PERGAMON

Journal of Structural Geology 24 (2002) 1139–1156

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.com/locate/jstrugeo

Pseudomorphs and associated microstructures of western Maine, USA

C.V. Guidotti, S.E. Johnson*

Department of Geological Sciences, University of Maine, Orono, ME 04469-5790, USA

Received 23 February 2001; revised 16 July 2001; accepted 18 July 2001

Abstract

In metapelitic rocks of western Maine, a pluton-related M3 metamorphic gradient ranging in grade from garnet to upper sillimanite zone was superposed on a fairly uniform M2 regional metamorphic terrain characterized by the assemblage andalusite + staurolite + biotite + / −garnet. As a result, M2 assemblages re-equilibrated to the P, T, and aH_2O conditions of M3, and both prograde and retrograde pseudomorphism of M2 porphyroblasts occurred. The type of pseudomorph and degree of development is directly related to the rock's position within the M3 metamorphic gradient, a function of its proximity to the Mooselookmeguntic pluton. Several 'hinge' zones occur in which the M3 minerals that pseudomorphed a particular M2 phase change. For example, M2 garnet was replaced by M3 chlorite or biotite, depending on its position within the M3 gradient. Similarly, in a transition zone between M3 upper staurolite and lower sillimanite zones, M2 staurolite was stable and shows M3 growth rims. Downgrade from this transition zone, staurolite was pseudomorphed by chlorite and muscovite, whereas upgrade, the pseudomorphs contain muscovite and some biotite. M3 pseudomorphs commonly retain crystal shapes of the original M2 porphyroblasts, reflecting relatively low regional deviatoric stress during and after M3. Although evidence for textural disequilibrium is common, chemical equilibrium was closely approached during M3. This study demonstrates for M3 that: (1) the pseudomorphic replacement was a constant volume process, and (2) fabrics produced by tectonic events can be erased by subsequent deformation and/or sufficiently intense subsequent recrystallization.

Keywords: Pseudomorphs; Metapelitic rocks; Porphyroblasts

1. Introduction

Pseudomorphs are common features in metamorphic rocks, and are particularly useful because they record the progressive stability of two or more metamorphic minerals, and can be used in reconstructing P–T–t evolution (e.g. Vernon, 1978, 1982; Johnson and Vernon, 1995). Although pseudomorphs can form by many different processes, they commonly result from one or more of the following types of polymetamorphism. (1) Retrograde recrystallization during slow cooling, especially if abundant fluids are available. (2) Temporally separated, either prograde or downgrade, recrystallization events. (3) Recrystallization during a single, temporally continuous, extended metamorphism involving changes in mineral assemblages, mineral chemistry and textural features. Distinguishing among these and other possible origins for pseudomorphs is important for establishing a more accurate tectonometamorphic history of an area.

This paper discusses the microstructural and metamorphic aspects of pseudomorphs after garnet, staurolite and andalusite in metapelites of western Maine, northern New England Appalachians (Fig. 1). We consider pseudomorphs that formed in response to two temporally separate recrystallization events (type 2 above), the later event involving both prograde and retrograde (called downgrade hereafter to reflect two separate events and approach to equilibrium in the second event) effects depending on proximity to plutonic heat sources. The two Devonian metamorphic events, M2 and M3, are extensively documented and affected many rocks in western and central Maine (see Guidotti and Holdaway, 1993, and references therein). This study focuses on only a portion of western Maine; the southeastern and southwestern corners of the Oquossoc and Rangeley 15′ quadrangles, respectively (Fig. 2). This restricted area was chosen for the following reasons. (1) M2 and M3 were originally defined in this area (Guidotti, 1970a). As noted in Guidotti and Holdaway (1993), 'M2' and 'M3' elsewhere in western Maine may not be the same two events. (2) In this area the M3 gradient was superimposed on an areally extensive M2 event of fairly uniform grade. (3) M3 recrystallization closely approached chemical equilibrium (e.g. Guidotti, 1970b, 1974; Guidotti and Holdaway, 1993; Guidotti et al., 1996). (4) Because M3 occurred very late in the regional deformation history of

* Corresponding author. Tel.: +1-207-581-2142; fax: +1-207-581-2202.
E-mail address: johnsons@maine.edu (S.E. Johnson).

0191-8141/02/$ - see front matter
PII: S0191-8141(01)00097-9

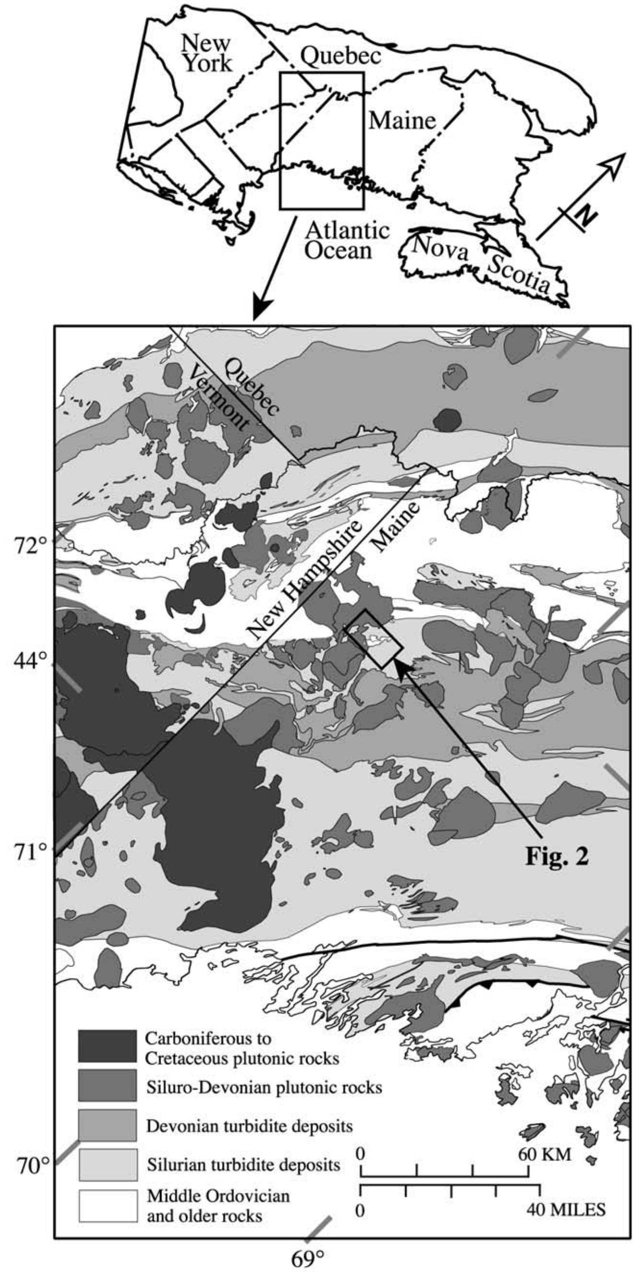

Fig. 1. Regional geologic setting of study area within the northern Appalachians, USA and Canada.

these rocks, the pseudomorphs are commonly euhedral. (5) The specific types of pseudomorphs formed are intimately tied to location within the M3 metamorphic gradient. (6) Pseudomorph formation can be closely tied to continuous and discontinuous reactions, including the chemical variation with grade of the crystalline solution phases present.

In the context of (1)–(6) above, we describe the pseudomorphs and discuss the metamorphic reactions by which they formed. We also discuss the areal distribution and nature of any deformation accompanying M3 in the area under consideration. Although we consider in detail only a small area, our discussion has implications for the tectonometamorphic history of the Acadian Orogeny in much of northern New England.

2. Overview of the geologic and metamorphic setting

Much of the study area is underlain by the Rangeley and Perry Mt Fms of the Silurian Rangeley Stratigraphic Sequence (Moench, 1971). These formations consist of several clastic rock types, but pelitic compositions are abundant and contain porphyroblasts that formed wherever the metamorphic grade was sufficiently high. The western and southwestern portions of the study area are underlain by the Mooselookmeguntic pluton (Fig. 2), a peraluminous two-mica granite to adamellite (Moench, 1971).

Key aspects of metamorphisms that affected the area are as follows. (1) During the M2 event, And + St + Bt + / −Grt formed in all rocks having the appropriate composition (abbreviations after Kretz, 1983). (2) All rocks affected by M2 were subsequently affected by M3 such that in the west they were prograded to upper Sil zone, but to the east they were downgraded to Grt zone. (3) M3 isogradic surfaces appear to dip gently to the east, particularly at grades above the Grt zone (Guidotti et al., 1996). (4) Some localized deformation accompanied the M3 recrystallization in this area, apparently associated with emplacement of the Mooselookmeguntic pluton. The euhedral habit of observed pseudomorphs indicates that this deformation was largely concluded prior to their formation. (5) Pressure during M3 was higher than during M2 by ca. 0.5 to 1 kbar (Guidotti and Holdaway, 1993). (6) The heat source for M2 remains unidentified, but the heat source for M3 in this area is attributed to the Mooselookmeguntic pluton (DeYoreo et al., 1989). (7) M2 and M3 in this area are separated in time by ca. 30 m.y. (Smith and Barreiro, 1990; Solar et al., 1998; Johnson and Guidotti, unpublished data), and cooling to ambient temperatures occurred between the two events (Guidotti, 1970a; Foster and Dutrow, 2000). (8) The combined effects of (1)–(7) are suggested as the cause of the euhedral M3 pseudomorphs of M2 porphyroblasts common throughout the Rangeley area.

3. M2 metamorphic event

The M2 event was a low-P, high-T metamorphism resulting in the typical assemblage And + St + Bt + /−Grt. This assemblage represents the product of the following reaction occurring in the And stability field:

$$\text{St} + \text{Mg-Chl} + \text{Na-Ms} + / - (\text{Grt?})$$

$$= \text{And} + \text{Bt} + \text{K-richerMs} + \text{Ab} + \text{Qtz} + H_2O \qquad (A)$$

Typically M2 produced large, euhedral porphyroblasts of And (to >4 cm) and St (to >1 cm), with smaller porphyroblasts of Grt (2–3 mm). Cordierite-bearing

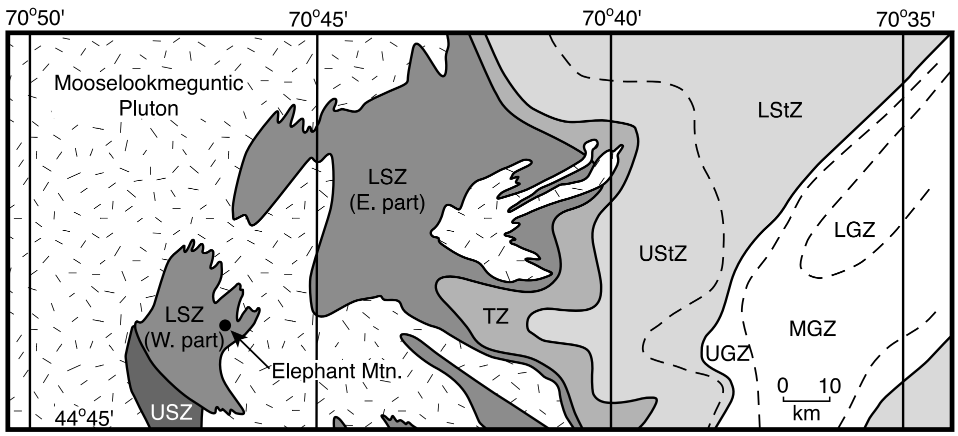

Fig. 2. Simplified metamorphic map of study area with associated heat source (Mooselookmeguntic pluton). LGZ = lower garnet zone, MGZ = middle garnet zone, UGZ = upper garnet zone, LStZ = lower staurolite zone, UStZ = upper staurolite zone, TZ = transition zone, LSZ = lower sillimanite zone and USZ = upper sillimanite zone.

assemblages formed locally in particularly Mg-rich rocks of the Rangeley Fm (Guidotti et al., 1975; Henry, 1981). Reactions producing these Crd-bearing assemblages have not been determined owing to the effects of superimposed M3. Nonetheless, Fig. 3 represents the AFM mineral compatibilities at peak M2 conditions; the portion involving cordierite is less well documented, but that involving St-bearing assemblages is well constrained.

4. M3 metamorphic event

M3 has been well described (Guidotti, 1970b, 1974; Guidotti and Holdaway, 1993; Guidotti et al., 1996); only salient features are given here. A key point is that using the mineral facies approach (Thompson, 1957), the M3 isograds and zones subdividing the metamorphic gradient are defined by unambiguous AFM (and at higher-grades, AKNa) topologies that are based on observed mineral assemblages in a given grade or zone (Fig. 4). Table 1 gives the essential discontinuous mineralogical reactions for each topology (i.e. metamorphic zone) change, and the AFM and AKNa continuous reactions that occur in key limiting assemblages of a given zone (shown with a ★ in the topologies). The number of phases equals the number of components ($P = C$) for these key assemblages; therefore, compositions of phases are a function of the intensive parameters. These reactions account for essentially all mineralogic changes between, and within, the grades of the M3 gradient, including assemblage changes, compositional changes of the crystalline solution phases, and modal changes in the amounts of the phases. As developed below, they also account for virtually all of the major pseudomorph features.

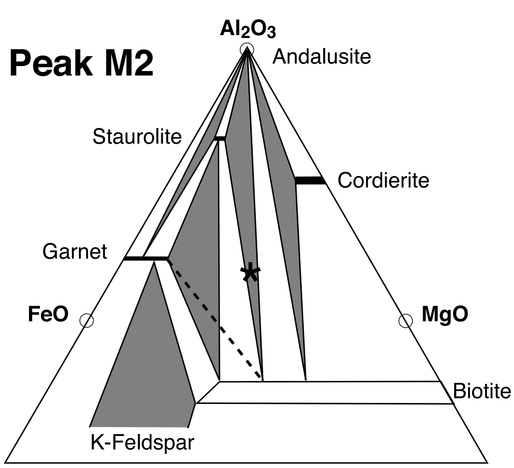

Fig. 3. AFM Topology for the peak M2 conditions; Qtz, Ms and uniform aH_2O in all assemblages. Dashed line indicates Grt as an additional phase in the ★ assemblage shown.

Based on compositional variations of the layer silicates owing to the continuous reaction that occurred within a given zone, it is possible to contour the increasing intensity of grade within some zones. The garnet zone (GZ) is subdivided into a lower, middle, and upper Grt zone (LGZ, MGZ, and UGZ, respectively) (Fig. 2). Similarly, the St zone (StZ) can be subdivided into a lower and upper St zone (LStZ, and UStZ, respectively). The lower Sil zone (LSZ) could be subdivided into a lower and upper portion, but this has not been done owing to insufficient pelitic outcrops in the critical portion of the zone.

The metamorphic conditions for the M3 LSZ were approximately 600°C and 3–3.5 kb (Guidotti and Holdaway, 1993; Holdaway et al., 1997). The T and P attained during M2 was probably only slightly lower.

Approach to chemical equilibrium during M3 is indicated by the following. (1) A systematic variation of mineral assemblages is shown by mineral facies diagrams (Fig. 4). (2) Fractionation of elements (Mg/Fe and Mn/Fe ratios) is systematic among minerals within a given zone (Guidotti, 1970b, 1974; Guidotti et al., 1996). Other systematic compositional patterns are exhibited by the minerals affected by M3. For rocks with a ★ assemblage, these include an inverse relationship between the Ti-content of Bt and its Mg/Mg + Fe ratio (Guidotti et al., 1977; Henry

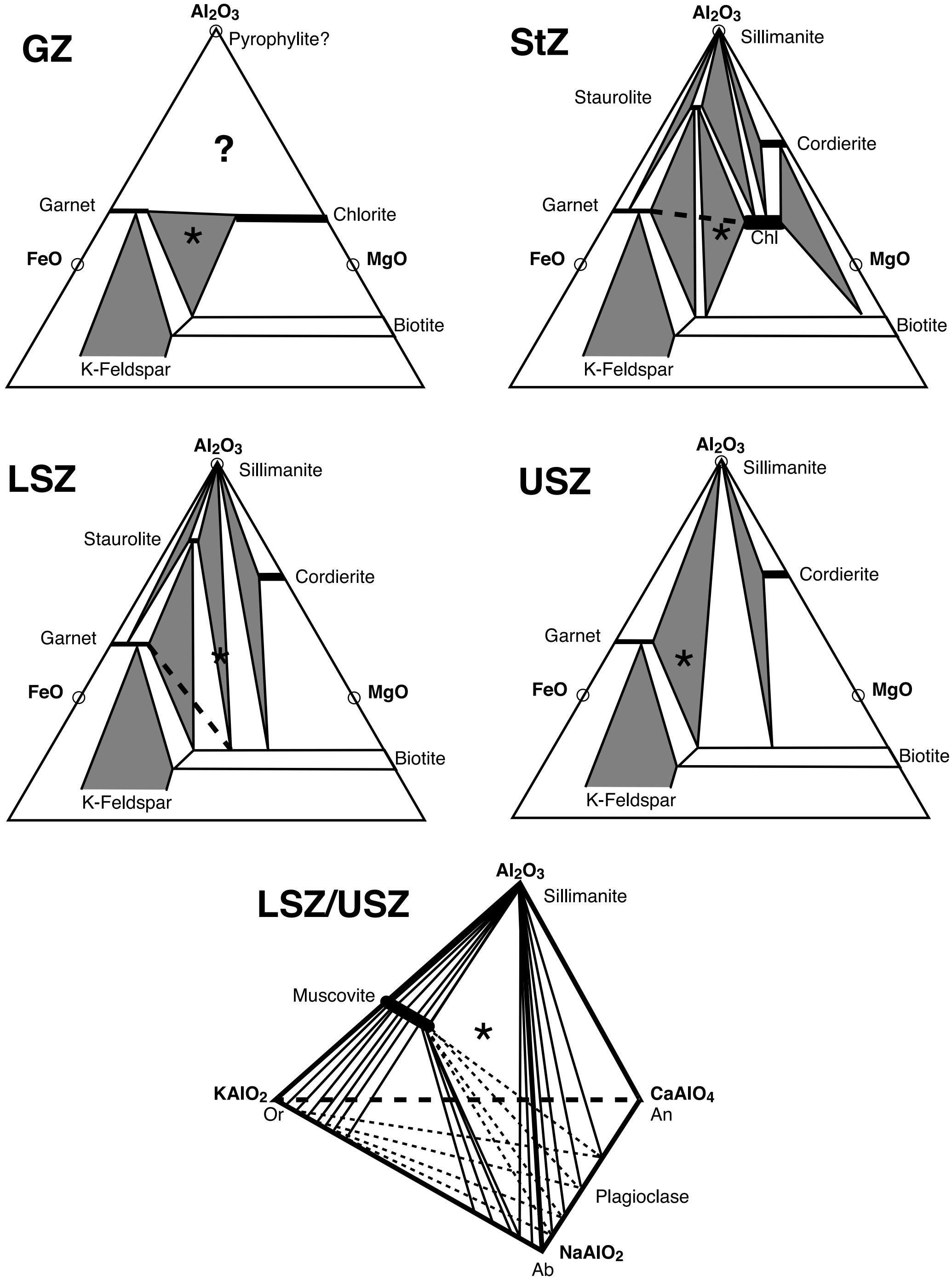

Fig. 4. AFM and AKNaCa topologies for M3. Key limiting assemblages indicated by ★. Qtz, Ms and uniform aH_2O in all assemblages. Dashed line indicates Grt as an additional phase in the ★ assemblage shown. Labels indicate M3 metamorphic zones: GZ = garnet zone, StZ = staurolite zone, LSZ = lower sillimanite zone, USZ = upper sillimanite zone.

and Guidotti, 2000), and a systematic increase of Mg/Mg + Fe ratio, and Mn-content in the minerals (especially evident for Grt and Ilm) as a function of the extent of sulfidation reactions as indicated by modal amount of pyrrhotite present (Guidotti, 1974; Henry, 1981). (3) Systematic compositional variations of the crystalline solution phases occur with grade. Details of these variations directly reflect changes in the continuous reactions that occur after grade-controlled AFM topology changes (Guidotti, 1970b, 1974, 1978; Guidotti et al., 1988). (4) Systematic relationships exist between the type and degree of pseudomorphing and the position within the M3 gradient.

Evidence suggesting chemical disequilibrium falls into the following two categories. (1) The number of phases present in some rocks appears to be too large ($P > C$), thereby violating the 'mineralogical phase rule' of $P \leq C$.

Table 1
The major AFM and AKNa continuous and discontinuous reactions that occurred during M3 from Lower Grt Zone through Upper Sil Zone (based on Guidotti et al., 1988)

(1) AFM continuous reaction in the Lower, Middle, and Upper Grt Zones:
Chl + Ms = Grt + Mg-richer Bt + Mg-richer Chl + Na-richer Ms + H_2O
(2) AFM discontinuous reaction marking the change from Upper Grt Zone to Lower St Zone:
Mg–Chl + Grt + Ms = St + Bt + Qtz + Na-richer Ms + H_2O
(3) AFM continuous reaction in the Lower and Upper St Zones:
Chl + Ms = St + Grt + Mg-richer Bt + Mg-richer Chl + Na-richer Ms + H_2O
(4) AFM discontinuous reaction marking change from Upper St Zone through Transition Zone to Lower Sil Zone:
St + Mg–Chl + Na–Ms + (Grt?) = Sil + Bt + K-richer Ms + Ab + Qtz + H_2O
(5) AFM continuous reaction in the Lower Sil Zone:
Mg–Bt + Ms + Grt + St + Qtz = Sil + Fe-richer Bt + Fe-richer St + Mn, Fe-Grt + Ab + H_2O
(6) AFM discontinuous reaction marking the change from Lower Sil Zone to Upper Sil Zones:
St + Na–Ms + Qtz = Sil + Bt + Grt + K-richer Ms + Ab + H_2O
(7) AFM continuous reaction in the Upper Sil Zone:
Grt + Na–Ms = Bt + Sil + Ab + H_2O
(8) AKNa continuous reaction in the Lower and Upper Sil Zones:
Na–Ms + Qtz = Sil + Pl + K-richer Ms + H_2O

One example involves the assemblage Sil + St + Bt + Grt + Chl that occurs in the transition zone (TZ; Fig. 2). However, this can be explained as a result of Grt being stabilized by Mn, a non-AFM component, and smearing out of the isograd marking the change from the UStZ to the LSZ (Guidotti, 1974). Owing to the gently-dipping isothermal surfaces, the TZ is relatively thin (100–200 m). Another example of this type involves the presence of And in many rocks affected by M3, suggesting one too many phases, which results in crossed tie lines (And + Bt vs St + Chl on the StZ AFM diagram, Fig. 4). However, Guidotti (1974) argued that this And is a metastable remnant from the M2 event, and the following two observations support this view. (a) With the exception of unusually graphite-rich samples, And invariably displays significant amounts of pseudomorphing and resorbtion. (b) With the occurrence of Reaction 4, Ms and Bt in rocks with ★ assemblages undergo major reversals in the effect of grade on their Na/(Na + K) and Mg/(Mg + Fe) ratios, respectively (Guidotti, 1978; Guidotti et al., 1988). This reversal is coincident with the formation of Sil, thereby indicating that the minerals in the rocks are 'oblivious' to the presence of And on either side of the isograd. (2) In addition to the above suggestions of possible chemical disequilibrium based on Phase Rule arguments, many rocks in the M3 sequence have not achieved general textural equilibrium. Several phases display markedly different grain sizes, especially the layer silicates. However, electron microprobe analyses show that the different-sized grains are chemically identical (Guidotti, 1974; Wood, 1981; Guidotti et al., 1988, 1991). Textural disequilibrium is not uncommon in metamorphic parageneses, but typically results in features like irregular and gradational grain boundaries (e.g. Bt irregularly altered to Chl), neither of which are important to pseudomorph formation. The evidence for a close approach to equilibrium based on mineral chemistry takes precedence over the textural evidence of disequilibrium in these rocks.

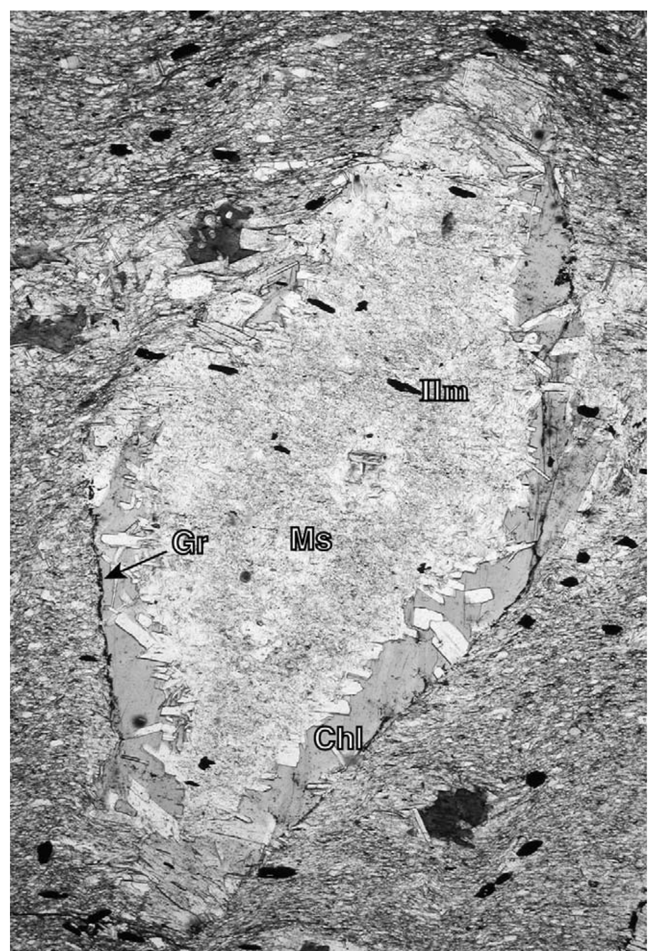

Fig. 5. Euhedral pseudomorph of St from M3 Grt zone. St is replaced primarily by chlorite and muscovite. Oriented ilmenite inclusions aligned parallel to foliation overgrown by porphyroblast. Plane polarized light. Long dimension of field 4 mm.

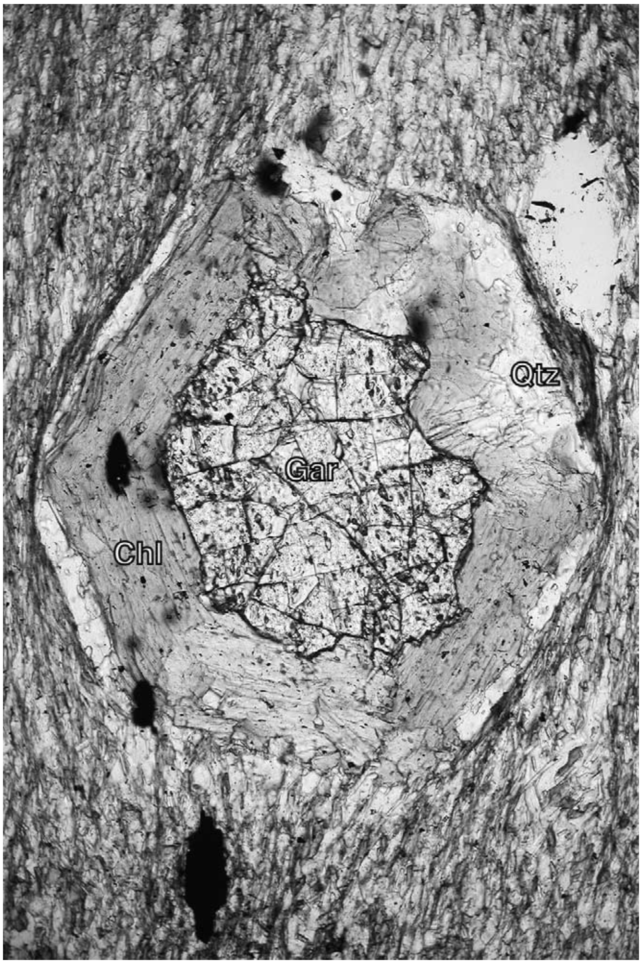

Fig. 6. Euhedral partial pseudomorphs of Grt from M3 Grt zone. Chl laths surrounding Grt core preferentially grew parallel to Grt crystal faces. Plane polarized light. Long dimension of field 1.5 mm.

In the following section, microstructural descriptions of pseudomorphs in each zone of the M3 metamorphic gradient are followed by a discussion of how they formed. Interpretations were formulated using the following two approaches. (1) For a given M3 grade, consider the implications of the tie-line geometry of the AFM and AKNa topologies when superimposed on the AFM and AKNa topologies that formed in response to M2 (compare Figs. 3 and 4). (2) Consider whether AFM and AKNa continuous reactions in the various M3 grades produce or consume a given phase.

5. Microstructures and metamorphic interpretations of pseudomorphs

5.1. Lower, middle and upper Grt zones

5.1.1. Microstructures

Pseudomorphs consisting of ragged, irregular aggregates of coarse-grained, randomly-oriented Ms appear to be remnants of M2 And in the Grt zone. These 1–2 cm aggregates are evident primarily in outcrop.

In all subzones of the GZ, M2 St is typically replaced by a core of medium-grained Ms that is rimmed by variable modal amounts of coarse-grained Chl, and the total aggregate generally maintains the euhedral shape of the original St (Fig. 5). The Ms and Chl in the pseudomorph are markedly coarser than the same minerals in the surrounding matrix (Wood, 1981).

Pseudomorphs after M2 Grt typically consist almost entirely of coarse-grained Chl, but the extent of replacement is generally incomplete so that some Grt persists (Fig. 6). The aggregate of coarse Chl is commonly arranged parallel to the dodecahedral faces of the original Grt so that the partial pseudomorph retains a euhedral Grt shape. The remaining Grt in the pseudomorph core commonly also retains subhedral to euhedral shape. The coarse Chl has the same composition as the much finer-grained groundmass Chl (Wood, 1981; Guidotti et al., 1991). Rims of the Grt in the cores of the partial pseudomorphs show some degree of Mn-enrichment (Wood, 1981).

In general, the extent of Chl pseudomorph development after Grt is related to grade. It is most pronounced in the LGZ, less developed in the MGZ, and absent in the UGZ. In the LGZ it is sufficiently developed to be observable in hand specimen mainly as 1–2 mm green dodecahedra. Only on more careful inspection with a hand lens are pink cores apparent in these partial pseudomorphs.

5.1.2. Metamorphic interpretation

Comparison of the GZ AFM topology (Fig. 4) with the AFM topology established in M2 (Fig. 3; consider ★ assemblage) shows that re-equilibration of M2 St-bearing assemblages under M3 GZ conditions will re-express the mineralogy as the assemblage Grt + Bt + Chl + Ms. Hence, given GZ M3 recrystallization conditions and addition of H_2O, M2 St will be replaced by some combination of these minerals. Details of the specific ionic diffusion that results in the pseudomorph mineralogy and microstructure are not evident by means of standard mineralogical/petrological approaches. However, C.T. Foster (in Guidotti et al., 1996) has suggested possible chemical potential gradients and resulting ionic diffusion paths that would result in the observed pseudomorphs of St in the GZ. Two aspects of the euhedral pseudomorphs of particular importance are: (1) they require that the replacement of St by Chl and Ms largely postdated any regional or pluton-related deformation, and (2) they provide a volume constraint for modeling diffusion processes.

Considering the ★ assemblage in the GZ AFM topology, bulk composition variation within the three-phase field could account for the variable degree of Grt pseudomorphing. However, the variations in mineral composition and modes, plus the fact that the UGZ is followed upgrade by the LStZ, demonstrates that grade (T) is the primary control on the extent of Grt pseudomorphing. The modal amount of Grt, and hence the extent to which it is pseudomorphed, reflects the position of the Grt + Bt + Chl three-phase field in response to the equilibration point of GZ continuous Reaction (1).

The pseudomorphs of M2 St in the M3 GZ essentially formed by reversal during M3 of the M2 reaction that first produced St (same as M3 Reaction (2), but at somewhat lower P). The partial pseudomorphing of M2 Grt by coarse Chl represents the M3 GZ continuous Reaction (1) equilibrating at a P, T, and aH_2O such that the modal amount of Grt permissible was less than that during the peak of M2. Pseudomorphs after M2 And occur in a few M3 GZ rocks. Their relative rarity may reflect the further removal of GZ rocks from conditions at which And was stable during M2, especially in the presence of the H_2O that was re-introduced into the GZ during M3. Moreover, it is conceivable that the Al required for Ms in the St pseudomorphs was partly obtained from the And as well as the St originally present, and the K from Bt as reflected by the marked decrease in M3 Bt mode in the GZ relative to that at the peak of M2.

5.2. Lower St zone

5.2.1. Microstructures

In some samples, M2 And has been completely replaced by elongate aggregates of scattered, unoriented, coarse-grained Ms. Other samples have only partially pseudomorphed, primary And persisting as ragged, very elongate aggregates of highly poikilitic grains, commonly associated with the Ms. These And grains appear to be remnants of crystals that had dimensions of several centimeters in length because the now scattered grains show optically uniform extinction. Only in unusually Gr-rich samples does M2 And (typically the chiastolite variety) seem to have escaped major textural modification. Apparently, the presence of abundant Gr inhibited the pseudomorphing reactions, possibly by having had a fluid with a lower amount of H_2O than required to form the layer silicates comprising most pseudomorphs (Guidotti, 1970a).

In some LStZ samples, M2 St is completely pseudomorphed as in the GZ. Commonly it also occurs as anhedral, ragged remnants of St immersed in an aggregate of largely unoriented, coarse-grained Chl and Ms. In some instances, it

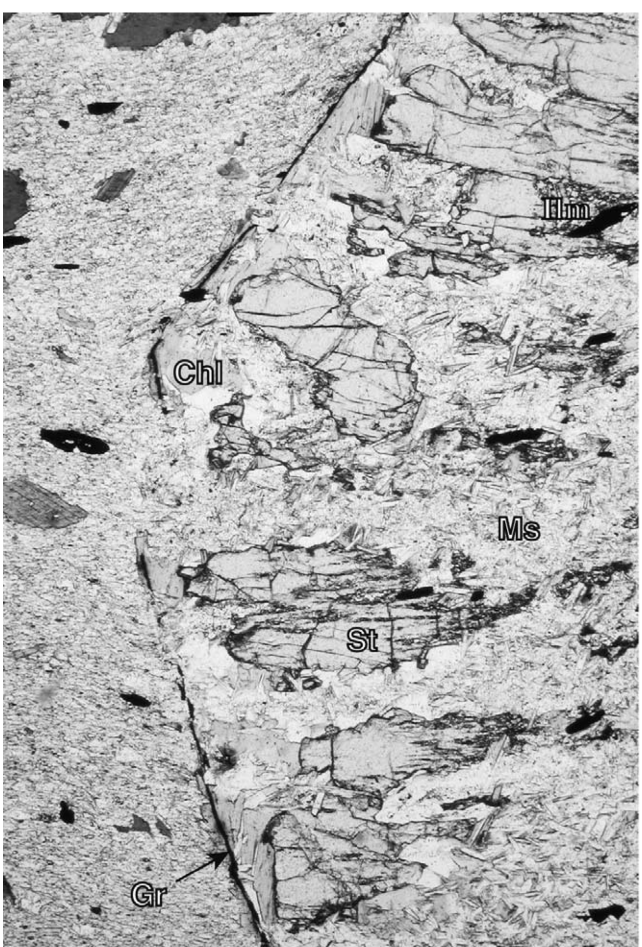

Fig. 7. Partial pseudomorph of St from M3 LStZ with blocky St remnants. Plane polarized light. Long dimension of field 5 mm.

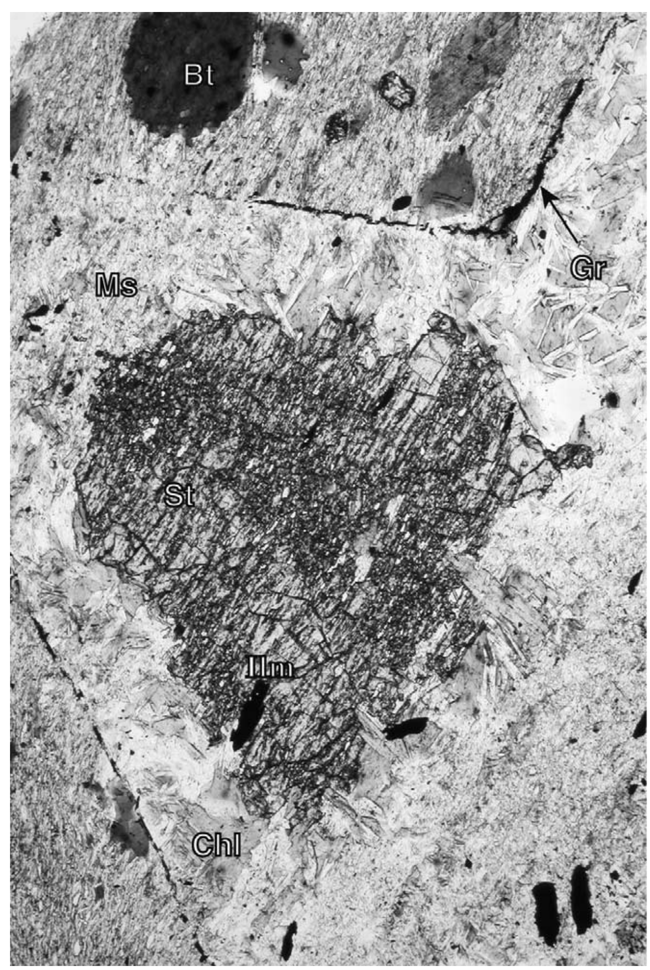

Fig. 8. Partial pseudomorph of St from M3 LStZ with poikilitic St remnants. Plane polarized light. Long dimension of field 3.2 mm.

occurs as irregular blocky remnants of the original crystal (Fig. 7), whereas in others the remnant St occurs as a highly poikilitic core with the inclusions (Qtz and Ilm) aligned approximately parallel to the fabric in the surrounding groundmass (Fig. 8).

5.2.2. Metamorphic interpretation

In the M3 StZ, the M2 And + Bt join is replaced by St + Chl and St + Grt joins. Hence, the bulk compositions plot in different three-phase fields relative to M2 peak conditions. All samples plot compositionally below the M3 St + Chl and St + Grt joins and so And is no longer a stable phase in any rocks, although it is commonly present in many StZ samples. We suggest that And merely persists in M3 rocks as a metastable relic from the M2 peak assemblage.

Two processes appear to have affected the original M2 And during M3 re-equilibration: (1) partial dissolution of the original And, plus possibly concomitant enlargement of Qtz inclusions formerly present in the And; and (2) replacement of some And by relatively coarse Ms, presumably with much of the required Al coming from the dissolving And, and K derived from the re-equilbration and attendant modal decrease of M2 Bt or from Ms.

Comparison of the M3 LStZ AFM topology with the M2 AFM topology shows that the key assemblage plots in the three-phase field St + Bt + Chl + /−Grt. The modal amounts of these M3 phases are controlled by the bulk composition of a given sample, and also by the specific position of the three-phase field as controlled by continuous Reaction (3). Inasmuch as this reaction produces St at the expense of Chl and Bt, the position of this three-phase field in the LStZ would cause a given rock to have modally less St and Bt, and more Chl, than the same rock in the UStZ. Visual estimates of modal St in the LStZ and UStZ confirm this (Guidotti, 1970a).

5.3. Upper St zone

5.3.1. Microstructures

The textural features of partial to complete pseudomorphs

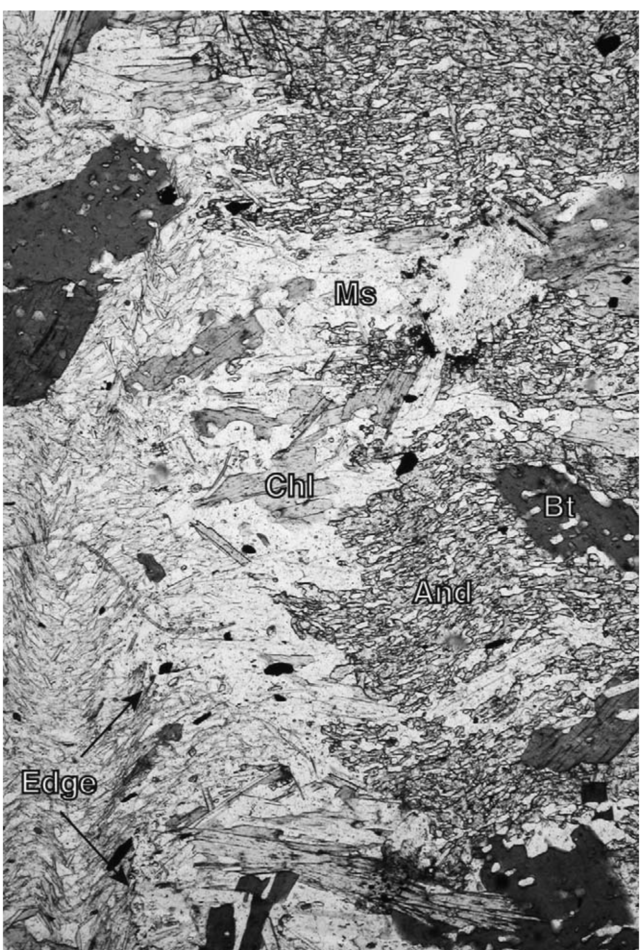

Fig. 9. Poikilitic And from M3 UStZ pseudomorphed mainly by coarse Ms and Bt. Note the pattern of poikilitic inclusions in the And relative to the fabric of the groundmass crenulation cleavage. Edges of pseudomorph shown. Plane polarized light. Long dimension of field 4 mm.

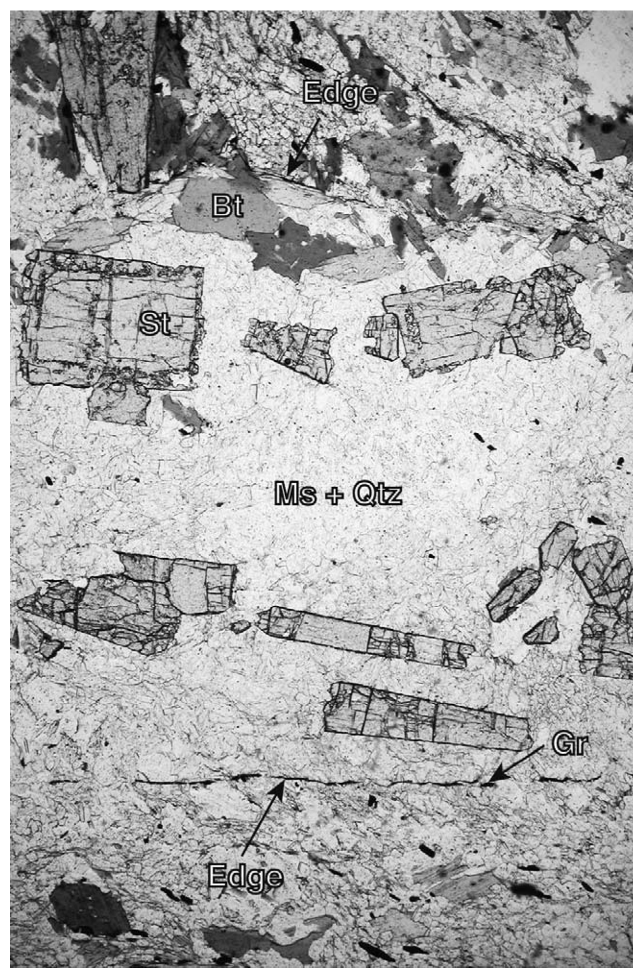

Fig. 10. Partial pseudomorph of St from M3 UStZ containing blocky, euhedral St remnants in a matrix of Qtz and Ms. These M2 remnants commonly have M3 overgrowths, as shown in Fig. 11. Edges of pseudomorph shown. Plane polarized light. Long dimension of field 8 mm.

of And in the UStZ are the same as those described for the LStZ (Fig. 9). In contrast, the textural aspects of St in the UStZ become markedly more varied. In some samples, euhedral, partial pseudomorphs are similar to those in the LStZ (Figs. 7 and 8), but are generally less well developed. In other samples, numerous small (a few millimeters in size), subhedral to euhedral M3 St crystals occur within partial pseudomorphs after a larger (1–1.5 cm) M2 St crystal (Fig. 10). The pseudomorphing phases are Qtz and unoriented Ms that is coarser-grained than matrix Ms with little or no Chl. In most instances, the small, euhedral M3 St crystals are oriented so that their long dimensions (*b*-axes) are parallel to the long dimension of the M2 St, including the direction of interpenetrating St twin crystals. In addition, some of the small euhedral crystals show distinct euhedral overgrowth rims on what are presumably remnant M2 St cores (Fig. 11). St also occurs as subhedral to euhedral crystals displaying little or no pseudomorph development. In some samples there is a gradation to St that becomes less euhedral to anhedral and highly poikilitic. In these instances, it even appears to be fragmented into optically continuous, remnant crystals (Fig. 12).

5.3.2. Metamorphic interpretation

The modal amount of St and Bt is systematically higher and Chl lower in the UStZ than the LStZ, and the coexisting Chl and Bt are richer in Mg. Most of the microstructures associated with M3 St, and the modal amounts of the phases, are best interpreted in terms of the bulk composition of a given rock considered in the context of continuous Reaction (3). However, the nature of partial pseudomorphs that involve the small euhedral St crystals is unique to the UStZ. An obvious question is whether or not the small euhedral crystals represent newly nucleated crystals following complete pseudomorphing of the M2 St. The presence of euhedral rims on many of these crystals, and their parallel orientation with the original M2 St, suggests that they represent M3 recrystallization around remnant grains of the original M2 St.

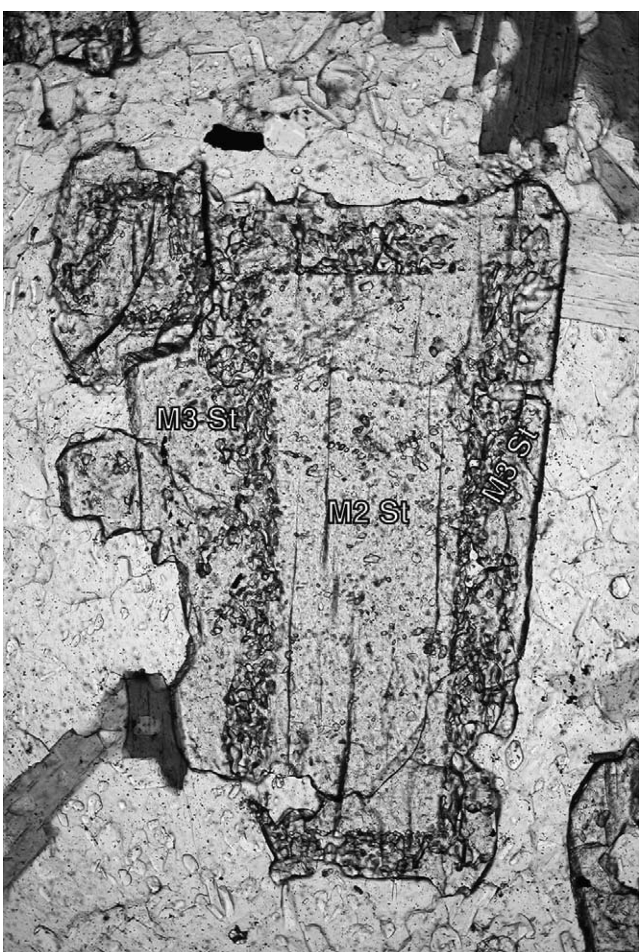

Fig. 11. Late-stage overgrowth of M3 St on M2 crystallite from the partial pseudomorph shown in Fig. 10. Plane polarized light. Long dimension of field 1.6 mm.

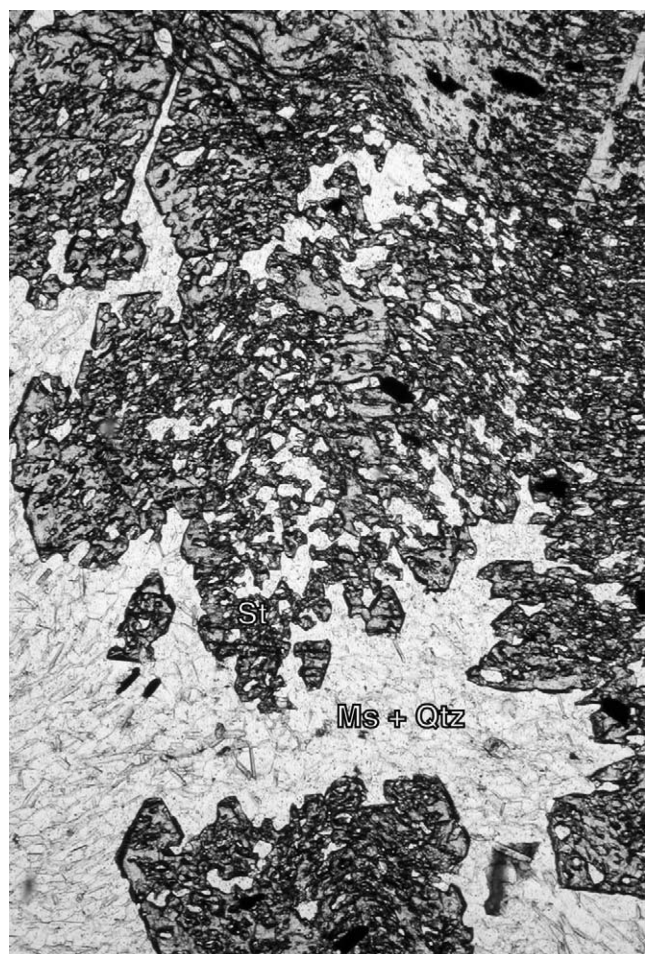

Fig. 12. Partial pseudomorph of St from M3 UStZ involving resorbtion and replacement by Qtz and Ms. Note the poikilitic inclusion pattern mimicking the groundmass foliation and the suggestion of subdivision into highly poikilitic euhedra of St. Plane polarized light. Long dimension of field 2.8 mm.

5.4. Transition zone

5.4.1. Microstructures

Pseudomorph textures involving And are much like those formed in the StZ. Excluding And, the TZ is characterized by a general lack of pseudomorphs, those present representing incipient stages of types that become well developed at higher grades.

The most notable textural feature of the TZ involves M3 growth rims on M2 St. These overgrowths are absent, or only very rarely developed, in the other M3 zones (e.g. Fig. 11). In general, M2 St porphyroblasts well away from the Mooselookmeguntic Pluton overgrew the regional foliation (Fig. 13a). In contrast, St in the TZ commonly shows M2 cores and M3 rims (Fig. 13b and c). The original M2 St cores preserve the same regional foliation shown in Fig. 13a as inclusion trails. These cores were overprinted by a crenulation cleavage, which we suggest may have formed during emplacement of the Mooselookmeguntic Pluton. The M3 St rims then overgrew this new cleavage.

5.4.2. Metamorphic interpretation

The TZ resulted from ‘smearing out’ of the M3 isogradic reaction marking the tie-line change that reflects Reaction (4) (Guidotti, 1974). It involved establishing a tie-line connecting an Al-silicate and Bt, but in contrast with the same Reaction (A) during M2, the Al-silicate was Sil instead of And. The TZ represents the map pattern of the narrow region in which the mineral assemblages of the isogradic reaction coexist (Sil + St + Bt + Chl + /−Grt). Although the TZ appears in map view to be as wide as 2–3 km, the reaction surface, as shown by its map pattern in relation to topography, dips very gently to the east and so the zone is at most 100–200 m thick.

The presence of M3 growth rims on St in the TZ may reflect the fact that, at grades above and below this thin zone, the prograde and downgrade M3 reactions relative to the regional M2 resulted mainly in a decrease in modal St. Only in the TZ were M3 conditions appropriate to result in a modal increase of St, and thus the TZ represents a metamorphic ‘hinge’ between upgrade and downgrade St pseudomorphism. The part of the Mooselookmeguntic pluton shown in Fig. 2 has an age of 370.3 ± 1 Ma (Solar et al., 1998), and so we suggest that the M3 St rims grew at approximately this time.

5.5. Lower- and higher-grade portions of lower Sil zone

5.5.1. Microstructures of lower-grade portion

Andalusite pseudomorphing is similar to that in the UStZ in all respects. In addition, formation of other types of pseudomorphs begins at the inception of the LSZ and becomes more pronounced with increasing grade.

The initial LSZ pseudomorphing of St porphyroblasts is manifest by the development of a few coarse-grained, usually unoriented laths of Ms (and Bt in some samples) around St (Figs. 14 and 15). This Ms is visually evident because of its contrast with the much finer-grained Ms that forms an intimate part of the surrounding groundmass. The extent to which St is replaced by the coarse Ms increases at higher grades in the LSZ until St is immersed in an aggregate largely consisting of coarse, unoriented Ms in which Sil has locally nucleated (Fig. 16). Otherwise, Sil nucleated mainly as fibrolite in association with Bt. Concomitant with pseudomorphing of St by Ms, the remaining St shows an increase in poikilitic Qtz inclusions that, in some instances, preserve a crenulation cleavage overgrown by the M2 St. Although we are currently investigating possible causes of this apparent increase in the poikilitic nature of St with increasing M3 grade, we suggest that the continuous reaction responsible for pseudomorphing of St may also have caused its partial resorbtion, some of the Al going to form Ms. The following observations support this suggestion. (1) In some LSZ samples there is little or no pseudo-

Fig. 13. (a) Poikilitic M2 St porphyroblast from well away from the Mooselookmeguntic pluton that has overgrown the regional foliation. (b) Poikilitic St from a rock closer to the Mooselookmeguntic pluton, in M3 TZ, showing an M2 St overprinted by a crenulation cleavage which was then overgrown by an M3 St rim. (c) Line diagram of (b). Plane polarized light. Long dimension of field (a) 4.2 mm, (b) 4.8 mm.

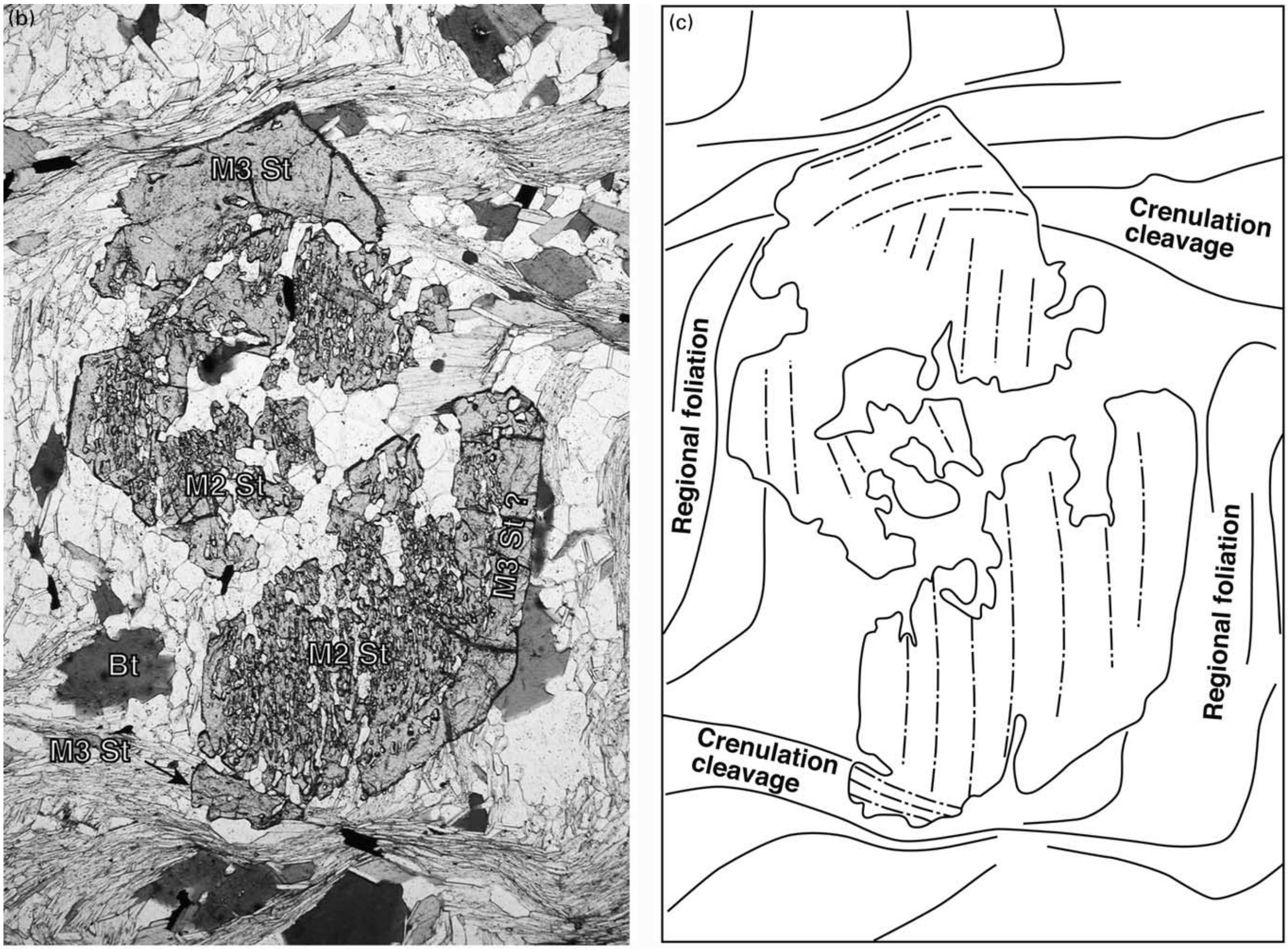

Fig. 13. (*continued*)

morphing of St with grade increase. Instead, the St merely decreases modally by becoming more poikilitic and eventually fragmental. (2) M2 St is partially pseudomorphed in the LStZ, but by continuous Reaction (3) (Table 1), and shows much less poikilitic texture (Fig. 7). Moreover, in contrast with the operation of Reaction (5) in the LSZ, the LStZ pseudomorphs are produced by the reaction proceeding in a downgrade direction involving re-hydration. (3) Poikilitic texture in LSZ St is markedly less developed in parts of the St crystal that overprinted Ms-rich domains containing modally less quartz. (4) As with the now highly fragmented And remnants, the highly poikilitic St retains optical continuity even when St becomes skeletal and constitutes only a fraction of its original area as seen in thin section, the intervening portions of the crystal having been replaced by Qtz and micas. (5) Samples of M2 St that have not been markedly affected by M3 are typically much less poikilitic than the St now seen in the LSZ.

Pseudomorphing of Grt by coarse Bt also occurs at the inception of the LSZ, typically retaining the euhedral dodecahedral shape of the original Grt (Fig. 17). Texturally, this pseudomorphing is identical to the Chl pseudomorphing of Grt in the LGZ and MGZ (Fig. 6). As grade increases, fibrolitic Sil commonly appears in Bt that replaced the Grt (Fig. 18), as well as in groundmass Bt. Metamorphically, it is also similar in that the degree of pseudomorph development varies with grade; however, in the case of Bt after Grt, pseudomorphism increases upgrade, instead of downgrade as with Chl.

The extent to which coarse Bt replaces Grt reaches a maximum at approximately the western edge of the eastern portion of the LSZ (Fig. 2). At this position in the M3 gradient fibrolitic Sil has largely replaced the Bt that had partially replaced Grt (Fig. 19). In many instances, the Sil mats retain an identifiable dodecahedral shape.

5.5.2. Microstructures of higher-grade portion

Along the eastern side of the western portion of the LSZ (Fig. 2), outcrops are well exposed on the summit of Elephant Mt. at 3700′ elevation. To the west, down slope, metamorphic grade increases and the isograd defining the USZ (the terminal stability of St, as seen on an AFM diagrams and Reaction (6)) is encountered at an elevation of approximately 2500′. Because the isograd trace nearly parallels topographic contours, the isogradic surface must be nearly flat-lying. Bedrock exposures are plentiful along

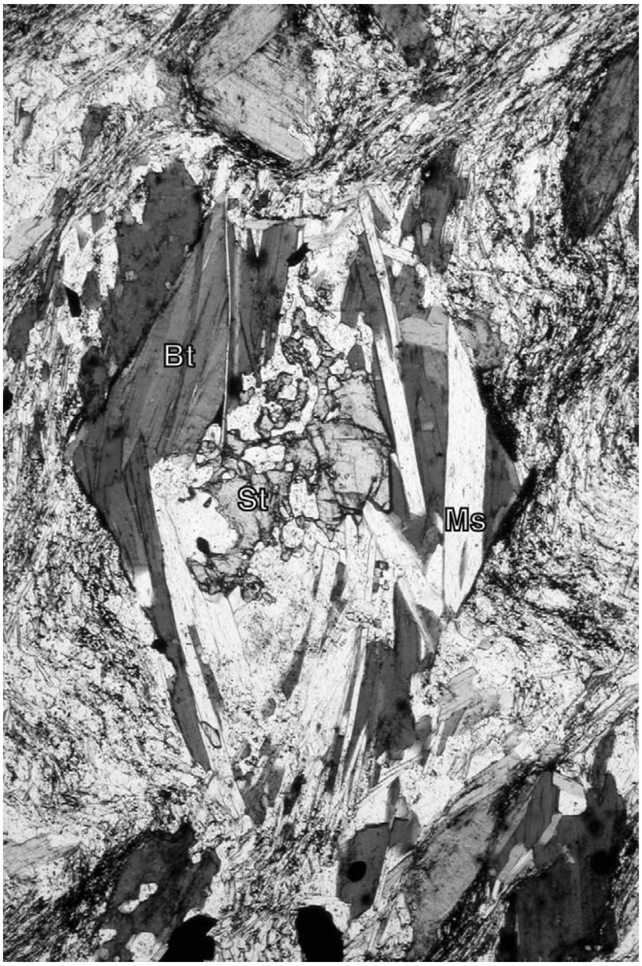

Fig. 14. Incipient pseudomorphing of St from M3 LSZ by Ms and Bt. Plane polarized light. Long dimension of field 3 mm.

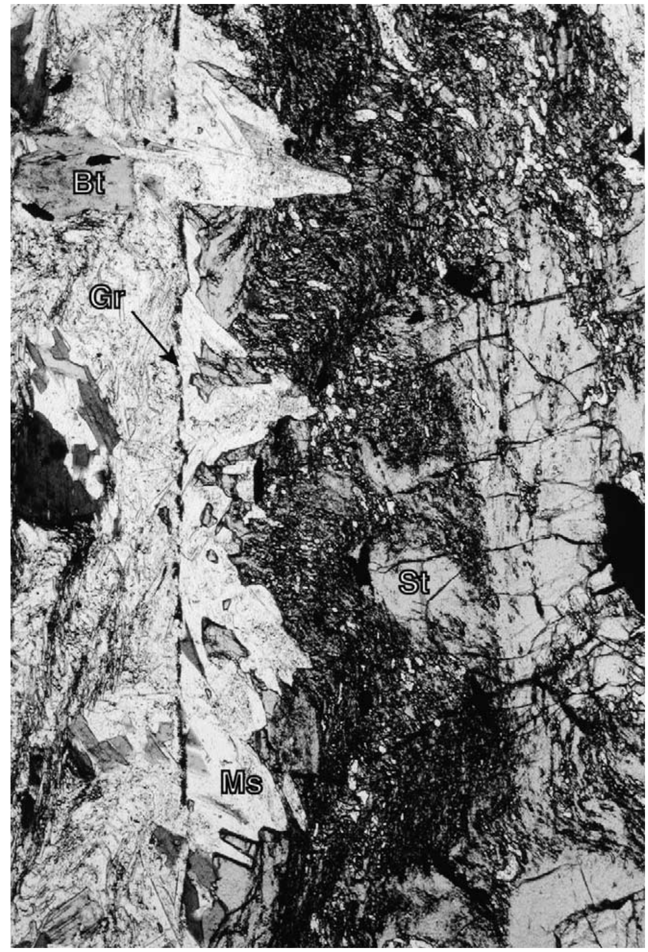

Fig. 15. Incipient pseudomorphing of St from M3 LSZ by Ms. Upper edge of pseudomorph defined by Gr concentration. Note the similarity in the patterns of poikilitic Qtz inclusions and the fabric of the groundmass crenulation cleavage. Plane polarized light. Long dimension of field 4 mm.

several westward-draining streams, allowing close monitoring of textural changes.

On the summit of Elephant Mt., pseudomorphing (by coarse Ms with intergrown Sil prisms) and resorbtion of any remaining And is nearly complete. St is largely replaced primarily by coarse Ms, in some instances the St merely persisting as anhedral remnants in an aggregate of coarse-grained, unoriented Ms containing intergrown Sil prisms. Some of the Ms aggregates retain the shapes of original St crystals (Fig. 20).

A notable feature in the western portion of the LSZ is that the replacement of St by Ms containing intergrown Sil prisms eventually becomes complete at the Reaction (6) isograd. As the isograd is approached, the pseudomorphs appear in hand specimen as round, white ‘eyes’ to 1 cm in diameter, some of which still mimic the shape of the original St crystal (Guidotti, 1968). In thin section the aggregates of Ms consist of coarse, unoriented plates (Fig. 21). Until the isograd is crossed, some of these aggregates contain a few tiny, remnant St grains.

Along the eastern side of the western portion of the LSZ, Bt rimming of Grt is nearly absent, the Bt having been largely replaced by fibrolitic Sil with an irregular Grt in the core, or in some samples lacking Grt altogether. Some of these rocks also contain anhedral to subhedral Grt with no rimming. In these instances, Sil that may have originally been present around the Grt has dissolved and re-nucleated in the now prominently developed mats of Sil associated with the matrix Bt, the latter being considerably coarsened compared with UStZ samples. As grade increases, the pseudo-dodecahedral aggregates of Sil lose their geometrical shape and become clots of concentrated Sil (in some cases associated with Grt) with ‘arms’ of fibrolite radiating out in a curved fashion (Fig. 22). At higher grades these clots become indistinct and merge with the growing clots of fibrolitic Sil associated with Bt, subhedral Grt with no rimming being present in most samples.

Modal and textural changes that in the western portion of the LSZ accompany the progression of pseudomorph features include decrease in modal Ms, darkened color for hand samples, development of a stronger foliation that is

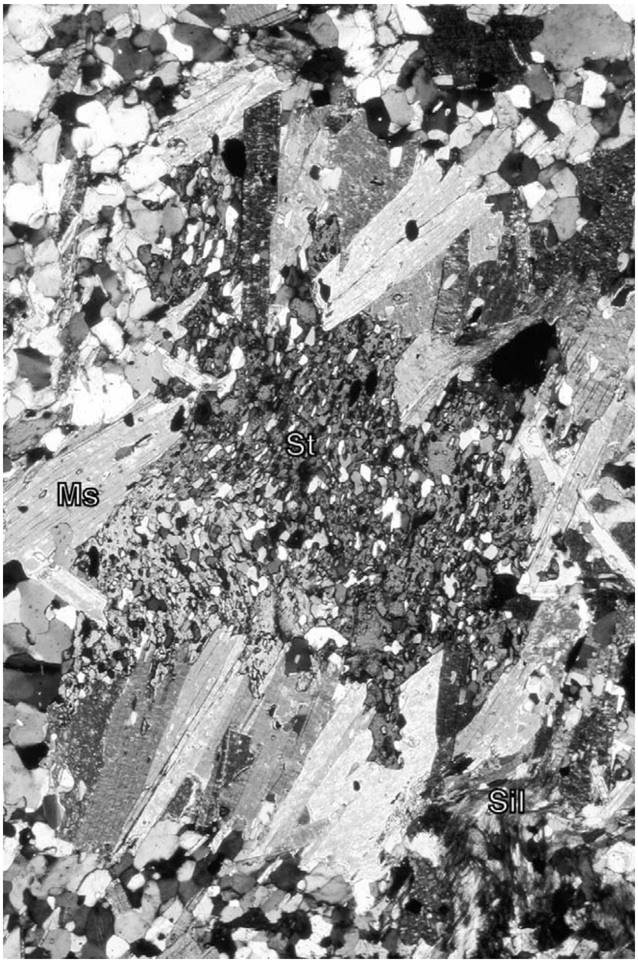

Fig. 16. Partial pseudomorph of St from M3 LSZ by coarse Ms, which radiates away from the St. Note the similar fold pattern for Qtz inclusions in St and the crenulation of the fibrolitic Sil. Cross polarized light. Long dimension of field 3.8 mm.

dominated by aligned Bt, and progressive disappearance of most vestiges of any crenulation cleavages.

5.5.3. Metamorphic interpretation of both lower- and higher-grade portions

All of the LSZ pseudomorphs occur in the main limiting assemblage Sil + St + Bt + /−Grt. Hence, the various textural features related to pseudomorph development can be generally understood by considering continuous Reaction (5). This equilibrium indicates how metamorphic grade affects the position of the four-phase volume Sil + St + Bt + Grt in composition space for the system AFM + MnO. Because the bulk compositions of the relevant rocks lie in this four-phase volume, pseudomorph development is also affected by bulk composition.

With increasing grade in the LSZ, Bt in the four-phase volume has progressively lower $Mg/(Mg + Fe^{2+})$ ratios, indicating that the Sil + Bt edge of the volume migrates toward an Fe-richer part of composition space (Guidotti, 1974). The $Mg/(Mg + Fe^{2+})$ ratios of Grt and St also decrease, but because they are such intrinsically Fe-rich phases the change is less obvious. These compositional changes, in conjunction with the observation that with increasing grade there is a modal increase of Bt and Sil but decrease of St and Grt, show that the entire four-phase volume migrates with grade toward an Fe-richer position in 3D composition space.

In essence, with increase in grade and migration of the compositional volume, a given point within the volume will become progressively closer to the Sil + Bt join, and farther from the compositional points for St or Grt, as also reflected by the modal changes described above. In general, the pseudomorphs of St and Grt seem to form because they are being modally decreased by Reaction (5), and this decrease is at least partly taken up volumetrically by precipitation of other phases actively participating in the reaction. Modal increase of Bt requires that modal Ms decrease to provide the required K^+. Therefore, Ms, a highly aluminous phase, was actively participating in the recrystallization process, and some of it recrystallized in the volume vacated by the continuous breakdown of St. In contrast, it appears that Bt filled volume vacated by the continuous breakdown of the less aluminous phase, Grt. Moreover, the new Bt forming in response to Reaction (5) was progressively richer in Fe, owing to Grt being the most Fe-rich silicate mineral present.

In addition to the modal Ms decrease required to provide K^+ for Bt, it also decreased in response to AKNa Reaction (8) to produce Sil and Ab. These modal decreases of Ms, in conjunction with its recrystallization as coarse aggregates after St, produced the groundmass fabric and hand-specimen color changes described above. The progressive replacement of St by coarse-grained, unoriented Ms continues to the isograd marking the USZ (discontinuous Reaction (6)). The change from a euhedral or subhedral Ms aggregate to a more nearly spherical aggregate consisting of coarser grains reflects grain-size increase with grade. Pseudomorphing of Grt by Bt, and then of Bt by Sil, reflects the long-known observation that fibrolitic Sil typically nucleates in Bt (e.g. Chinner, 1961). These roughly spherical to dodecahedral-shaped concentrations subsequently develop into the radial clots of concentrated Sil (Fig. 22).

It is not clear why St continues to be pseudomorphed throughout the LSZ, whereas Grt does not. Possibly it relates to a propensity of Sil at higher T to nucleate as progressively larger prisms, especially associated with both Bt and Ms as the transition from fibrolite to prismatic Sil occurs. Conceivably, some aspect of the compositional zoning of Grt and how it is affected at higher T also becomes a factor. For example, where Grt has well developed rims of coarse-grained Bt or Sil, it displays distinct Mn-enrichment in its outer rims compared with the interior of the grain. Concomitantly, the coexisting Ilm in such rocks shows an increase in MnO. In contrast, the un-rimmed, less euhedral Grt at higher grades shows no evidence of Mn-enriched

Fig. 17. Coarse Bt rims around Grt from M3 LSZ. Bt laths surrounding Grt core preferentially grew parallel to Grt crystal faces. Plane polarized light. Long dimension of field 1.5 mm.

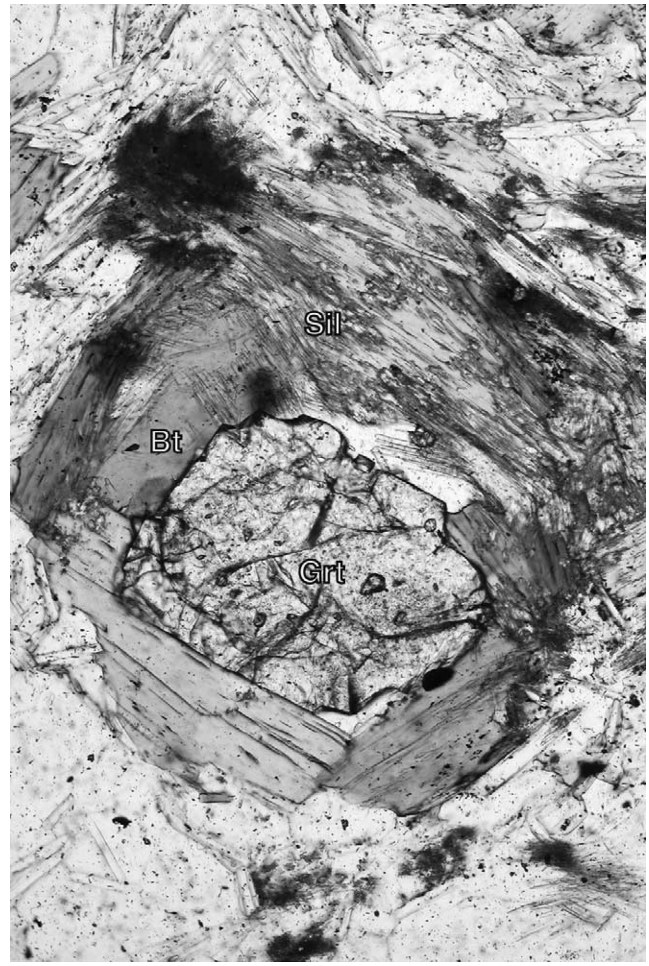

Fig. 18. Fibrolitic Sil has replaced Bt that had previously replaced Grt from M3 LSZ. Euhedral form of original Grt still apparent. Plane polarized light. Long dimension of field 1.3 mm.

rims, possibly reflecting a change to new M3 Grt rim overgrowths (Guidotti, 1970b, 1974).

The lack of uniform increase in any particular type of pseudomorphism with grade is readily understood in terms of the compositional variation that is possible within the four-phase volume at any given set of values for the intensive parameters. This compositional variation influences the modal mineralogy and, hence, the extent to which intensive parameters affect pseudomorph development. Although the intensive parameters do control compositions of the crystalline solution phases, they control the modal mineralogy only in the backdrop of the bulk compositional variation permissible within the four-phase volume.

5.6. Upper Sil zone

5.6.1. Microstructures

Upon entering the USZ, the only textural change directly related to pseudomorph development involves additional coarsening of the unoriented Ms in the 'white eye' aggregates. Eventually the aggregates completely lose their circular (spherical in 3D) shape, and their origin as pseudomorphs after St becomes progressively less obvious. At the final peak metamorphic conditions attained in M3, the aggregates of Ms consolidate by recrystallization into 1 cm or larger 'spangles' that typically contain intergrown prisms of Sil and trains of fibrolite. The only other textural changes on crossing into the USZ are a coarsening of grain size with an incipient development of a gneissose texture, and a further darkening in color due to a marked decrease of matrix Ms. Concomitantly, there is a progressive transformation of fibrolitic Sil into prismatic Sil.

5.6.2. Metamorphic interpretation

In the USZ continuous Reactions (7) and (8) occur in the AFM and AKNa systems, respectively. The textural changes described above appear to result from the continued progress of these reactions plus the fact that as T increases, the minerals in metamorphic rocks tend to become more coarse-grained.

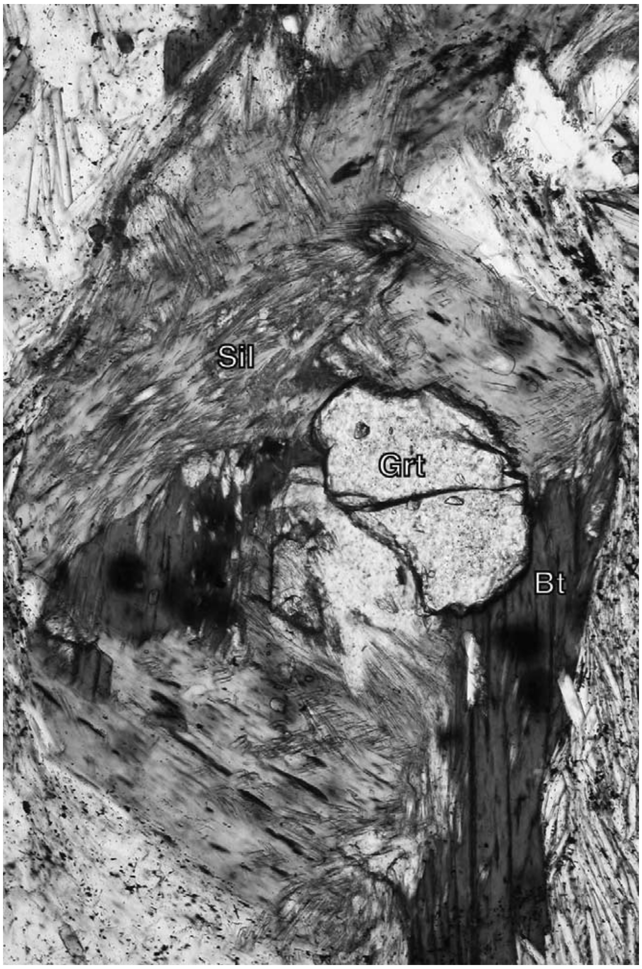

Fig. 19. Similar to Fig. 18, but Bt rims progressively more replaced by Sil. Euhedral form of original Grt still apparent, though less so than Fig. 18. M3 LSZ. Plane polarized light. Long dimension of field 1.2 mm.

Fig. 20. Anhedral St remnant in an aggregate of coarse Ms retaining the shape of original St; from M3 LSZ. Plane polarized light. Long dimension of field 3.8 mm.

6. Discussion and conclusions

A systematic progression of pseudomorphic replacements of M2 And, St, Grt, and Bt resulted from superposition of a later thermal event, M3, on a regionally-developed high-T, low-P terrain characterized by the assemblage And + St + Bt + /−Grt. The M3 event involved a range in grades owing to the thermal gradient imposed by emplacement of the gently east-dipping Mooselookmeguntic pluton. Arguments based on mineral chemistry and AFM phase diagrams support the suggestion that each of the various M3 grades closely approached chemical equilibrium even though textural disequilibrium is clearly evident.

The types and extent of pseudomorphic replacements are systematically related to the M3 metamorphic gradient. Moreover, for the most part, pseudomorph development in each grade can be readily understood by considering the difference between the configuration of M2 AFM tie lines and the configuration attained in any particular M3 grade, plus the nature of the continuous reactions that occur in that grade. Deviation from a rigorous 1:1 correlation between grade and the extent to which a given pseudomorph has developed can be understood by considering how bulk compositional variation affects the modal amounts of a given phase, even if it occurs in a thermodynamically constrained limiting assemblage. Detailed understanding of the textural development of individual samples would require application of the approaches pioneered by Fisher (1977) and used successfully by Foster (1977, 1981) on western Maine rocks. Such an analysis is beyond the scope of this paper, but we note that the two approaches have been in good agreement.

In most instances, the pseudomorphing involved layer silicates replacing the earlier M2 minerals, but two exceptions are worth noting. (1) In the LSZ, M3 Sil replaced earlier-formed M3 Bt, which itself had partially replaced Grt. (2) In the TZ, M2 St was stable during peak M3 conditions, and so M3 rim overgrowths occurred on M2 St cores, rather than M2 St being pseudomorphed or resorbed. Hence, various stages in the progressive textural evolution during M3 are preserved, and so the rocks do not show textural equilibrium.

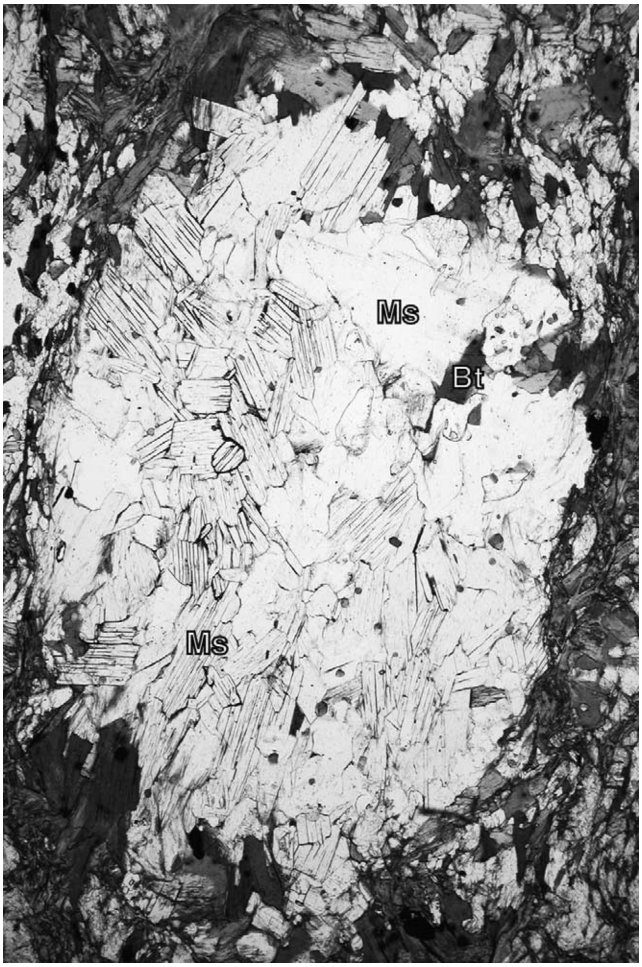

Fig. 21. Ms 'eye' after St in M3 LSZ near USZ isograd. Plane polarized light. Long dimension of field 5 mm.

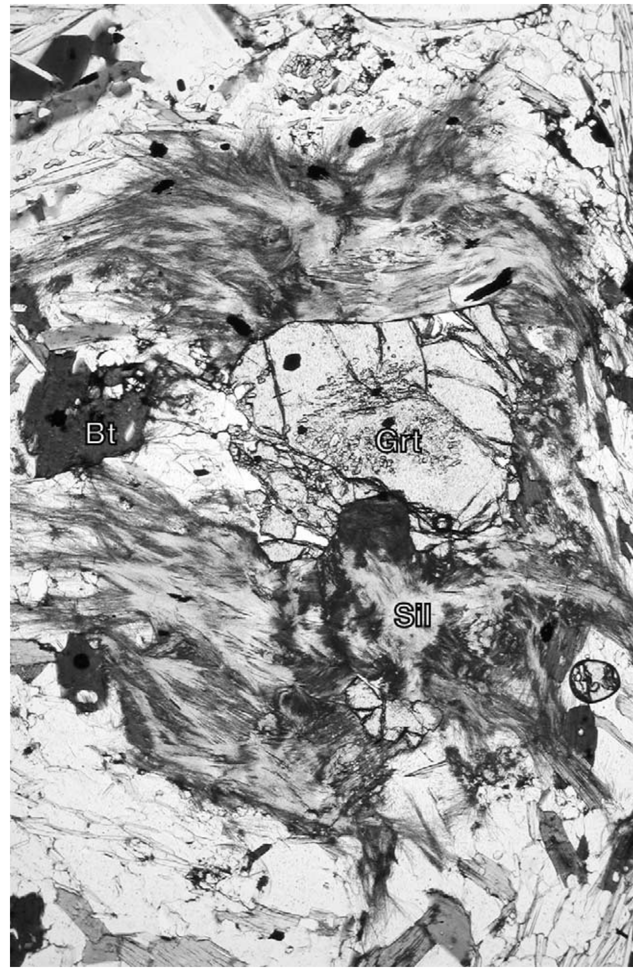

Fig. 22. Fibrolitic Sil that has almost completely replaced Bt that originally pseudomorphed Grt from M3 LSZ. Plane polarized light. Long dimension of field 5 mm.

The preservation of euhedral pseudomorphs argues strongly for low regional deviatoric stress during and after their formation. Otherwise, we would have expected the layer silicate-rich pseudomorphs to deform. That the pseudomorphs consist largely of layer silicates apparently reflects the fact that all of the M3 continuous and discontinuous reactions involve these minerals as major participants. To a large extent, metamorphism of metapelitic bulk compositions involves addition or removal of layer silicates (in conjunction with subtracting or adding H_2O) depending upon whether the metamorphism is prograde or downgrade. If, under relatively uniform stress conditions, the given M3 reaction destroys a mineral such as Grt or St, the volume formally occupied can be progressively filled by a replacement mineral. Because the layer silicates were intimately involved in the various reactions, and were changing composition to adjust to the new P and T conditions of the various M3 grades, it seems that they, along with Qtz, readily crystallized with their new compositions into these volumes.

Along with describing the progressive development of pseudomorph microstructures, we have also noted accompanying changes occurring in the groundmass. The following two changes are particularly noteworthy. (1) The disappearance of a crenulation cleavage defined by groundmass Ms occurs in the higher-grade portions of the LSZ and continues into the USZ. We present the following two possible explanations, which are not mutually exclusive. (a) A marked modal decrease of Ms occurs in these zones due to Reactions (7) and (8) in conjunction with the relocation of much of the remaining Ms into the pseudomorphs after St. This explanation for obliteration of the fabric calls on the effects of recrystallization and grain-coarsening with increasing temperature. (b) The crenulation cleavage may be related to emplacement of the Mooselookmeguntic pluton, as noted for Fig. 13b. In this instance, the progressive obliteration of the crenulation may reflect its intensification as the pluton is approached. If the crenulation cleavage and pseudomorphism are both related to the Mooselookmeguntic pluton, then the deformation must have outpaced the thermal front that caused the M3 event. This is evidenced by the late timing of St overgrowth relative to crenulation cleavage development in Fig. 13b, and the lack of deformation of any of the pseudomorphs in the area. Regardless of whether deformation or recrystallization played the dominant role in obliterating evidence for the crenulation cleavage, if one looked only at thin sections from the USZ, where the rocks now have an incipient gneissose texture, evidence for fabrics present earlier in the history of the rocks may not be apparent. (2) The other textural change involves the origin of coarse Ms spangles in the higher-grade portions of the USZ. They apparently resulted from consolidation by progressive re-crystallization of Ms that grew initially as part of a pseudomorph of St. Such spangles of Ms are not uncommon in high-grade pelitic gneisses and have been ascribed to a number of origins. Our observations suggest one origin that should be considered among the competing possibilities.

To varying degrees, similar types of subhedral to euhedral pseudomorphs of porphyroblasts formed during earlier low-P, high-T metamorphism(s) are common along much of the northern limit of high-grade metamorphism in New England from the central coast of Maine into northeastern Vermont (Guidotti, 1993). In many (most?) instances it appears that the heat sources for the pseudomorph-forming event(s) were medium- to high-level felsic plutons. The potential implication is that the final 'thermal structure' imposed in this region was controlled by plutons emplaced during and after the waning stages of the Acadian Orogeny. We are currently attempting to unravel some of this history by applying electron microprobe techniques to in-situ age dating of metamorphic monazite (see Williams and Jercinovic in this issue).

Finally, in terms of tectonic history and the detailed nature of metamorphic reactions, the various pseudomorphs described herein have important implications. Specifically, the last significant deformation in the area occurred before M3, and for the conditions that prevailed during M3, the pseudomorphing of M2 porphyroblasts involved constant-volume replacement processes.

Acknowledgements

We thank Ron Vernon for his friendship and scientific insight over the years. Barb Dutrow, Dave West, and Mike Williams are thanked for constructive reviews of the manuscript.

References

Chinner, G.A., 1961. The origin of sillimanite in Glen Clova Angus. Journal of Petrology 2, 312–323.

DeYoreo, J.J., Lux, D.R., Guidotti, C.V., Decker, E.R., Osberg, P.H., 1989. The Acadian thermal history of western Maine. Journal of Metamorphic Geology 7, 169–190.

Fisher, G.W., 1977. Nonequilibrium thermodynamics as a model for diffusion-controlled metamorphic processes. American Journal of Sciences 273, 897–924.

Foster, C.T., 1977. Mass transfer in sillimanite-bearing pelitic schists near Rangeley, Maine. American Mineralogist 62, 727–746.

Foster, C.T., 1981. A thermodynamic model of mineral segregations in the lower sillimanite zone near Rangeley, Maine. American Mineralogist 66, 260–277.

Foster, C.T., Dutrow, B.L., 2000. Evidence for separate hydration and thermal pulses during M3 regional-contact metamorphism in western Maine. Geological Society of America, Abstracts with Program 32, A113.

Guidotti, C.V., 1968. Prograde muscovite pseudomorphs after staurolite in the Rangeley–Oquossoc area, Maine. American Mineralogist 53, 1368–1376.

Guidotti, C.V., 1970a. Metamorphic petrology, mineralogy and polymetamorphism of a portion of N.W. Maine. In: Boone, G.M. (Ed.). New England Intercollegiate Geologic Conference Guidebook. Department of Geology, Syracuse University, Syracuse, NY, USA, pp. 1–29.

Guidotti, C.V., 1970b. The mineralogy and petrology of the transition from the lower to upper sillimanite zone in the Oquossoc area, Maine. Journal of Petrology 11, 277–336.

Guidotti, C.V., 1974. Transition from staurolite to sillimanite zone, Rangeley Quadrangle, Maine. Bulletin of the Geological Society of America 85, 475–490.

Guidotti, C.V., 1978. Compositional variation of muscovite in medium to high-grade metapelites of northwestern Maine. American Mineralogist 63, 878–884.

Guidotti, C.V., 1993. Textural aspects of high T-low P polymetamorphism in the Rangeley area, western Maine: general implications for studies of Acadian metamorphic rocks in New England. Geological Society of America Abstract with Programs 25, A21.

Guidotti, C.V., Holdaway, M.J., 1993. Petrology and field relations of successive metamorphic events in pelites of west-central Maine. In: Cheney, J.T., Hepburn, J.C. (Eds.). Field Trip Guidebook for the Northeastern United States. Department of Geology and Geography, University of Massachusetts, Amherst, MA, USA, pp. L1–L26 Contribution 67, 1.

Guidotti, C.V., Cheney, J.T., Conatore, P.D., 1975. Coexisting cordierite + biotite + chlorite from the Rumford Quadrangle, Maine. Geology 3, 147–148.

Guidotti, C.V., Cheney, J.T., Guggenheim, S., 1977. Distribution of titanium between coexisting muscovite and biotite in metapelites from N.W. Maine. American Mineralogist 62, 438–448.

Guidotti, C.V., Cheney, J.T., Henry, D.J., 1988. Compositional variation of biotite as a function of metamorphic reactions and mineral assemblage in the pelitic schists of western Maine. American Journal of Science 288A, 270–292.

Guidotti, C.V., Teichmann, F., Henry, D.J., 1991. Chlorite-bearing polymetamorphic metapelites in the Rangeley area, Maine: evidence for equilibrium assemblages. American Mineralogist 76, 867–879.

Guidotti, C.V., Cheney, J.T., Foster, C.T., Hames, W.E., Henry, D.J., Kinner, D.A., Lux, D.R., 1996. Polymetamorphism in western Maine: mineralogic, petrologic, and textural manifestations and regional implications. In: Van Baalen, M.V. (Ed.). New England Intercollegiate Geological Conference Guidebook. Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA, USA, pp. 171–202.

Henry, D.J., 1981. Sulfide–silicate relations of the staurolite grade pelitic schists, Rangeley Quadrangle, Maine. Ph.D. Thesis, University of Wisconsin, Madison, Wisconsin, 437pp.

Henry, D.J., Guidotti, C.V., 2000. Ti in biotite from metapelitic rocks: some petrologic applications. Geological Society of America Abstracts with Programs 32, A53.

Holdaway, M.J., Mukhopadhyay, B., Dyar, M.D., Guidotti, C.V., Dutrow, B.L., 1997. Garnet–biotite geothermometry revisited: new Margules parameters and a natural specimen data set from Maine. American Mineralogist 82, 582–595.

Johnson, S.E., Vernon, R.H., 1995. Stepping stones and pitfalls in the determination of an anticlockwise P–T–t-deformation path: the low-P, high-T Cooma Complex, Australia. Journal of Metamorphic Geology 13, 165–183.

Kretz, R., 1983. Symbols for rock-forming minerals. American Mineralogist 68, 277–279.

Moench, R.H., 1971. Geologic map of the Rangeley and Phillips quadrangles, Franklin and Oxford Counties, Maine. United States Geological Survey Miscellaneous Investigations Map I-605.

Smith, H.A., Barreiro, B., 1990. Monazite U–Pb dating of staurolite grade metamorphism in pelitic schists. Contributions to Mineralogy and Petrology 94, 1281–1288.

Solar, G.S., Pressley, R.A., Brown, M., Tucker, R.D., 1998. Granite ascent in convergent orogenic belts: testing a model. Geology 26, 711–714.

Thompson Jr, J.B., 1957. The graphical analyses of mineral assemblages in pelitic schists. American Mineralogist 42, 842–858.

Vernon, R.H., 1978. Pseudomorphous replacement of cordierite by symplectic intergrowths of andalusite, biotite and quartz. Lithos 11, 283–289.

Vernon, R.H., 1982. Isobaric cooling of two regional metamorphic complexes related to igneous intrusions in southeastern Australia. Geology 10, 76–81.

Wood, C., 1981. Chemical and textural zoning in metamorphic garnets, Rangeley Area, Maine. Ph.D. Thesis, University of Wisconsin, Madison, Wisconsin, 568pp.