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Evolution of Perthite Composition and Microstructure During Progressive Metamorphism of Hypersolvus Granite, Rhode Island, USA

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Abstract. The Scituate Granite in central Rhode Island, USA contains very coarse alkali feldspar mesoperthite and has been subjected to prograde metamorphism subsequent to original igneous cooling. The modal abundance and grain size of relics of alkali feldspar mesoperthite decrease systematically as metamorphic grade increases. The composition and microstructures of coexisting phases in the relict perthite grains also vary systematically with increasing metamorphic grade. Microstructures coarsen and become more complex, and compositions record increasing metamorphic temperatures.

We suggest that the microstructures and compositions have been produced by exsolution, either during post-igneous cooling or early metamorphism, followed by partial homogenization during prograde metamorphism. The principal control on the evolution of the microstructures and compositions was probably the maximum temperature achieved during prograde metamorphism, with the abundance and size of perthite relics determined by recrystallization during deformation.

Introduction

The way in which homogeneous alkali feldspar exsolves to become coexisting grains of sodium-rich and potassium-rich feldspar is only partly understood. Recently, considerable progress has been made in understanding the early stages of the exsolution processes during which homogeneous alkali feldspar becomes cryptoperthitic (e.g., Owen and McConnell 1974; Sipling and Yund 1976; Yund and Davidson 1978). The later stages of exsolution remain poorly understood but some ideas have been offered in recent papers by Parsons (1978) and Yund and Akermand (1979).

Parsons (1978) has summarized evidence showing that, in many hypersolvus intrusive complexes, exsolution textures are coarser in the more fractionated rocks. He suggested that increasing magmatic water and decreasing An content of the feldspar were important controls on the coarsening. In contrast, Yund and Ackermand (1979) have described the microstructures of perthites from a Precambrian granite and have shown that the microstructures are systematically coarser in more calcic feldspar grains. They suggested this could be explained by the higher temperatures and longer times available for exsolution of the more calcic grains. In this paper, we discuss the origin of perthite microstructures that have evolved, at least in part, during the progressive regional metamorphism of the Scituate Granite in central Rhode Island, USA. We attempt to show that the compositions of coexisting phases in perthite and perthite microstructures are directly related to the thermal history of metamorphism and that perthite abundance is related to metamorphic grade and deformation of the granite.

The Scituate granite (Fig. 1) forms part of the basement terrain in southeastern New England that appears to be similar in age (500–650 m.y.) and geologic history to the Avalon zone of the northern Appalachians (Williams 1976; Robinson 1976). Day and others (1980) have described the petrology and metamorphism of the Scituate and have shown that it is a true granite (I.U.G.S., 1973) with only small compositional variation. Quartz and the feldspars constitute 89% to 99% by volume of the rock; the principal varietal minerals are biotite, hastingsitic hornblende and magnetite. A subtle chemical variation matches modal composition quite well. These data suggest that the least fractionated or most mafic parts of the granite are in the southern and central parts of the exposed area and that fractionation may increase to the east, west and north of the less fractionated 'core' (Day et al. 1980).

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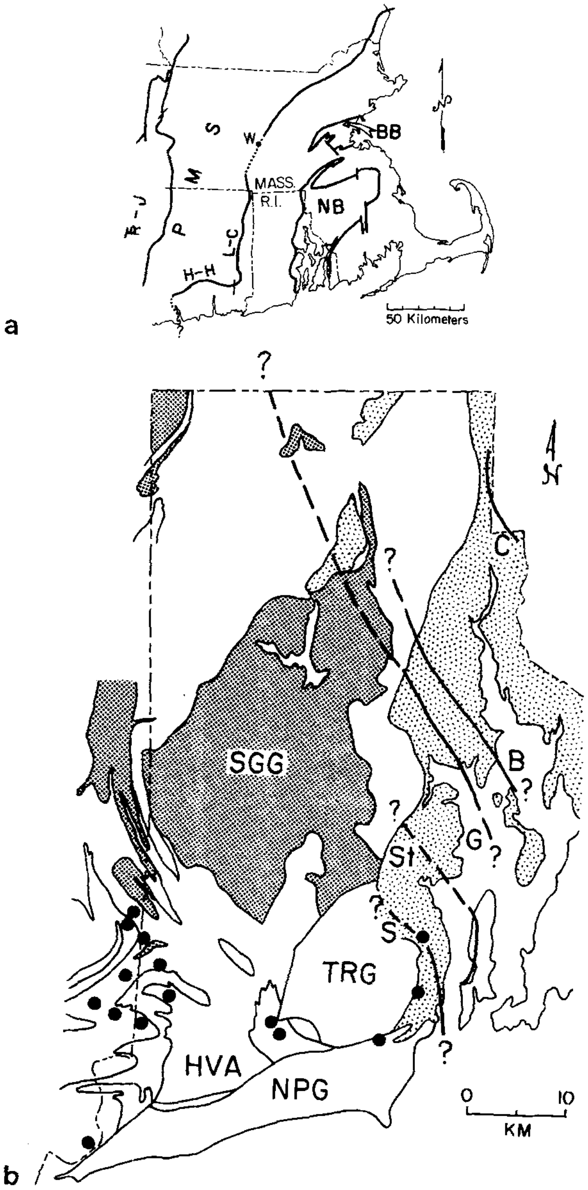


Fig. 1. **a** Sketch map of southeastern New England. *Tr-J* post-tectonic Mesozoic sedimentary basin. *PMS* Paleozoic Metamorphic sequence. *H-H, L-C* Honey-Hill-Lake Char Fault. *W* Worcester; Massachusetts. *BB* Boston Basin. *NB* Narragansett Basin. **b** Sketch Map of Rhode Island. *Heavy stipple:* Scituate Granite Gneiss (SGG). *Light stipple:* Pennsylvanian rocks of the Narragansett Basin. *White:* undifferentiated pre-Pennsylvanian igneous and metamorphic rocks. *HVA* Hope Valley Alaskite. *TRG* Ten Rod Granite. *NPG* Permian Narragansett Pier Granite (after Quinn 1971). *C, B, G, St, S* are the chlorite, biotite, garnet, staurolite, and sillimanite isograds in the Narragansett Basin

The northeastern portions of the Scituate Granite contain original igneous textures that permitted Day and others (1980) to estimate that the granite crystallized from a magma having no more than about four weight percent of initial water at a pressure of from 1 to 3 kbar. The subsequent history of the granite is not well-known but circumstantial evidence suggests that the pluton was largely unroofed by Cambrian time and may have suffered no high temperature thermal effects until the upper Paleozoic. Nearby granites of similar age at Hoppin Hill, Massachusetts (Fairbairn et al. 1967) and Conanicut Island, Rhode Island (Skehan et al. 1977; Smith and Giletti 1978) are overlain unconformably by fossiliferous Cambrian sediments. The Narragansett Basin contains fossiliferous sediments of Pennsylvanian age (Quinn 1971; Lyons and Chase 1976; Brown and others, 1978) that overlie the basement terrain unconformably (Quinn 1971). These fluvial sediments had a granitic provenance, suggesting that they may have been derived from exposures of the surrounding basement terrain (Mutch 1968).

Quinn and Glass (1958) and Grew and Day (1972) have shown that the Pennsylvanian sediments have been metamorphosed at grades ranging from subchlorite and chlorite zones in the north to sillimanite and sillimanite + orthoclase zones in the southwestern part of the basin. This Permian metamorphism culminated with or was immediately followed by the intrusion of Narragansett Pier Granite in southernmost Rhode Island (Grew and Day 1972; Brown et al. 1978; Kocis et al. 1978; Day et al. 1980).

Day et al. (1980) have summarized the evidence suggesting that the granitic basement west of the Narragansett Basin, including the Scituate Granite Gneiss, was metamorphosed and possibly deformed at the same time as the Pennsylvanian rocks. Metamorphic isograds (Fig. 1) may be extrapolated in a northwesterly direction across the basement terrain to the west but, outside of the Basin itself, the only control on the postulated extrapolations is the occurrence of garnet in fossiliferous Pennsylvanian rocks at Worcester, Massachusetts (Grew 1973) and in Pennsylvanian (?) rocks in north-central Rhode Island (Quinn 1951). Map patterns in western and southwestern Rhode Island (Fig. 1) clearly suggest the presence of multiple generations of minor structures and examination of the regional distribution of mineral foliations and lineations led Day et al. (1980) to suggest that this deformation becomes less intense and either disappears or changes style in the northeastern part of the Scituate Granite. The transition from less deformed granite to ductilely deformed basement rocks takes place in the same direction as the progressive metamorphism suggesting that metamorphism and deformation may have been simultaneous. However, available data are not sufficient to rule out a pre-Permian age for some of the deformation or the possibility of pre-Permian metamorphism of the granites.

Variation of Perthite Abundance

A dramatic decrease in the modal abundance of perthitic feldspar appears to be correlated directly with the direction of increasing metamorphism in the Scituate granite. The proportion of feldspar in the Scituate Granite Gneiss that occurs as mesoperthite varies from zero to approximately 100 percent (Day et al. 1980). At low metamorphic grade, in the north (Fig. 2), most of the feldspar is mesoperthite whereas at higher metamorphic grades; further to the southwest, separate grains of coexisting albite and microcline become more abundant until, in the southernmost portions of the Scituate Granite, no recognizable perthite can be found in many specimens. The principal complications in the pattern of perthite abundance are the abrupt decrease in perthite abundance and the pronounced north-trending lobe of low perthite content observed in the north-central portions of the Scituate granite. These features may be artifacts of late or post-metamorphic(?) deformation. It is notable that the pattern of perthite abundance is markedly discordant to the subtle pattern of whole rock chemical variation that presumably is the result of igneous fractionation (Day et al. 1980).

The association of low perthite abundance with the areas of higher metamorphic grade and ductilely deformed basement suggests to us that the observed decrease in perthite content represents the progressive destruction of original perthite during concurrent deformation and metamorphism. The presence of obvious igneous textures in the northern exposures of the granite and their absence in areas of higher grade (Day et al. 1980) support this interpretation. As discussed below, textural relationships between perthitic feldspars and other grains in thin-section either support or permit this interpretation.

In the northeastern Scituate granite, where a high proportion of feldspar occurs as mesoperthite, perthitic grains are set in a finer grained groundmass containing a high proportion of quartz. In areas where deformation has been especially intense, the groundmass also contains abundant fine-grained feldspar. It is typical in the northern Scituate that large perthitic feldspars are separated into fragments by narrow, linear, or curved zones of fine-grained, commonly polygonal, feldspar und quartz. Figure 3a illustrates these features in a sample from an especially deformed zone. A large, carlsbad-twinned, perthitic feldspar contains fine-grained feldspar and quartz along the twin plane and parallel to cleavage. Zones of fine grains are also common that bear no relation to cleavage. The groundmass surrounding the perthitic grain consists of smaller fragments of perthite and fine-grained quartz and feldspar.

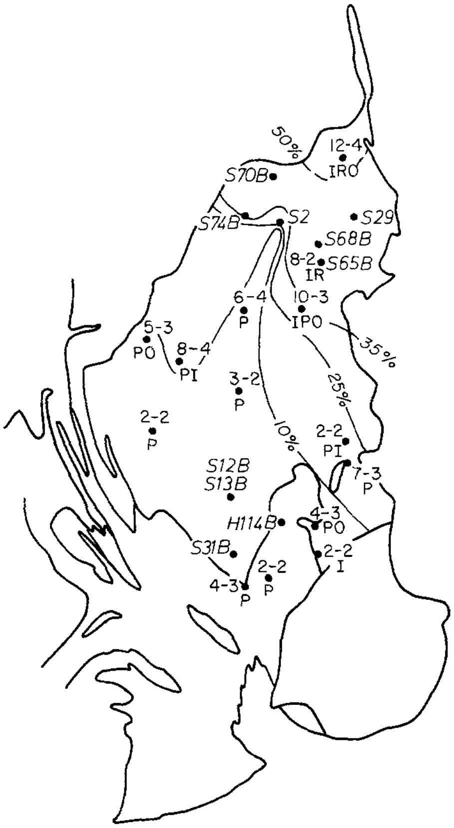


Fig. 2. Variation in modal abundance, grain size, and microstructure of Scituate perthites. *Contours* give the modal abundance (volume per cent) of mesoperthite in Scituate granite (Contours are based on more extensive data given by Day et al. 1980). Symbols *R, I, P, O* indicate order of decreasing abundance of perthite types for sample locality above the letters. *Numbers* above a sample locality (e.g. 12-4) indicate in mm the largest maximum dimension of a perthite grain and the mean value of maximum dimensions observed in a sample. Locations with sample numbers identify the samples in Figs. 3, 4, and 5

In the right side of Fig. 3a, there are two large, monomineralic, polycrystalline patches of quartz. Such patches are common in the northern Scituate granite. The quartz may be flattened with prominent undulatory extinction but more commonly grains are sub-equidimensional with moderately sutured, or smooth grain boundaries. It is typical that this quartz is coarser than the feldspar in the groundmass. These large patches of quartz may represent grains that were originally igneous but now have recovered following deformation.

The presence of mylonite zones (Day et al. 1980) and the abundance of disrupted grains (Fig. 3a) throughout the northeastern Scituate granite leave little doubt that the fine-grained groundmass and zones in perthites are in large part the products of deformation. The presence of extremely fine-grained material along some carlsbad twin boundaries and cleavage

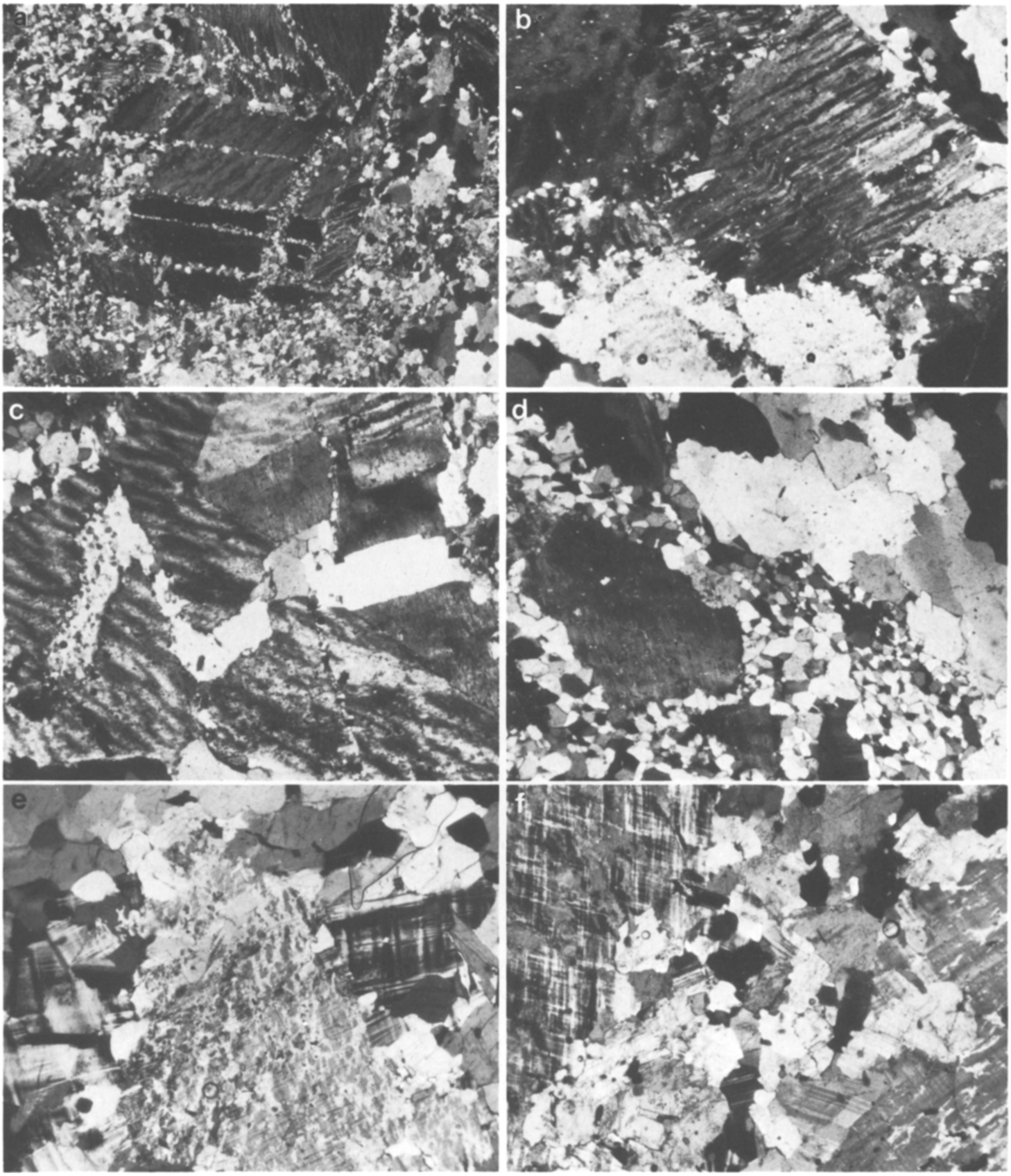


Fig. 3a–f. Textural features of perthites. Sample locations are shown in Fig. 2. Short dimension of picture (*a*) is 5.6 mm. All others are 2 mm. **a** Perthite grain from an intensely deformed zone. S65B. **b** Kink band in perthite. S29. **c** 'Pull-apart' zone in twinned perthite filled with quartz. S29. **d** Relationship of perthite relic to feldspar in groundmass. S2. **e** Coarse-grained microcline and albite around a relic of perthite. S13B. **f** groundmass of albite and microcline between two perthite relics. S12B

planes, and weak undulatory extinction in some perthites suggest that strain induced recrystallization may have occurred. Other features indicate, however, that brittle or semi-brittle deformation of the feldspars has been important. Figure 3b and c illustrates in perthites a kink band and a 'pull-apart' feature respectively. Although polygonal microcline and albite are the only minerals found in some of the narrow zones in perthites, many zones are predominantly quartz and others contain biotite and opaque minerals, indicating that extensive mass transport has occurred during deformation. Many of these narrow zones may, indeed, be filled fractures.

Deformation features such as those shown in Fig. 3a, b and c, become progressively less abundant as perthitic feldspar itself becomes less abundant toward the southwest. The size of feldspar and quartz in the groundmass surrounding perthite tends to be much larger in the south than in the north. This may possibly be the result of more extensive grain growth at higher metamorphic temperatures. In the south, perthite grains tend to be smaller (see next section) and it is more typical in the south than in the north, to find that perthite grains are surrounded by quartz-absent or quartz-poor groundmass (Fig. 3d).

Figure 3d shows the relationship of perthite fragments to fine-grained albite and microcline in a sample collected from the northern Scituate Granite. Figure 3e and f show coarser grained feldspathic groundmass adjacent to perthite relics in the southern Scituate. Such textures are common in dynamically recrystallized materials. However, as discussed above, significant chemical migration has occurred on a grain scale and it does not appear possible to decide what other processes might also have contributed to the evolution of these textures. These textures, together with the absence of igneous textures in the north, and the presence of tectonite fabrics in the south, suggest that the reduced abundance and size of perthitic feldspar in the southern Scituate granite may be the result of recrystallization of the perthite at higher metamorphic temperatures under different conditions of deformation than observed in the north.

The word 'recrystallization' is used here in its most general sense to indicate any process by which new grains of feldspar may appear at the expense of perthite. The dominant driving force and physical and chemical processes by which the recrystallization takes place must remain unspecified.

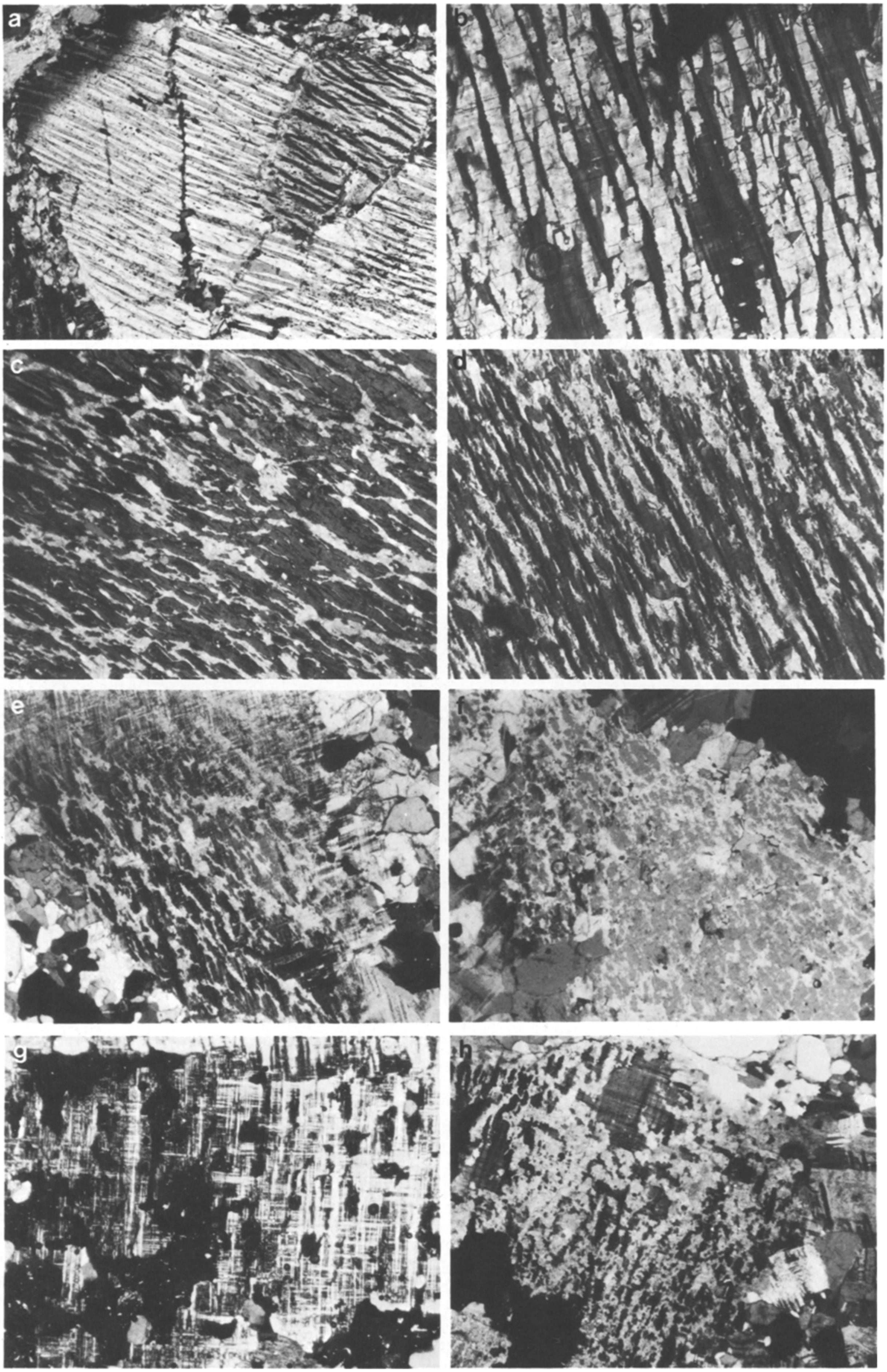
Variation in Perthite Microstructure

A variety of perthite microstructures is present in these rocks but there appears to be recognizable correlation of microstructure and grain size with increasing metamorphic grade. In order to evaluate textural changes in a systematic and semi-quantitative way, a qualitative and arbitrary classification scheme was established: regular vein perthite (R), irregular vein perthite (I), patchy and patch perthite (P), and other (O). Examples of these microstructures are illustrated in Fig. 4a–h). Regular vein perthites contain albite lamellae up to 100 μm but more commonly only about 50 μm in thickness. Branching of lamellae occurs but is uncommon. Irregular vein perthites display abundant branching lamellae that are usually less than 50 μm in width. Smaller veins at high angles to major lamellae may connect the latter. Patch perthites contain extremely variable proportions of host and patch. Patches are commonly about 100 μm in diameter but range up to 500 μm. 'Other' perthites consist of examples that were difficult to classify in the former three categories. Because the R, I, P and O (?) type microstructures appear to represent a regular progression leading towards a subsolvus texture, the I and especially the P types are considered to be more 'evolved' textures.

A variety of microstructures may be found in most thin-sections but an especially wide variety may be found in samples that contain abundant evidence of deformation. Figure 5a–d illustrates microstructures in perthite grains found in one such sample (S65B, Fig. 3a).

Point counts were made of fourteen thin sections in which each perthite grain encountered was classified and measured. The number of perthite grains counted was always less than fifty so no claim for statistical significance is made. Figure 2 summarizes the textural data. At each sample locality, the order of abundance of the perthite types is indicated as well as the maximum observed dimension and the mean value of all the maximum dimensions of individual grains. Where perthite is most abundant in the north, irregular and regular vein perthites are most common. Further south, where perthite is less abundant, patchy perthites predominate, little or no regular vein perthite is found, and unclassifiable or 'other' intergrowths are common. The distribution of grain sizes is less regular. Maximum perthite grain size varies from 12 mm in the north to 2 mm in the south but the distribution of maximum grain sizes observed is very erratic. Mean grain sizes for individual thin sections appear to provide no useful information.

Using electron microprobe analyses, Day et al. (1980) have shown that the host and lamellae in perthite grains have compositions comparable to those of coexisting grains of free albite and microcline from the same rock. Plagioclase compositions vary from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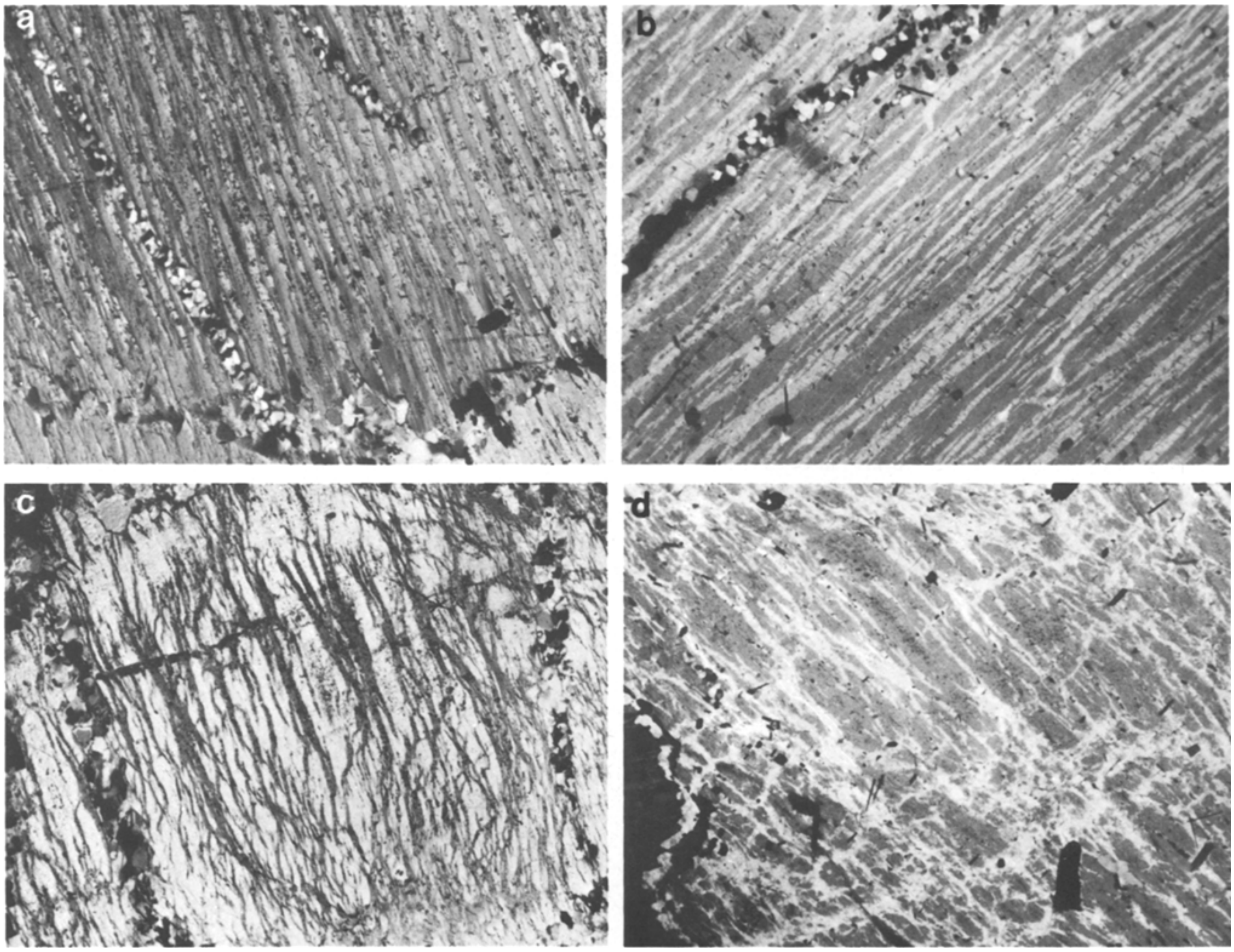

Fig. 5a–d. Perthite microstructures from sample S65B (also shown in Fig. 3a). The short dimension of each picture is 2 mm. **a** Regular vein perthite, **b** and **c** irregular vein perthites. Note the presence of narrow zones of fine-grained quartz and feldspar. **d** 'Other' perthite. Note 'swapped' rims in lower left portion of the picture. A wide variety of microstructures is typical of samples which appear to lie in zones of intense deformation

An_0 to An_8, with the exception of one sample that was An_{14}. Most analysed samples contained plagioclase in the range An_0 to An_4 suggesting that these rocks with subequal abundance of microcline and albite must have been hypersolvus feldspars with very low calcium content. The sodium content of microcline varies from Ab_2 to Ab_8 in the Scituate granite, with the higher values corresponding to the portions of the granite at higher metamorphic grade.

Controls of the Evolution of Perthite Microstructures

As mentioned above, Parsons (1978) suggested that the size of perthite lamellae is correlated with the availability of water and low anorthite component in feldspar while Yund and Ackermand (1979) suggest that coarsening is directly correlated with *higher* calcium contents. The perthite microstructures in the

Fig. 4a–h. Perthites from the Scituate Granite. Short dimension of each picture is 2 mm. Sample locations are given in Fig. 2. **a** Regular vein perthite. S29. **b** Extremely coarse regular to irregular vein perthite from the nearby and related Hope Valley Alaskite. H114B. **c** Irregular vein perthite. S68B. **d** Irregular vein perthite. S74B. **e** Irregular vein perthite, incipient patches. S68B. **f** Patch perthite, remnant irregular veins, S13B. **g** Patch perthite. S31B. **h** Patch perthite, S70B

Scituate Granite are coarser (100 versus 25 μm) than those discussed by Yund and Ackermand (1979) and the variation and complexity of microstructures types is also greater. The complexity and coarsening of these microstructures must be examined in light of a history including igneous crystallization, prograde metamorphism, deformation, interaction with fluids and retrograde cooling.

The principal factor controlling the coarsening and shape evolution of perthite microstructures seems to have been the maximum temperature achieved during metamorphism. The evolved textures (Fig. 4b, g, h) characteristic of the southern and western Scituate are directly correlated with areas of higher metamorphic temperatures. This may be seen in the more sodic compositions of the microcline in the south as well as in the extrapolated metamorphic isograds (Fig. 1).

The driving force for coarsening is the reduction in surface free energy that accompanies the reduction in total surface area of lamellae. The role of temperature in the process is probably to serve as a means of surmounting an activation barrier. The perthite microstructures observed in the Scituate Granite are complex and variable (Figs. 4 and 5) and it is not clear that all stages in the evolution of these textures do, in fact, represent a reduction in the surface area of lamellae. The presence of metamorphic fluids (Day et al. 1980), expecially in zones of intense deformation, may have played a role in the development of complex branching and anastomosing lamellae (Fig. 5c and d) and ragged lamellae and patches (Fig. 4e and g). Presumably such fluids increase the rate at which alkali elements can be transported and deformation may increase the accessibility of fluids to sites of alkali diffusion. Although rapid alkali diffusion is necessary to permit coarsening and evolution of microstructures, the rate limiting process governing the migration of albite-microcline grain boundaries is not known.

High temperatures and the driving force provided by surface energy reduction are not, by themselves, adequate to account for the variability of perthite microstructures. In the southern SGG, where temperature was high and almost complete recrystallization and reconstitution of the Scituate granite took place, extreme coarsening of perthite relics has occurred without losing the integrity of a regular or slightly irregular lamellar structure (Fig. 4b). Clearly, temperature alone does not necessarily produce the observed textural variation.

Finally, it does not appear that there is significant control of the microstructures either by the composition of Scituate feldspars or by the duration of subsolvus *cooling*. Although one patch perthite has plagioclase with the composition An_{14}, other patch perthites contain An_2–An_4 and are comparable to the compositions of regular and irregular vein perthite. Patchy perthites in the south, which are morphologically more 'exsolved', are *less* exsolved compositionally than regular vein perthites in the north. The more sodic compositions of microcline in the southern patch perthites indicate that effective alkali diffusion, and presumably coarsening and shape evolution, terminated at higher temperatures in the south than in the north. Consequently, the more evolved microstructures of patch perthites must have been achieved largely prior to final cooling from peak metamorphism and during a shorter temperature interval for cooling than the regular vein perthites in the north. It appears, therefore, that differences in neither the calcium content of the feldspars nor the cooling history of the felspars explain the observed differences in perthite microstructures.

Evolution of Perthite Composition During Metamorphism

It is a common hope among petrologists that feldspars might be used to infer something about the thermal history of their enclosing host rock. In this section, we attempt to estimate the way in which the feldspars changed during Permian metamorphism by assuming the pre-metamorphic composition of the feldspar, using determined feldspar compositions to estimate temperatures achieved during metamorphism, and finally, using information from the literature to constrain the time and thermal history of metamorphism.

Initial and Final State of the Feldspars

The inferred evolution of the perthite depends in an important way on the nature of the intergrowth and structural state of the felspar at the onset of deep burial during Pennsylvanian time. As a starting point for discussion, we will assume that the pre-metamorphic feldspar was an orthoclase microperthite that had coarsened at least to the extent that coherency between host and lamellae was lost (cf. Yund 1975). In addition, we will assume that the compositions of the coexisting phases in the perthite lay substantially inside the low temperature limbs of the microcline-low albite solvus.

Although all potassium feldspars are now maximum microcline (Brown 1976), assuming that the pre-metamorphic feldspar was more disordered is not unreasonable. Orthoclase is commonly found in high level plutons. Parsons (1978) has argued that ordering and exsolution are sensitive primarily to the presence of water during the cooling history of a pluton. In particular, orthoclase will probably persist if water is not available in the cooling interval through which microcline becomes a stable phase. In view of the inferred low water content of the Scituate magma and its relatively shallow level of emplacement (Day et al. 1980), it is possible that a disordered potassium feldspar was preserved.

The compositions of coexisting phases in the pre-metamorphic perthite were probably controlled by a strain-free solvus intermediate between the sanidine-high albite and the microcline-low albite solvii (Smith and Parsons 1974; Bachinski and Muller 1971) (see Fig. 6). Unless exsolution continued to unusually low temperatures, it seems probable that the potassium phase in the pre-metamorphic perthite contained at least 10% of albite component and possibly more. We will assume tentatively that this represents the minimum sodium content of the potassium rich phase at the onset of metamorphism.

The present compositions of Scituate microclines are about Ab_8 at high metamorphic grade and about Ab_2 at lower grades. Coexisting albites have compositions appropriate for the sodic limb of the microcline-low albite solvus (Day et al. 1980).

Figure 6 illustrates the location of the low-grade and high-grade feldspar compositions on the microcline-low albite solvus of Bachinski and Muller (1971). Based on the locations of post-Pennsylvanian isograds, Fig. 1, these feldspars appear to retain temperatures comparable to or perhaps somewhat lower than those that must have been achieved during metamorphism.

Brown (1976) has shown that all potassium feldspar samples from the Scituate and associated granites are maximum microcline. Microcline hosts contain microscopically observable grid twinning and albite lamellae are commonly twinned on the albite law. It seems unlikely that coarsening of the twinned domains could have taken place without significant alkali diffusion so it is reasonable to assume the present compositions of the coexisting feldspars were controlled by the microcline-low albite solvus.

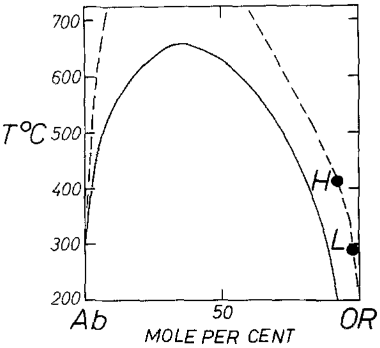

Fig. 6. Alkali feldspar solvii at one kilobar. *Solid curve:* Sanidine-high albite (Smith and Parsons 1974). *Dashed curve:* microcline-low albite (Bachinski and Muller 1971) corrected to one kilobar by 16° C/kbar. *H* and *L* represent compositions of the high and low grade microclines respectively

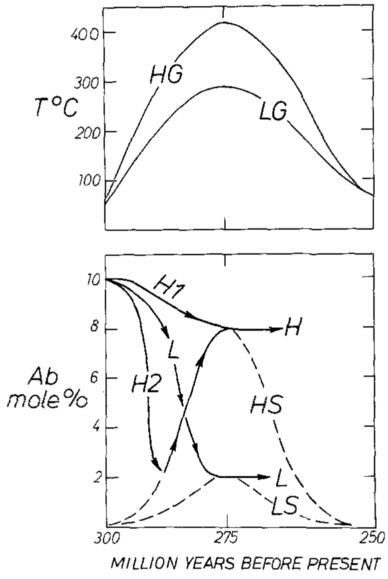

Fig. 7. **a** Estimated thermal history of high grade (*HG*) and low grade (*LG*) perthites. **b** Possible paths of compositional evolution for Scituate microclines from an initial composition of Ab_{10}. *Dashed curves HS and LS* represent the microcline-low albite solvus along temperature paths HG and LG respectively. *Curve L* represents one possible path describing the evolution of a low grade perthite such that the solvus is reached at peak metamorphism. *Curves H1 and H2* represent paths that require the high grade microcline to reach the solvus at peak metamorphism or at 290° C respectively

Constraints on the Thermal History of Metamorphism

For the purpose of estimating the evolution of the observed feldspar compositions, we have assumed the simplest possible model for the Permian metamorphism (Fig. 7a). The onset of Pennsylvanian burial was no later than about 300 m.y. because fossils corresponding to Westphalian C and D are found in the Narragansett Basin (Lyons and Chase 1976; Brown et al. 1978). Grew and Day (1972) and Day et al. (1980) have argued that the Narragansett Pier Granite in southern Rhode Island was intruded at or just after the peak of metamorphism. This granite has yielded U-Pb ages on monazites of about 276 m.y. (Kocis et al. 1978) and this age is assigned to the peak of metamorphism. Most of Rhode Island and large parts of adjoining states are part of a large terrain that yields apparent K-Ar ages (biotite and muscovite) ranging from 230 to 260 m.y. (Zartman et al. 1970; Hurley et al. 1960). This suggests that by about 250 m.y. ago, the basement granites had cooled sufficiently to retain argon in micas. This apparent age is interpreted as the close of Permian metamorphism. A low argon closure temperature is assumed because biotite in the Scituate is iron-rich (Day et al. 1980; Giletti 1974). Figure 7a illustrates the maximum temperatures achieved by the Scituate granite during Permian metamorphism based on the assumption that the least sodic and most sodic microclines (Fig. 6) record temperatures at the peak of metamorphism. Pressure during metamorphism is assumed to be one kilobar, but may have been somewhat higher. Day et al. (1980) have applied the microcline-low albite geothermometer of Whitney and Stormer (1977) to coexisting feldspars from the Scituate Granite. Their results are comparable to the estimates based only on the sodium content of the microcline (Fig. 6). Since the following discussion does not depend on the apparent temperatures in a critical way, only the simpler estimates are used here. Consideration of the complications introduced if the Scituate feldspars record temperatures achieved during the retrograde portion of the metamorphism is deferred.

Evolution of Feldspar Compositions

Figure 7b illustrates some postulated composition paths that may describe the evolution of the perthites in the low grade (L) and high grade (H) rocks. Dashed curves LS and HS show compositions on the microcline-low albite solvus that would be expected if complete equilibrium could be attained at all stages of metamorphism of the low grade (L) and high grade (H) rocks. The position of curve L, describing the evolution of the low grade perthites, is based on the assumed composition of the pre-metamorphic orthoclase (Ab_{10} or more sodic) and the assumption that exsolution is fast enough to allow the evolving composition to reach the microcline-low albite solvus no later than the peak of metamorphism at about 300° C. The low slope of this curve near the beginning of metamorphism is suggested by the lower rates of exsolution to be expected at lower temperatures. A low slope is shown again as the composition approaches equilibrium at the solvus. It is assumed that during this exsolution process at low temperature, the compositional evolution, coarsening, and ordering of the feldspar are simultaneous processes. Retention of the peak metamorphic feldspar composition is assumed for simplicity.

Curve H1 illustrates a similar history that might be inferred for the high grade perthite that is also assumed to reach its equilibrium composition on the solvus at the peak of metamorphism. While it is not possible to rule out such a history on the basis of observations made here, this path is not very appealing. Curve H1 requires that rate of composition change for the high grade feldspars be much slower than the rate of change at low grades (curve L), despite the fact that the high grade samples have been at higher temperatures throughout the prograde metamorphism.

An alternate explanation is that the high grade feldspars reached equilibrium on the solvus at some lower temperature, say 300° C, despite the shorter time implied by the thermal history of this sample (Curve H2, Fig. 7a). According to this hypothesis, the composition of the potassium feldspar would evolve rapidly to the limb of the ordered microcline-low albite solvus (curve HS). Equilibrium would be reached by the time that temperature had reached 300° C and further rise in temperature would then lead to partial homogenization of the perthite as the compositions changed slowly up the limbs of the solvus.

Curves H1 and H2 (Fig. 7b) probably represent limiting cases for the evolution of the high grade perthites. It is difficult to argue that the high grade perthites should reach the solvus later than the low grade perthites (i.e., that curve H2 is less steep than curve L), and a significant part of the evolution of the high grade perthite must therefore represent partial homogenization of previously exsolved perthite.

The most important insight derived from the extremely oversimplified model in Fig. 7 is the recognition that, during the evolution of perthite microstructures, exsolution *and* homogenization may have played equally important roles in the evolution of the perthite compositions. Several assumptions have been made in order to arrive at this conclusion and it is desirable to examine the basis for these assumptions and the consequence of their failure.

Alternate Composition Paths

The compositions for low grade samples are important constraints on the path inferred for high grade samples during the early stages of metamorphism. If, at low grades, compositions migrate to the solvus faster than illustrated, both low grade and high grade perthites must have a history of early exsolution followed by homogenization. If compositions migrate more slowly than illustrated, we may still anticipate that maximum rates of exsolution for the low grade samples occur near the peak metamorphic temperatures for these samples and that a close approach to the solvus was attained at that time or slightly thereafter. If this is so, we may safely assume that the high grade samples reached the solvus at about the same temperature, implying that the solvus limb controlled feldspar homogenization during the remainder of the prograde history.

Figure 7 shows final feldspar compositions attained at peak metamorphic temperatures. Especially for the high grade felspars, it is possible, even probable, that the final compositions represent apparent temperatures realized during the retrograde phase. Fluids were present during metamorphism (Day et al. 1980) and the composition path of the feldspars may not have departed significantly from the solvus during the early stages of cooling. The presence of a retrograde phase of metamorphism would account for the presence of occasional samples in which some perthite grains and microcline-albite grain margins record slightly lower apparent temperatures than feldspar grain cores in the same samples (Day et al. 1980).

Either possible deviation of composition paths from the ones illustrated in Fig. 7 seems to lead to the same conclusion. Namely, for at least some samples of Scituate feldspar, early exsolution was followed by partial homogenization and only minor exsolution occurred during retrograde metamorphism.

Role of Al-Si Ordering

We have assumed that ordering of Al and Si took place primarily in the early stages of metamorphism so that the microcline-low albite solvus represents the equilibrium condition toward which the feldspars evolved during prograde metamorphism. If significant ordering took place prior to metamorphism, the composition of pre-metamorphic microcline may have been less sodic than assumed and the homogenization of the high grade samples during metamorphism must have been even more important than assumed above. If ordering were delayed until the retrograde phase of metamorphism, it must have been complete by the time the low grade feldspar attained its observed composition.

The widespread occurrence of grid twinning suggests that the free microcline grains were formed above the triclinic-monoclinic transition temperature. The high grade portions of the SGG probably reached the amphibolite facies of metamorphism but the low grade portions probably never reached the transition temperature (500° ± 50° C?). This observation may imply that times of feldspar ordering vary from place to place in the SGG. Alternatively, the distribution of perthite abundance and the recrystallization to free microcline plus plagioclase may represent a pre-Pennsylvanian deformation. Further modification of perthite microstructures and compositions may have occurred during Permian time.

Does Equilibrium Prevail at Any Stage of Evolution?

The preceding discussion has been based on the assumption that the microcline-low albite solvus represents the equilibrium state toward which the Scituate feldspars tended to evolve. In addition, we have assumed that the solvus actually controls compositions during at least some small part of the heating cycle (e.g., curve L, Fig. 7b).

If the thermal cycle we have assumed is approximately correct, the shape and position of the curve LS (Fig. 7b) may be used to place constraints on equilibration rates necessary to satisfy the assumptions mentioned above. In order for a microcline having composition Ab_{10} to reach the solvus, curve LS, at 300° C, the apparent average equilibration rate until peak metamorphism must be about 3×10^{-7} mole %/year for the observed perthite lamellae widths of about 25 μm. This value is not much different than the value implied by the steep portion of curve L, 7×10^{-7} mole %/year. In order for compositions to evolve along the solvus limb during retrograde metamorphism, the slope of curve LS suggests that apparent equilibration rates should be no less than 1×10^{-7} mole %/year. If, for observed lamellae widths of about 25 μm, composition changes at a rate less than about 1×10^{-7} mole %/year under greenschist facies conditions, it is unlikely that the compositions can evolve rapidly enough to remain on the solvus and must therefore depart from it during cooling. These 'equilibration rates' are only apparent rates because the true rates must vary across the lamellae and with time.

Qualitative arguments suggest that rates of equilibration are not a limiting factor. The observation (Day et al. 1980) that coexisting phases in perthites have compositions comparable to one to four millimeter grains of coexisting feldspars suggests that neither the distance over which mass transfer has occurred nor the time available for equilibration has played a significant role in the history of the feldspar compositions. Consequently, rates of alkali transport were probably sufficient to permit compositions to migrate to the solvus early in the metamorphic history.

A rigorous quantitative evaluation of permissable rates of equilibration does not appear possible based on data available in the literature. The rates of lamellar coarsening determined experimentally for *coherent* perthites (Yund and Davidson 1978) are clearly not applicable to Scituate feldspars with coarse non-coherent intergrowths. Isothermal coarsening at 500° C at the rates determined for *coherent* feldspars (Yund and Davidson 1978) requires about 100 m.y. to achieve lamellae with a 5 μm spacing. Likewise, the rate of potassium self-diffusion in orthoclase (Foland 1974) does not appear to permit significant amounts of alkali exchange over distances of 25 μm, at the lowest temperatures (275° C) inferred for the Scituate Granite in times less than about 10^{12} years. Foland (1972) has calculated similar times using different boundary conditions. It appears, therefore, that volume diffusion of potassium in coarse lamellar perthites cannot be the most important mechanism by which lamellae change composition.

It is possible, however, to find a crude confirmation of the feasibility of equilibration rates required by Fig. 7 using a combination of experimental data and the activation energy for potassium self-diffusion in orthoclase. Müller (Bachinski and Müller 1971, Table 6) has examined the homogenization of microcline-albite aggregates under dry conditions. Presumably the grain sizes were on the order of 1 to 10 μm. At 600° C and 1 bar, microcline gained albite component at about one mole percent per day. Assuming that the activation energy for self-diffusion of potassium in orthoclase (Foland 1974) applies for interdiffusion, we used the Arrhenius relation to extrapolate the Müller rate to lower temperatures. If the equilibration rate for micron size particles is 1 mole percent per day at 600° C, it is estimated to be about 4×10^{-7} mole percent per year at 300° C. This crude estimate confirms the feasibility of the model presented in Fig. 7.

Conclusions

The systematic southwesterly decrease in perthite abundance in the Scituate granite does not seem to be primarily the result of igneous crystallization (Day et al. 1980). Rather, the direct correspondence of abundance with the inferred grade of Permian metamorphism and with macroscopic and microscopic evidence of deformation suggests that reconstitution during deformation has had an important role in producing the abundance pattern. It is possible, however, that the abundance pattern was produced during a pre-Pennsylvanian deformation and that microstructures and compositions were further modified during Permian metamorphism. Unfortunately, this possibility cannot be ruled out on the basis of our current understanding.

Although minor modifications may have occurred during retrograde metamorphism, it appears that the compositions of Scituate feldspar are substantially the product of prograde metamorphism during Permian time and that partial homogenization of feldspar compositions has been an important part of their evolution. The preservation of a prograde sequence of feldspar compositions during the final cooling suggests that fluids played an important role during metamorphism.

The rate determining factors governing the modification of perthite microstructures are not known but the temperatures achieved during metamorphism appear to have had an important influence on the development of the observed textures. The variability and complexity of microstructures in Scituate feldspars, compared to those observed in bodies having a single stage cooling history (Yund and Akermand 1979), is probably a reflection of additional possibilities for mass transfer during reheating and deformation in the presence of volatiles.

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