Zoned plagioclase and peristerite formation in phyllites from southwestern Massachusetts

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Abstract

Compositionally-zoned microporphyroblasts of plagioclase are found in phyllites from southwestern Massachusetts. Rocks from the lowest metamorphic grade yield unzoned albite. At slightly higher grade, albite constitutes the core and a thin outer rim with an intervening narrow zone of An 13-17. At higher grades, plagioclase is complexly zoned in one of two patterns: either the composition drops stepwise from an oligoclase core to an albite rim, or the composition of the core gradually increases outward from An 19 to An 24, then abruptly drops to an albite rim. All of these patterns are present in rocks at metamorphic grades below the first appearance of chloritoid and garnet. Above the garnet isograd, the zoning pattern is simple: a core of An 13 and a gradual outward increase to the maximum value of An 25.

Transmission-electron-microscopy studies of an oligoclase core, an An 9-16 intermediate zone, and an An 1-5 outer albite rim show that two sets of lamellae are present in the composition range An 2-25. In the range An 9-16, the (1,18,T) set of lamellae is strong, has a periodicity of about 122Å, and gives rise to satellites; the other set, (20T), is weak. In the range An 22-25 both sets are very weak, and diffuse streaking is parallel to [20T]*. All areas have only a single lattice. The strong microstructures are interpreted as products of spinodal decomposition, and the weak lamellar microstructures as fluctuations in the nucleation-only zone of the peristerite solvus.

The rocks were metamorphosed probably at about 350°C and under at most a few kilometers overburden, which represents conditions considerably below the peak of the peristerite solvus. Metastable crystallization is indicated. Available data, however, do not permit an unequivocal conclusion on whether the zoned plagioclase grew during a single episode of metamorphism, or whether the albite rim represents a second Acadian metamorphism superposed on preexisting Taconian mineral assemblages.

Introduction

The composition and “structural state” of plagioclase have been commonly used as an indicator of the geologic record in many types of petrologic and geologic problems. In detail, however, plagioclase is exceedingly complex and contains submicroscopic intergrowths and domains of distinct compositions or structural types even for samples homogeneous on an optical and microprobe scale. Subsolidus decomposition products such as intergrowths in the compositional regions of peristerite (An2–An18), Böggild (An45–An60), and Huttenlocher (An79–An89) (Smith, 1974, p. 519) are fairly common in high-temperature igneous and metamorphic rocks. In low-grade metamorphic rocks, where plagioclase only forms with compositions in the albite–oligoclase range, the peristerite two-phase field is commonly expressed by the absence of peristerite compositions or by the presence of two coexisting plagioclases. Multiply-zoned plagioclase porphyroblasts in low-grade greenschist facies pelitic rocks from southwestern Massachusetts and adjacent areas (Zen and Hartshorn, 1966; Zen and Ratcliffe, 1971), however, contain compositional zones that are within the peristerite field (An9–An19) mantled by Ca-free albite rims. Such multiply-zoned plagioclase is present only in a relatively narrow north-northeast trending belt, coinciding with or just below the metamorphic zone where garnet makes its first appearance in rocks of suitable composition. At lower metamorphic grade, the porphyroblasts of plagioclase are nearly Ca-free albite of uniform composition, whereas at higher grades they are gradationally zoned, and the An content increases steadily outward.

This paper presents a systematic microprobe study
probably to the chloritoid zone, and were subsequently regionally metamorphosed again during the Acadian deformation (Zen and Hartshorn, 1966) to grades ranging from subchloritoid–subbiotite zone to kyanite–staurolite zone; the metamorphic grades increase to the SE and cut across the regional structural trend.

Interpretation of the Acadian mineral assemblages in light of experimental phase-equilibrium data suggests that rocks of the kyanite–staurolite grade, southeast of the area shown on Figure 1, recrystallized at a temperature of about 550°C and a pressure in excess of the triple point of the aluminum silicate polymorphs—at least 4 kbar or about 14 km of overburden. Yet only about 35 km to the northwest, at Becraft Mountain in New York, Silurian and Lower Devonian sedimentary rocks are unmetamorphosed and probably were not buried under more than about 1 km of stratigraphic overburden (T ~ 50°C). Interpolation of pressure and temperature values is uncertain. The mineral-assemblage data for the zone of complexly-zoned plagioclase (below chloritoid zone), however, suggest temperatures of about

### Table 1. Representative plagioclase analyses from specimen 3-3

<table>
<thead>
<tr>
<th>Distance into crystal</th>
<th>30µ</th>
<th>45µ</th>
<th>60µ</th>
<th>75µ</th>
<th>100µ</th>
<th>130µ</th>
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<tr>
<td>SiO₂</td>
<td>67.71</td>
<td>67.70</td>
<td>65.58</td>
<td>66.00</td>
<td>64.12</td>
<td>63.07</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>20.55</td>
<td>20.04</td>
<td>21.00</td>
<td>21.63</td>
<td>23.02</td>
<td>24.00</td>
</tr>
<tr>
<td>CaO</td>
<td>0.19</td>
<td>0.78</td>
<td>2.09</td>
<td>2.43</td>
<td>3.52</td>
<td>4.77</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.15</td>
<td>0.19</td>
<td>0.0</td>
<td>0.13</td>
<td>0.16</td>
<td>0.20</td>
</tr>
<tr>
<td>Na₂O</td>
<td>11.65</td>
<td>11.57</td>
<td>10.48</td>
<td>10.45</td>
<td>9.79</td>
<td>8.96</td>
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<tr>
<td>E</td>
<td>100.25</td>
<td>100.28</td>
<td>99.15</td>
<td>100.64</td>
<td>100.61</td>
<td>101.00</td>
</tr>
<tr>
<td>Si</td>
<td>2.955</td>
<td>2.958</td>
<td>2.902</td>
<td>2.884</td>
<td>2.813</td>
<td>2.764</td>
</tr>
<tr>
<td>Al</td>
<td>1.056</td>
<td>1.032</td>
<td>1.095</td>
<td>1.113</td>
<td>1.189</td>
<td>1.238</td>
</tr>
<tr>
<td>Ca</td>
<td>0.007</td>
<td>0.036</td>
<td>0.099</td>
<td>0.113</td>
<td>0.165</td>
<td>0.224</td>
</tr>
<tr>
<td>K</td>
<td>0.007</td>
<td>0.010</td>
<td>0.0</td>
<td>0.006</td>
<td>0.009</td>
<td>0.010</td>
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<tr>
<td>Na</td>
<td>0.985</td>
<td>0.979</td>
<td>0.898</td>
<td>0.885</td>
<td>0.833</td>
<td>0.760</td>
</tr>
<tr>
<td>E</td>
<td>5.010</td>
<td>5.015</td>
<td>4.994</td>
<td>5.001</td>
<td>5.009</td>
<td>4.996</td>
</tr>
</tbody>
</table>

Oxide weight per cent corrected for background, drift, deadtime, and matrix effects by an on-line Bence-Albee data reduction scheme (1968). Standards: calcic labradorite from Lake Co., Ore. (Stewart et al., 1966), orthoclase from the Benson Mine, St. Lawrence Co., N.Y. (Stewart and Wright, 1974) and albite from the Tiburon Peninsula, Calif. (Crawford, 1966b).

Cations calculated on the basis of 8 oxygens per formula.

Operating conditions 15 kV, .03 µA beam current for 3-3 analyses.

Each element counted for 20 secs or 20,000 counts; no Fe detected in appreciable amounts.
Fig. 2. Photomicrographs of plagioclase porphyroblasts, showing different modes of zoning. (a) Specimen 3-3, two views of the same crystal at slightly different extinction positions to bring out zoning features. (b) Specimen 1032-1, showing a simple twinned and zoned crystal; the core has the same composition as the rim but an intermediate zone (dark band) has a composition of An 13. (c) Specimen 693-1, showing continuous zoning from core outward with increasing An content and no albite rim. (d) Specimen 360-1, showing multiple zoning as in 3-3 but having a core lower in An content than the intermediate zone. Photographs under crossed polarizer.
grains in hand specimens. A conspicuous foliation and crenulated cleavage due to layers of aligned muscovite and chlorite are usually present. The porphyroblasts of plagioclase, the only feldspar phase in the rocks, are subsequent to crudely elliptic in outline and are interfingering; the long dimensions of the crystals are aligned with the foliation direction. In general each single crystal forms in a discrete area; porphyroblasts are well separated.

Reconnaissance compositional data on the multiply-zoned plagioclase porphyroblasts showed that the Na-rich oligoclase cores were continuously zoned to more Ca-rich oligoclase and then mantled with Ca-free albite. The Na- to Ca-rich zoning of the oligoclase core could be readily interpreted as a record of a normal regional prograde metamorphic event. The presence of the reversal to a Ca-free albite rim led Zen (1969) to the interpretation that the albite rim records the Acadian metamorphic event but the oligoclase core is part of a slightly higher-grade Taconian mineral assemblage. The detailed microprobe and TEM observations lead to a reevaluation of the earlier interpretation.

Optical description and microprobe analysis of the porphyroblasts

Several zoning patterns were discovered in plagioclase porphyroblasts from seven sample localities shown in Figure 1. Plagioclase compositions were determined by analysis of porphyroblasts in thin sections using an automated ARL microprobe system (Finger and Hadidiascos, 1972). Representative analyses are given in Table I for a traverse in sample 3-3 in terms of corrected oxide weight percent, calculated cations, and sums. Four representative porphyroblasts are shown in Figure 2, and Figure 3 provides a

300–400°C at a few kilometers of overburden, compatible with a simple straight-line interpolation of the distance between Becraft Mtn. and the kyanite occurrence. The temperature estimates and the mineral assemblage both conflict with the temperature for the crest of the peristerite solvus, which was suggested by Crawford (1966a) to be well in the staurolite zone of regional metamorphism; Crawford based this suggestion on study of compositions of discrete coexisting plagioclase crystals.

The phyllites of the Everett Formation containing the plagioclase porphyroblasts are typically green and purplish-green and show few visible mineral

Fig. 4. Reflected-light micrograph of a part of a porphyroblast from specimen 3-3 showing two optically distinct boundaries and An content of microprobe points.
summary of the microprobe data and a schematic drawing of the compositional zoning pattern across each crystal from rim to rim.

Three specimens from the lowest-grade part of the study area, 1032-1, 1102-1, and 1114-1, have albite cores and rims (Fig. 3). Specimen 1102-1 contains slightly rounded plagioclase porphyroblasts which are virtually unzoned (An 0–3). Porphyroblasts in both 1032-1 and 1114-1 have a 40- to 70-micron-wide and optically distinct band of peristerite composition, which separates the albite rim from the albite core (Fig. 2b). Maximum An content in these crystals is An 13 in the center of this band, and the An content drops off symmetrically towards the rim and core.

Plagioclase in specimen 693-1 (Fig. 2c) contains cores of albite (An 1–4). The An content increases outward from the core through peristerite compositions to a maximum of An 15–17 at the crystal margin; no discrete rim was observed. Without its albitic rim, 1032-1 would be closely similar to 693-1.

The area containing specimens 3-3, 360-1, and 45-1 marks a change from porphyroblasts having albitic core compositions to porphyroblasts with more calcic cores. Specimen 360-1 (Fig. 2d) has a core of An 18 which increases outward to a maximum of An 23 and then trails off through peristerite compositions to a distinct albite rim. It also has a well-developed rim separated from the inner parts of the crystal by a zone of alteration; the inclusions are aligned parallel to crystal length and are more concentrated in the core than in the rim. At higher grades, as in specimen 45-1, zoning is continuous, typically from An 13 at the core to An 25 at the rim.

Specimen 3-3 has been studied in detail and was also used for the TEM observations. It is a conspicuously foliated chlorite-plagioclase-muscovite-paragonite-quartz phyllite containing optically- and compositionally-zoned porphyroblasts (Fig. 2a). The boundaries of the crystals are locally complex, having jagged or embayed rims enclosing single or composite

Fig. 5. (a) Electron micrograph of lamellar microstructure in zone II of part of a porphyroblast from 3-3. \( \mathbf{g} = 201 \). (b) A selected-area electron diffraction pattern, showing satellites about each reflection. Inset is a magnified view of a reflection showing well-developed satellites. 200 kV.

Fig. 6. (a) The coarser lamellar microstructure in zone II (Fig. 5) changes to a finer lamellar microstructure in zone III. (b) Weak lamellae in center of this core area. This fine microstructure gives rise to diffuse scattering in the diffraction pattern (inset in Fig. 6b). \( \mathbf{g} = 201 \). 200 kV.
core crystals. Boundaries between zones are readily
seen because of the different extinction positions of
the zones. Rim compositions are nearly end-member
albite (An 0–5). The An content increases steadily
across the first optical boundary into a transition
zone of composition An 9–16. Numerous point anal-
yses, closely spaced step traverses, and backscatter
images failed to reveal the existence of any abrupt
compositional boundaries in the transition zone. The
core of the crystal is homogeneous oligoclase, An 22–
25. The core is separated from the transition zone by
an optical boundary which marks a jump in composi-
tion from An 16 to 22.

In some crystals, the boundary between the oligo-
clase core and transition zone is partially or entirely
occupied by a zone of fine-grained mixture of mica,
zoisite(?), and quartz. These may be zones of altera-
tion, and are most readily explained if they repre-
sented a zone of maximum anorthite content sub-
sequently retrograded, and if the outer rims are due
to metamorphism at a later time. Such an inter-
pretation would be compatible with the observation
of rimming of apparently embayed cores mentioned
before. In favor of a single episode of crystal growth
is the fact that the orientations of mineral inclusions
in the crystals (especially ilmenite) seem to persist
through all the zones of a given crystal, although the
rims tend to have fewer inclusions, and the interface
between the rim and the transition zone may show
concentrations of inclusions. The oriented inclusions
of the rims could have been inherited from a pre-
existing mineral fabric originally in the matrix.

**TEM observations**

A 1-mm-long porphyroblast was chosen from
sample 3-3 for the TEM study, because the composi-
tional zones were optically distinct and the crystal
was large and relatively unfractured. Three detailed
microprobe traverses were made across it. The TEM
samples were then prepared by ion-thinning two frag-
mants, each containing a microprobe traverse. Figure
4 shows one fragment, with the microprobe analyses
indicated, before thinning. The optically-visible
boundaries marking compositional breaks divide the
crystal into three zones: the rim (I), the transition
zone (II), and the core (III).

In the TEM, the very albitic edge of zone I is
featureless except for an occasional microtwin. In the
part of zone I having the composition of peristerite
(An 2–16), a very faint lamellar microstructure is
visible, with a wavelength of about 100Å. The electron
diffraction pattern has only sharp (a) reflections.

The compositional gap between zones I and II is
unrecognizable in the electron microscope; the only
change is a continued gradual increase in black–white
contrast of the lamellar microstructure. Once in the
composition range of zone II, however, the lamellar
microstructure is easily imaged (Fig. 5a), and appears
to be developed evenly across this zone. The lamella
split and recombine, exhibiting a connectiveness.

The contrast of the lamellae is strong for operating

![Fig. 8. A phase diagram showing the peristerite solvus of Crawford (1966a) and two-phase field of Orville (1974). The 3-3 porphyroblast compositions studied in TEM are shown between 300°C and 400°C, the estimated temperature of crystallization.](image-url)
Fig. 9. The strain-free solvus and estimated coherent spinodal are shown with the TEM observations from the various portions of porphyroblast 3-3. Spinodal decomposition can occur only under the spinodal curve whereas nucleation can occur anywhere under the strain-free solvus. Thus both mechanisms compete within the coherent spinodal.

$\mathbf{g}$ vectors containing components in the plane of the lamellae (20T, 02T, 001) and weak for those vectors containing components normal to the plane of the lamellae (020) (see also McLaren, 1974, and Nord et al., 1974). In addition, when $\mathbf{g} = 020$ and the strong set of lamellae visible in Figure 5a is out of contrast, a faint set of lamellae normal to the strong set is visible.

The selected-area diffraction pattern for this area (Fig. 5b) shows that the lamellae have a high degree of periodicity, because satellite reflections are found about all the main reflections. The average lamellae wavelength can be calculated from the pattern by dividing the satellite-to-main spot spacing into the appropriate camera constant $K$. The average real-space spacing is 122Å, although a diffuse streak connects the satellites and even extends slightly beyond, indicating a range of wavelengths. In all diffraction patterns taken of the modulated structures, all main reflections were sharp and no splitting was observed. This is surprising because $\gamma^*$ is the reciprocal lattice parameter that undergoes the greatest change between the exsolved phases in peristerite (1.7° between An 0 and An 25, Ribbe, 1960); even in $a^*b^*$ diffraction patterns, only single diffraction spots were present from all three zones. Satellites were found only in zone II.

The compositional break between zones II and III is manifested as an abrupt change in lamella contrast from relatively strong contrast in zone II to weak contrast in zone III (Fig. 6a). The size and orientation of the lamellae appear constant. Within zone III, weak lamellae can be observed even at the center of the core area (Fig. 6b). Diffuse scattering seen in Figure 6b is parallel to the row [20T]* in diffraction patterns from zone III. Type (e) reflections characteristic of intermediate plagioclase would, if present, occupy the position midway between the 20T reflections [20T would be indexed 202 for the 14Å cell and (b) reflections would be 10T, 303, etc.].

The orientation of the two sets of lamellae, one strong and one weak, is shown in Figure 7 in a stereographic projection of the crystallographic axes of low albite. Many zone-axis patterns were used for the analysis; three which nearly contain the vector connecting the satellites, (001), (100), and (102), are plotted. The satellite vector was located at the intersection of great circles containing the zone normal and the vector trace. The satellite vector falls 6° from (08T) ($c = 7Å$) to near (1,18,1) plotted as a heavy great circle. The orientation of the weak lamellae near (20T) was determined by trace analysis from the image plates, as no streaking from this lamellar set was in the diffraction pattern.

Discussion and conclusions

Peristerite phase relations

The peristerite two-phase field (recently reviewed by Smith, 1975) has been described as either a solvus or as a two-phase binary loop. Both types of phase relations are shown in Figure 8. The solvus is asymmetrical; Crawford (1966a) estimated the low-temperature endmembers from a study of coexisting metamorphic plagioclases to be about An₉ and An₄. She placed the crest of the solvus between the almandine and staurolite isograds at 450°-500°C. More recent data on staurolite stability suggest that the staurolite isograd should be placed at least at 550°C (Thompson, 1976), raising the crest nearer to the high albite-low albite transition (575-625°C, McConnell and McKie, 1960). In contrast to the solvus model, a two-phase field consisting of low albite and high- to intermediate-albite solid solution is preferred by Smith (1972) and Orville (1974). Orville (1974) rejected a solvus, on the basis of experimentally-determined ideal solution behavior which occurred over the range An₉ to An₉₀ at 700°C (Orville, 1972) and at 600°C (Orville, 1974).

The maximum temperature of crystallization of the porphyroblasts is estimated to be between 300°C and 400°C, as discussed previously, and this is indicated in Figure 8 by areas representing the compositions found in the porphyroblast 3-3, studied by TEM. The compositional breaks, however, have no significance, since the total compositions represented by all the
analysed porphyroblasts from all the samples completely span the range An₉₆ to An₂₈ (Fig. 3). The breaks probably represent polyphase metamorphism or local changes in growth rate or reacting phases.

The homogeneous distribution, diffuse interfaces, and connective and wavelike morphology of the peristerite lamellae, as well as the formation of satellites about the main reflections in the strong contrast lamellae, suggest that the exsolution mechanism is spinodal decomposition. This conclusion is consistent with those of previous authors who have studied peristerite microstructures (Christie, 1968; Weber, 1972; Lorimer et al., 1974). It should be pointed out, however, that the spinodal decomposition mechanism can only be proven by observing the progress of decomposition with time (Laughlin and Cahn, 1975; Yund, 1975b). The peristerite microstructure, therefore, could possibly have formed by homogenous nucleation and growth, but this is unlikely, in view of the difficulty of forming a critical nucleus in feldspars, especially at low temperatures (Yund, p. Y-35, 1975b), contrasted with the relative ease of spinodal decomposition, which requires no nucleation.

Unmixing in the two-phase field of the binary “loop” model can proceed only by a nucleation and growth mechanism, since the free energy curves for the two phases are discrete, and therefore spinodal decomposition is not possible (Champness and Lorimer, p. 175, 1976). Nucleation and growth, as well as spinodal decomposition, is possible in the solvus model.

**Peristerite microstructure**

The types of microstructures are summarized in Figure 9 on a phase diagram showing an asymmetric strain-free solvus and an asymmetric coherent spinodal curve (Christie, 1968) (see Yund, 1975a, for a detailed discussion of the curves). In the region An₉₋₁₆ of our sample, compositional differences exist between the coherent lamellae, as indicated by the strong image contrast obtained using operating vectors for which the structure factor difference between albite and oligoclase is large [i.e., for $g^2 = 02T$, $F_c(\text{albite}) = 0$, $F_c(\text{oligoclase}) = 20$]. This area lies within the coherent spinodal.

Spinodal theory predicts a critical wavelength $\lambda_c$ that is amplified during decomposition while all other wavelengths decay (Cahn, 1968). Once the decomposition is complete, the lamellae will coarsen and other waveforms will grow at the expense of $\lambda_c$, eliminating the sine waveform and periodic quality of the original microstructure. We suggest that the sharp satellites in the An₉₋₁₆ region and small ~122A wavelength of the lamellae indicate that the microstructure has not coarsened to any appreciable extent. Therefore, $\lambda_c$ is ~120A for a composition An₉₋₁₆ at an undercooling of 100 to 200°C (Cahn, 1968).

Crosshatched lamellar microstructures which exhibited only weak contrast were also present outside the estimated spinodal curve in the An₂₂₋₂₅ core (Fig. 7). McLaren (1974) found similar weak microstructures in both An₂₃ and An₂₆. Although the wavelengths are similar to those in the An₉₋₁₆ region, no satellite is present and the contrast is weak. We suggest that this microstructure is in the nucleation-only field and consists of minor fluctuations (1–2 mole percent An) in composition or structure of variable wavelength. These compositional fluctuations are the precursors to decomposition; they can amplify in the spinodal field about $\lambda_c$ but can only decay in the nucleation-only field. The diffuse scattering in the diffraction pattern from this region may represent an attempt to form the intermediate plagioclase superlattice structure. The two sets of lamellae found in the porphyroblasts lie very close to the predicted positions of strain energy minima calculated by Willaime and Brown (1974).

**Geologic inferences**

Our data do not permit us to decide whether the zoning pattern of the plagioclase is the product of a single or two discrete episodes of regional metamorphism. Because the TEM observations show that the continuous microstructure is superimposed across the already-formed core–rim boundary, the data are compatible with either hypothesis for the formation of the entire porphyroblasts. In any event, however, the various rimmed porphyroblasts indicate a complexity in spatial and sequential arrangement of metamorphism not revealed by conventional microscopic petrography.

The rocks were metamorphosed probably at temperatures no higher than about 350°C and under at most a few kilometers of overburden. These conditions are considerably below estimates of the peristerite solvus (~550°C). The areas of peristerite composition therefore crystallized metastably, and those compositions within the coherent spinodal subsequently exsolved by spinodal decomposition. The low temperature of formation apparently suppressed coarsening of the microstructure and therefore preserved the high degree of lamellar periodicity.
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References

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