar system (*c* and *n*) and three in the H_2O–saturated ternary feldspar system (*j*, *c′* and *n′*). Only points *c* and *c′* can be located with any degree of precision. Both points are on the univariant line for the Ab–Or critical point. They are

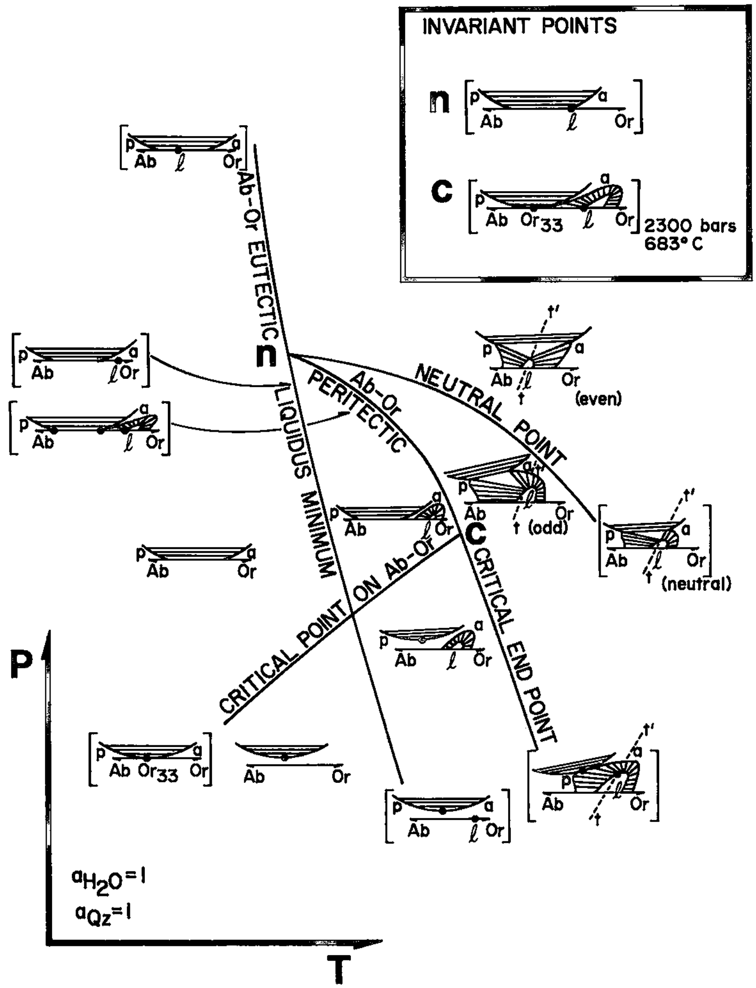

FIG. 4. Set of schematic isobaric-isothermal sections through the ternary feldspar system projected from Qz [a(Qz)=1] and H_2O [$a(H_2O)$=1] for values of P and T near the terminal critical end-point (*c*) and terminal neutral point (*n*); a = K-rich alkali feldspar, p = plagioclase, *l* = silicate liquid. Univariant sections are enclosed in brackets. Sections showing a three-phase region (ap*l*) also show the tangent (*tt′*) to the two-feldspar liquidus boundary at the liquid *l*. When the liquid is on the odd portion of the two-feldspar boundary the tangent *tt′* does not intersect the three-phase region. When the liquid is on the even portion of the two-feldspar boundary, the tangent *tt′* intersects the three-phase region along the plagioclase–alkali feldspar join (ap). The reader should note that the tangent *tt′* is coincident with the alkali feldspar–liquid join(a*l*) of the three-phase region everywhere along the locus of neutral points.

both within 3 or 4°C of the liquidus minimum at their respective pressures. The conditions at *c* are about 2300 bars and 683°C; at *c′*, 5000 bars and 720°C. The pressure at *n* is greater than 2300 bars but less than 4000 bars. In order of increasing pressure the unique points are: c = 2300 bars $< n <$ 4000 bars $< j$ (probably) $< c$ = 5000 bars $< n'$; in order of increasing temperature, $n < c = 683°C < c' = 720°C < j$.

The locus of the liquidus minima in the H_2O-saturated system An–Ab–Or–H_2O (*y′z′* in Fig. 5) is displaced to lower temperatures as a(Qz) is increased. When a(Qz)=1, the locus is of course coincident with the locus of Qz–saturated minima (*yz* in Fig. 5). For various degrees of undersaturation with respect to Qz the liquidus minimum in the ternary feldspar projection can be anywhere within the region *yzz′y′*. The region *yzz′y′* has been contoured in terms of the Ab content of the normative feldspar, Ab/(Or+Ab), in the minimum liquids. The contours refer specifically to the position of the liquidus minimum in the ternary feldspar projection when *a*(Qz) is less than one. Because the minimum is always on the Ab–Or join (projected through Qz and H_2O) only the Ab content need be specified. The Ab content of the normative feldspar in the minimum liquids when *a*(Qz)=1 *(yz)* and when normative Qz is absent *(y′z′)* were obtained from Tuttle & Bowen (1958). The region itself *(yzz′y′)* was contoured by extrapolating the values for the Ab content between the limiting positions of the locus of minima (*yz* and *y′z′*).

The Qz-absent terminal critical end-point (*c′* in Fig. 5) moves along the univariant line for the Ab–Or critical point as *a*(Qz) is increased, generating the line *cc′*. Along this line the critical end-point is on the Ab–Or join in the ternary feldspar projection. In the absence of normative Qz *(c′)* the special line is in the plagioclase field. However, when *a*(Qz)=1 *(c)* the special line is in the alkali feldspar field. Somewhere on the line *cc′* the special line moves from the plagioclase field to the alkali feldspar field with increasing *a*(Qz). Hence, there is a point *i* on *cc′* where the neutral point, critical end-point, Ab–Or critical point and liquidus minimum all have the same composition ($Ab_{67}Or_{33}$) in the ternary feldspar projection. The point *i* is therefore at the intersection of *cc′* and the Ab_{67} contour. The terminal neutral point *(n′)* and neutral-critical end-point *(j)* in the Qz-absent system (*y′z′*) generate the lines *nn′* and *ji* respectively as *a*(Qz) is increased.

At the point *i* in Fig. 5, the neutral point is on the Ab–Or join of the ternary feldspar projection. This indicates that the trace of the terminal neutral points *(nn′)* must touch the trace of the terminal critical end-points *(cc′)* at *i*. The trace of the terminal neutral points can never cross the trace of the terminal critical end-points. Hence the two traces *(nn′* and *cc′)* must be tangent at their point of contact *i*. Because the neutral point and critical end-point are coincident at *i*, the trace of the neutral-critical end-point *j* must terminate at *i*.

The trace of the neutral-critical end-points *(ji)* separates two P–T regimes, *(jin′* and *jinyy′)*. In the high-pressure regime *(jin′)* the special line is in the plagioclase field on the ternary feldspar projection. This regime is confined to the portion of the system where *a(Qz)* is less than one on the liquidus. In the low-pressure regime *(jinyy′)* the special line is in the alkali feldspar field on the

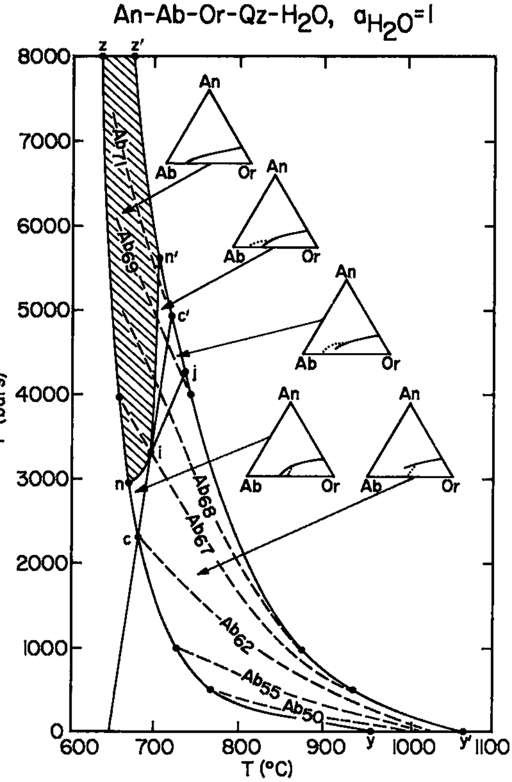

FIG. 5. Selected P–T relationships in the system An–Ab–Or–Qz–H_2O in the presence of a vapor phase [$a(H_2O)=1$] but where *a*(Qz) is allowed to vary. The locus of Qz-absent minima *(y′z′)* is displaced to successively lower temperatures until *a*(Qz)=1 on *yz*. The region *yzz′y′* is contoured on the basis of the Ab content of the minimum liquid projected from Qz and H_2O. The contours refer specifically to the position of the minimum on the Ab–Or join of the ternary feldspar projection. Control points for the Ab contours (filled circles) are from Tuttle & Bowen (1958, p. 40 75), Steiner *et al.* (1975) and Luth *et al.* (1964). The terminal neutral point *(n′)*, terminal critical end-point *(c)* and neutral-critical end-point*(j)* generate the lines *nn′*, *cc′* and *ji* as *a*(Qz) is increased. The lines meet at the point *i*. The lines *nn′*, *cc′* and *ji* divide the Qz-undersaturated region into five P–T regimes, each associated with a distinct ternary liquidus topology (projected from Qz and H_2O). The ternary-feldspar-liquidus projection is shown qualitatively for each of the five regions. In each ternary feldspar projection the solid line represents the two-feldspar liquidus boundary; the dotted line represents the special line.

ternary feldspar liquidus. The special line is in the alkali feldspar field in the presence of quartz [a(Qz)=1] at all pressures below P_n. The dividing line between the two regimes *(ji)* may intersect the locus of Qz–absent minima *(y′z′)* at a lower pressure, but not below 500 bars. Hence, regardless of the degree of undersaturation with respect to normative Qz, the special line cannot be in the plagioclase field below 500 bars.

H_2O–Undersaturated Systems

The locus of the minima in the Qz– and H_2O–saturated system An–Ab–Or–Qz–H_2O (*yz* in Fig. 6) is displaced to higher temperatures as $a(H_2O)$ is decreased. When $a(H_2O)=0$, the locus is of course coincident with the locus of dry minima [*yx*, $a(H_2O)=0$]. It is assumed that the locus of dry minima is essentially straight. Because the dry minimum and H_2O–saturated minimum are coincident at zero bars pressure, the slope of the locus of dry minima *(yx)* is fixed by the temperature at 4000 bars, slightly higher than 1000°C (Steiner *et al.* 1975). For various degrees of undersaturation with respect to H_2O the Qz–saturated liquidus minimum can be anywhere within the region *xyz* (Fig. 6). The region *xyz* has been contoured on the basis of the Ab content of the normative feldspar, Ab/(Or+Ab), in the minimum liquids. As in Figure 5 the contours refer specifically to the position of the liquidus minimum in the ternary feldspar projection. Actual data on the H_2O–undersaturated portion of the system are available only for 4000 bars (Steiner *et al.* 1975). However, the contours must be continuous with the values for the Ab content on the locus of H_2O–saturated minima *(yz)*. These data are readily available for a wide range of pressures up to 10000 bars (Tuttle & Bowen 1958, Luth *et al.* 1964, Steiner *et al.* 1975).

Along the locus of H_2O–saturated minima (*yz* in Fig. 6), it has been shown that the special line is in the alkali feldspar field from 1 bar to at least 2300 bars. At some higher pressure but below 4000 bars the locus of neutral points meets the locus of minima (at *n*).

As $a(H_2O)$ decreases, the terminal critical end-point *c* and terminal neutral point *n* trace out lines in the region *xyz*. The lines divide the H_2O–undersaturated region into areas of distinct liquidus topology in the ternary feldspar projection. In the previous example (Fig. 5) it was shown that the trace of the terminal neutral points meets the trace of the terminal critical end-points at a point on the univariant line for the Ab–Or critical point. This point (*i* in Fig. 5) must lie at the intersection of the Ab_{67} contour and the univariant line for the Ab–Or critical

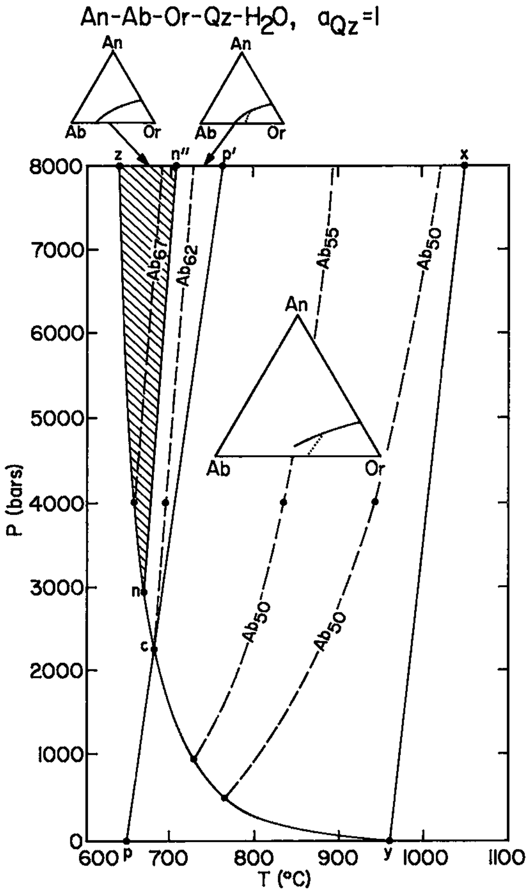

Fig. 6. Selected P–T relationships in the system An–Ab–Or–Qz–H_2O where a(Qz)=1 but $a(H_2O)$ is allowed to vary. The locus of H_2O–saturated minima *(yz)* is displaced to higher temperatures as $a(H_2O)$ decreases and ultimately becomes coincident with the locus of dry minima (*yx*, $a(H_2O)=0$). The region *xyz* is contoured in terms of the Ab content of the minimum liquid projected from Qz and H_2O. Hence, the contours refer specifically to the position of the minimum on the Ab–Or join projected from Qz and H_2O. Control points (filled circles) for the Ab contours are from Tuttle & Bowen (1958, p. 75) and Steiner *et al.* (1975). As $a(H_2O)$ decreases the terminal neutral point *(n)* and terminal critical end-point *(c)* generate the lines *nn″* and *cp′*. The lines divide the H_2O–undersaturated region into three areas, each having a distinct ternary-feldspar-liquidus topology (projected from Qz and H_2O). In each ternary-feldspar-liquidus diagram the solid line represents the two-feldspar liquidus boundary; the dotted line represents the special line.

point. It was also shown that the point *i* in Figure 5 divides the trace of the terminal critical end-points into two segments. On one segment the special line is in the alkali feldspar field; on the other segment the special line is in the plagioclase field. In the present case (Fig. 6) the Ab_{67} contour is confined to a lower temperature than the univariant line for the Ab–Or critical point. The position of the Ab_{62} contour indicates that the Ab_{67} contour probably never crosses the univariant line for the Ab–Or critical point regardless of the degree of undersaturation with respect to H_2O. *It follows that the special line can never be in the plagioclase field of the Qz–saturated liquidus regardless of the degree of undersaturation with respect to H_2O.* As a result, there are only three types of distinct liquidus topology in the Qz–saturated system. In the region *nzn″* the two-feldspar boundary is even along its entire length (Fig. 6). In the region *nn″p′c* the two-feldspar boundary terminates on the Ab–Or join but a portion of the boundary is odd, with the special line in the alkali feldspar field. In the region *cp′xy*, the two-feldspar boundary terminates at a critical end-point and the special line is in the alkali feldspar field.

The procedure used to construct Figure 6 was applied to the system An–Ab–Or–H_2O (no normative Qz) in order to evaluate the effects of H_2O–undersaturation in the absence of normative Qz. The results are presented in Figure 7.

The locus of H_2O–saturated minima (*y′z′* in Fig. 7) is the same as in Figure 3. The H_2O–undersaturated region was contoured in terms of the Ab content of the normative feldspar in the minimum liquids projected from H_2O. The Ab contours were assumed to be more or less parallel to the univariant line for the Ab–Or critical point and the locus of dry minima (*y′x′*). There are no experimental data for the H_2O–undersaturated portion of the system. On the locus of H_2O–saturated minima (*y′z′*) the terminal critical end-point (*c′*), terminal neutral point (*n′*) and neutral-critical end-point (*j*) are the same as in Figures 3 and 5.

It should be noted that there is a region in P–T space where leucite is stable on the liquidus. However, even at 1 bar, the liquidus minimum is in the feldspar field (Tuttle & Bowen 1958, p. 40). At higher pressures, the leucite field shrinks and ultimately disappears from the H_2O–saturated liquidus at about 2500 bars (Tuttle & Bowen 1958, p. 40). This indicates that the liquid at the minimum is probably never in equilibrium with leucite. The low density of leucite (2.47–2.50 g/cm^3) suggests that in the H_2O–under-

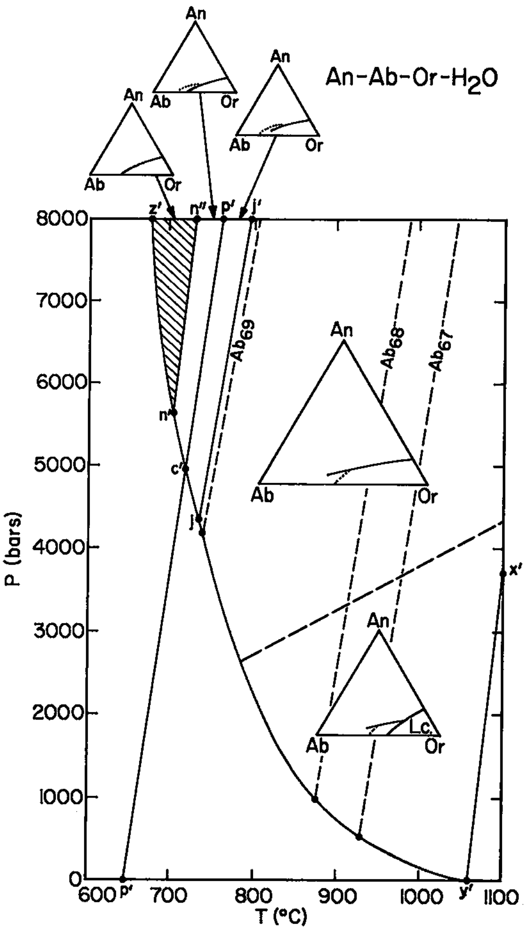

FIG. 7. Selected P–T relationships in the system An–Ab–Or–H_2O where $a(H_2O)$ is allowed to vary. The locus of H_2O–saturated minima (*y′z′*, $a(H_2O) = 1$) is displaced to higher temperatures as $a(H_2O)$ decreases and ultimately becomes coincident with the locus of dry minima (*y′x′*, $a(H_2O = 0)$. The region *x′y′z′* is contoured in terms of the Ab content of the minimum liquid projected from H_2O. The contours refer specifically to the position of the minimum on the Ab–Or join projected from H_2O. Control points (filled circles) for the Ab contours are from Tuttle & Bowen (1958, p. 40) and Yoder *et al.* (1957). As $a(H_2O)$ decreases the terminal neutral point (*n′*), terminal critical end-point (*c′*) and neutral-critical end-point (*j*) generate the lines *n′n″*, *c′p′* and *jj′*. The lines divide the H_2O–undersaturated region into four areas, each having a distinct ternary feldspar liquidus topology (projected from H_2O), excluding the region where leucite (Lc) has a stable field on the liquidus. In each ternary feldspar diagram (projected from H_2O), the solid line represents the two-feldspar liquidus boundary; the dotted line represents the special line.

saturated region of Figure 7 a liquidus field for leucite is present only at low pressures. The leucite field most likely disappears along a line (heavy dashed line in Fig. 7) having a fairly low P–T slope. The actual slope of the line is unknown. Hence the high-pressure limit of the leucite field can only be shown qualitatively.

As $a(H_2O)$ decreases the neutral-critical end-point (j), terminal critical end-point (c') and terminal neutral point (n') trace lines separating regions of different ternary feldspar liquidus topology. Because the Ab_{67} contour does not intersect the univariant line for the Ab–Or critical point *(pp')*, neither can the trace of the neutral-critical end-points *(jj')*. Hence, the trace of the neutral-critical end-points *(jj')* must be more or less parallel to, but between, the univariant line for the Ab–Or critical point *(pp')* and the Ab_{67} contour. The H_2O–undersaturated portion of the system is divided into five regions, each having a topologically distinct ternary-feldspar liquidus projection. At lower temperatures than the trace of the terminal neutral points (in the shaded area) the two-feldspar boundary is even along its entire length. Between the trace of the terminal neutral points and the univariant line for the Ab–Or critical point *(nn'c'p')* the two-feldspar boundary terminates on the Ab–Or join but a portion of the boundary is odd with the special line in the plagioclase field. Between the univariant line for the Ab–Or critical point and the trace of the neutral-critical end-points *(c'p'jj')* the two-feldspar boundary terminates at a critical end-point with the special line in the plagioclase field. At higher temperatures than the trace of the neutral-critical end-points *(j'jy'x')* the two-feldspar boundary terminates at a critical end-point with the special line in the alkali feldspar field. In this region the liquidus topology remains the same except for the presence of a field for leucite at low pressures.

Provided the trace of the neutral-critical end-points *(ji)* in Figure 5 has a positive P–T slope the special line cannot be in the plagioclase field at a lower pressure than about 3300 bars (point *i* in Fig. 5) regardless of the degree of undersaturation with respect to Qz, H_2O or both. In the event that the slope of the trace of the neutral-critical end-point *(ji)* in Figure 5 is negative *the special line may be in the plagioclase field at pressures as low as 500 bars but only in systems that are strongly undersaturated with respect to normative Qz.* It should be noted that *the special line is never in the plagioclase field* in the *Qz–saturated systems regardless of degree of undersaturation with respect to H_2O* (Fig. 5).

Application to Geological Problems

Anti-rapakivi textures

The mantling of plagioclase by alkali feldspar has been reported from many intrusive and extrusive rocks, particularly from the latter. Examples cited by Bowen (1928) and Tuttle & Bowen (1958) occur in rocks of widely varying bulk composition, including absarokite, shoshonite, banakite and syenite. Certain of these rocks, shoshonite in particular, contain separate phenocrysts of plagioclase and alkali feldspar in addition to the anti-rapakivi phenocrysts. The individual phenocrysts of plagioclase and alkali feldspar are chemically zoned in a way that suggests crystallization from a liquid initially cooling on the two-feldspar liquidus boundary (Carmichael *et al.* 1974). Typically, the plagioclases in these rocks range from labradorite to andesine. Some of the plagioclases are mantled by sodic orthoclase, giving rise to the anti-rapakivi texture. It is interesting to note that these rocks contain little or no normative Qz and were extruded at the surface ($P = 1$ bar). Under these conditions in the ternary feldspar projection, the special line is on the alkali feldspar side of the two-feldspar boundary. Adjustment of the liquid to rapidly decreasing temperature, as would be expected under volcanic conditions, could result in the anti-rapakivi configuration. With decreasing temperature, the liquid would leave the peritectic portion of the two-feldspar boundary and move into the primary liquidus field for alkali feldspar.

In the Adirondacks of New York, Buddington (1939) observed anti-rapakivi textures in a series of plutonic rocks ranging in composition from syenite through quartz syenite to granite. In the series, plagioclase (An_{38} to An_{30}) occur as the cores of large alkali feldspar phenocrysts. It is interesting to note here that the anti-rapakivi configuration occurs in a plutonic series of widely varying SiO_2 and mafic content. The persistence of the anti-rapakivi texture throughout the series suggests an origin that is not outside the normal course of fractional crystallization. Although the rocks show evidence of later metamorphic recrystallization, the anti-rapakivi phenocrysts were reported as primary. During the formation of the anti-rapakivi texture it appears that the liquid portion of the magma was never in equilibrium with more than one feldspar longer than it took for the plagioclases to become completely rimmed. This is consistent with fractional crystallization involving a two-feldspar liquidus boundary, in part peritectic, with the special line in the alkali feldspar field.

In all of the rocks described by Buddington (1939), both oligoclase and perthite occur in the matrix. No rimming relationship was observed there. Evidently, after the formation of the anti-rapakivi phenocrysts, the last liquids to crystallize were in equilibrium with two feldspars. This is to be expected during fractional crystallization under moderately high pressures as the liquid may become sufficiently enriched in SiO_2 or H_2O to enter a region of P–T space (Fig. 5) where the two-feldspar liquidus boundary is even (cotectic) along its entire length. If the granitic phase of the series were at least close to being saturated with respect to H_2O when the anti-rapakivi phenocrysts were formed, an isobaric crystallization path between P_n (2300 bars $<$ P_n $<$ 3300 bars) and 3300 bars (Fig. 5) would be consistent with the textures.

The anti-rapakivi texture has been observed in hornblende granophyres from the Red Beach granite in extreme eastern Maine (Abbott 1977). Here 3mm plagioclase phenocrysts (An_{40} to An_{20}) are mantled by rims of alkali feldspar. The alkali feldspar is optically continuous with alkali feldspar in the matrix where it is micrographically intergrown with quartz. Plagioclase phenocrysts are absent in the matrix such that quartz is rarely found in contact with plagioclase. In the eastern part of the intrusion the plagioclases are euhedral and the alkali feldspar rims are thin (0.05mm). The micrographic matrix is fine grained. In the western part of the intrusion, the plagioclases are rounded, the alkali feldspar rims are thicker (0.5mm) and the micrographic matrix becomes coarser. This change in texture is gradational and has been attributed to a systematic decrease in the rate of cooling from east to west. All of the rocks contain miarolitic cavities indicating the presence of a vapor phase at least during the final stages of crystallization.

After the rimming of plagioclase, the liquid portion of the magma was in equilibrium with one feldspar, alkali feldspar, until crystallization was completed. The texture is consistent with an isobaric liquid path at some pressure less than P_n (2300 bars $<$ P_n $<$ 3300 bars, Fig. 6). Rapid cooling in the east preserved the euhedral morphology of the plagioclases. In the more slowly cooled western part of the intrusion, partial resorption of the plagioclases indicates a closer approach to equilibrium crystallization. The rounding of the plagioclases indicates that the liquid remained on the peritectic portion of the two-feldspar boundary for a brief interval before moving into the alkali feldspar field.

Rapakivi textures

The classical rapakivi granites of Finland and Sweden are characterized by large (up to 10 cm) ovoid alkali feldspar phenocrysts that are mantled by thin rims of oligoclase. The alkali feldspar as well the rimming plagioclase typically contain inclusions of quartz. All three minerals are present in the matrix where they have no systematic relationship to one another. Stewart & Roseboom (1962) suggested that the mantling texture may have originated as the result of fractional crystallization involving a peritectic two-feldspar liquidus boundary where the special line was in the plagioclase field. However, the quartz inclusions indicate otherwise: evidently the liquid portion of the magma was saturated with respect to SiO_2 before, during and after the formation of the plagioclase rims. Referring to Figure 6, it is apparent that under such conditions there is no region of P–T space where the special line is in the plagioclase field. An alternative explanation is required.

Examples of rapakivi texture from along the coast of Maine (Doggett 1930, Stewart 1956) prove equally disappointing when compared to the present model for much the same reasons: quartz inclusions occur in both the alkali feldspar and rimming plagioclase as well as in the matrix. In the coarse-grained biotite granite of the Red Beach pluton (Abbott 1977), rapakivi phenocrysts are common and in most respects similar to examples cited by Stewart (1956) and Doggett (1930). Here individual euhedral to well-rounded perthite phenocrysts (up to 8mm) are each enclosed by a thin shell (2mm) of oligoclase. The contact between the perthite and the enclosing plagioclase is invariably beaded by minute grains of quartz. As in the classical examples from Finland and Sweden, the liquid portion of the magma was saturated with respect to SiO_2 when the plagioclase rims were formed.

The writer favors an origin that involves a rapid degassing of the liquid phase. Degassing is supported by the presence of miarolitic cavities in the rapakivi granites from Maine. A decrease in $P(H_2O)$ accompanying degassing would cause the projected two-feldspar liquidus boundary to move closer to the Ab–Or join so as to decrease the area of the alkali feldspar field (Whitney 1975). A liquid originally in the alkali feldspar field close to the two-feldspar boundary, or on it, may be left in a metastable state below the primary liquidus field for plagioclase as the result of a rapid decrease in $P(H_2O)$. Crystallization of plagioclase as rims on already existing alkali feldspars would tend to drive the liquid back into a region where alkali feldspar is stable. The crystallization of plagioclase would also tend to increase the activity of what little H_2O may have remained after degassing, causing the two-feldspar boundary to return to its original, equilibrium position.

The origin of the rapakivi texture remains open to other explanations. The present interpretation is only one possibility among many cited elsewhere in the literature. Hopefully this paper will promote interest in the investigation of the rapakivi texture so that criteria can be established for its correct interpretation in different examples.

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