The Canadian Mineralogist
Vol. 34, pp. 133-146 (1996)

INTERPRETATION OF PLAGIOCLASE ZONATION IN CALCIC PELITIC SCHIST, SOUTH STRAFFORD, VERMONT, AND THE EFFECTS ON THERMOBAROMETRY

THOMAS MENARD

Department of Geology and Geophysics, University of Calgary, Calgary, Alberta T2N 1N4

FRANK S. SPEAR

Department of Earth and Environmental Sciences, Rensselaer Polytechnic Institute, Troy, New York 12180, U.S.A.

Abstract

Metamorphic plagioclase in calcic pelitic schists from South Strafford, Vermont, grew during heating of the assemblage garnet + biotite ± chlorite + plagioclase + epidote ± calcite + quartz + muscovite + graphite + fluid during garnet growth with chlorite in the assemblage, or during garnet consumption after chlorite was removed from the assemblage. These grains have a variety of patterns of compositional zoning. The simplest pattern is continuous concentric zoning, which records the sequence of plagioclase compositions produced in the rock during progressive metamorphism. The most strongly zoned single grain found varies from An_{20} to An_{70} from core to rim. Sodic plagioclase was consumed during growth of calcic plagioclase, and the locations of growth and consumption can be affected by partitioning of deformational strain in a rock. As a result of discontinuous growth of a particular grain, plagioclase can have discontinuous zoning or patchy zoning. Zoning patterns in plagioclase can also reflect the character of the matrix overgrown: smoothly zoned plagioclase overgrew relatively homogeneous matrix, whereas plagioclase with complex zoning patterns overgrew crenulated muscovite or other inhomogeneities. The peristerite gap is displayed as alternating lamellae of two plagioclase compositions, as a simple gap in the zoning of concentrically zoned grains, and as portions of grains that are nearly unzoned with compositions near An_{18}. This variety of zoning features and the complexity of possible zoning patterns make it imperative to document carefully any correlation of mineral compositions. Petrologically unreasonable interpretations can potentially lead to wild errors in thermobarometric estimates.

Keywords: plagioclase, compositional zoning, calcic pelitic schists, metamorphism, thermobarometry, South Strafford, Vermont.

Sommaire

Le plagioclase d'origine métamorphique des schistes pélitiques calciques de South Strafford, au Vermont, s'est formé aux dépens de l'assemblage grenat + biotite ± chlorite + plagioclase + épidote ± calcite + quartz + muscovite + graphite + fluide pendant la croissance du grenat avec la chlorite, ou durant la résorption du grenat une fois la chlorite éliminée de l'assemblage. Ces grains font preuve de zonation compositionnelle variable. La zonation la plus simple est concentrique et continue; elle témoigne de la production d'une séquence de compositions de plagioclase au cours du métamorphisme prograde. Le cristal le plus fortement zoné va de An_{20} à An_{70} du coeur vers la bordure. Le plagioclase sodique a été éliminé pendant la croissance du plagioclase calcique; les sites de croissance et de résorption dépendent de la distribution de la déformation dans un échantillon. A la suite de la croissance discontinue d'un cristal quelconque, le plagioclase peut montrer une zonation discontinue ou une zonation en tache. Le schéma de zonation peut aussi dépendre des propriétés de la matrice que le plagioclase a englobé: un grain ayant une zonation monotone résulte d'une croissance aux dépens d'une matrice relativement homogène, tandis qu'un grain ayant un agencement complexe de zones pourrait résulter d'une croissance aux dépens de la muscovite plissée ou d'autres hétérogénéités. La lacune de miscibilité dite péristerite est la cause de lamelles alternantes de deux compositions, d'une lacune dans la distribution des compositions de plagioclase dans un grain à zonation concentrique, et de portions de grains non zonés, de composition proche de An_{18}. Cette gamme de phénomènes de zonation et la complexité des tracés de zonation possibles nécessitent une documentation soignée des corrélations des compositions des minéraux. Des interprétations pétrologiquement irraisonnables pourraient bien mener à des erreurs très importantes dans les reconstructions thermobarométriques.

(Traduit par la Rédaction)

Mots-clés: plagioclase, zonation en composition, schistes pélitiques calciques, métamorphisme, thermobarométrie, South Strafford, Vermont.

Introduction

The compositions of garnet and plagioclase are commonly used in studies of metamorphic P–T path of pelitic schists (*e.g.*, Selverstone & Spear 1985, Spear *et al.* 1990a). Although the compositional zoning of garnet has been the subject of numerous studies (*e.g.*, Hollister 1966, Atherton 1968, Thompson *et al.* 1977, Tracy 1982), the compositional zoning of metamorphic plagioclase has received less attention (Crawford 1966, Goldsmith 1982). Understanding the variety of zoning patterns in metamorphic plagioclase and how they form is essential for a proper interpretation of the metamorphic reactions, thermobarometry, and calculation of P–T paths in many metamorphic rocks. In this paper, we show how proper and improper interpretation of compositional zoning of plagioclase affects thermobarometric estimates, and we provide some guidelines for the proper interpretations. We consider here metamorphic plagioclase in calcic pelites from east-central Vermont because the phase petrology is well understood (Menard & Spear 1993), as is the metamorphic P–T history (Menard 1991, Menard & Spear 1994). The patterns of compositional zoning reflect the sequence of metamorphic reactions, the heterogeneity of strain in the rock, and the texture of the matrix that the plagioclase overgrew. Some of the features described here were predicted by Spear *et al.* (1990b) on the basis of thermodynamic modeling, and we provide documentation from natural samples.

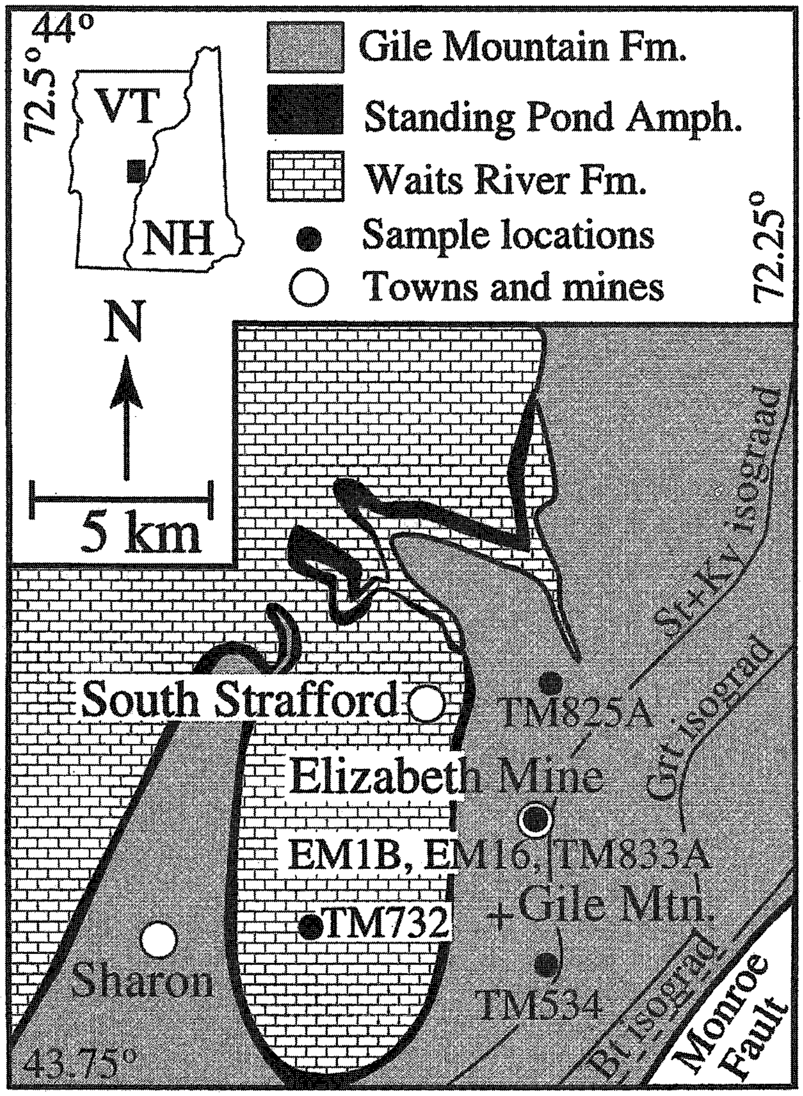


FIG. 1. Geology of the Strafford, Vermont, 15′ Quadrangle (Doll 1944, White & Jahns, 1950, Rolph 1982, Menard & Spear 1994) with sample locations.

Geological Setting

The rocks collected for this study are from the Silurian–Devonian Waits River Formation and Gile Mountain Formation from near South Strafford, Vermont (Fig. 1). The geology of the area was described by Doll (1944) and White & Jahns (1950). More recent contributions to the regional geology include those by Woodland (1977), Hatch (1987), Ferry (1992), and Menard & Spear (1994). One of the sample locations is the Elizabeth copper mine, which operated intermittently between 1809 and 1958 and was discussed by White & Eric (1944), Howard (1969), Rolph (1982), and Slack *et al.* (1993). These rocks were deformed and metamorphosed at amphibolite-facies conditions during the Devonian Acadian Orogeny, which involved two thrust- or nappe-style deformational events and subsequent doming. Metamorphic P–T paths computed from calcic pelitic schists from the Strafford Dome generally display early heating, followed by a nearly isothermal increase in pressure during D_2 nappe-style deformation, followed by more heating (Menard & Spear 1994). Studies of metamorphic plagioclase in or near the area were carried out by Lyons (1955), Crawford (1966), and Spear (1977, 1980).

Analytical Methods

Forty samples were analyzed using the electron microprobe at the Rensselaer Polytechnic Institute. Plagioclase grains in six samples discussed here illustrate the variety of zoning patterns observed. Zoning patterns for more than half of the plagioclase grains in a polished thin section were examined using back-scattered electron imaging supplemented by spot analyses and line traverses. The back-scattered electron images provide excellent compositional maps of the plagioclase grains, with a spatial resolution of approximately one μm. In the line traverses, spatial resolution of compositional differences is three μm, estimated from a traverse across a sharp compositional break at a grain boundary. The effective diameter of the volume analyzed in plagioclase thus was between one and two μm. The analytical conditions used for plagioclase were 15 kV and 17 nA for a maximum of 40 seconds per element sought. Na was invariably the first element analyzed for. Natural and synthetic silicates and oxides were used as standards; natural plagioclase, garnet, and hornblende were used as secondary standards. In low-K plagioclase, there are two independent measures of the mole fraction of anorthite, the cation ratios Ca/(Ca + Na) (shown in the Figures) and (Al − 1)/(Al + Si − 3). On the basis of the good agreement between the two compositional ratios, we do not consider the loss of Na during analysis to have been a problem for the analytical conditions used (Menard 1991).

Petrological Background

Miscibility gaps or solvi in subsolidus plagioclase have the potential to complicate the interpretation of plagioclase zoning. Three major miscibility gaps or solvi are well documented in igneous plagioclase: the peristerite gap at An_3–An_{20}, the Bøggild gap at An_{47}–An_{58}, and the Huttenlocher gap at An_{67}–An_{90} (Smith 1983). Temperature-composition diagrams showing positions and interpretations of the gaps were given by Smith (1983) and Grove *et al.* (1983). The peristerite gap is also well documented in metamorphic rocks (Crawford 1966, Cooper 1972, Morteani & Raase 1974, Nord *et al.* 1978, Franceschelli *et al.* 1982, Maruyama *et al.* 1982), and a pressure dependence of the peristerite gap was suggested by Maruyama *et al.* (1982). A variety of other gaps has been proposed in metamorphic plagioclase (Hunahashi *et al.* 1968, Wenk *et al.* 1975, Wenk & Wenk 1977, Garrison 1978, Spear 1977, 1980, Goldsmith 1982).

A miscibility gap in plagioclase is expected to lead to the decomposition of metastable plagioclase into two compositions (Nord *et al.* 1978, Wenk 1979) or to the nucleation and growth of two distinct equilibrium compositions (Wenk *et al.* 1975, Wenk & Wenk 1977) sequentially or alternately. Although well documented in igneous rocks (Ribbe 1982), exsolution lamellae are less likely to be observed in plagioclase equilibrated at lower temperature in middle-grade metamorphic rocks because the diffusion kinetics are much slower. If such lamellae are present, they likely will be so small as to require TEM analysis for identification (*e.g.*, Grove 1976, Grove *et al.* 1983).

The textures, mineral compositions, and reaction history of sample EM1B (Fig. 2a), from the Gile Mountain Formation at the Elizabeth mine (Fig. 1), are typical of many calcic pelitic schists in the area. The matrix assemblage is garnet + biotite + plagioclase + calcite + quartz + muscovite + ilmenite, with minor graphite and epidote, and retrograde K-feldspar and chlorite. Muscovite and biotite are foliated in S_1, which was later crenulated by F_2. Biotite also occurs in S_2 orientations. Garnet has inclusions of ilmenite, quartz, calcite, epidote, chlorite, biotite, and plagioclase. Layering of inclusion abundance describes S_0, orientations of included minerals describe an S_1 schistosity parallel to S_0, S_1 inclusions trains are bent outside garnet cores decorated with graphite, but the S_2 foliation in the matrix drapes around grains of garnet (Fig. 2a). Thus, garnet grew following D_1 and prior to and during the initial stages of D_2. Compositional zoning in the garnet is shown in Figure 2b. At the core–rim boundary, X_{Grs} increases and X_{An} decreases. In other samples from the area, these compositional trends are associated with a pressure increase during D_2 (Menard & Spear 1993). Most of the garnet in the samples discussed here grew by the reaction (Menard & Spear 1993):

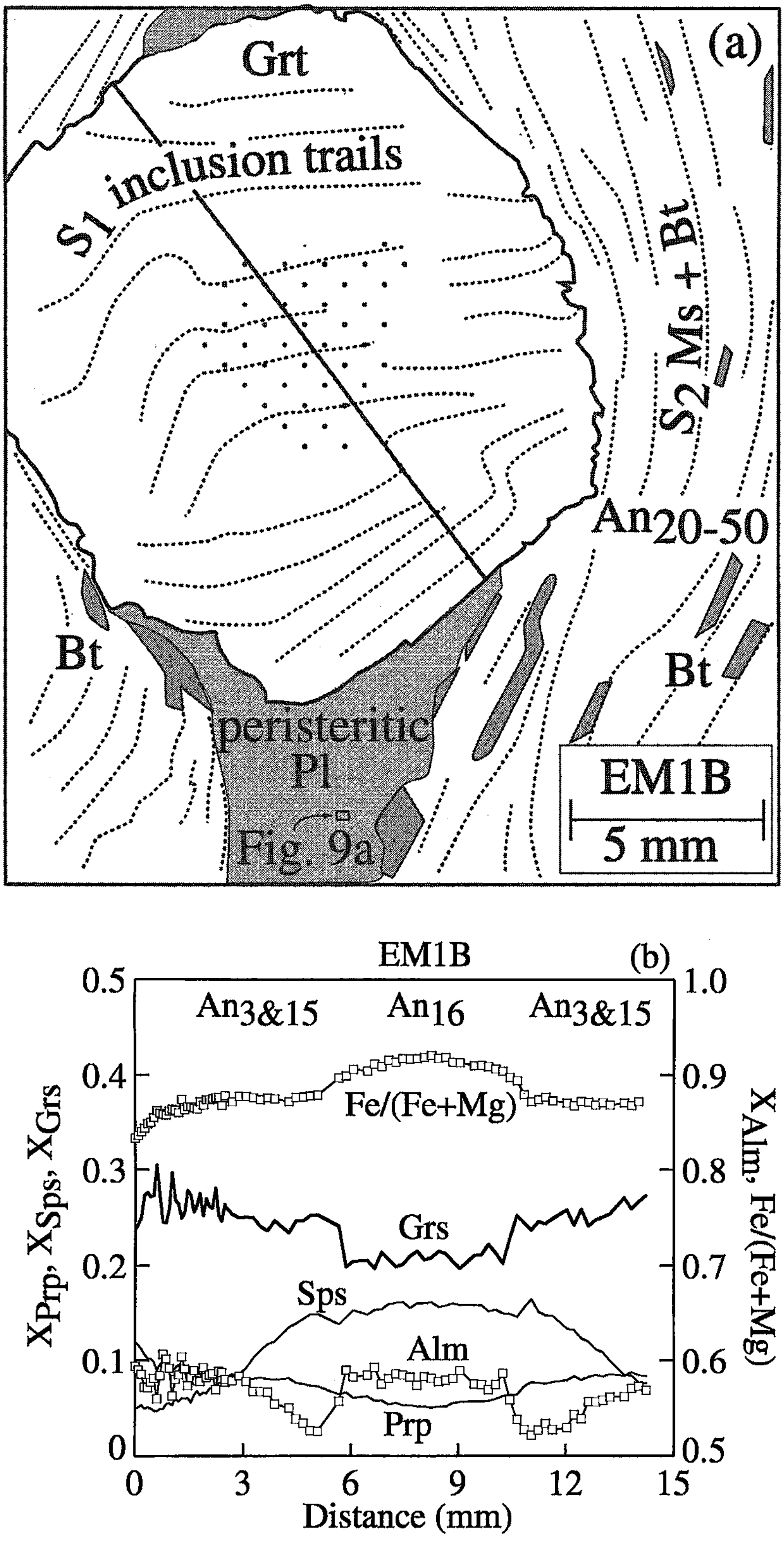


FIG. 2. Sample EM1B from the Elizabeth mine. (a) Sketch of a thin section showing the spatial distribution of matrix plagioclase compositions. Peristeritic plagioclase is preserved as inclusions in the garnet and also in the pressure shadow around garnet, whereas calcic plagioclase overgrew the matrix S_2 fabric, suggesting that sodic plagioclase was consumed in parts of the sample where the S_2 fabric is well developed. Trends of S_1 inclusion trails in garnet and the matrix S_2 fabric are shown by dashed lines. The garnet core (dotted) is marked by graphite inclusions and exhibits distinct compositions and patterns of inclusion trails. Also shown are location of the traverse in part b (heavy line) and location of Figure 9a. (b) Garnet compositions in sample EM1B along traverse shown in Figure 2a. Scale for X_{Prp}, X_{Sps}, and X_{Grs} shown on the left; scale for X_{Alm} and Fe/(Fe+Mg) shown on the right. Symbols show the points analyzed. Compositions of included plagioclase are also shown.

$$\mathrm{Chl + Ep \pm Cal + Ms + Qtz + Gr = Grt + Bt + Pl + H_2O + CO_2}$$

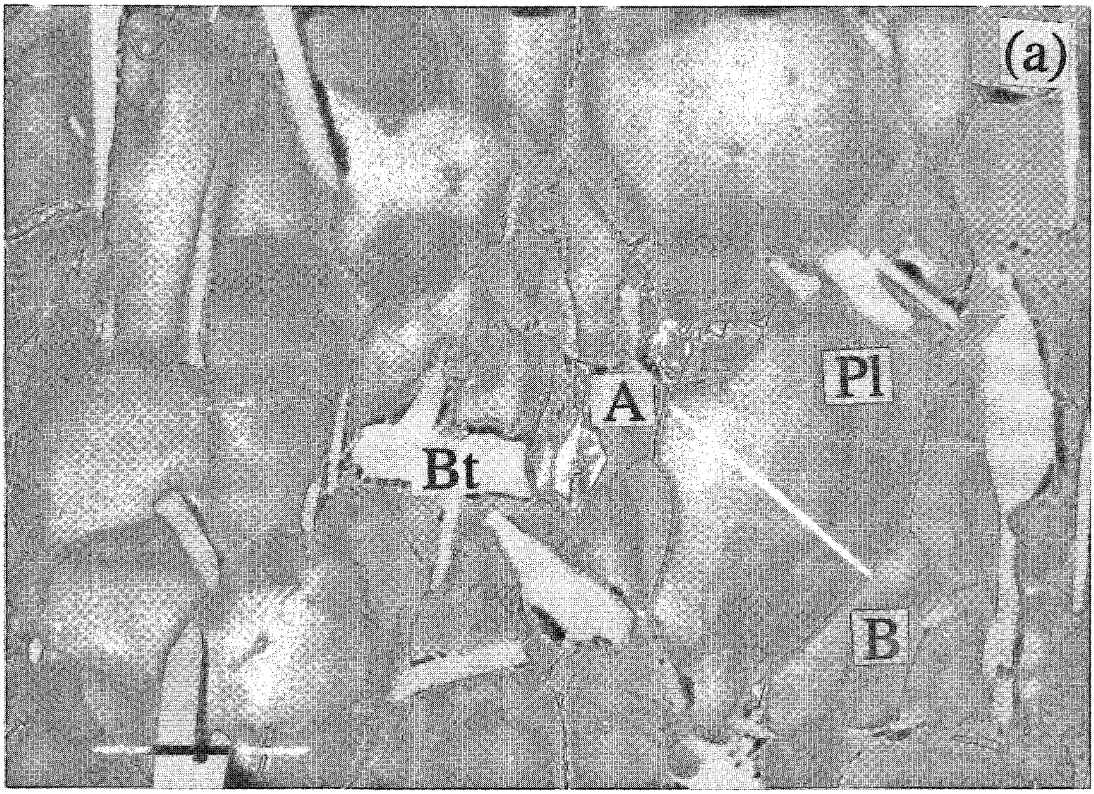
and garnet growth was followed by plagioclase growth with increasing X_{An} by the reaction:

$$\mathrm{Grt + Ep \pm Cal + Ms + Qtz = Pl + Bt + H_2O + CO_2}$$

Patterns of Zoning

Continuous concentric zoning

Continuous concentric zoning (Fig. 3) is the most common type of plagioclase zoning in the sample collection and occurs in at least some plagioclase grains in all samples. In sample TM825A (Menard &



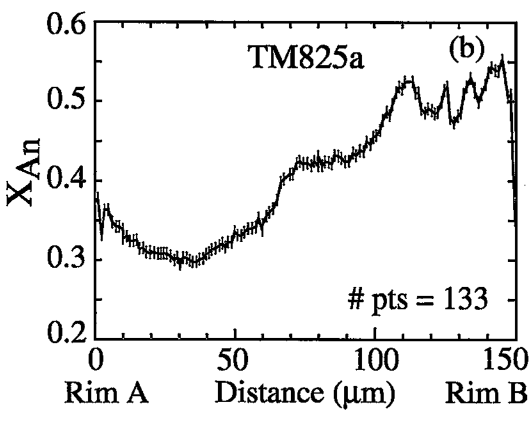
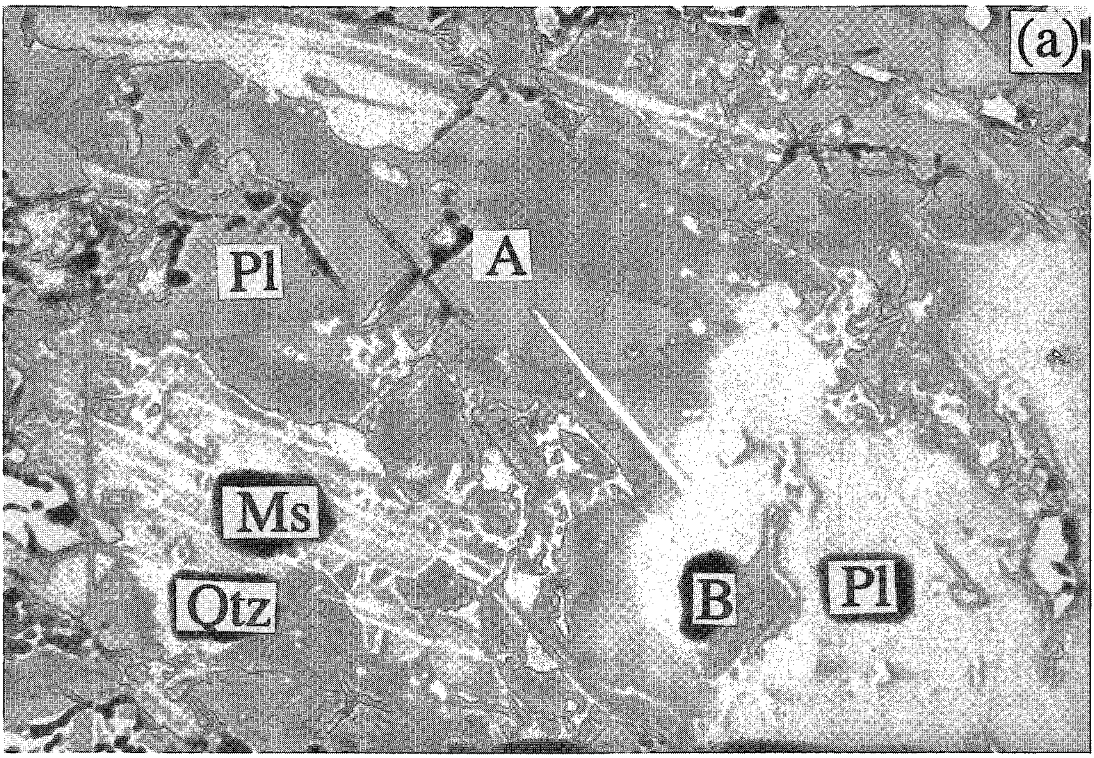


FIG. 3. Concentrically zoned plagioclase. (a) Back-scattered electron image of concentrically zoned plagioclase in sample TM825A. Some of the compositional rings are not complete because of later overgrowth by neighboring grains. Those grains that are pale all the way across may have been cut off-center, and only their rims are displayed. White grains are biotite. Length of traverse A–B is 150 µm. (b) Plagioclase compositions, X_{An} = Ca/(Ca + Na), along traverse A–B shown in Figure 3a. Tic marks show points analyzed.

Spear 1993), from 2.1 km north of the Elizabeth mine, the plagioclase has concentric shells with a mostly continuous sequence of compositions from An_{30} in the core to An_{50-55} at the rim (Fig. 3), although some shells do not go all the way around the grains. Interpretation of the apparent discontinuity between An_{35} and An_{40} is ambiguous: the gap may be a real break in the compositional zoning or may reflect smooth zoning over a distance narrower than the resolution of the electron microprobe. Near the rim, the grain displays zoning with an oscillatory pattern, which reflects a complex history of plagioclase compositions. This sample contains more plagioclase and less mica than the other samples discussed here. Its plagioclase also has a higher X_{An} and still contains matrix epidote, whereas in other samples the epidote was removed during prograde reactions.

Discontinuous concentric zoning

Sample TM732 from the Waits River Formation in the core of the Strafford Dome contains calcic pelitic layers interlaminated with layers of micaceous limestone. X_{An} generally increases from core to rim in plagioclase grains in this sample. Figure 4 shows part of a grain of plagioclase with discontinuous zoning in



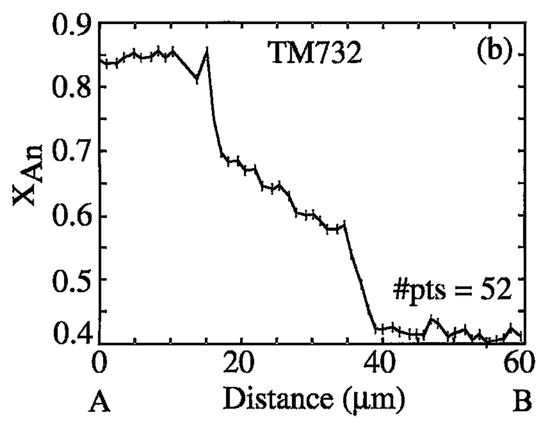


FIG. 4. Discontinuous concentric zoning in plagioclase. (a) Back-scattered electron image of plagioclase (shades from light grey to black) that overgrew S_2 muscovite (grey mica) and quartz (black) in sample TM732. Base of photo is 240 µm. (b) Plagioclase compositions along traverse shown in Figure 4a. The compositional breaks are interpreted as hiatuses in local growth of plagioclase and not as miscibility gaps because the missing compositions are found elsewhere in the rock (Menard & Spear 1993).

a calcic pelitic layer of this sample: An_{43} in the core, An_{58} to An_{68} part way out, and finally An_{84} near the rim. These zones continue on the other sides of the grain as well as in the part shown in the figure. Three analyses between An_{55} and An_{65} occur spread over a distance of 3 μm, but interpretation is ambiguous: the intermediate values may be the result of good analyses, but they may be an artifact of a sharp compositional boundary between An_{43} and An_{58} that is inclined at a shallow angle to the surface of the sample. Thus, the pattern of compositional zoning allows the interpretation of miscibility gaps. Nevertheless, some of the missing compositions are found elsewhere in the sample. For example, a plagioclase grain in the pressure shadow of a grain of garnet in this sample has concentric zones with a continuous sequence of compositions from An_{43} in the core, increasing to An_{67}, decreasing to An_{50}, and increasing to An_{85} at the rim (Menard & Spear 1993). Therefore, at least some of the apparent gaps suggested by Figure 4 are best interpreted as the result of intermittent growth of the grain. Compositions from An_{70} to An_{75} are not found in the rock, which suggests the possible influence of the Huttenlocher gap.

Cannibalism

Figure 5 shows the partial consumption and replacement of the sodic core (An_{30}) of a large grain of plagioclase by the more calcic rim (An_{65}) of a neighboring grain in sample TM825A, discussed above. This cannibalistic texture demonstrates that plagioclase of lower X_{An} was consumed during net growth of plagioclase, providing the required source of Na. The sample has a high mode of plagioclase, increasing the number of plagioclase–plagioclase grain contacts and increasing the chance of cannibalism.

Patchy zoning and pseudomorphs

Figure 6 shows patchy zoning in a plagioclase grain from sample EM16 from the Elizabeth mine. Although the lower plagioclase grain in Figure 6a has patchy zoning, the adjacent grain of plagioclase has the same range of compositions, which suggests that it grew during the same interval of time. All of the compositions missing in the first grain are found in the adjacent grain, where some portions have smooth compositional zoning from An_{20} to An_{70}.

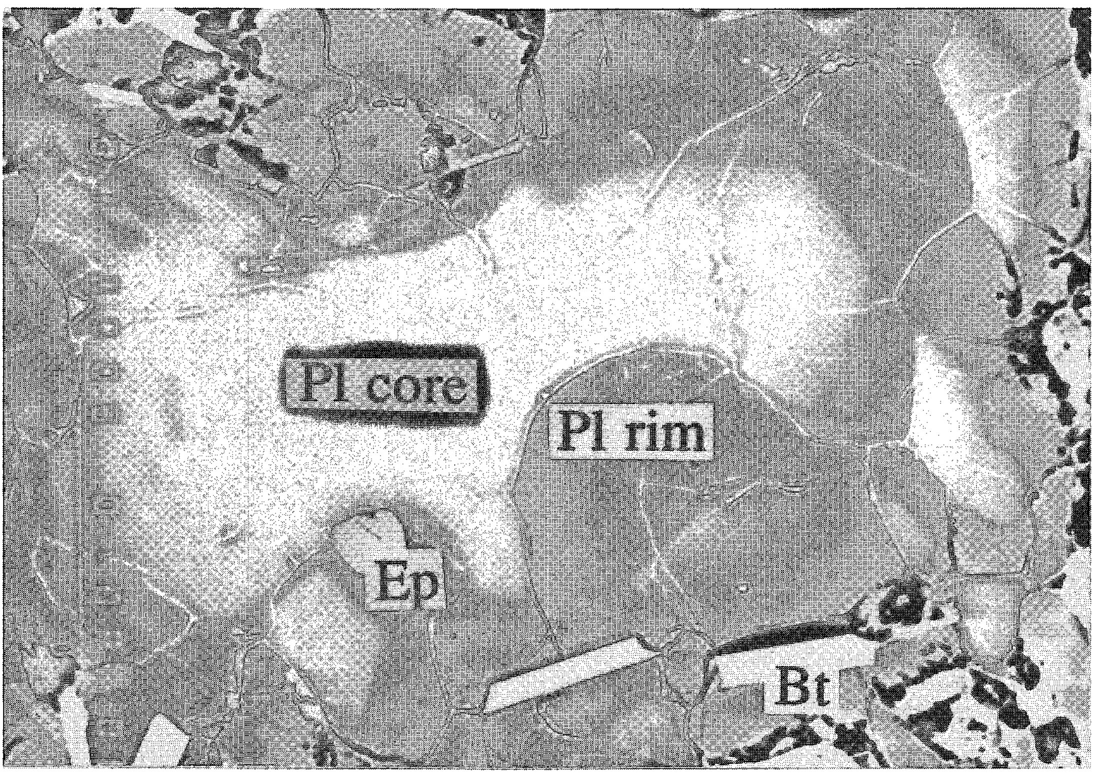
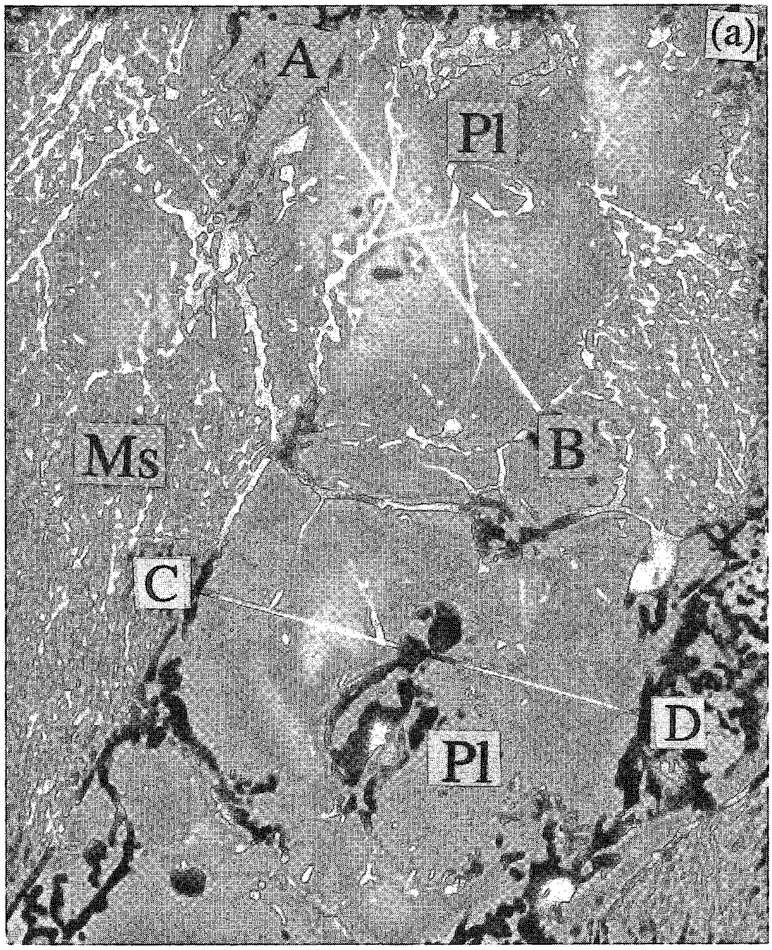


FIG. 5. Cannibalism in plagioclase. Back-scattered electron image of plagioclase in sample TM825A. The sodic core of the larger grain was replaced by the more calcic rim of the smaller grain. This reaction texture demonstrates that pre-existing plagioclase was consumed during growth of plagioclase. Scale bar represents 100 μm.



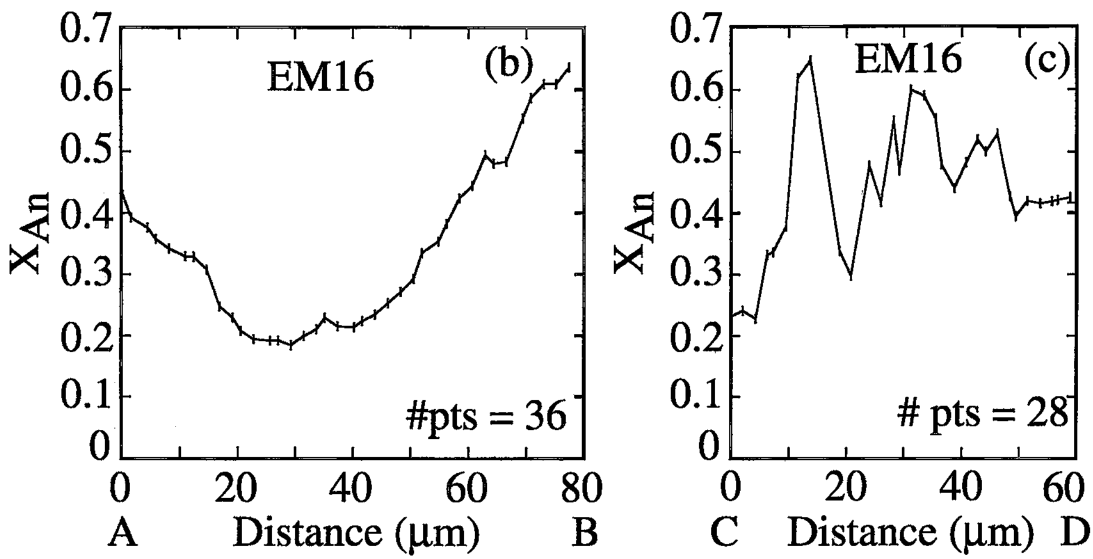


FIG. 6. Patchy zoning in plagioclase. (a) Back-scattered electron image of plagioclase surrounded by muscovite in sample EM16. Parts of the upper grain have continuous concentric zoning, whereas the lower grain has patchy zoning. Locations of traverses in Figure 6b and c are shown. Base of photo is 150 μm. (b) Plagioclase compositions along traverse A–B in Figure 6a. This grain has the same range of compositions as in Figure 9c and demonstrates that the patchiness is not simply due to growth at temperatures at which miscibility gaps were present. (c) Plagioclase compositions along traverse C–D shown in Figure 6a.

Consequently, the patchy zoning is interpreted as the result of locally discontinuous growth and possible resorption, and not the direct result of miscibility gaps. This sample is nearly identical to sample EM1B, described above, but has a greater range of plagioclase compositions.

Figure 7 shows plagioclase grains in sample TM732 that also displays patchy zoning. The plagioclase partially consumed inclusions of biotite and quartz, as well as older parts of the plagioclase grain. The general trend of increasing X_{An} during plagioclase growth in this sample (see above and Menard & Spear 1993) allows the relative timing of the growth of different parts of the plagioclase grain to be interpreted. The zoning is patchy because different portions of the grain replaced quartz, biotite, and plagioclase at different times. Minerals may have been consumed at different times because of chemical or deformational factors. The patchy zoning in the previous example may also record the texture of the minerals replaced during growth of plagioclase, but we cannot demonstrate it for that example.

Figure 8 shows a second type of zoning pattern resulting from pseudomorphism, from sample TM833A from the Elizabeth mine. Muscovite and biotite display an S_1 foliation and an S_2 crenulation, and the pattern of the foliation and crenulation is preserved in the zoning pattern of plagioclase. Relict grains of muscovite preserved as inclusions in the plagioclase have the same orientation as the pattern of compositional zoning in plagioclase. As in previous samples, other plagioclase grains are zoned, with X_{An} increasing from core to rim. Compositions between An_{70} and An_{83} are not found in this sample, which may reflect a miscibility gap. In contrast with the other samples, this one contains kyanite, which partially replaced muscovite and plagioclase. Garnet, kyanite, and plagioclase have inclusions of epidote, indicating that epidote was in the assemblage until late in the reaction history.

The peristerite gap

The peristerite gap was described by Crawford (1966) in biotite-grade calcic pelites in the Gile Mountain Formation, sampled 15 km northeast of South Strafford, Vermont. Those plagioclase grains have discontinuous concentric zoning, with albite in

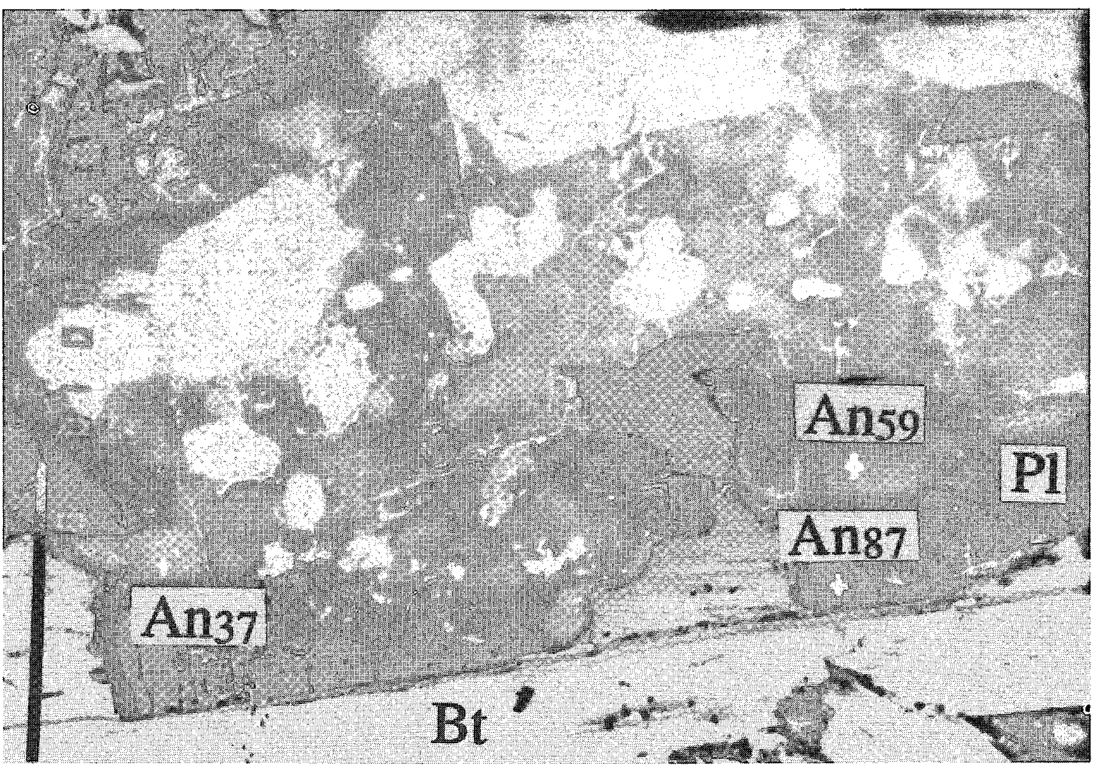
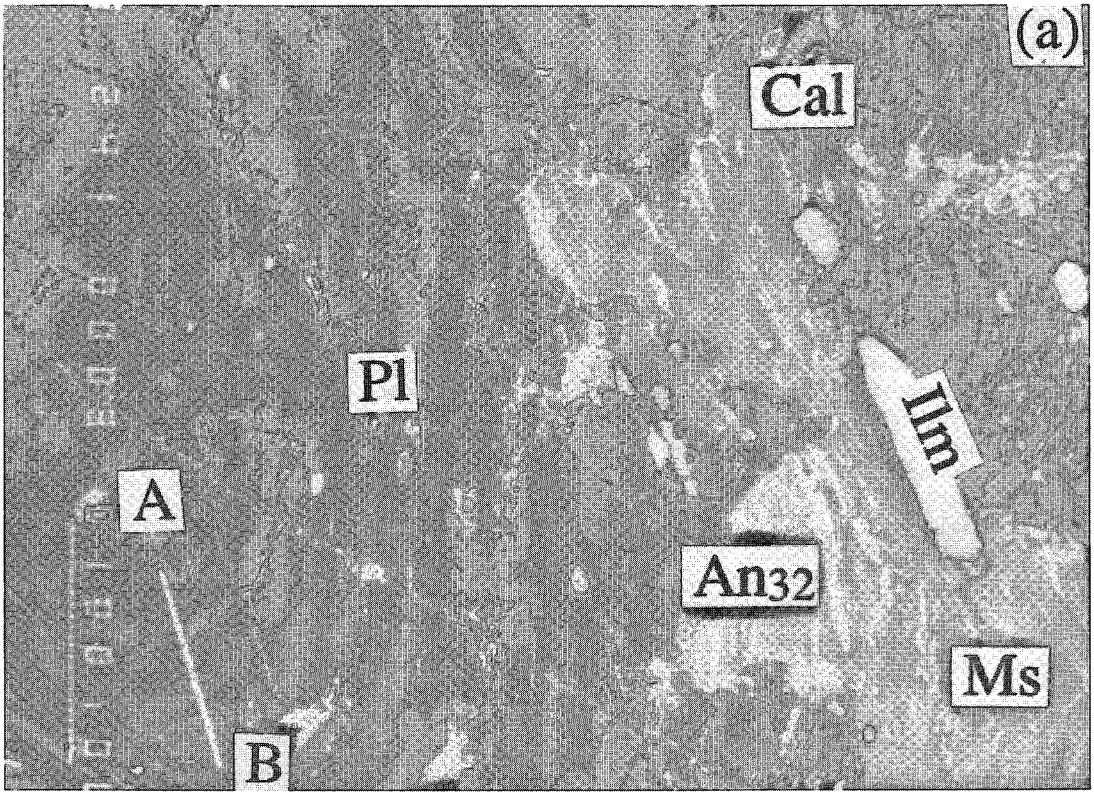


FIG. 7. Patchy zoning in plagioclase. Back-scattered electron image of plagioclase in sample TM732 with compositions as labeled. The zoning pattern follows the shapes of biotite (white), quartz (black), and muscovite (grey mica in upper, left corner). An_{37} plagioclase is the youngest, as determined by rimming relations. Base of photo is 380 μm.



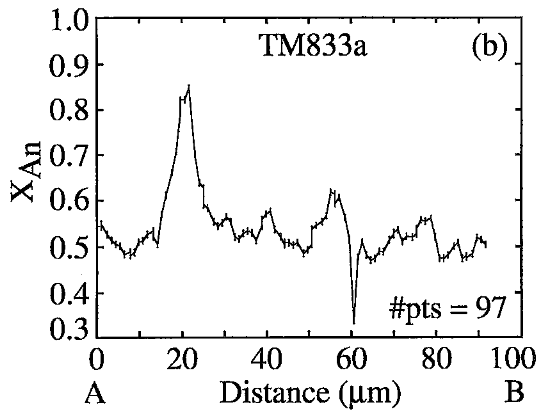


FIG. 8. Zoning patterns in plagioclase pseudomorphic after crenulated muscovite. (a) Back-scattered electron image of matrix plagioclase in sample TM833A. Plagioclase compositions are interpreted as showing relative timing of replacement of muscovite grains during a continuous increase of X_{An}. Also shown are quartz (black), ilmenite (white), and retrograde calcite. White scale-bar represents 100 µm. (b) Plagioclase compositions along traverse A–B shown in Figure 8a. The absence of compositions between An_{70} and An_{80} may reflect the Huttenlocher gap.

the core and a sharp compositional break to oligoclase in the rim. The same patterns of zoning were found in the present study, and they are similar to the discontinuous concentric zoning shown in Figure 4, except that the missing compositions span the peristerite gap and are not found elsewhere in the rock.

Figure 9a shows a second texture reflecting the peristerite gap. Plagioclase in the pressure shadow of the garnet in sample EM1B illustrated in Figure 2a has lamellae 3 to 12 µm wide with compositions An_4 and An_{15}. The lamellae are much thicker than exsolution lamellae reported for igneous plagioclase (0.3 to 0.7 µm: Goldsmith 1952, Nord *et al.* 1974, Grove *et al.* 1984). Exsolution requires diffusion of cations in the plagioclase, but the plagioclase grains shown here grew at lower temperatures and would have been

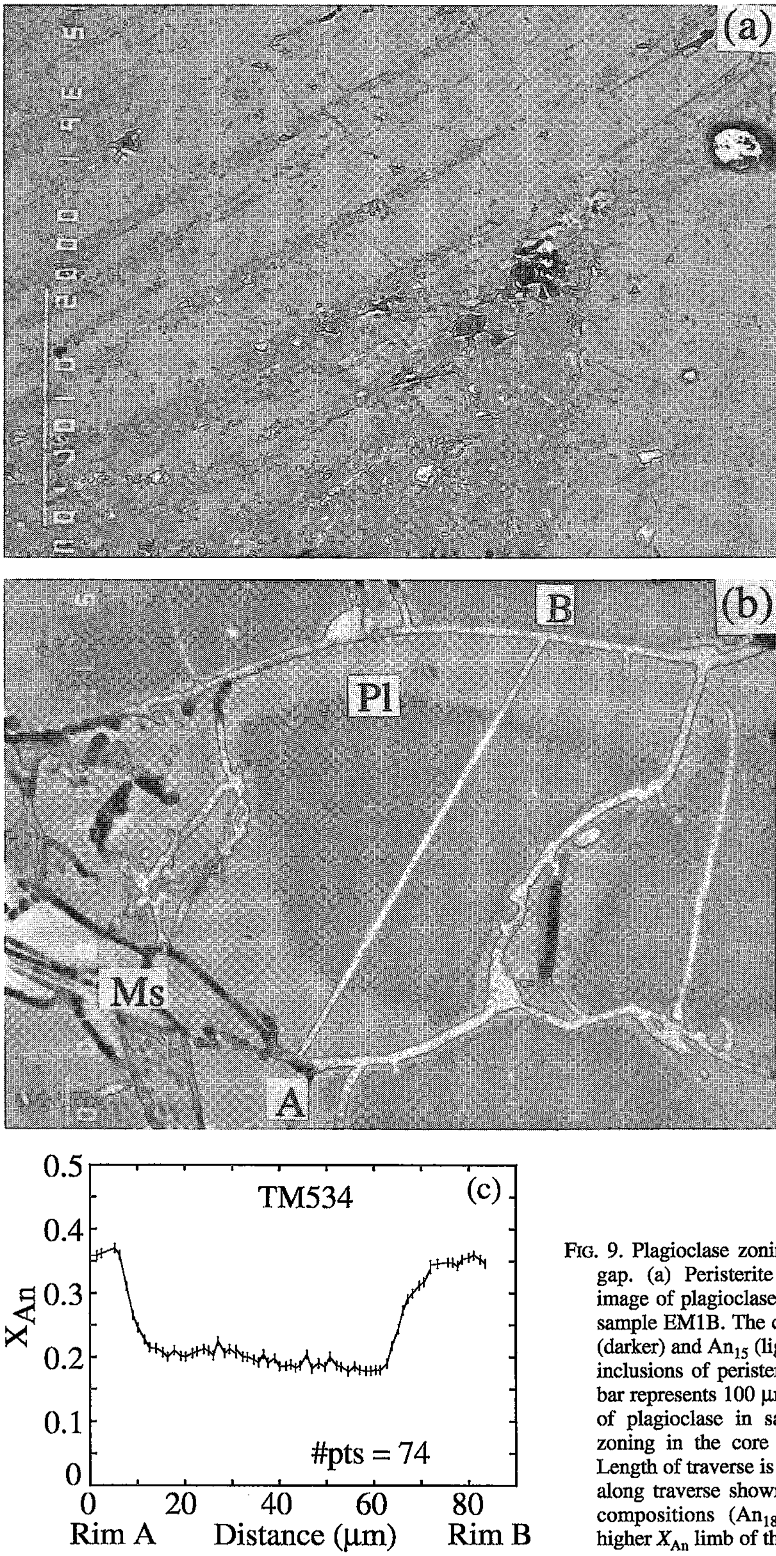


FIG. 9. Plagioclase zoning patterns related to the peristerite gap. (a) Peristerite lamellae. Back-scattered electron image of plagioclase in the pressure shadow of garnet in sample EM1B. The compositions of the lamellae are An_4 (darker) and An_{15} (lighter), and hence, are correlated with inclusions of peristeritic plagioclase in the garnet. Scale bar represents 100 µm. (b) Back-scattered electron image of plagioclase in sample TM534 showing nearly flat zoning in the core and concentric zoning in the rim. Length of traverse is 76 µm. (c) Plagioclase compositions along traverse shown in Figure 9b. The nearly constant compositions (An_{18-20}) in the core may reflect the higher X_{An} limb of the peristerite gap.

subject to slower rates of diffusion than the igneous plagioclase. Therefore, the lamellae here are interpreted as a growth feature.

During growth of plagioclase with compositions increasing from within the peristerite gap to higher X_{An}, the early compositions could be pinned at the calcic side of the peristerite gap as temperature and pressure changed. Thus, a third texture reflecting the peristerite gap is expected, with nearly constant X_{An} in the core. Continued growth of plagioclase as X_{An} increased above the peristerite gap would result in increasing X_{An} near the rim. Clear, unambiguous examples of this type of zoning pattern were not found. The closest example (Figs. 9b, c) is a matrix plagioclase in the pressure shadow of a garnet in sample TM534 (Menard & Spear 1993) that has a weakly zoned core with compositions An_{18}–An_{20}, and X_{An} increasing to An_{38} at the rim. This sample contains smaller grains of garnet (0.5 cm) than does sample EM1B (3 cm), but otherwise is similar.

Case Example: Sample EM1B

Sample EM1B was described above and is used here as an example of how compositional zoning of plagioclase can be interpreted. In addition to the plagioclase with lamellae shown in Figure 9a, plagioclase grains elsewhere in the matrix overgrew the S_2 fabric and are concentrically zoned from An_{20} to An_{35} from core to rim. Rim compositions range from An_4 to An_{35}.

Plagioclase inclusions in the core of the garnet have compositions of An_{16}; plagioclase inclusions in the outer half of the garnet have compositions of An_3 and An_{15}, interpreted as spanning the peristerite gap (Fig. 2b). As discussed above, the garnet overgrew S_1 prior to and during the initial stages of the development of S_2. Thus, low-X_{An} plagioclase preserved in the S_2 pressure shadow around garnet may have grown at the same time as the outer 5 mm of the garnet. Plagioclase grains with intermediate X_{An} that overgrew S_2 in the matrix likely postdate garnet growth. Presumably, low-X_{An} plagioclase was present throughout the rock, but was preferentially consumed where D_2 deformation was strongest and was preserved in the S_2 shadow of the garnet. Consequently, plagioclase grains of different ages can be looked for in different parts of a sample because localized strain can lead to localized progress of metamorphic reactions. Such spatial partitioning of deformational strain was proposed by Bell *et al.* (1986).

A common assumption in thermobarometric analyses is to correlate the rim compositions of minerals, especially if the rims are in mutual contact. This assumption, however, is invalid in some cases. Figure 3a, for example, shows examples of plagioclase grains in mutual contact where it cannot be argued that

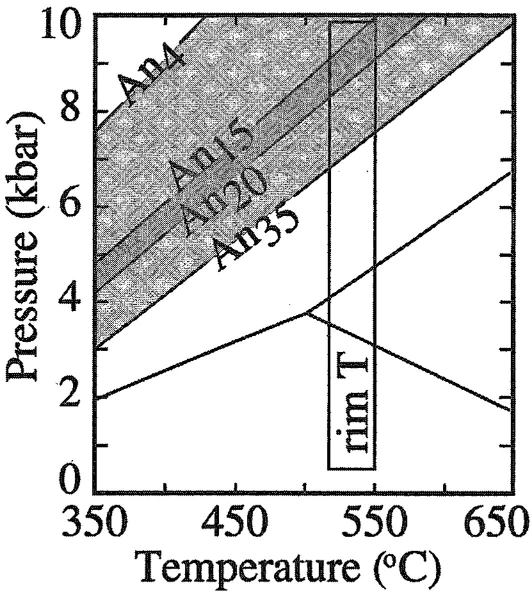


FIG. 10. Thermobarometric estimates for sample EM1B using garnet rim and matrix micas with various plagioclase compositions. The long box outlines barometric estimates possible using all plagioclase rim compositions (An_{4-35}). The dark grey band outlines estimates using petrologically reasonable plagioclase compositions, An_{15-20}.

adjacent compositions in neighboring grains were in equilibrium with each other. Instead, the figure demonstrates that the observed series of plagioclase compositions is a sequential record. For the observed range of rim compositions of plagioclase in sample EM1B, calculated pressures range from 7.5 to 13.6 kbar (Fig. 10) at a rim temperature of 550°C, using the garnet + plagioclase + muscovite + biotite barometer of Hodges & Crowley (1985). Petrography and phase petrology, however, indicate that neither the lowest X_{An} nor the highest X_{An} plagioclase were ever in equilibrium with the garnet rim. Our interpretation for the proper plagioclase composition is between An_{15} (the highest X_{An} plagioclase composition included in the garnet and relict in the garnet pressure shadow) and An_{20} (the first post-D_2 composition). This range propagates into a narrower range of pressures of 9.1 to 9.9 kbar (Fig. 10). Finally, we do not calculate a metamorphic P–T path for this sample because the portion of the plagioclase sequence that correlates with growth of garnet has compositions controlled by the peristerite gap, with the result that the activity of anorthite will be the same in differing compositions of plagioclase (An_4 to An_{15}).

Conclusions

The compositional zoning of plagioclase in the calcic pelitic schists from South Strafford, Vermont, reflects the sequence of plagioclase compositions that grew during prograde metamorphism. Most changes of the equilibrium composition of plagioclase were recorded in the compositional zoning of at least some plagioclase grains. Individual grains of plagioclase, on the other hand, might not record a complete sequence of compositions if growth is locally intermittent, even during continuous net growth of plagioclase. Some plagioclase grains in the calcic pelites studied were consumed during net growth of plagioclase because plagioclase was the only major Na-bearing phase. The oldest matrix plagioclase preserved in the samples studied is commonly in pressure shadows around garnet, a location that had the least deformation-induced strain. The locations of simultaneous growth and consumption of plagioclase may be controlled by heterogeneous distribution of strain. Zoning textures also can reflect the heterogeneity of the matrix overgrown by the plagioclase.

Acknowledgements

This contribution was part of a doctoral dissertation submitted to Rensselaer Polytechnic Institute. The paper has benefitted from comments by F.P. Florence, H.H. Stowell, W.D. Carlson, M.L. Crawford, S.S. Sorensen, W. Trzcienski, Jr., P. Raase, and R.F. Martin. Financial support was provided by National Science Foundation grants EAR85–14659 and EAR87–08609 to F.S. Spear.

References

ATHERTON, M.P. (1968): The variation in garnet, biotite and chlorite composition in medium grade pelitic rocks from the Dalradian, Scotland, with particular reference to the zonation in garnet. *Contrib. Mineral. Petrol.* **18**, 347-371.

BELL, T.H., RUBENACH, M.J. & FLEMING, P.D. (1986): Porphyroblast nucleation, growth and dissolution in regional metamorphic rocks as a function of deformation partitioning during foliation development. *J. Metamorph. Geol.* **4**, 37-67.

COOPER, A.F. (1972): Progressive metamorphism of metabasic rocks from the Haast Schist group of southern New Zealand. *J. Petrol.* **13**, 457-492.

CRAWFORD, M.L. (1966): Composition of plagioclase and associated minerals in some schists from Vermont, U.S.A., and South Westland, New Zealand, with inferences about the peristerite solvus. *Contrib. Mineral. Petrol.* **13**, 269-294.

DOLL, C.G. (1944): A preliminary report on the geology of the Strafford Quadrangle, Vermont. *Vermont Geol. Surv. Rep. of the State Geologist* **24**, 14-28.

FERRY, J.M. (1992): Regional metamorphism of the Waits River Formation, eastern Vermont: delineation of a new type of giant metamorphic hydrothermal system. *J. Petrol.* **33**, 45-94.

FRANCESCHELLI, M., MEMMI, I. & RICCI, C.A. (1982): Ca distribution between almandine-rich garnet and plagioclase in pelitic and psammitic schists from the metamorphic basement of north-eastern Sardinia. *Contrib. Mineral. Petrol.* **80**, 285-295.

GARRISON, J.R., JR. (1978): Plagioclase compositions from metabasalts, southeastern Llano uplift: plagioclase unmixing during amphibolite-grade metamorphism. *Am. Mineral.* **63**, 143-149.

GOLDSMITH, J.R. (1952): Diffusion in plagioclase feldspars. *J. Geol.* **60**, 288-291.

________ (1982): Review of the behavior of plagioclase under metamorphic conditions. *Am. Mineral.* **67**, 643-652.

GROVE, T.L. (1976): Exsolution in metamorphic bytownite. *In* Electron Microscopy in Mineralogy (H.-R. Wenk, P.E. Champness, J.M. Christie, J.M. Cowley, A.H. Heuer, G. Thomas & N.J. Tighe, eds.). Springer-Verlag, Berlin, Germany (266-270).

________, BAKER, M.B. & KINZLER, R.J. (1984): Coupled CaAl–NaSi diffusion in plagioclase feldspar: experiments and applications to cooling rate speedometry. *Geochim. Cosmochim. Acta* **48**, 2113-2121.

________, FERRY, J.M. & SPEAR, F.S. (1983): Phase transitions and decomposition relations in calcic plagioclase. *Am. Mineral.* **68**, 41-59.

HATCH, N.L. (1987): Lithofacies, stratigraphy, and structure in the rocks of the Connecticut Valley Trough, eastern Vermont. *In* Guidebook for Field Trips in Vermont (D.S. Westerman, ed.). *New England Intercollegiate Geol. Conf.* **2**, 192-212.

HODGES, K.V. & CROWLEY, P.D. (1985): Error estimation and empirical geothermobarometry for pelitic systems. *Am. Mineral.* **70**, 702-709.

HOLLISTER, L.S. (1966): Garnet zoning: an interpretation based on the Rayleigh fractionation model. *Science* **154**, 1647-1651.

HOWARD, P.F. (1969): The geology of the Elizabeth mine, Vermont. *Vermont Geol. Surv., Econ. Geol.* **5**, 73 pp.

HUNAHASHI, M., KIM, C.W., OHTA, Y. & TSUCHIYA, T. (1968): Co-existence of plagioclases of different compositions in some plutonic and metamorphic rocks. *Lithos* **1**, 356-373.

LYONS, J.B. (1955): Geology of the Hanover Quadrangle, New Hampshire–Vermont. *Geol. Soc. Am., Bull.* **66**, 105-146.

MARUYAMA, S., LIOU, J.G. & SUZUKI, K. (1982): The peristerite gap in low-grade metamorphic rocks. *Contrib. Mineral. Petrol.* **81**, 268-276.

MENARD, T. (1991): *Metamorphism of Calcic Pelitic Schists, Strafford Dome, Vermont.* Ph.D. thesis, Rensselaer Polytechnic Inst., Troy, New York.

________ & SPEAR, F.S. (1993): Metamorphism of calcic pelitic schists, Strafford Dome, Vermont: compositional zoning and reaction history. *J. Petrol.* **34**, 977-1005.

________ & ________ (1994): Metamorphic P–T paths from calcic pelitic schists from the Strafford Dome, Vermont, U.S.A. *J. Metamorph. Geol.* **12**, 811-826.

MORTEANI, G. & RAASE, P. (1974): Metamorphic plagioclase crystallization and zones of equal anorthite content in epidote-bearing amphibole-free rocks of the western Tauernfenster, eastern Alps. *Lithos* **7**, 101-111.

NORD, G.L., JR., HAMMARSTROM, J. & ZEN, E-AN (1978): Zoned plagioclase and peristerite formation in phyllites from southwestern Massachusetts. *Am. Mineral.* **63**, 947-955.

________, HEUER, A.H. & LALLY, J.S. (1974): Transmission electron microscopy of substructures in Stillwater bytownites. *In* The Feldspars (W.S. MacKenzie & J. Zussman, eds.). Manchester Univ. Press, Manchester, U.K. (522-535).

RIBBE, P.H. (1983): Exsolution textures in ternary and plagioclase feldspars; interference colors. *In* Feldspar Mineralogy (second edition; P.H. Ribbe, ed.). *Rev. Mineral.* **2**, 241-270.

ROLPH, A.L. (1982): *Structure and Stratigraphy around the Elizabeth Mine, Vermont.* M.S. thesis, Univ. Cincinnati, Cincinnati, Ohio.

SELVERSTONE, J. & SPEAR, F.S. (1985): Metamorphic P–T paths from pelitic schists and greenstones from the south-west Tauern Window, eastern Alps. *J. Metamorph. Geol.* **3**, 439-465.

SLACK, J.F., OFFIELD, T.W., SHANKS, W.C., III & WOODRUFF, L.G. (1993): Besshi-type massive sulfide deposits of the Vermont Copper Belt. *Soc. Econ. Geol., Field Trip Guidebook* **17**, 32-73.

SMITH, J.V. (1982): Phase equilibria of plagioclase. *In* Feldspar Mineralogy (second edition; P.H. Ribbe, ed.). *Rev. Mineral.* **2**, 223-239.

SPEAR, F.S. (1977): Evidence for a miscibility gap in plagioclase feldspar in the composition range An_{39}–An_{38}. *Carnegie Inst. Washington, Year Book* **76**, 619-621.

________ (1980): NaSi $\rightleftharpoons$ CaAl exchange equilibrium between plagioclase and amphibole: an empirical model. *Contrib. Mineral. Petrol.* **72**, 33-41.

________, HICKMOTT, D.D. & SELVERSTONE, J. (1990a): Metamorphic consequences of thrust emplacement, Fall Mountain, New Hampshire. *Geol. Soc. Am., Bull.* **102**, 1344-1360.

________, KOHN, M.J., FLORENCE, F.P. & MENARD, T. (1990b): A model for garnet and plagioclase growth in pelitic schists: implications for thermobarometry and P–T path determinations. *J. Metamorph. Geol.* **8**, 683-696.

THOMPSON, A.B., TRACY, R.J., LYTTLE, P.T. & THOMPSON, J.B., JR. (1977): Prograde reaction histories deduced from compositional zonation and mineral inclusions in garnet from the Gassetts schist, Vermont. *Am. J. Sci.* **277**, 1152-1167.

TRACY, R.J. (1982): Compositional zoning and inclusions in metamorphic minerals. *Rev. Mineral.* **10**, 355-397.

WENK, E. & WENK, H.-R. (1977): An-variation and intergrowths of plagioclases in banded metamorphic rocks from Val Carecchio (central Alps). *Schweiz. Mineral. Petrogr. Mitt.* **57**, 41-57.

________, ________, GLAUSER, A. & SCHWANDER, H. (1975): Intergrowth of andesine and labradorite in marbles of the central Alps. *Contrib. Mineral. Petrol.* **53**, 311-326.

WENK, H.-R. (1979): Superstructure variation in metamorphic intermediate plagioclase. *Am. Mineral.* **64**, 71-76.

WHITE, W.S. & ERIC, J.H. (1944): Preliminary report on the geology of the Orange County copper district, Vermont. *U.S. Geol. Surv., Open-File Rep.* **36**, 37 pp.

________ & JAHNS, R.H. (1950): Structure of central and east-central Vermont. *J. Geol.* **58**, 179-220.

WOODLAND, B.G. (1977): Structural analysis of the Silurian-Devonian rocks of the Royalton area, Vermont. *Geol. Soc. Am., Bull.* **88**, 1111-1123.

Received July 4, 1995, revised manuscript accepted September 27, 1995.