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THE CLASSIC HIGH-*T* – LOW-*P* METAMORPHISM OF WEST-CENTRAL MAINE: IS IT POST-TECTONIC OR SYNTECTONIC? EVIDENCE FROM PORPHYROBLAST–MATRIX RELATIONS

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ABSTRACT

Devonian polymetamorphism of the Central Maine belt of sedimentary rocks has been regarded as "static", the result of advective heat due to sequential emplacement of "post-tectonic" granite plutons. The following evidence is cited in support of pluton-driven static metamorphism: (1) a spatial relationship between higher-grade metamorphic zones and pluton margins, and (2) a reported random orientation of euhedral porphyroblasts within matrix fabrics. In contrast, our observations of porphyroblast–matrix relations show that regional metamorphism was synchronous with progressive accumulation of plastic strain. Metasedimentary rocks have penetrative grain-shape fabrics defined by mica and quartz. Spatial variations in the style of matrix fabrics reflect contrasts in rheology as a function of lithology, stratigraphy and metamorphic grade. Strain partitioned into zones characterized by a high degree of parallelism between steeply oriented compositional layering and foliation (higher-strain zones) that surround zones in which variably oriented, moderately dipping foliation is not as strongly developed (lower-strain zones). A well-developed moderately to steeply northeast-plunging mineral-elongation lineation is pervasive in both types of structure, and is defined by the same mineral assemblage at the same grade of metamorphism. Thus, we interpret mineral growth to record the accumulation of plastic strain. Biotite "fish" and quartz-dominated polycrystalline aggregates in asymmetrical pressure-shadows around porphyroblasts, which are elongate in the direction of mineral elongation, show consistent dextral-reverse displacement along the mineral-elongation lineation in the plane of the foliation. Andalusite and staurolite porphyroblasts have preferred orientations, statistically parallel to matrix fabrics, and garnet and staurolite porphyroblasts include a foliation (S_i) that is discontinuous with matrix foliation (S_e). In staurolite, the obliquity of S_i with respect to S_e decreases through up to three textural zones from core to rim, to record episodic interkinematic growth of porphyroblasts and progressive modification of the matrix. In lower-strain zones, granite plutons are associated with retrogressive replacement of andalusite and staurolite, which reflects preferential contact metamorphism in these structures.

Keywords: Appalachian orogen, grain-shape fabrics, high-*T* – low-*P* metamorphism, microstructures, strain partitioning, syntectonic growth, porphyroblast, Maine.

SOMMAIRE

On considère généralement le polymétamorphisme des roches sédimentaires de la ceinture centrale des Appalaches de l'état du Maine dans un contexte "statique", résultant de l'advection de chaleur due à la mise en place séquentielle de plutons granitiques à caractère "post-tectonique". Les critères suivants sont cités à titre d'évidence d'un métamorphisme statique régi par les plutons: (1) une relation spatiale entre les zones métamorphiques de degré élevé et la bordure des plutons, et (2) une orientation de porphyroblastes idiomorphes décrite comme étant aléatoire dans la structure de la matrice. En revanche, nos observations des relations entre porphyroblastes et matrice démontrent que le métamorphisme régional était contemporain de l'accumulation de déformation plastique. Les roches métasédimentaires possèdent une structure pénétrante découlant de la morphologie des cristaux de mica et de quartz. Les variations dans l'espace du style de structure dans la matrice des roches témoignent de contrastes en rhéologie en fonction de la sorte de roche, la position stratigraphique et l'intensité du métamorphisme. La déformation est répartie sur des zones à fort degré de parallelisme entre le litage sédimentaire original à pendage abrupt et la foliation (les zones plus fortement déformées); celles-ci entourent des zones dans lesquelles l'orientation de la foliation est variable et à pendage moins marqué (les zones moins fortement déformées). Une linéation due à l'étirement des minéraux, bien développée et à pendage modéré ou abrupt vers le nord-est, est répandue dans les deux types de structure, et contient les mêmes assemblages de minéraux qui marquent donc la même intensité de métamorphisme. La croissance des minéraux témoignerait donc de l'accumulation de déformation plastique. Des "poissons" de biotite et des agrégats polycristallins à dominance de quartz en zones asymétriques de faible pression près des porphyroblastes, qui sont allongés dans la direction d'allongement des minéraux, révèlent un déplacement conforme à un mouvement dextre et renversé le long de la linéation d'allongement des minéraux dans le plan de la foliation. Les porphyroblastes d'andalousite et de staurolite font preuve d'une orientation préférentielle, statistiquement parallèle à la structure

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de la matrice; les porphyroblastes de grenat et de staurolite contiennent des vestiges d'une foliation (S_i) qui est discontinue par rapport à la foliation de la matrice (S_e). Dans la staurolite, l'obliquité de S_i par rapport à S_e diminue en trois zones texturales du coeur vers la bordure, et sont le témoin d'une croissance de porphyroblastes entre episodes de mouvement et d'une modification progressive de la matrice. Dans les zones relativement peu déformées, les plutons sont associés au remplacement rétrograde de l'andalousite et de la staurolite, résultat des effets d'un métamorphisme de contact préférentiel dans ces structures.

(Traduit par la Rédaction)

Mots-clés: ceinture orogénique des Appalaches, morphologie des grains, métamorphisme à température élevée et faible pression, répartition de la déformation, croissance syntectonique, porphyroblaste, Maine.

Introduction

An early observation made about high-T – low-P metamorphic belts is their association with granites [*e.g.*, the Abukuma (Miyashiro 1958, Shidô 1958) and Ryoke (Miyashiro 1961) belts in Japan]. In these metamorphic belts, higher-grade metamorphic zones may be spatially related to pluton margins [*e.g.*, the Abukuma belt in Japan (Shidô 1958)], although discordance between zones and granites also occurs [*e.g.*, the Ryoke belt in Japan (Ikeda 1991, 1993, Morikiyo 1984)]. The high geothermal gradient implied by high-T – low-P metamorphism, and the association with granites, have led to the suggestion that the heat that caused the metamorphism was largely transported by granitic magma [*e.g.*, west-central Maine (Moench & Zartman 1976) and the Sierra Nevada (Barton & Hanson 1989)].

In Maine, an association between high-T – low-P metamorphism and granites has been interpreted to imply that the regional metamorphism was related to the granites (*e.g.*, Guidotti 1989), although granites in Maine occur with equal frequency in lower-grade metamorphic rocks, where they are associated with narrow contact aureoles (Fig. 1). Local discordance between bodies of granite and tectonic structures is interpreted to imply post-tectonic emplacement of plutons. Together, these interpretations have led to the perception that the thermal peak in this high-T – low-P metamorphic belt postdated penetrative deformation, and was achieved as heat was advected through the crust by granitic magma that ponded to form post-tectonic plutons (*e.g.*, De Yoreo *et al.* 1989). For example, mineral growth in the metasedimentary rocks, in particular of index porphyroblast phases, has been regarded as post-tectonic (*e.g.*, Guidotti 1989) and essentially static (Guidotti 1993). However, the interpretation that pluton emplacement and metamorphism are post-tectonic and independent of orogenic deformation is open to question (*e.g.*, Brown & Solar 1998a, b, Solar *et al.* 1998).

How the connection between deformation and granite emplacement is perceived in orogenic belts is dependent on the scale of observation and the exposed level in the crust, so that locally discordant contacts at the site of emplacement do not preclude overall syntectonic ascent and emplacement of granitic magma when viewed at the crustal scale (Karlstrom 1989, D'Lemos *et al.* 1992, Brown & Solar 1998a, b). Furthermore, there is a feedback relation between progressive deformation and advective heat due to ascent of pulses of granitic magma that leads to a complex interplay between metamorphism and deformation (D'Lemos *et al.* 1992, Brown & Solar 1998a). Although granite plutons emplaced in the upper crust commonly produce discrete narrow contact-metamorphic aureoles against steep side-wall contacts, a more important thermal effect occurs beneath large horizontal tabular plutons. This may be a significant control on distribution of isograds seen at shallow levels, exposed after the plutons have been lost to erosion (*e.g.*, Stewart 1989, Brown & Solar 1998b).

What are the implications of a feedback relation between deformation and metamorphism for the interpretation of textures in rocks from high-T – low-P metamorphic belts? Microstructural criteria to resolve the relative timing between mineral growth and deformation were introduced by Zwart (1962), leading to the classification of metamorphic crystallization into pre-, syn- and post-tectonic. The simple application of this classification was questioned by Ferguson & Harte (1975) and Olesen (1978), and the importance of interkinematic growth of minerals was recognized. Subsequently, a better understanding of the significance of microstructures in metamorphic rocks has been developed (see Passchier & Trouw 1996), and our knowledge of deformation mechanisms (*e.g.*, Knipe 1989, Knipe & Rutter 1990), strain partitioning (*e.g.*, Bell & Rubenach 1983) and strain localization (*e.g.*, Ord & Hobbs 1989, Knipe & Rutter 1990) has expanded. Granite ascent through crustal-scale shear zone systems produces overprinting textures that individually might be interpreted as pre-, syn- or post-tectonic, although the range of microstructures represents stages in the progressive evolution of a feedback relation between deformation, thermal evolution and crystallization (D'Lemos *et al.* 1992). Also, an understanding of how the matrix foliation evolves during progressive deformation, and how this relates to the geometrical arrangement between a matrix foliation and an included foliation in porphyroblasts, has improved (Bell & Rubenach 1983, Bell 1986). Individual porphyroblast minerals need not exhibit uniform relations with matrix foliation (*e.g.*, Reinhardt & Rubenach 1989). At the scale of stratigraphic units and bedding, the inhomogeneous rheology of

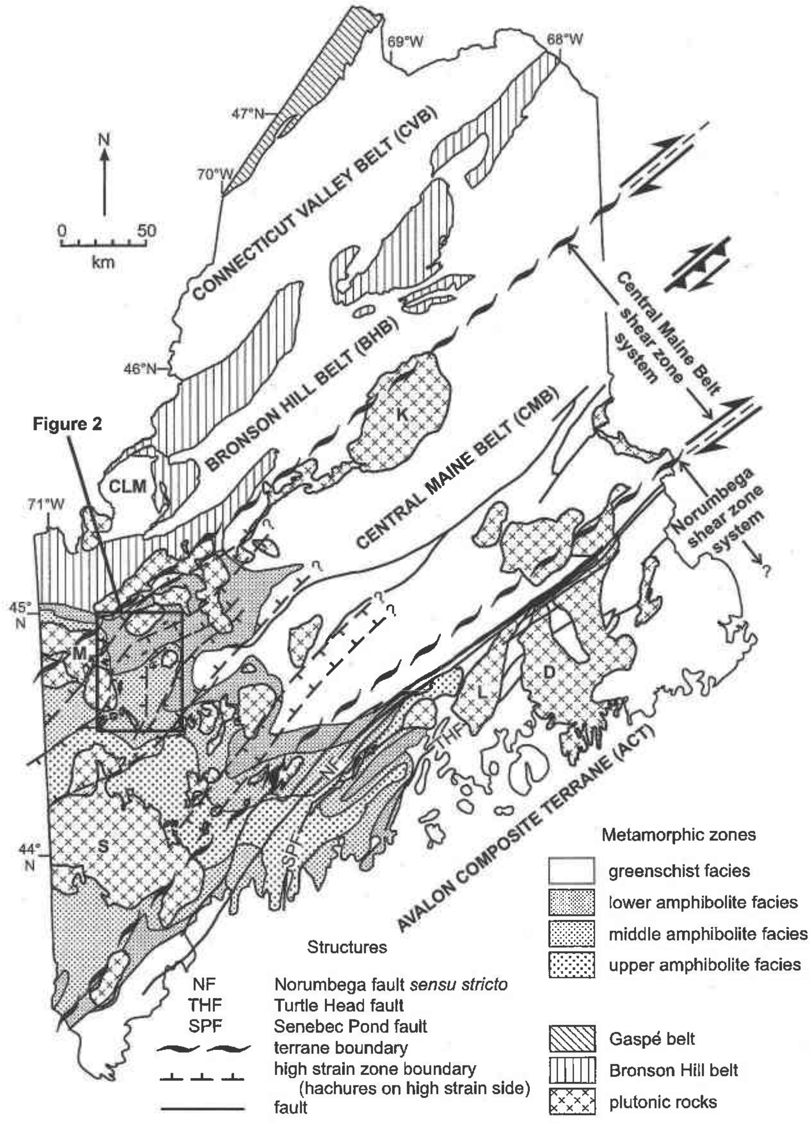

FIG. 1. Geological map of Maine, presented to show the principal belts, structural features, metamorphic zones and plutons [modified after Osberg *et al.* (1985) and Guidotti (1989), using data from Solar (1996) and Brown & Solar (1998a)]. Boundaries of higher-strain zones are located on the basis of mapping in the west-central Maine study area (box indicating area of Figure 2), and extrapolation based on the maps, field data and field descriptions in Osberg *et al.* (1985, 1995) and West & Hubbard (1997). Notice the distribution of plutons, which is apparently independent of the metamorphic zones (increasing grade along strike to the southwest), although plutons are arranged into belts that parallel the northeast–southwest regional structural trend. This suggests that the effect on metamorphism of the crust by advective heat due to plutons is local rather than regional. Granite plutons are labeled as follows: D: Dublois pluton, K: Katahdin pluton, L: Lucerne pluton, M: Mooselookmeguntic pluton, and S: Sebago pluton. CLM is the Chain Lakes Massif.

layered rocks causes partitioning of strain between weaker and stronger lithological domains over a large range of temperature in the crust, and strain is accommodated preferentially within the weaker units. Strain partitioning between units may cause fabric refraction (*e.g.*, Treagus 1983), and within units may exert control on sites of mineral dissolution, and nucleation and growth during metamorphism (Bell & Rubenach 1983, Bell *et al.* 1986, Bell & Hayward 1991, Spiess & Bell 1996). Thus, any interpretation about timing of mineral growth based on microstructural criteria must consider strain partitioning at all scales, the effects of protolith composition on rheology and metamorphic reactions, episodicity of mineral growth (whether due to sequential reactions during prograde metamorphism or successive overprinting of reactions due to multiple thermal events during pulsed flow of granitic magma), and possible diachroneity of processes at the length scale of an orogenic belt.

In this paper, we discuss some complexities that arise when metamorphism is synchronous with ductile deformation in a convergent, transpressive orogen. We illustrate these complexities using examples of matrix fabrics and porphyroblast geometries, including geometries of included foliations, from the Central Maine belt in west-central Maine. Our data show that some features of the metamorphic evolution do relate directly to contact metamorphism associated with granite plutons, particularly some polymetamorphic textures (*cf.* Guidotti 1993). The main regional metamorphism in this classic example of a high-T – low-P metamorphic belt, however, was strictly syntectonic and involved episodes of mineral growth during progressive deformation in a crustal-scale shear zone.

Regional Geological Setting

The Central Maine belt (CMB) of the northeastern United States, which corresponds to the Central Mobile belt of Maritime Canada (*e.g.*, Williams 1979, van der Pluijm & van Staal 1988), is one of several northeast–southwest-trending belts of rocks that comprise the northern Appalachian orogen. It is bounded in the northwest by Ordovician metasedimentary and metavolcanic rocks and Neoproterozoic basement rocks of the Bronson Hill belt (BHB), and is truncated in the southeast by the dextral-transcurrent Norumbega shear zone system (NSZ) (Fig. 1), along which the Neoproterozoic-to-Silurian Avalon Composite Terrane (ACT) was juxtaposed against the CMB. The CMB is composed of greenschist- to upper-amphibolite-facies metasedimentary rocks (Siluro-Devonian protoliths; Hatch *et al.* 1983), and plutonic rocks, dominantly granite. Metamorphic grade increases along strike to the southwest (Fig. 1). The main deformation, metamorphism and plutonism recorded within the CMB were the result of Devonian orogenesis (Eusden & Barreiro 1988, Smith & Barreiro 1990, Bradley *et al.* 1996, Solar *et al.* 1998).

In Maine, rocks within the CMB and the NSZ record Devonian – Carboniferous dextral transpression where strain was partitioned between synchronous, yet structurally distinct systems (Fig. 1): the dextral-transcurrent NSZ (Hubbard *et al.* 1995, West & Hubbard 1997, Ludman 1998) and the dextral-reverse (contractional) CMB shear zone system (Brown & Solar 1998a, b). Consequently, the sense of displacement of crustal blocks changes across strike from dextral-transcurrent in the southeast (along the NSZ) to dextral-reverse in the northwest (inside the CMB). To the north, in Maritime Canada, the dextral transpression followed earlier sinistral transpression recorded in rocks of the Brunswick subduction complex in the northern Miramichi Highlands of New Brunswick (de Roo & van Staal 1994, van Staal & de Roo 1995). Toward the end of Devonian–Carboniferous orogenesis in Maine, after deformation had ceased within the contractional CMB system, deformation continued along the NSZ, accommodating the dextral translation of the ACT from the northeast. This deformation produced narrow zones of mylonite during progressive localization of strain, overprinting structures associated with an originally wide (~30 to 40 km) zone of ductile shear (Hubbard *et al.* 1995, West & Hubbard 1997, Ludman 1998).

Structural geology

Much of the early work in the study area (Pankiwskyj 1964, Moench 1971, Moench & Hildreth 1976) concentrated on determining the stratigraphic units of the high-grade metasedimentary rocks, based on the compositional layering preserved as cm- to m-scale layers of pelite–psammite interpreted to reflect bedding. Individual stratigraphic units were defined based on thickness and relative proportion of each type of layer (the "Rangeley stratigraphic sequence" of Moench 1970). The stratigraphic units (Fig. 2) produced regional differences in structural style, discussed below.

In the study area, partitioning of strain has resulted in the development of zones of enhanced deformation (Fig. 2), which are shown by a high degree of parallelism between compositional layering and foliation. The foliation is a well-developed, domainal fabric that is continuous and pervasive at all scales. There is a consistent northeasterly strike and steep southeasterly dip of compositional layering and foliation across the width of the zones, and a penetrative moderately to steeply northeast-plunging lineation due to mineral elongation (Solar 1996, Brown & Solar 1998a). These steep zones anastomose around rocks in which compositional layering has variable strike and moderate dips, and foliation is not as strongly developed, although a penetrative moderately to steeply northeast-plunging lineation due to mineral elongation is present. A major difference between the two types of structural zone is seen in the style of folds (Fig. 2). Folds of stratigraphic sequences are delineated primarily at the map scale, but the inferred

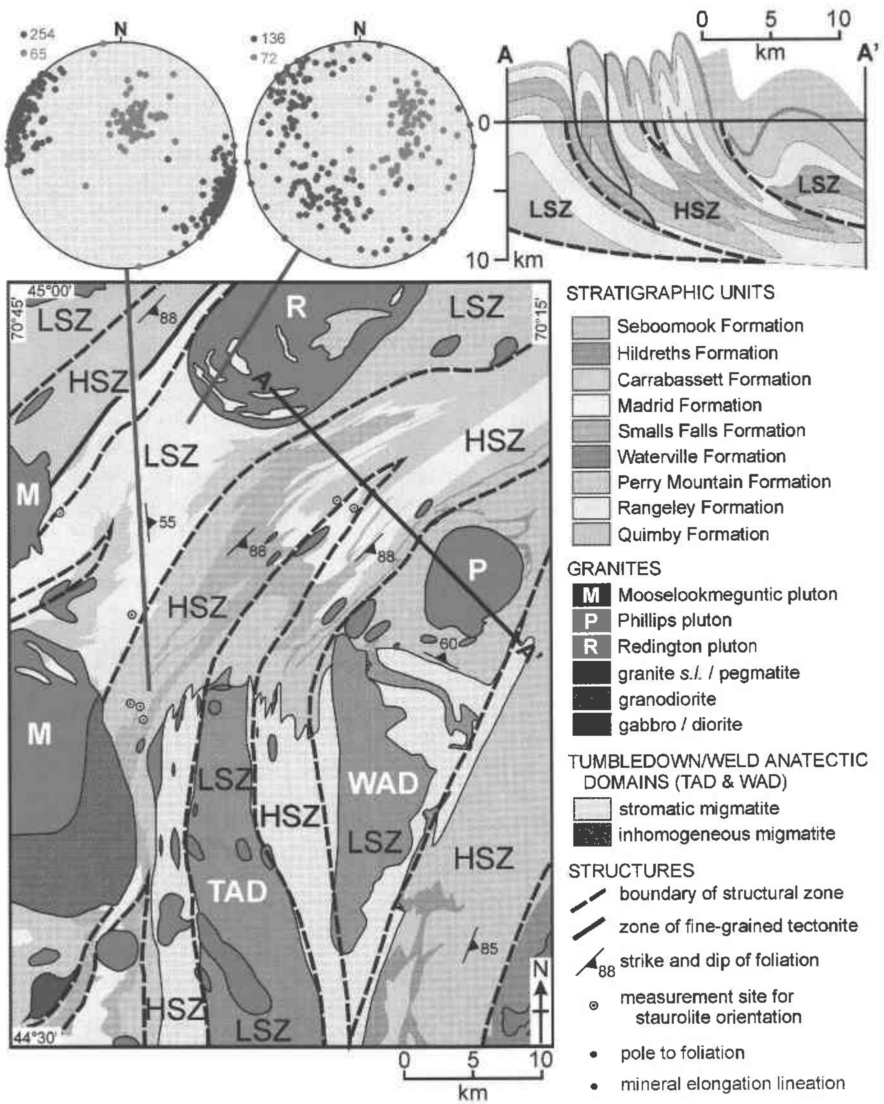

FIG. 2. Geological map of the study area, west-central Maine [modified after Pankiwskyj (1964, 1978), Moench (1971), Moench & Hildreth (1976), and Solar (1996); redrawn from Brown & Solar (1998a, Fig. 5b)], with representative structural data and true-scale structure section along the line A–A' with plutons omitted for clarity. Regional structures are superimposed on the stratigraphy (metasedimentary rocks of the "Rangeley stratigraphic sequence", Moench 1970) and the Tumbledown and Weld anatectic domains (TAD and WAD) as alternating higher- and lower-strain zones (HSZ, LSZ; see text for details on the distinction between these types of zones). Higher-strain zones include a well-developed pervasive and parallel, steeply southeast-dipping continuous foliation and a pervasive, moderately to steeply northeast-plunging mineral-elongation lineation. Lower-strain zones contain non-parallel structural elements, with weak or no foliation but a pervasive moderately northeast-plunging mineral-elongation lineation. There is a correlation between boundaries of stratigraphic sequences and the structural zones, which suggests *a priori* a stratigraphic control on the development of inhomogeneous regional plastic strain; strain was partitioned into rheologically weaker units. Stereograms are lower-hemisphere equal-area (Schmidt) projections of data on foliation and mineral-elongation lineations. The two stereograms are representative and show data from a larger set; these representative stereograms illustrate the differences in orientation of fabrics in higher-strain zones (consistent northeast–southwest striking, steeply dipping foliation and a moderately northeast-plunging mineral-elongation lineation) and lower-strain zones (variable orientation of planar structures and a moderately northeast-plunging mineral-elongation lineation). Sites of measurements of staurolite orientation are shown for comparison with data in Figure 4.

style of folding is corroborated by rare m-scale folds of compositional layering seen at outcrop. In the steep zones, folds are moderately to shallowly northeast-plunging, upright to overturned, and close to tight, whereas in the intervening zones, folds are shallowly northeast-plunging and upright, but open (Fig. 2). The transition in fold style coincides with the margins of the steep belts. In both types of structural zone, hinge lines of folds have northeasterly plunges that are similar in trend to the mineral-elongation lineation throughout the area. From these observations, we contend that all metasedimentary rocks in the study area are highly strained. However, rocks in the steep zones show nearly complete transposition of structures. Consequently, we interpret rocks in the steep zones to record qualitatively higher strain (higher-strain zones, HSZ in Figs. 2 and 4) than rocks in the intervening zones which we interpret to record qualitatively lower strain (lower-strain zones, LSZ in Figs. 2 and 4). At a regional scale, this belt of orogenic deformation is called the Central Maine belt shear-zone system (Fig. 1). We suggest that the higher-strain zones have accommodated relatively greater displacement than the lower-strain zones within the structural system.

Rocks in both types of zone record similar microstructures because they have a similar range of compositions, but in different proportions. Rock sequences in the higher-strain zones have a higher ratio of pelite to psammite in contrast to rock sequences that characterize the lower-strain zones. Non-anatectic metasedimentary rocks within the higher-strain zones have S > L to S–L fabrics, suggesting flattening to approximately plane strain. In contrast, non-anatectic metasedimentary rocks within the lower-strain zones have L > S fabrics, where mineral-elongation lineation is dominant, but foliation is weak, suggesting constrictional strain. Boundaries between these two types of structural zone are sharp, and coincide in many locations with contacts between stratigraphic units (Fig. 2). This suggests rheological control on the partitioning of strain by contrasting sequences in the stratigraphic succession.

Characterizing the rheology of rocks at mid-crust conditions is difficult because the strength of polyphase aggregates depends on the strengths, volume proportions, and geometrical arrangement of the individual phases; even at the same P–T–X_{fluid} conditions, these factors may change with progressive strain. Our field observations, however, suggest that units that have a higher proportion of pelite to psammite were weaker than those in which the proportion is lower. Consequently, deformation of the Rangeley stratigraphic sequence in west-central Maine was heterogeneous, and at the map-scale, strain was partitioned between stratigraphic units of contrasting rheology, but localized preferentially into the rheologically weaker units (*e.g.*, the Perry Mountain and Smalls Falls Formations, Fig. 2; Solar 1996, Brown & Solar 1998a). Within the weaker stratigraphic units, strain also was partitioned between cm- to m-scale pelite and psammite layers. As a result, strain was localized within the pelites at all scales during deformation. This is because the pervasive mica-dominated fabric in the pelites makes them weaker at higher grades of metamorphism (Shea & Kronenberg 1992, 1993), so that it is the relative proportion of pelite to psammite that governs the plastic strength of these rocks.

A non-coaxial component of deformation is suggested by the asymmetric microstructures described in this paper and by a consistent obliquity between boudinaged sheets of granite–pegmatite and layering or foliation, and is required to prevent space incompatibilities between the structural zones. The kinematics suggest that the Central Maine belt system of shear-zones accommodated dextral-reverse displacement during convergent, transpressive orogenesis (Brown & Solar 1998a). Thus, blocks on the southeastern side were obliquely thrust inboard to the northwest and along strike to the southwest along the higher-strain zones; further details about the structural framework are available in Brown & Solar (1998a, b).

Metamorphic zones

This area of west-central Maine (Fig. 2) marks the northern limit of migmatite in the CMB, the Tumbledown and Weld Anatectic Domains (TAD and WAD). This is also the part of the CMB where greenschist-facies rocks to the northeast increase in grade to upper-amphibolite-facies rocks to the southwest within 20 km along strike (Fig. 1). In both higher- and lower-strain zones, amphibolite-facies rocks are characterized by porphyroblasts of garnet, staurolite and andalusite (Fig. 3) enclosed within a matrix dominated by muscovite, biotite, quartz, plagioclase, and accessory opaque phases, generally graphite and pyrite. "Fibrolite" is an important fabric-forming matrix phase at upper amphibolite facies, especially in migmatitic rocks. Thus, the metamorphism is of high-T – low-P type, although the metamorphic field-gradient is the product of a minimum of two thermal pulses (*e.g.*, Guidotti 1989). Smith & Barreiro (1990) determined U–Pb monazite ages from samples of pelite collected from staurolite-zone rocks. Their results revealed two distinct concentrations of ages, interpreted to reflect regional metamorphism at 405–399 ± 2 Ma and contact metamorphism close to the Mooselookmeguntic pluton at 374–363 ± 2 Ma. Apart from the rocks surrounding the Mooselookmeguntic pluton, an important observation is the weak correlation between isograd undulations and structural zones (Fig. 4), suggesting that the thermal peak of regional metamorphism occurred before the end of the deformation. There is also a relation between plutonism and metamorphism suggested by the correlation between metamorphic zones and pluton margins.

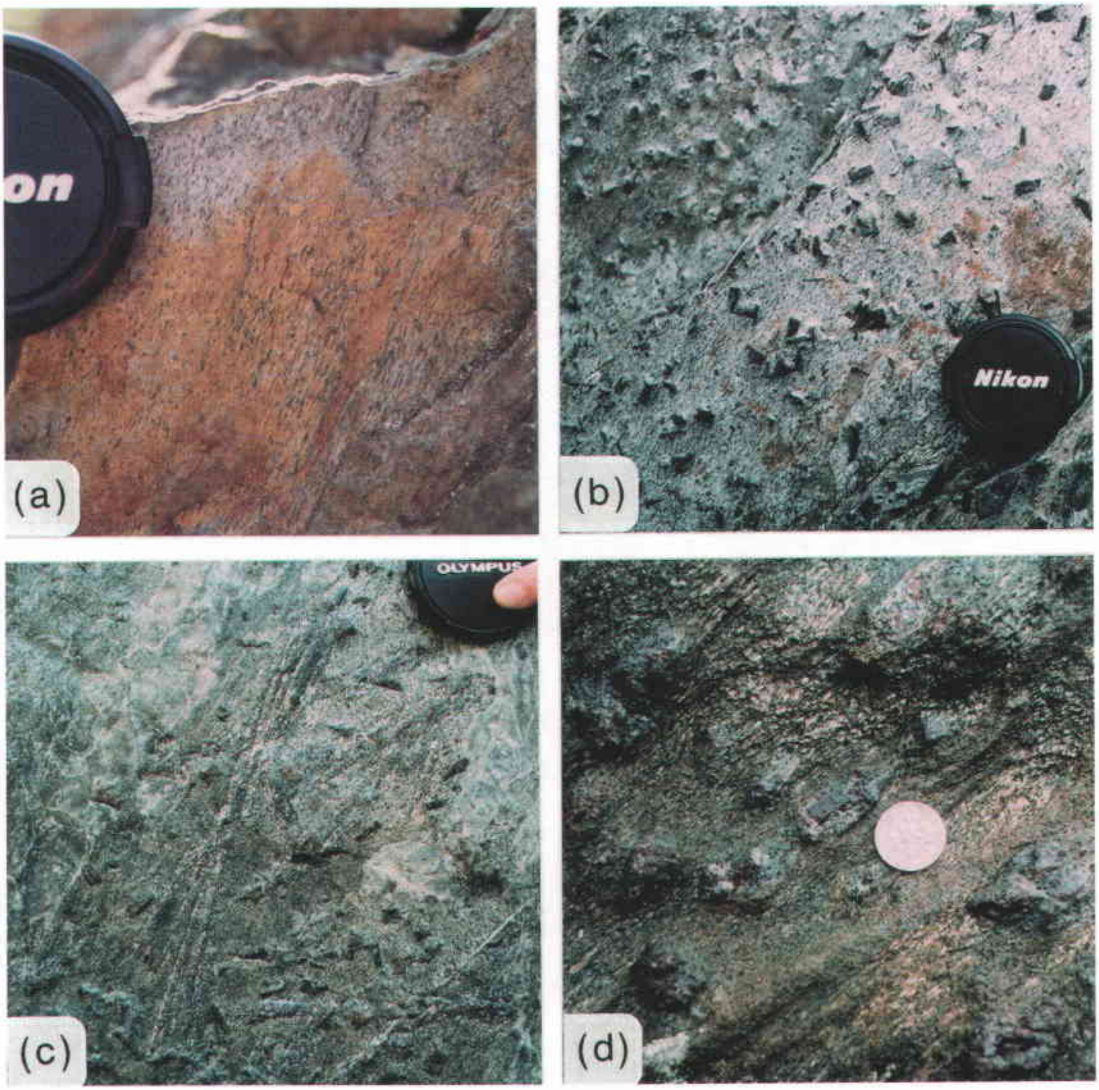

FIG. 3. (a) Steeply northeast-plunging foliation-parallel mineral-elongation lineations, shown in this example as biotite and opaque mineral blades in garnet–mica schist (pelite), higher-strain zone, Perry Mountain Formation, Coos Canyon, Byron, Maine (view is onto a vertical foliation plane, 016°, 90°; 016° is to left). Muscovite blades that define the foliation are preferentially aligned parallel to the biotite blades. (b) Staurolite porphyroblasts along a foliation plane in garnet – staurolite – mica schist (pelite), higher-strain zone, Perry Mountain Formation, Coos Canyon, Byron, Maine (plane = 017°, 88°E; 017° is to the left). Note the apparent preferred orientation of staurolite on the foliation surface, typical of all non-anatectic rocks in the staurolite zone. This is site (c) for staurolite measurements in Figure 4. (c) Partial pseudomorphs after andalusite, and staurolite porphyroblasts, on a foliation plane in garnet – staurolite – andalusite – mica schist (pelite), higher-strain zone, Perry Mountain Formation, Coos Canyon, Byron, Maine (north–northeast is to left). Note the pink core of the cm-scale pseudomorph after andalusite at right center and the subparallel alignment of the andalusite porphyroblast with the mineral-elongation lineation (steeply northeast-plunging). (d) Two phases of growth of staurolite porphyroblasts in garnet – staurolite – mica schist (semipelite), lower-strain zone, Rangeley Formation, Maine Rt. 17 (northbound), Township D, Maine (view is oblique across a weak foliation; northeast is to the left). Notice the staurolite porphyroblast near center grown inside a pseudomorph after staurolite. This locality is proximal to the northeast contact of the Mooselookmeguntic pluton, and the second growth of staurolite is interpreted to be associated with contact metamorphism in the aureole of the pluton.

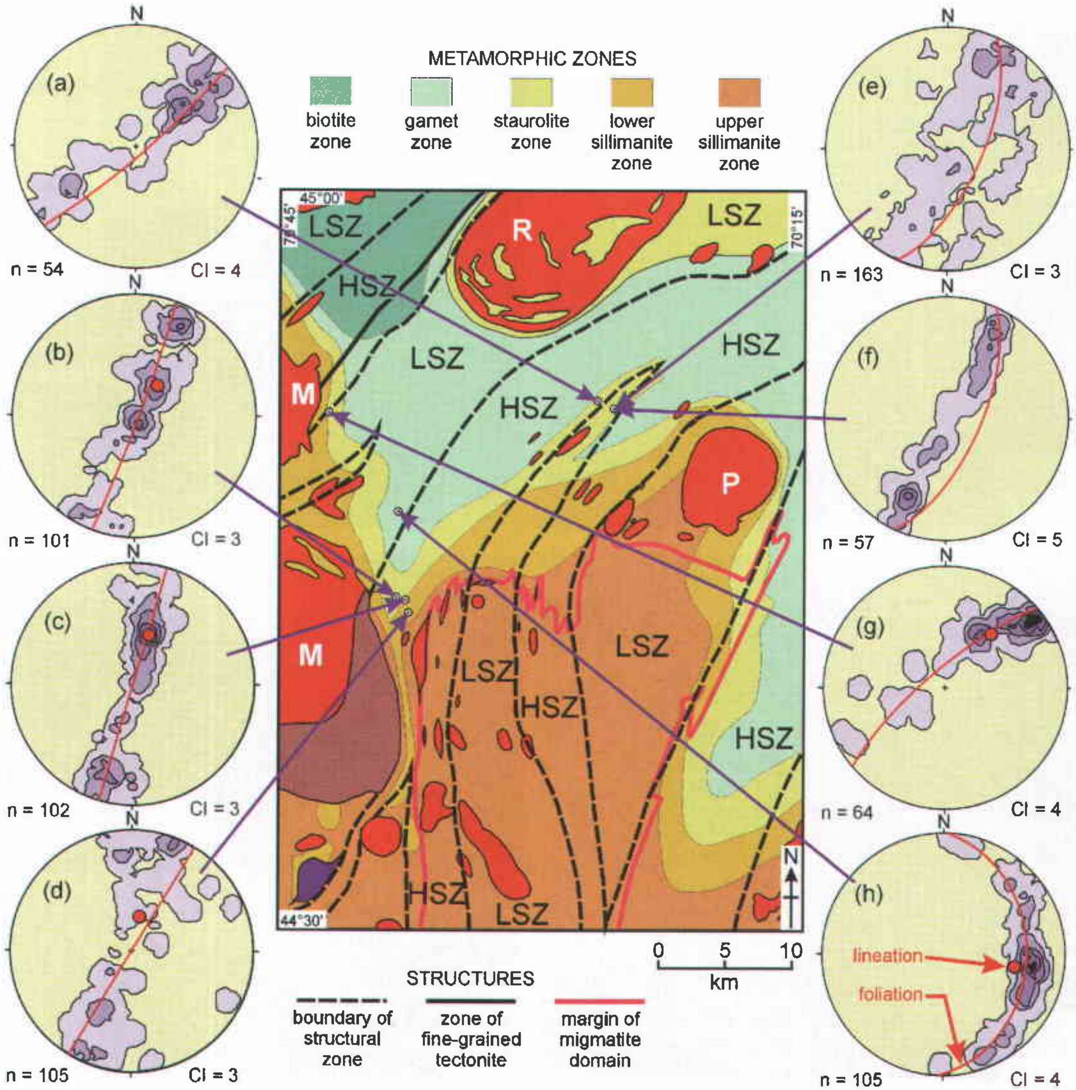

FIG. 4. Map of the study area, west-central Maine, to show metamorphic zones in relation to higher-strain and lower-strain zones, and plutons. Structural boundaries and plutons are taken from Figure 2. Notice the weak correlation between isograds and structural zones. Stereograms are contoured lower-hemisphere equal-area (Schmidt) projections of data on orientation of the long axis of staurolite (n = 7) and andalusite (n = 1) from seven localities, four from higher-strain zones (a, b, c, d) and three from lower-strain zones (e and f are from the same measurement surface at the same location, g, h). Stereogram (c) shows data from the foliation plane in Figure 3b. Contour intervals (CI) are indicated for each stereogram, lowest contour at 1% of data per 1% of area. All data represent measured euhedral porphyroblasts except for (f) and (h), which represent data from euhedral partial pseudomorphs after andalusite and staurolite, respectively. For comparison, each stereogram shows the great circle orientation of foliation and the attitude of matrix mineral-elongation lineation (where observed) measured at each site. Note that none of these data indicate random orientation of porphyroblasts. Instead, the porphyroblasts at all sites, irrespective of structural zone, show a robust correlation with foliation, describing a girdle of data whose average great circle attitude is subparallel to the foliation great circle. Also, most sites (stereograms a, b, c, g, h) show a correlation between the largest concentration of data and the attitude of the matrix lineation. The two sites that show the most scatter and the least robust correlation with fabric orientations (stereograms d, e, and f) correspond to the two localities of lowest strain among the measurement sites. Although data in (d) are from a site in a higher-strain zone, the locality measured is within a lenticular zone of lower strain 10 m wide, as discussed in text, and the poorer correlation of data with foliation and lineation at that site is interpreted to be the result of the lower strain in the rock.

Granites

Bodies of granitic rock occur at several scales, from individual cm-scale leucosomes in migmatite and m-scale sheets and lenses to km-scale plutons (Fig. 2). Inside the zones of higher strain, granite occurs as thin leucosomes and highly elliptical lenses (length-to-width ratio ≈ 6 to 10) that are concordant or weakly discordant to regional fabrics. The largest body of granite – granodiorite in the area, the Mooselookmeguntic pluton (Fig. 2), crosses boundaries between structural zones. The occurrence of the smaller plutons and the inhomogeneous migmatites in zones of lower strain suggests a relationship between structure, granite ascent and emplacement (Brown & Solar 1998a, b). It has been argued that in the zone of higher strain, melt was pumped along the flattening fabric (foliation) in the direction of the maximum principal finite elongation (manifested in the rocks as the mineral-elongation lineation), whereas in zones of lower strain, *en masse* transfer of melt plus residue occurred by granular flow (Brown & Solar 1998a, b). Melt stuck in zones of higher strain during transfer crystallized as thin leucosomes, and as irregular sheet-like bodies and lenses, whereas melt in zones of lower strain ponded to form plutons. Fugitive melt ponds in plutons because the solidus is approached with decreasing P, and stalls ascent in the upper crust. The flow path intersects the solidus around the level where increasing supported differential stress favors failure by fracturing at a high angle to the plane of ascent, enabling the formation of horizontal tabular plutons (Brown & Solar 1998b). These plutons may have discordant relations with the country-rock structures, and extend across the major structural zones within the CMB shear zone system, yet at the scale of the crust, they are syntectonic. Concordant U–Pb ages of zircon and monazite crystallization in granite from lenses in higher-strain zones from plutons are similar, in the range *ca.* 410–404 Ma, and distinctly older than the Mooselookmeguntic pluton (Solar *et al.* 1998).

Porphyroblast–Matrix Textural Relations

Non-anatectic rocks exhibit a penetrative grain-shape fabric defined by matrix phases (Fig. 3); this fabric is better defined within pelites. Pelites exhibit a continuous foliation in which P- and Q-domains are well developed (Fig. 5). These layers are most useful for this study because porphyroblast–matrix relations can be examined in both domains within the same thin section. We do not describe microstructures from rocks of the TAD and WAD areas because partial melting increases the potential for fabric overprinting, so that the migmatitic rocks are of limited use in the context of the present paper. To examine and assign structural significance to the microstructures in relation to macroscopic structures, thin sections from each sample were oriented as foliation-perpendicular orthogonal pairs, one parallel to the mineral-elongation lineation (defined by bladed muscovite and polycrystalline quartz in elongate ribbons), and the other perpendicular to lineation.

Matrix textures

Throughout the region, in non-migmatitic metasedimentary rocks, matrix crystals generally are 0.05 to 0.3 mm in diameter, and only phases that have high aspect-ratios with elongate or platy habits (*e.g.*, mica) are ~1 mm in length. In typical samples of the higher-strain zone, a pervasively planar continuous foliation is defined by ~0.1 mm thick, preferentially aligned laths of muscovite, and quartz that occurs as ~0.05 to 0.2 mm thick tabular crystals and 0.1 to 0.3 mm thick polycrystalline ribbons parallel to the main mica foliation (Fig. 5). The foliation is domainal where P-domains 3 to 15 mm thick are separated by Q-domains 4 to 8 mm thick. Each domain is defined by the same assemblage of minerals (muscovite – quartz – biotite – plagioclase – opaque phases ± garnet ± staurolite ± chlorite), but their proportions are different (*e.g.*, the P-domains are mica-rich), and the grain size is smaller in the P-domains (Figs. 6a, b). Quartz in ribbons shows no evidence of significant intracrystalline strain, but exhibits a preferred *c*-axis fabric (Figs. 6a, b). Quartz is segregated into layers of variable thickness, thickest in Q-domains and thinnest in P-domains (~0.05 mm), resulting in the more narrowly spaced foliation occurring within P-domains (Figs. 6c, d). Similar matrix microstructures are seen in lower-strain-zone rocks (Figs. 6e, f); however, planar grain-shape fabrics are much less well developed, and fabric elements are more widely spaced (~0.2 to 0.3 mm) (Fig. 7).

The same grain shapes of mica and quartz also define the mineral-elongation lineation in all rocks (Fig. 3a). In both higher- and lower-strain-zone rocks, muscovite laths are elongate, with a strongly preferred orientation, consistently moderate to steeply northeast-plunging; crystals exhibit a bladed habit, with their long dimension pervasively aligned within the plane of the foliation (Figs. 5, 7). Whereas the preferred linear alignment of bladed muscovite is pervasive in lower-strain-zone rocks, the planar alignment is less strongly developed (Figs. 6e, f, 7). In higher-strain-zone rocks, polycrystalline aggregates of quartz occur in ribbons elongate in the direction subparallel to coexisting bladed muscovite, whereas in lower-strain-zone rocks, polycrystalline quartz aggregates are rod-shaped, and their long dimension is oriented parallel to the long dimension of coexisting bladed muscovite (Figs. 6e, f, 7). Therefore, shapes of both muscovite and polycrystalline aggregates of quartz define ellipsoidal grain-shape fabrics in each structural zone, a stretched oblate ellipsoid in higher-strain zones and a prolate ellipsoid in lower-strain zones.

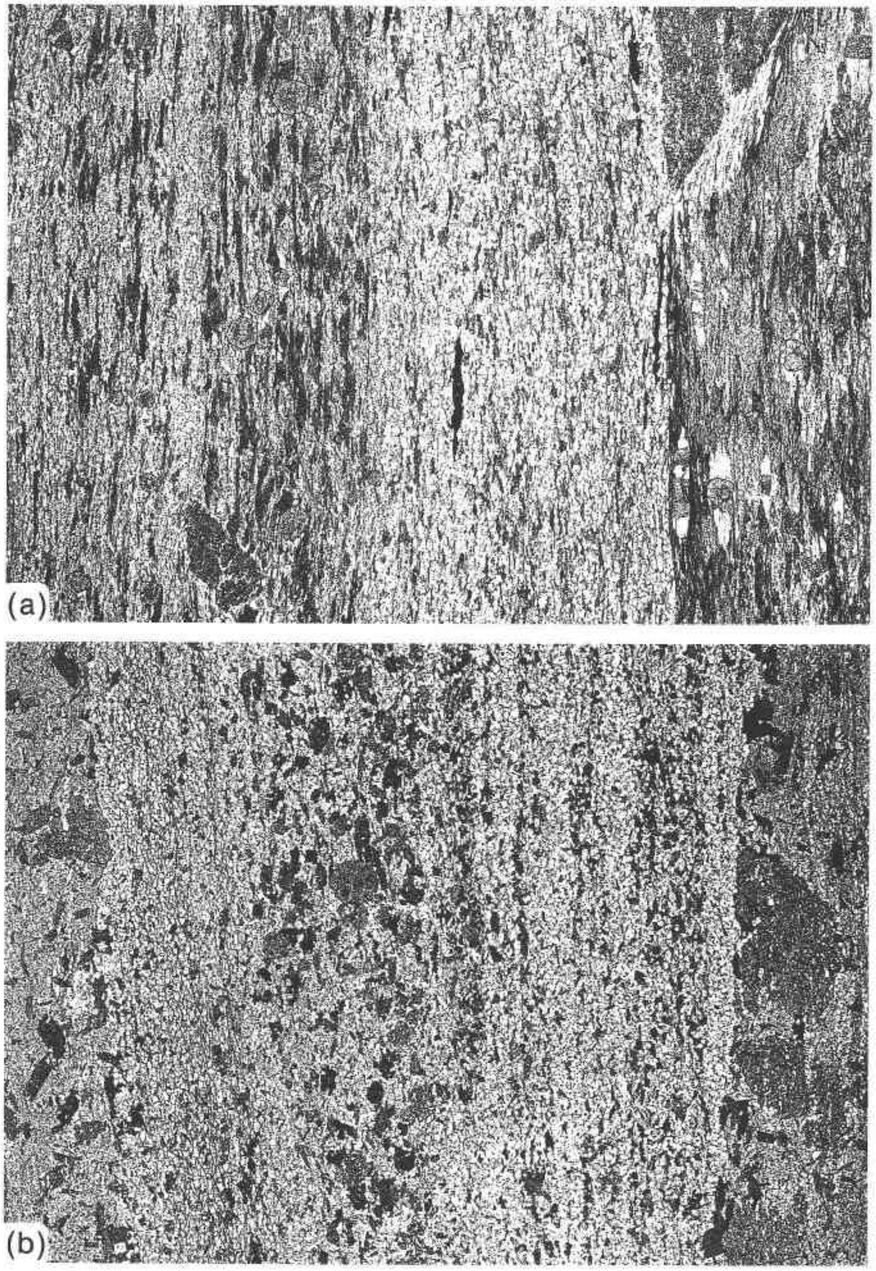

FIG. 5. Typical S ≥ L fabric in a rock from a higher-strain zone in thin-section-scale plane non-polarized transmitted light photomicrographs (garnet – staurolite – mica schist, Perry Mountain Formation; fields of view are ~17 mm in long dimension). Photographs (a) and (b) are paired lineation-parallel and lineation-perpendicular fields of view, respectively, from the same rock, but both are foliation-perpendicular. Compositional layering is seen in both views (mm-scale darker, finer-grained layers are P-domains, and lighter, coarser-grained layers are Q-domains). There is a pervasive layer-parallel continuous foliation, but a contrast in microstructure between the lineation-parallel view (a), which illustrates the elongate fabric, and the lineation-perpendicular view (b) down-plunge of the lineation. Notice in (a) the two texturally different porphyroblasts of staurolite. The lower left porphyroblast is in a Q-domain; it exhibits planar S_i inclined to and discontinuous with the S_e. The upper right porphyroblast is in a P-domain; it has planar S_i that is parallel to S_e, and unlike the first porphyroblast, it has a quartz-dominated pressure-shadow tail.

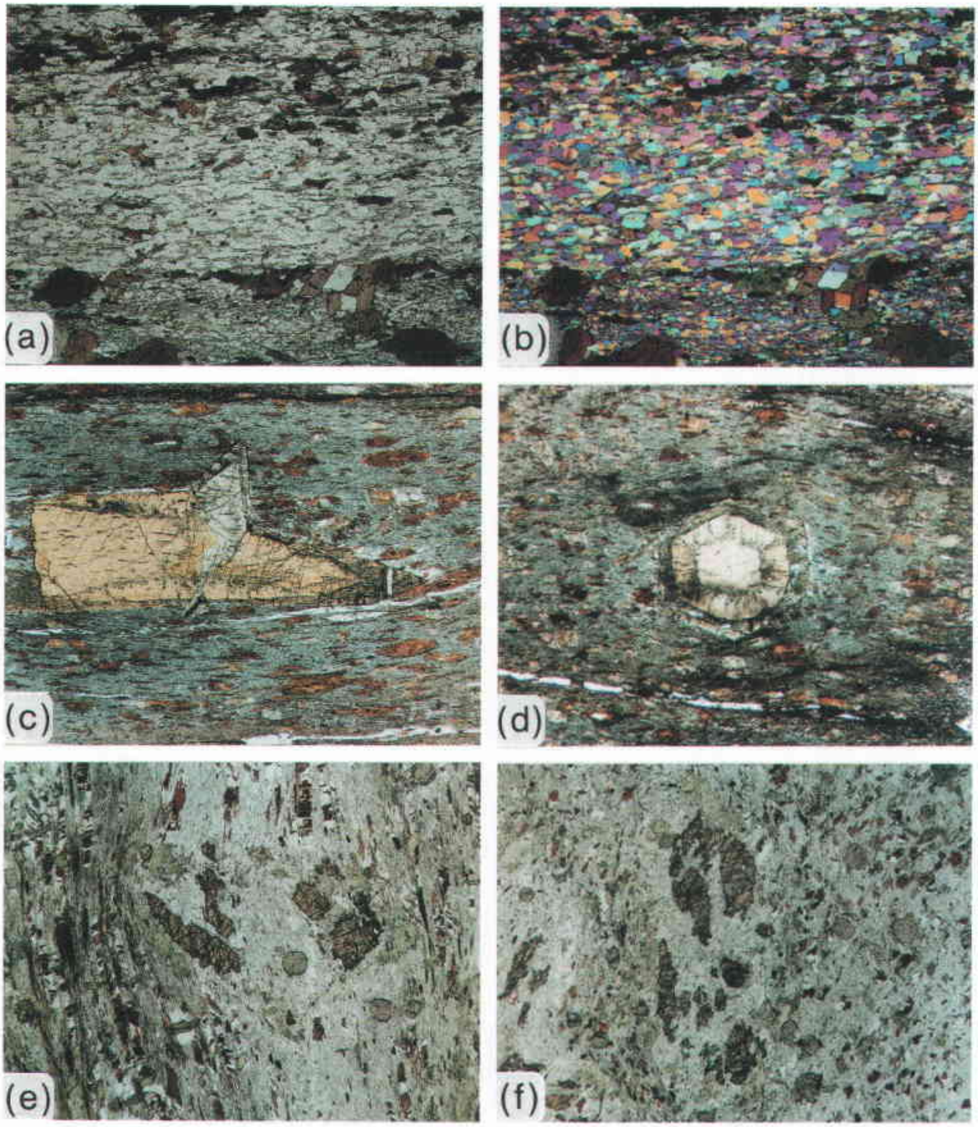

FIG. 6. Photomicrographs of lineation-parallel and lineation-perpendicular thin sections to illustrate preferred crystallographic fabric and the difference in strain recorded by rocks in the higher-strain (a, b, c, d) and lower-strain zones (e, f). (a) and (b) Views of matrix in a lineation-parallel photomicrograph of garnet – staurolite – mica schist from a higher-strain-zone rock in PPL and XPL, with first-order plate (long dimension is 5.5 mm). Transposed compositional layering is represented by a P-domain – Q-domain contact (P-domain at bottom). Notice that foliation is parallel to the compositional contact, and that grain size in the matrix is smaller in the pelite layer, showing a sharp transition in texture between the domains. The difference in *c*-axis fabric of quartz between P- and Q-domains is illustrated in (b). Notice the better alignment of quartz *c*-axes in the pelite layer (bottom) to indicate grain-size reduction recorded by that layer during matrix recrystallization. (c) and (d) Lineation-parallel and lineation-perpendicular views to illustrate the state of strain (stretched oblate ellipsoid) recorded by a pelite layer in a higher-strain zone (PPL, long dimension is 13.75 mm). Notice the pervasive foliation in both views, but in the lineation-parallel view (c), the elongate biotite has a higher aspect-ratio and the staurolite is more elongate than in the lineation-perpendicular view (d). (e) and (f) Lineation-parallel and lineation-perpendicular views to illustrate the state of strain (weakly flattened prolate ellipsoid) recorded by a typical pelite layer in a lower-strain zone (PPL, long dimension is 13.75 mm). Notice the biotite "pull-aparts" and the pervasively parallel development of the fabric in (e) in comparison with (f). The lineation-perpendicular view in (f) shows the biotite "pull-aparts" in down-plunge view. Both (e) and (f) show partial pseudomorphs of white mica and chlorite after staurolite porphyroblasts, typical of rocks in the lower-strain zones.

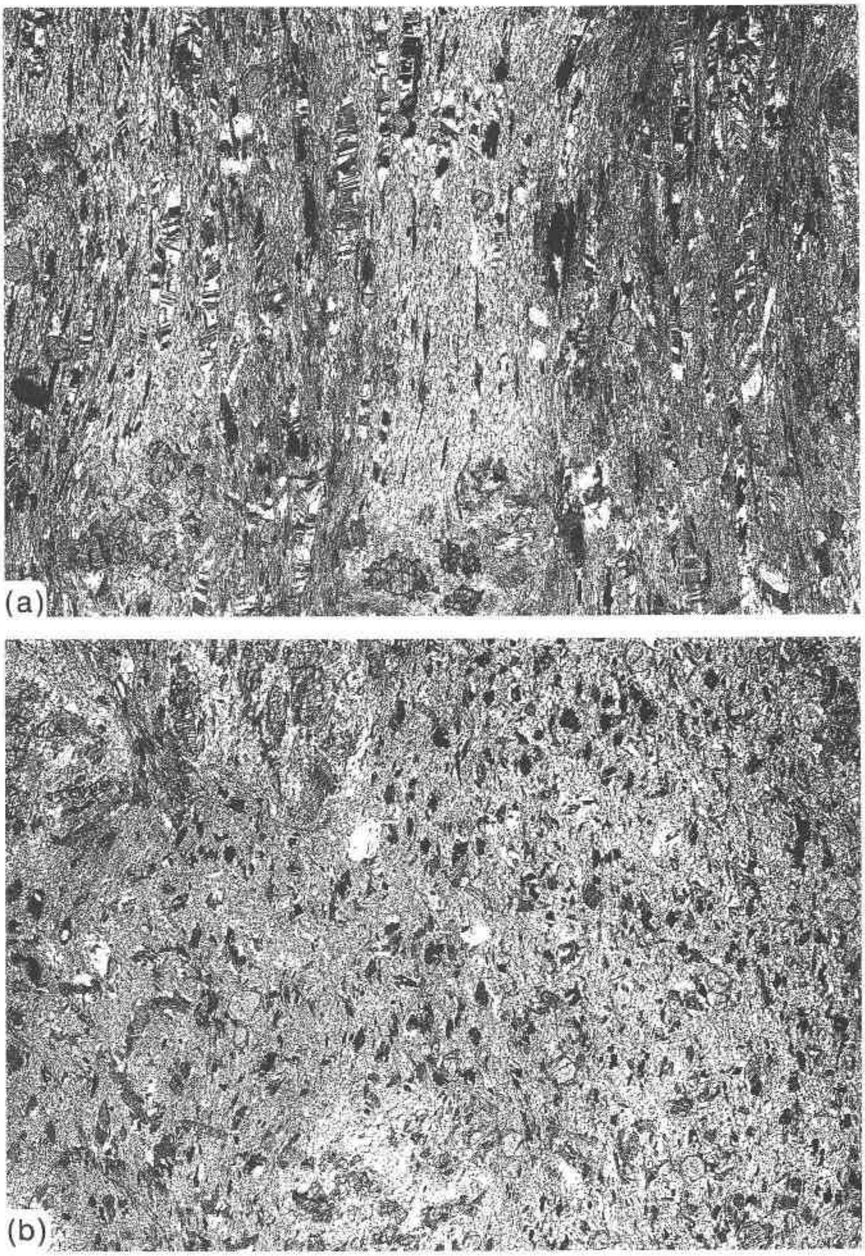

FIG. 7. Typical L > S fabric in a lower-strain zone rock in thin-section-scale plane non-polarized transmitted light photomicrographs (garnet – staurolite – mica schist, Rangeley Formation, fields of view are ~17 mm in long dimension). Photographs (a) and (b) are paired lineation-parallel and lineation-perpendicular fields of view, respectively, from the same sample, but both are perpendicular to the weak foliation. There is a contrast in microstructure between the lineation-parallel view (a), which illustrates the elongation fabric, and the lineation-perpendicular view (b) down-plunge of the lineation. Biotite, as "pull-aparts", records this microstructural difference; biotite "pull-aparts" are seen in long-axis section in the lineation-parallel view (a) (biotite is apparently spread perpendicular to the basal section with polycrystalline quartz in between); in contrast, these "pull-aparts" in lineation-perpendicular view (b) are seen in their down-plunge view (biotite is subequant along the basal section). The difference in grain shapes in the matrix between the two views records the L > S fabric typical in lower-strain-zone rocks; notice the lack of a well-defined planar microstructure, in contrast to fabrics in higher-strain zones (Fig. 5).

The major difference in matrix texture between rocks in the higher- and the lower-strain zones is illustrated using biotite microstructures. In higher-strain zones, biotite crystals commonly are bladed, with their long dimension subparallel to the muscovite lineation; they occur as ~0.2 to 0.3 mm thick "fish" in lineation-parallel view that record a dextral component of displacement. Biotite "fish" exhibit quartz-dominated pressure-shadow tails in the lineation-parallel sections (Fig. 8a). These tails are mostly asymmetrical with respect to matrix foliation. In comparison, lineation-perpendicular sections show biotite to be "fish"-shaped only rarely, without development of tails (Fig. 8b). Other biotite crystals have their *c* axis oriented within the plane of the foliation and are internally crenulated (Figs. 8c, d); typically they have symmetrical quartz-dominated tails (Fig. 8c). In contrast to biotite "fish" in higher-strain zones, biotite in lower-strain zones appears to have been pulled apart. In lineation-parallel view, these biotite crystals are ~0.3 to 0.5 mm thick and up to ~8 mm long (Figs. 6e, 7a, 8e). Quartz has infilled between the segments of each biotite crystal; we call these features biotite "pull-aparts". Biotite *c* axes are oriented subparallel to the long dimension of the "pull-aparts". In lineation-perpendicular view, the long dimension of biotite "pull-aparts" is seen down-plunge; biotite is mostly subequant and 0.2 to 0.3 mm across in this view (Figs. 6f, 7b, 8f). Thus, the "pull-aparts" are rod-shaped with long axes parallel to mineral-elongation lineation to define a stretching lineation in the same direction. This is an important difference in comparison with biotite in higher-strain-zone rocks, where *c* axes of fabric-forming biotite are subnormal to foliation (Figs. 8a, b), except where crenulated (Figs. 8c, d).

Matrix fabric in higher-strain zones is variable at the meter scale. Between m-scale zones of planar and uniform foliation (Fig. 5), lenticular zones of crenulated and non-parallel foliation 1 to 10 m wide exist with their long dimension parallel to regional fabric trend (northeast – southwest). These zones have axial ratios of 3 to 5, surrounded by foliation that is typically planar and define a pattern of anastomosing foliation. Besides a pervasive crenulation (Fig. 9), a major textural difference between these zones and their surrounding rocks is that their fabric has thicker (~0.3 to 0.5 mm) polycrystalline quartz in ribbons between mica folia in comparison to the surrounding pervasively planar and more narrowly foliated grain-shape fabric.

Garnet porphyroblasts

Garnet porphyroblasts are 0.4 to 2 mm in diameter and euhedral to subhedral, rarely anhedral. In samples from higher-strain zones, crystals vary from relatively inclusion-free (Figs. 10a, b) to inclusion-rich (up to 40% inclusions by area) (Figs. 10c, d, e). Commonly, garnet has quartz-dominated pressure-shadow tails, best developed in staurolite-zone pelitic rocks (Figs. 10a, b, c, d, e); most of these tails are symmetrical about the garnet crystals, but some are asymmetrical (Fig. 10a). Tails are present in both lineation-parallel and lineation-perpendicular views; the longer tails are always seen in the lineation-parallel sections, similar to coexisting biotite. In contrast, garnet crystals in lower-strain zones have tails in the lineation-parallel section only.

Garnet porphyroblasts in samples from higher-strain zones have inclusion-free rims of variable thickness around cores with common inclusions (Figs. 10c, d). Inclusion density is nominally constant in any one thin section. In garnet porphyroblasts with a larger volume of inclusions, these inclusions define a straight foliation (S_i) that is discontinuous with and typically shallowly oblique to matrix foliation (S_e) (Figs. 10c, d). Inspection among populations of garnet porphyroblasts in fifteen lineation-parallel thin sections shows the angular relationship between S_i and S_e to be 10 to 50° (Figs. 10c, d). In most thin sections, some porphyroblasts have S_i parallel to S_e. Furthermore, in garnet where S_i is not parallel to S_e, S_i in most garnet crystals in a single thin section has the same sense of obliquity with respect to S_e (Figs. 10c, d), which is similar to the obliquity of S_i in coexisting porphyroblasts of staurolite (Fig. 10e). The sense of obliquity in each lineation-parallel thin section is the same; apparent dips of S_i have pitches relative to S_e either in an up- or down-plunge direction of the mineral-elongation lineation. This varies with location across the regional strike. Only rarely does S_i apparently dip in both directions, and in these cases, one direction of dip is dominant (~90° of observations).

Rocks from close to the Mooselookmeguntic pluton have garnet porphyroblasts that show inclusion-free rims that progressively cut matrix foliation with proximity to the pluton, whatever the structural zone (Fig. 10f); we interpret these rims to be later overgrowths. The thickness of these overgrown rims systematically increases with proximity to the Mooselookmeguntic pluton, until nominally inclusion-free garnet porphyroblasts are developed that completely overgrow matrix foliation (compare Figs. 10c, f). Some garnet porphyroblasts are partially to completely replaced by chlorite, principally in samples of lower-strain-zone rocks collected from inside the aureole of the Mooselookmeguntic pluton.

Staurolite and andalusite porphyroblasts

Staurolite and andalusite porphyroblasts are euhedral to subhedral mm- to cm-size crystals; all are inclusion-rich. Both phases show different degrees of pseudomorphic replacement, dominantly by muscovite and chlorite ± biotite; the replacement varies with location. Typically, foliation is wrapped around these porphyroblasts and openly crenulated, even where the crystal was completely replaced (Figs. 6d, f). In rocks within higher-strain zones, uniformly distributed porphyroblasts of staurolite with S_i parallel to S_e occur (Figs. 11a, b), as

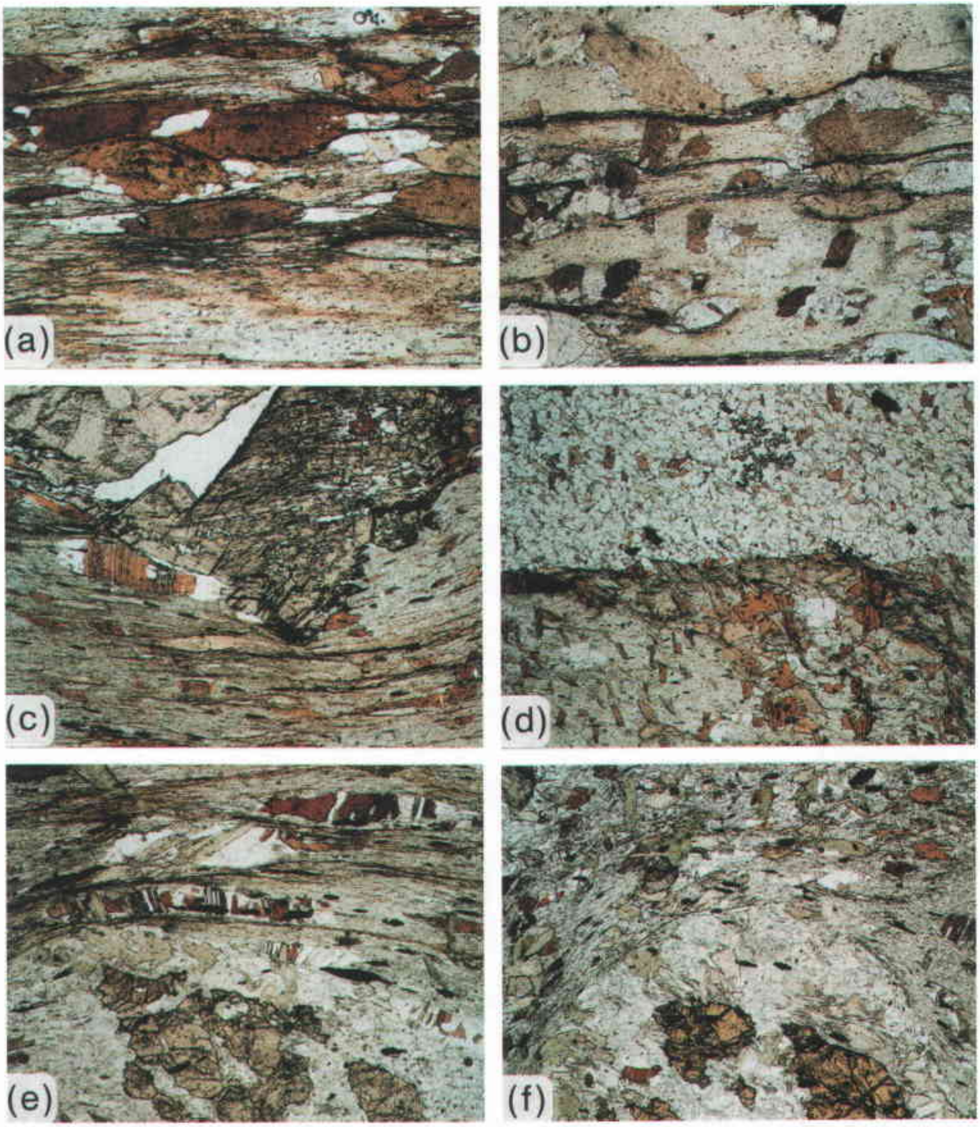

FIG. 8. Photomicrographs of biotite microstructures in rocks from higher-strain and lower-strain zones. (a) and (b) Biotite "fish" in higher-strain-zone pelite in lineation-parallel and lineation-perpendicular views, respectively (PPL, long dimension is 5.5 mm). Notice the quartz-dominated pressure-shadow tails around the central biotite "fish" in the lineation-parallel view that are not seen in the lineation-perpendicular view, where "fish" are seen end-on. This geometry illustrates tail elongation in the lineation-parallel direction, consistent with fabric geometry of the matrix, and the asymmetry of the tails in (a) is consistent with the asymmetry of tails around garnet porphyroblasts. (c) and (d) Biotite flattened across the foliation in higher-strain-zone pelite in lineation-parallel and lineation-perpendicular views, respectively (PPL, long dimension is 5.5 mm). Notice the crenulated biotite with symmetrical quartz-dominated pressure-shadow tails in the lineation-parallel view (c) that is seen end-on in the lineation-perpendicular view (d). Also notice the textural zones in the staurolite porphyroblast in (c), and the P-domain (lower) – Q-domain (upper) contact, and secondary high-angle foliation defined by these biotite crystals in (d). (e) and (f) Biotite "pull-aparts" in lower-strain-zone pelite in lineation-parallel and lineation-perpendicular views, respectively (PPL, long dimension is 5.5 mm). Quartz fills in between the biotite flakes, interpreted to have been spread apart. The "pull" is illustrated by comparing (e) and (f), where biotite "pull-aparts" are seen along their lengths in the lineation-parallel view, but down-plunge in the lineation-perpendicular view. The "pull" was, therefore, in a direction parallel to the mineral-elongation lineation, defined by bladed muscovite, which suggests the biotite "pull-aparts" also define the stretching lineation. Notice the partial pseudomorphs of white mica and chlorite after staurolite in both views.

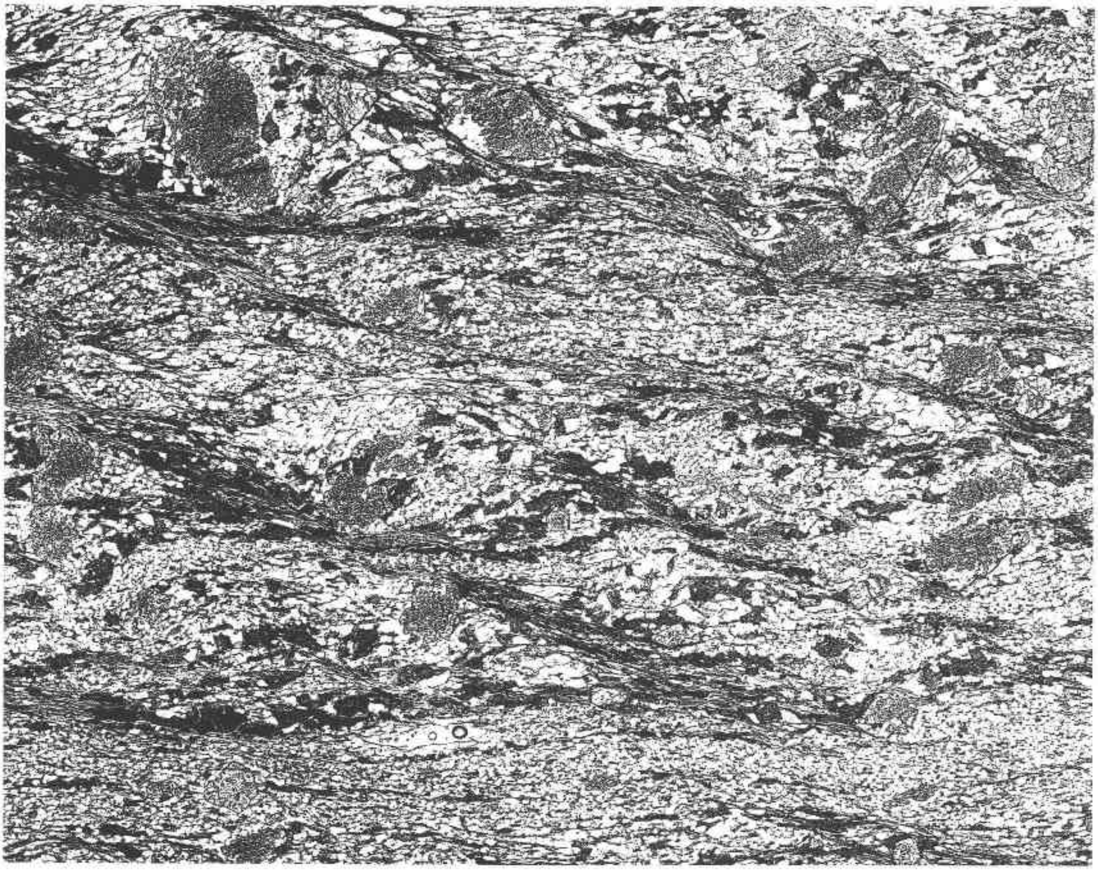

FIG. 9. Pervasive anastomosing matrix foliation typical of fabric in rocks that occupy lower-strain zones within the higher-strain zones (garnet – staurolite – mica schist, Perry Mountain Formation, plane non-polarized transmitted light photomicrograph, long dimension is ~17 mm). This section is oriented lineation-parallel, and the main foliation is parallel to the long dimension of the field of view. Staurolite and garnet porphyroblasts are located inside Q-domain microlithons. Asymmetry of folia is consistently dextral in this view, consistent with other kinematic indicators (*e.g.*, Figs. 10a, b).

well as staurolite porphyroblasts with S_i inclined to S_e (Figs. 10e, 11c). Similar to the populations in garnet porphyroblasts, S_i in staurolite porphyroblasts is inclined at a consistent angle and sense of obliquity to S_e, and with the same sense of obliquity as S_i in garnet in the same thin section (Fig. 10e). Internally, some staurolite crystals are distinctly zoned; each zone has a different density and orientation of S_i relative to adjacent zones (commonly two to three zones, Figs. 11c, d). This feature is developed best in staurolite within P-domains. Staurolite porphyroblasts in Q-domains generally do not show as pronounced zoning (Fig. 10e). The different textures are found in the same sample or closely spaced samples. Typically, the rims of these crystals exhibit inclusions that are less elliptical than inclusions in the other zones (Fig. 11c). In each case, staurolite porphyroblasts have pronounced quartz-dominated pressure-shadow tails, longest in the lineation-parallel view (Figs. 11a,b), but also seen in the lineation-perpendicular view in samples from higher-strain zones, consistent with tail geometries around both biotite and garnet.

White mica, biotite and chlorite, in clusters of relatively coarse-grained laths (0.4 to 0.6 mm thick), variably replace staurolite, and appear as reaction rims to complete pseudomorphs; these occur throughout the region arranged in m-scale zones whose margins are concordant with lithological layering and foliation. Typically, replacement of staurolite has preserved the porphyroblast – matrix textural relations. In rocks within higher-strain zones, staurolite is partially replaced, whereas in rocks in lower-strain zones, replacement commonly is nearly complete (*e.g.*, Figs. 6e, f, 8e, f),

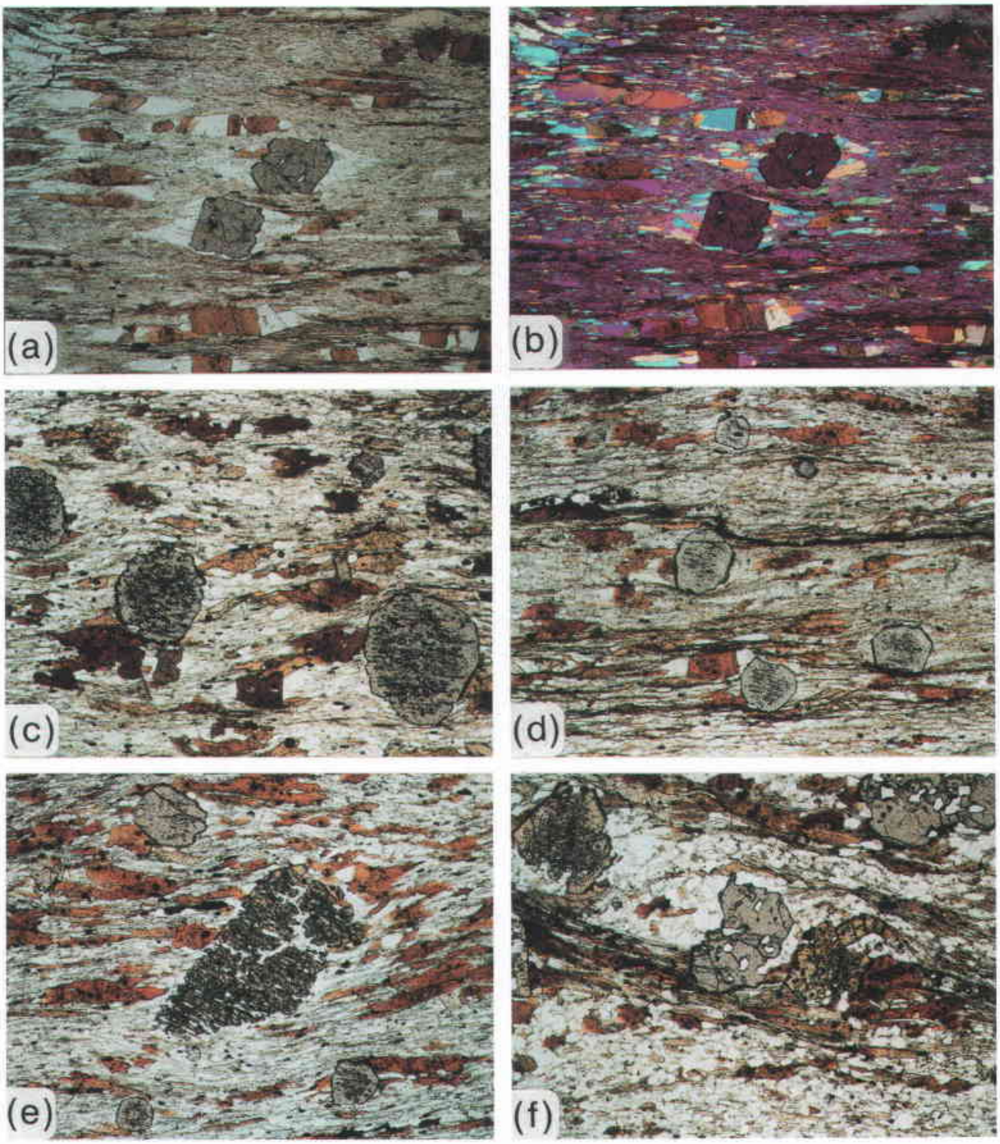

FIG. 10. Photomicrographs of garnet and staurolite microstructures in higher-strain zone rocks. (a) and (b) PPL and XPL views, with first-order plate, respectively, of inclusion-poor garnet in lineation-parallel view in a P-domain (long dimension is 5.5 mm). Notice the coarser-grained quartz-dominated pressure-shadow tails around the garnet porphyroblasts. The asymmetrical geometry of these tails is the same as the tail geometry around biotite "fish" and shows elongation parallel to the mineral-elongation lineation in the matrix. Also notice in (b) the preferred crystallographic fabric in quartz in the top left portion in the field of view. (c) and (d) Garnet porphyroblasts in Q-domains show obliquity of planar S_i relative to S_e (oriented parallel to the long dimension of the field of view) and inclusion-poor rims (PPL, long-dimension is 5.5 mm). S_i in each porphyroblast of garnet makes a similar angle with S_e, which suggests that growth of the porphyroblasts took place prior to final modification of the matrix. Notice the thicker inclusion-free rims around garnet in (d), which is located closer to the Mooselookmeguntic pluton (≈ 5 km and 3 km from the contact, respectively). (e) Garnet and staurolite porphyroblasts in a Q-domain (lineation-parallel view) that illustrate similarly oblique S_i relative to S_e (PPL, long dimension is 5.5 mm). Note the inclusion-free rims around garnet porphyroblasts. (f) Inclusion-poor garnet and staurolite grown into and across the crenulated foliation in the matrix (lineation-parallel view) to indicate porphyroblast growth after the end of matrix modification (PPL, long dimension is 5.5 mm). This rock is located approximately 100 m from the mapped contact of the Mooselookmeguntic pluton with the metasedimentary rocks.

particularly in rocks proximal to the Mooselookmeguntic pluton. In rocks in higher-strain zones close to the margin of the Mooselookmeguntic pluton, unaltered and texturally zoned grains of staurolite exhibit rim growth that cuts matrix foliation (Fig. 10f).

Partial to complete replacement of andalusite by muscovite and chlorite is commonly observed, but the original generally euhedral shape is preserved. Andalusite is preferentially oriented within the foliation and subparallel to lineation (Figs. 11e, f), as they are longest in lineation-parallel sections. The matrix around these porphyroblasts preserves quartz-dominated pressure shadows, even around replaced crystals. The mica that replaces andalusite generally is preferentially aligned with the cleavage of andalusite and the fabric of the matrix. This is seen in both lineation-parallel and lineation-perpendicular views. Where andalusite has survived, generally it has a pink core inside euhedral partial pseudomorphs. Commonly, small blebs of sillimanite (0.01 to 0.05 mm in diameter) are seen inside the pink cores, which we interpret to replace andalusite, whereas no sillimanite occurs in the matrix.

Orientation of porphyroblasts

On inspection, porphyroblasts of staurolite and andalusite are aligned with the foliation, and many are aligned subparallel to the mineral-elongation lineation defined by matrix phases (Figs. 3b, c). The relation between porphyroblast orientation and major structures was investigated by using the orientation of long axes of staurolite measured in the field at seven localities (HSZ: n = 4, LSZ: n = 3), and long axes of partial pseudomorphs after andalusite were measured in the field at one of these localities. At each measurement site, a single foliation plane was selected on which positive relief of staurolite grains was produced by the natural preferential erosion of grains of matrix minerals. Since most staurolite porphyroblasts are euhedral, this texture enables the determination of crystal faces of staurolite on foliation-parallel surfaces. Care was taken to avoid measuring any grain more than once, and to measure grains uniformly over each surface. In one case (Fig. 4h), long axes of pseudomorphs after euhedral staurolite were measured.

Results are presented in Figure 4. Note that on each contoured stereogram, the long axes of porphyroblasts have a strongly preferred orientation, whatever the structural zone. There is a uniform correlation between the girdle of data defined by the long axes of staurolite and the orientation of the foliation surface measured (plotted as the red great circle), and between the trend and plunge of the largest concentration of data and the orientation of the mineral-elongation lineation defined by matrix minerals on that foliation surface (plotted as the red filled circle). In relation to structural zone, there is generally a stronger alignment in samples from the higher-strain-zone localities in comparison to samples from the lower-strain-zone localities.

INTERPRETATION

Although some porphyroblast–matrix relations from the study area in west-central Maine suggest static metamorphism after the end of regional penetrative deformation (*e.g.*, progressive overgrowth of fabric by rims on porphyroblasts during contact metamorphism by the Mooselookmeguntic pluton), most regionally developed textures reported in this paper require an alternative explanation. The following data are consistent with an interpretation of syntectonic metamorphism:

(i) Regardless of structural zone, matrix textures have pervasively developed preferred grain-shape fabrics that record a tectonic strain ellipsoid (*cf.* Passchier & Trouw 1996). Since fabrics in both types of zone are defined by the same assemblage of minerals at the same metamorphic grade, we interpret the parallelism of mineral-elongation lineation at the regional scale to reflect essentially synchronous development of the fabric. In rocks in higher-strain zones, the following microstructures describe a flattening fabric and a stretched oblate ellipsoid, close to plane strain ($k \leq 1$): 1) the pervasively planar and closely spaced penetrative mica and tabular-quartz continuous foliation, with bladed muscovite, biotite and elongate polycrystalline quartz ribbon lineations, and 2) pressure-shadow tails in the plane of foliation, biotite "fish" and crenulated porphyroblasts of biotite. Thus, we interpret the higher-strain zones to be zones of apparent flattening. In contrast, in rocks of lower-strain zones, the following microstructures describe a constrictional fabric and a prolate ellipsoid ($k > 1$): 1) the fabric, which is defined by a pervasively parallel, penetrative high-aspect bladed muscovite lineation but only weak foliation, and 2) polycrystalline quartz rods, pressure-shadow tails and biotite "pull-aparts". Thus, we interpret the lower-strain zones to be zones of apparent constriction. The regionally consistent northeast-plunging long dimension of these linear features in both higher-strain and lower-strain zones suggests a genetic relation between partitioned regional deformation and the development of shapes of matrix grains. Preferred *c*-axis fabrics in quartz, and smaller grain-size in P-domains relative to Q-domains, suggest dynamic recrystallization. If regional metamorphism were static, grain-size coarsening would be expected to have occurred; this is not observed. Alternatively, we interpret these fabrics to record grain-size reduction and recrystallization to accommodate accumulation of plastic strain.

(ii) Pressure-shadow tails around biotite "fish", and porphyroblasts of garnet and staurolite are well-established indicators of strain (*e.g.*, Passchier & Trouw 1996), and their existence records dynamic matrix strain during regional penetrative deformation. As seen in mutually perpendicular thin sections, tails exhibit preferred elongation in a direction parallel to the coexisting mineral-elongation lineation defined by bladed muscovite and biotite, and by elongate polycrystalline quartz ribbons and rods (Figs. 5, 7). Where asymmetrical, these

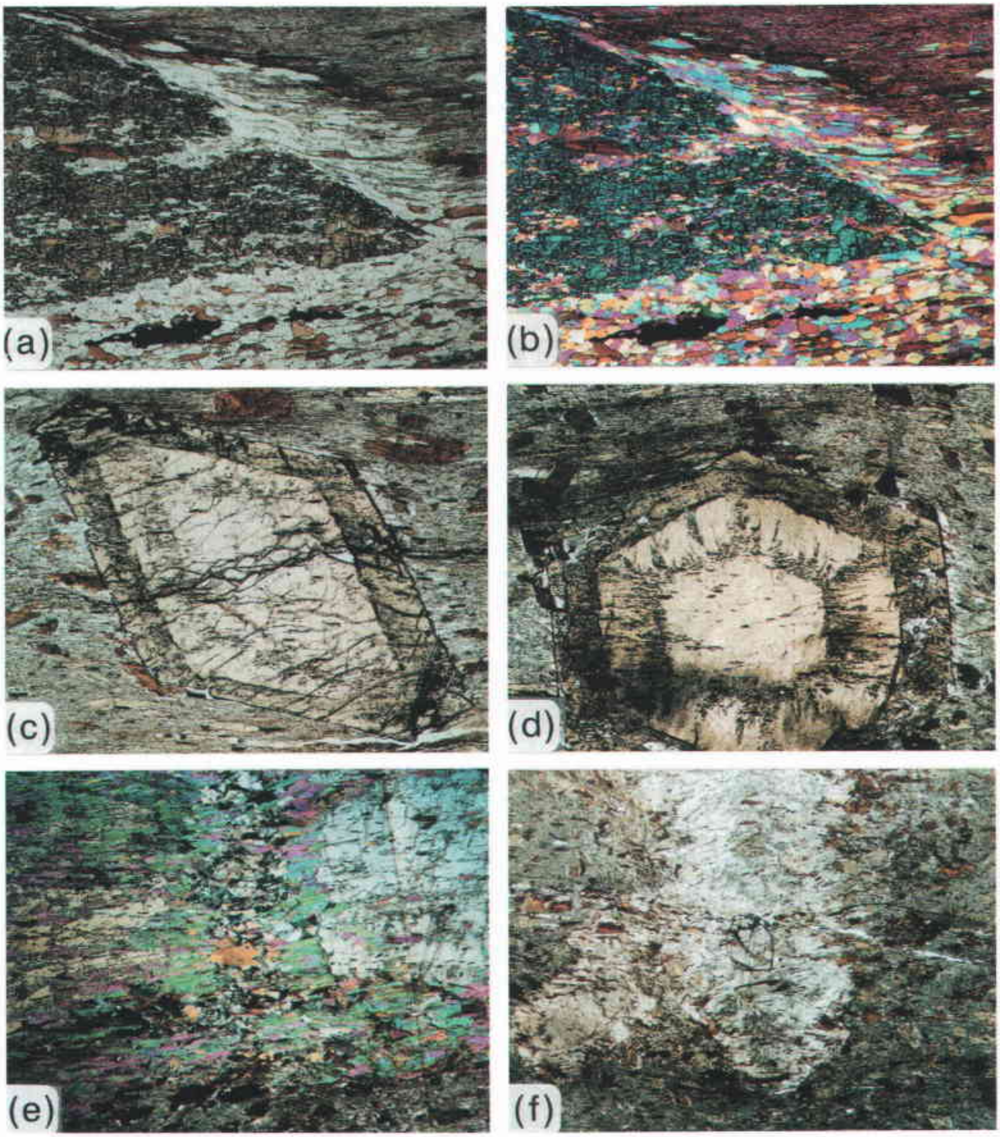

FIG. 11. Photomicrographs of staurolite and andalusite microstructures in higher-strain-zone rocks. (a) and (b) PPL and XPL, with first-order plate, views of a staurolite porphyroblast in lineation-parallel view with planar S_i oriented sub-parallel to S_e in a P-domain (long dimension is 5.5 mm). Notice the well-developed quartz-dominated pressure-shadow tail around the staurolite crystal on its upper right-hand side, elongate in the lineation-parallel direction. Also notice the subgrain development in the quartz illustrating plastic strain in the tail. The bottom of the porphyroblast represents a change in composition between a P-domain (above) and a Q-domain (below). (c) and (d) Microstructural and textural zoning of staurolite porphyroblasts in lineation-parallel and lineation-perpendicular views, respectively (PPL, long dimension is 5.5 mm). Each of these porphyroblasts contain three major textural zones, illustrated by both S_i density and S_i geometry, and between zones 2 and 3 by concentration of the opaque mineral along the interface. Note the difference in matrix geometries where biotite in (c) has a higher aspect-ratio than in (d), showing the elongation of these crystals parallel to the mineral-elongation lineation. (e) and (f) Partial white mica and opaque mineral pseudomorphs after andalusite in lineation-parallel (XPL) and lineation-perpendicular (PPL) views, respectively (long dimension 13.75 mm). Each view shows the same pseudomorph (~18 cm long parallel to lineation), along its length in (e) and down-plunge in (f). In lineation-parallel view, this pseudomorph is seen to be boudinaged, with quartz and mica infilling the interboudin partition. The stretch of the boudins indicates andalusite growth before the end of deformation, and the alignment of pseudomorphic minerals with the matrix foliation suggests replacement during dynamic modification of the matrix.

tails illustrate shear strain along the direction of these mineral elongations. Thus, tail geometries provide a reliable kinematic indicator; they show dextral-reverse oblique shear in the plane of the foliation, in the direction of the lineation during recrystallization or reorientation (or both) of matrix minerals around porphyroblasts. The asymmetrical pressure-shadows conform with outcrop- and map-scale kinematic indicators in the area (Solar 1996, Brown & Solar 1998a). The existence of the tails precludes post-tectonic growth of porphyroblasts.

(iii) S_i in garnet and staurolite porphyroblasts is found to be both parallel and non-parallel to S_e. Where non-parallel, S_i in porphyroblasts in the same thin section is consistently oblique in the same sense. This suggests that porphyroblasts could not have grown statically after deformation had ceased. Instead, porphyroblast growth was completed before the end of matrix modification, and either the porphyroblasts rotated during shear (*e.g.*, Passchier *et al.* 1992), or S_e changed in orientation without rotating porphyroblasts relative to each other (*e.g.*, Bell *et al.* 1992), or some combination of these. Whatever the explanation, both interpretations require strictly syntectonic crystallization of porphyroblasts, even if growth of individual crystals was interkinematic during progressive reorientation of the matrix, as suggested by the discontinuous nature of S_i with S_e, or late in the overall history of deformation. Further, the coexistence of porphyroblasts with both parallel and oblique S_i suggests either differential timing of growth of individual porphyroblasts relative to matrix reorientation, or growth during strain partitioning where the strain regime varied between the different domains within the rock. Strain partitioning is supported by staurolite textures in thin sections that exhibit staurolite in both P- and Q-domains, but in which only the staurolite in P-domains has parallel S_i and S_e. We do not see successive overprinting of crenulation cleavages (*cf.* Bell *et al.* 1986), from which we infer that the fabric was reoriented or reactivated during deformation rather than crenulated or transposed. Whatever the explanation, these porphyroblast – matrix microstructures (Figs. 10, 11) show that matrix modification outlasted growth of individual porphyroblasts (even where S_i is parallel to S_e, the porphyroblasts have pressure shadows), except porphyroblasts in rocks proximal to the Mooselookmeguntic pluton (Fig. 10f). Thus, we interpret metamorphism and deformation to have been coeval, and we interpret the fabrics to record microstructures that developed syntectonically, although some of these developed late during the progressive deformation.

(iv) Syntectonic growth of minerals is illustrated by the textural zones inside garnet and staurolite porphyroblasts. These zones suggest episodic growth of porphyroblasts because S_i is discontinuous from zone to zone, with up to three growth zones being recognized. Since each zone preserves a different matrix geometry, as recorded by S_i from core to rim, each stage of growth occurred at a different stage of matrix orientation with respect to the orientation of S_i. This finding suggests a progressive modification of the matrix during punctuated growth of the porphyroblasts. Although final porphyroblast – matrix fabrics show late syntectonic development, we interpret these internal zones to record a cyclic history of porphyroblast growth and matrix modification synchronous with accommodation of progressive plastic strain.

(v) Porphyroblasts of staurolite are statistically aligned with the matrix foliation (Fig. 4). In populations measured in higher-strain-zone rocks, the alignment of porphyroblasts in the plane of the matrix foliation is accompanied by statistically parallel alignment with matrix mineral-elongation lineation. Although the mesoscopic correlation between alignment of porphyroblasts and structural zone could be taken to suggest that the orientation was influenced by matrix strain during growth, these data do not uniquely support either a model of post- or syntectonic metamorphism. The general agreement with the orientations of structures could be the result of either static mimetic growth *or* dynamic rigid-body rotation during flattening strain. The better planar alignment seen at localities in the higher-strain zones may be the result of flattening strain to cause shape-preferred orientation of planar porphyroblasts. In contrast, in lower-strain-zone localities, there is a weaker planar alignment, which may be the result of constrictional strain indicated by the better linear alignment. Furthermore, the microstructural evidence presented here (*e.g.*, pressure-shadow tails, oblique S_i and textural zones) precludes growth of porphyroblasts after final modification of the matrix. Thus, we interpret the preferred orientation of staurolite to show that alignment occurred during accumulation of strain that controlled either shape orientation or porphyroblast rotation.

(vi) One microstructure that could be taken to record static crystallization is the pseudomorphic replacement of staurolite and andalusite porphyroblasts (*e.g.*, Guidotti 1970, 1974, 1989). However, in each case where replacement white mica and chlorite are coarsest (~0.3 mm), they are found mostly subparallel to matrix fabric, as seen in lineation-parallel thin sections (Fig. 11e). We interpret these microstructures to record retrograde metamorphism during deformation.

One area where textures are consistent with a model of static metamorphism is in the contact aureole of the Mooselookmeguntic pluton. Here, progressive development of rims and overprinting of matrix by growth of a rim on porphyroblasts (Fig. 10f) occur as the margin of the pluton is approached. This most likely reflects advected heat that drove contact metamorphism in the aureole of this pluton.

Discussion

High-T – low-P metamorphism in the CMB has been interpreted as post-tectonic (*e.g.*, Guidotti 1989) and static (Guidotti 1993), driven by intrusion of post-tectonic plutons (Moench & Zartman 1976, Guidotti 1970, 1989, De Yoreo *et al.* 1989). One line of evidence used in support of post-tectonic and static metamorphism has been the allegation that cm-scale euhedral porphyroblasts of staurolite (Fig. 3b) and andalusite (Fig. 3c) are apparently random in orientation (*e.g.*, Guidotti 1989). Another line of evidence used to suggest post-tectonic metamorphism is the pseudomorphic replacement of staurolite and andalusite porphyroblasts (Fig. 3d) that retained the euhedral shape of the parent porphyroblasts. The model of post-tectonic metamorphism would require regional coarsening of the foliation with increasing grade to be the result of mimetic growth of matrix phases along the pre-existing lower-grade structures, such as bedding and axial-planar cleavage. Such an interpretation conflicts with the existence of pressure shadows, oblique S_i and textural zones in porphyroblasts. The correlation of matrix grain-shape fabrics with structural zone reflects syntectonic recrystallization to record the tectonic strain ellipsoid in these rocks: stretched oblate, but close to plane strain, and prolate, respectively, in zones of flattening-dominated microfabrics (higher-strain zones) and in zones of constriction-dominated microfabrics (lower-strain zones). At the scales of outcrop and thin section, these inhomogeneities are likely the result of strain partitioning between zones with a higher proportion of pelite, and zones with a higher proportion of psammite, respectively. The logical conclusion to be drawn from these interpretations is that regional-scale metamorphism within the CMB was syntectonic and was synchronous with orogenic deformation. Furthermore, it has been suggested that the plutons are syntectonic, with ascent and emplacement controlled by the regional deformation (Brown & Solar 1998b). Thus, deformation, metamorphism, and plutonism were synchronous in west-central Maine.

Strain partitioning during porphyroblast growth is illustrated within single lineation-parallel thin sections where S_i in staurolite porphyroblasts occurs both parallel and oblique to S_e, according to compositional domain (Bell *et al.* 1986, Vernon 1989, Williams 1994). As described in the model of Bell & Rubenach (1983), progressive strain in the matrix works to overprint prior porphyroblast – matrix textures. Evidence of prior orientations of S_e is recorded by S_i in porphyroblasts. We interpret this additional growth of staurolite to occur because of episodic growth during progressive deformation.

The similarity of obliquity and pitch between S_i and S_e in any one thin section suggests a common growth history of porphyroblasts in each sample as matrix was reoriented during progressive deformation (Fig. 12). During tightening of folds, porphyroblast growth includes matrix foliation that is subparallel to the axial surface of these folds (Fig. 12b). As the fold tightens and fold limbs rotate, foliation progressively is reoriented into the plane of the axial surface so that successively younger episodes of porphyroblast growth include differently oriented foliation in the matrix (Fig. 12c). If porphyroblasts do not rotate with respect to compositional layering, each successive zone of porphyroblast growth has a progressively smaller obliquity between S_i and S_e and an identical direction of pitch until a fold limb is parallel to foliation, or the folds are isoclinal, in which case S_i remains parallel to S_e. Such a model is consistent with the field and microstructural data presented above. The folds of stratigraphic sequences in the higher-strain zones are close to being tight (Fig. 2), so that porphyroblast growth late in the fold development produces only a small degree of obliquity between S_i and S_e and a constant pitch between S_i and S_e.

The localized retrogression and pseudomorphic replacements in rocks in lower-strain zones may be the result of preferential syntectonic transfer of magma and plutonism in these zones. Since they are zones of apparent constriction, there was not sufficient flattening strain to eliminate the porphyroblast – matrix textures, which are preserved in pseudomorphs in rocks in the lower-strain zones. These observations may account for the weak correlation between metamorphic zones and structures (Fig. 4). We contend that the thermal peak occurred late in the orogenic cycle, and the temperatures achieved depended in part on advective heat due to late syntectonic plutons (Brown & Solar 1998b, Solar *et al.* 1998).

In conclusion, preservation of different microstructures in different parts of the study area may reflect different stages of evolution; in higher-strain zones, flattening strain produced flattened grain-shape fabrics, whereas in lower-strain zones, constrictional strain produced constrictional grain-shape fabrics. During the progressive deformation in the CMB shear-zone system, different parts of the crust participated in one or other type of strain at different times and conditions of deformation; at any one time, porphyroblast – matrix relations recorded the state of strain for that period. As conditions of deformation changed, the porphyroblast – matrix textures were modified by partial to complete overprinting of the previous relations. If these conditions changed progressively, a cycle of textures would be developed in the same rock. Such cyclicity is recorded in the textural zones of staurolite porphyroblasts. Matrix phases are rheologically weak in relation to porphyroblasts (Vernon 1989), such that these minerals would more easily recrystallize or rotate to modify their previous geometry, which remains preserved inside the porphyroblasts. Thus, the classic high-T – low-P metamorphism of west-central Maine was syntectonic.

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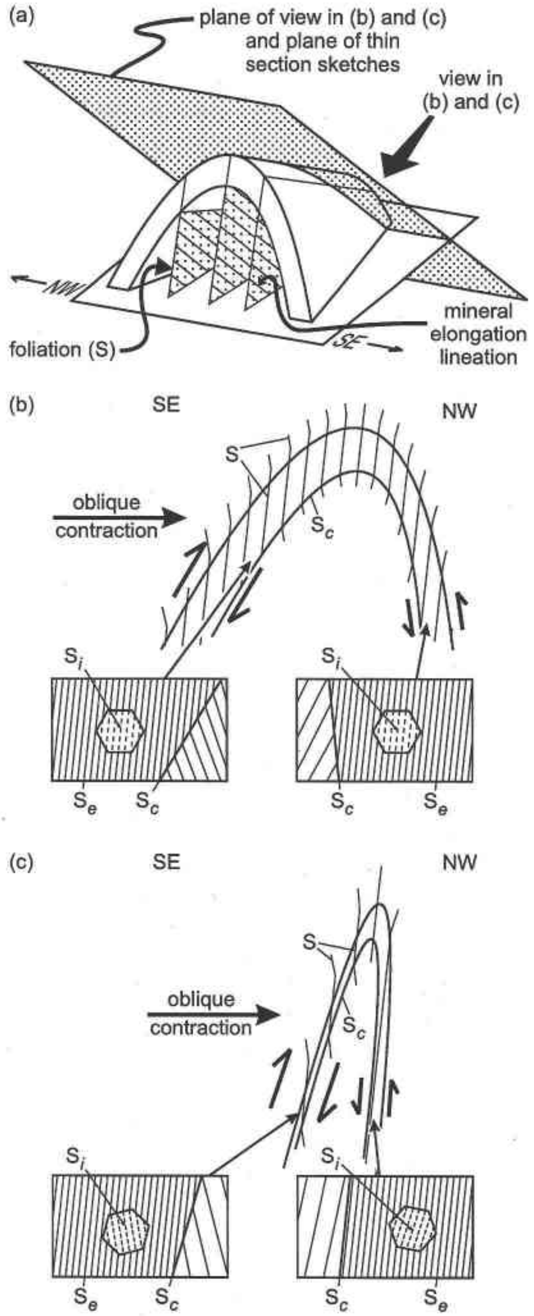

Fig. 12. Simplified model of interkinematic episodic growth of porphyroblasts as foliation is progressively reoriented during fold tightening. (a) Reference frame for the field of view in (b) and (c). A shallowly northeast-plunging anticline of compositional layers includes a penetrative axial-planar foliation and lineation. The views in (b) and (c) are normal to foliation, along the lineation, in the up-plunge direction of the anticline. (b) Stage t_1 of fold tightening. Oblique contraction led to development of the asymmetrical close fold and caused layer-parallel shear along the limbs (oblique-reverse displacement). Axial-planar foliation (S) developed oblique to compositional layering (S_c). Porphyroblasts that grew in this regime overgrew S on both limbs to incorporate an included foliation (S_i) parallel to S (or S_e). (c) Stage t_2 of fold tightening. The asymmetrical fold of (b) is now tight. New axial-planar foliation (S) is oblique to S_c, but at a smaller angle than in (b). The porphyroblasts that grew in both limbs during t_1 have rotated passively with the transposition of fold limbs. As a result, S_i has not rotated with respect to S_c, but S_e has reoriented to become oblique with respect to S_i.

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