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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: DISCUSSION

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Introduction

Solar & Brown (1999) (S & B) wrote an interesting, highly provocative paper that could lead unwary readers to accept uncritically a tectonometamorphic history for western Maine that is somewhat controversial. Moreover, some aspects of their paper, which are strongly emphasized, are such that they have inadvertently misrepresented much of my work and that of others on the metamorphic petrology of western Maine. It appears that they did not read carefully the previous literature on the area or failed to understand it fully.

Their paper may be an example of "model-driven" work in which the authors overtly sought tectonometamorphic evidence to support the ideas of Brown & Solar (1998a) regarding emplacement of granitic plutons in western Maine. This approach may have subconsciously clouded their objectivity, and hence, misguided their interpretations. The two major proposals of S & B are (1) that metamorphism was syntectonic, and (2) that there are important northeast-trending zones of *higher* and *lower* strain (HSZ and LSZ). In the context of these two proposals, I discuss below a number of their "observations" which, I believe, are highly questionable. Because so much of the observational part of S & B seems flawed, I concentrate mainly on it, focusing on some critical aspects which, broadly considered, seem to undercut their proposals, and hence, their whole tectonometamorphic interpretation.

In this discussion, I have two goals. The first goal is to make clear the manner in which they inadvertently misrepresented much of the metamorphic petrology that has been done in western Maine, specifically my findings in the area covered by their study. The second goal is to point out what I perceive are serious flaws in their tectonometamorphic interpretation. In this context, it is left to readers to decide whether or not to accept the interpretations and conclusions made in S & B.

To maintain a focus, discussion is concentrated on features present in roughly the northwestern two-thirds of their Figure 2, the area in which much of my own work has been carried out. I begin with a brief overview of the geological and petrological setting of this area. Then follows a description of the main geological features at Coos Canyon, the key exposures for assessing their suggested HSZ. To better assess the validity of the proposed higher strain for the rocks at Coos Canyon, some new observations are presented. These can be compared with observations made by S & B regarding textures and fabric in the proposed HSZ. With this as background material, I then discuss two general problems, and several representative specific illustrations bearing on the two major proposals of S & B. I believe that these general and specific problems seriously undermine much (most?) of what they have proposed regarding syntectonic metamorphism and hence, the existence of any high-strain and low-strain zones.

Regional Geological Features

Figure 2 of S & B shows that the region of concern involves northeast-trending folded metasedimentary units. The strata, part of the Siluro-Devonian Rangeley sequence of Moench (1971) and Moench & Hildreth (1976), consist of clastic lithologies, including thinly interbedded quartzites and pelites, thickly interbedded dirty quartzites and pelites, meta-arkose, calcareous biotite granofels, and variably interbedded calcareous quartzite and metamorphosed black shale. At least two periods of folding can be distinguished, the more prominent phase (F1) controlling the map pattern and involving a strong foliation, S1, which is usually bedding-parallel or close thereto. Folds range from tight and isoclinal (Figs. 1a, b) to somewhat broader, more open structures. Lithology clearly influences the openness of the folds, but in part this is a matter of easier perception

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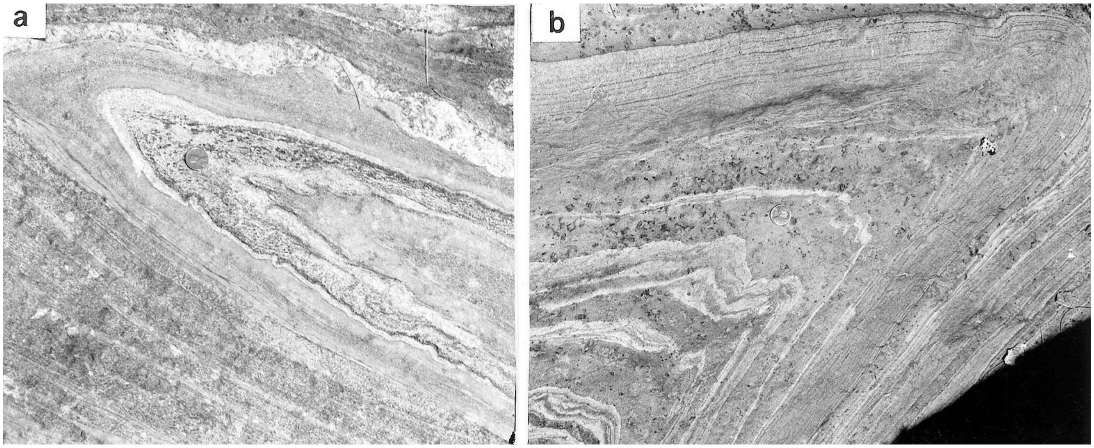

FIG. 1. Isoclinal folds of Perry Mountain Formation at Coos Canyon. (a) Beds at the penny along the axial plane of the fold involve garnet coticule. (b) Nose of an isoclinal fold showing some aspects of a crenulation that may not be axial planar to the fold, thereby suggesting that it is an S2 foliation. Note the suggestion of a weak alignment of the staurolite crystals parallel to this cleavage.

of tight noses of folds related to the ease with which bedding is seen in some units. Fold axes typically plunge moderately to the northeast.

At least one period of later folding (F2) has occurred. It is only locally developed or evident, and typically involves northeast-trending upright structures that are more open than the F1 folds. An important aspect of this later folding, where it is well developed, is that it involves a prominent axial-plane crenulation cleavage (S2) that cuts the typically bedding-parallel S1 (Figs. 2a, b). S2 is variably but commonly developed throughout much of the region, ranging from being obscure to nearly equal in intensity to S1 (especially in graphite-rich rocks). It is defined mainly in terms of microfolding of the muscovite and ilmenite laths (in lower-grade rocks, also by tiny laths of chlorite) that define S1. Typically, these laths have been recrystallized into straight platelets, thereby forming the polygonal arc textures

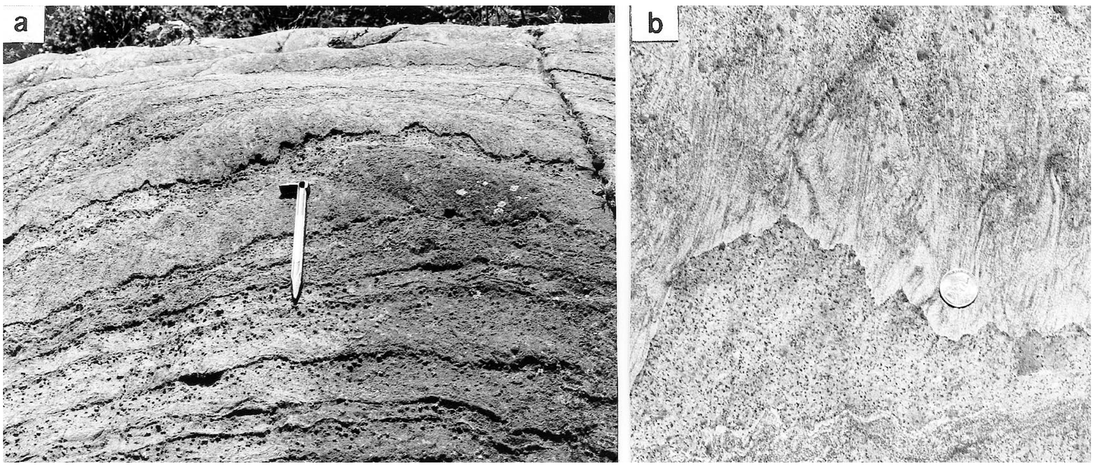

FIG. 2. Broad, open fold and axial-planar cleavage in Perry Mountain Formation at Coos Canyon. (a) Note the strongly graded aspect of bedding in this formation. (b) Close-up view of the S2 crenulation cleavage disrupting the fine-scale bedding typical of the formation. Some control by S2 of the alignment of biotite and staurolite is evident at the upper edge of photo.

described long ago by Zwart (1962). Where well developed, S2 involves generation of new P and Q domains. Biotite and coarser laths of chlorite show little evidence of being part of the original S2 crenulations. Instead, not uncommonly they (especially the coarse flakes of chlorite) contain patterns of quartz inclusions indicating that they have overprinted S2. Especially chlorite, but also biotite and staurolite, tend to grow as relatively coarse crystals oriented parallel to the S2 direction (Figs. 3a, b). Although the biotite and chlorite probably grew coarser in response to M3 (see below), they nonetheless serve as subtle indicators of the presence of S2, even where it is otherwise largely obscure. The staurolite shown in Figure 3b very likely grew during M2 (see below).

The polymetamorphic aspects (at least three events, M1, M2, and M3) of the region have been described by the author and various co-investigators (*e.g.*, Guidotti 1970a, b, 1974, Guidotti & Holdaway 1993, Guidotti *et al.* 1996, DeYoreo *et al.* 1989a). A key point is that the area has been affected by two high-*T* events, M2 and M3, probably after an earlier low-*T* event, M1, that was coincident with the first deformation (D1). Only M2 and M3 are of direct importance for this discussion. Over most (all?) of the area of concern, M2 attained at least a sufficiently high grade to produce the AFM assemblages St + Bt + Chl and And + St + Bt in the metapelites, the latter assemblage being most typical of the grade attained in M2. It has been "suggested" (*e.g.*, Guidotti 1970a, Guidotti & Holdaway 1993, Guidotti *et al.* 1996), but never discussed in detail, that M2 was largely a static recrystallization event. The grade may have reached the upper sillimanite zone, or even the Sil + Kfs zone in the south in the TAD and WAD areas (Tumbledown and Weld Anatectic Domains, respectively, on Fig. 2 of S & B), but it is not at all certain that these higher grades were attained as part of M2. This ambiguity has been discussed by Guidotti (1970a) and Guidotti *et al.* (1996), and it was noted that none of the now highly migmatitic TAD rocks contain coexisting Sil + Kfs. In fact, the migmatitic TAD rocks very commonly show sillimanite with variable degrees of major resorption or back-reaction. Not even semidetailed petrological work exists that allows one to trace the lower sillimanite zone (staurolite still stable) shown on Figure 4 of S & B directly into the upper sillimanite zone to the south. Moreover, at least in the western portions of their Figure 4, the lower sillimanite zone is due to M3. The uncertainty is further illustrated by the fact that their diagram shows the margin of the migmatite domain almost coincident with the transition from lower to upper sillimanite zone. In western Maine (and elsewhere?), there is usually a broader area of upper-sillimanite-zone rocks separating staurolite-bearing rocks from migmatites. Possibly a southwestern extension of the late Hurricane Mountain Fault of Moench (1971) separates lower-sillimanite- and upper-sillimanite-zone rocks at the north end of TAD? The author has found signs of brittle deformation (breccia) in rocks at the northern end of TAD. Basically, for the northern half of the TAD migmatitic domain they show on their Figure 2, there is little or no control on either the number or ages of the

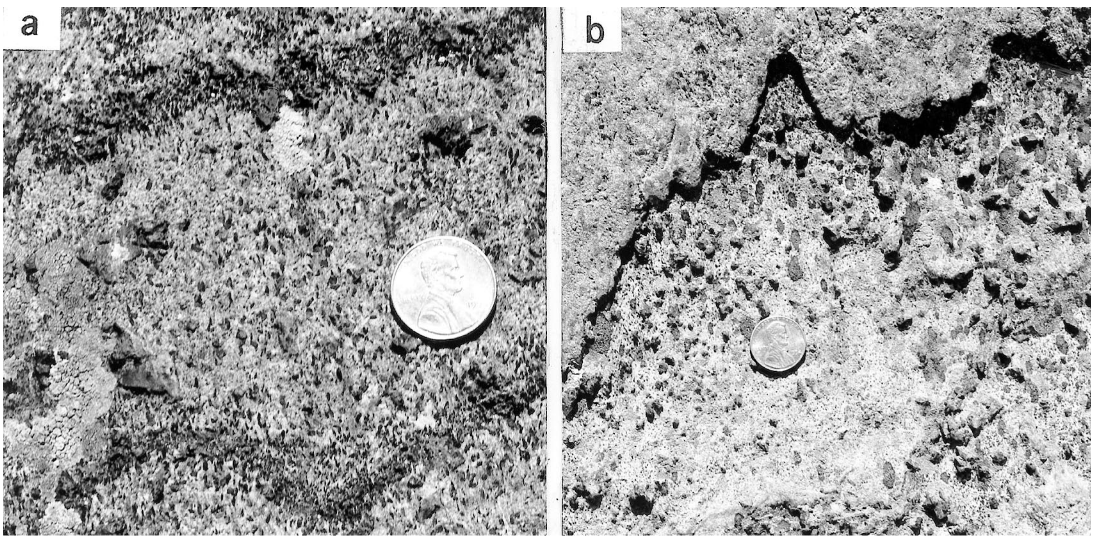

FIG. 3. Moderately strong control by S2 of the biotite and staurolite alignment (same locality and view orientation as in Fig. 2). (a) Coarse biotite plates showing a moderately strong alignment parallel to the S2 crenulation cleavage. (b) Staurolite porphyroblasts fairly strongly aligned, with long dimensions parallel to the S2 crenulation cleavage.

metamorphic events that have occurred therein. In the case of WAD, there is also virtually no information on the metamorphic history whatsoever because there is essentially no outcrop in that whole domain. Indeed, Pressley (1997) found only two outcrops in the whole area shown as the WAD domain. Formerly, the area shown as WAD was mapped as being a southern extension of the Phillips pluton (Pankiwskyj 1978).

By far, most of my work has been directed at the M3 event. Its areal distribution is very closely related to the intrusion of the low northeast-dipping sheet-like Mooselookmeguntic granitic pluton. Because M3 is regionally extensive in places, it has been referred to as a "regional-contact metamorphism" (De Yoreo *et al.* 1989a). For example, in the context of Figures 2 and 4 of S & B, consider an east–west-trending rectangular area lying south of the Reddington pluton, extending south to include the northern 5 km of TAD, and stretching west–east from the contact of the Mooselookmeguntic pluton over toward the Phillips pluton. Therein, M3 effects extend eastward to a north–south line passing about 5–10 km west of the Phillips pluton. However, it should be emphasized that in the southeastern corner of this rectangular area, the metamorphic petrology is at best poorly understood, and possibly involves more than just the M1, M2, and M3 events. Several aspects of M3 are crucial for a discussion of the suggestions of S & B.

(1) Monazite dating by Smith & Barreiro (1990) has shown the M2 preceded M3 by about 30 m.y. Moreover, arguments based on observations concerning mineralogy or petrology (Guidotti 1970a, 1974, Guidotti & Holdaway 1993, Guidotti *et al.* 1996) and thermal modeling arguments (De Yoreo *et al.* 1989a) clearly indicate that the rocks affected by M2 cooled to ambient temperatures before being overprinted by M3.

(2) In the west, adjacent to the Mooselookmeguntic contact, the M2-affected rocks were metamorphosed in a prograde manner to as high as the upper sillimanite zone. Eastward, M3 grade decreases progressively to the staurolite zone and down to what Guidotti (1970a, 1989a) and Guidotti & Holdaway (1993) have described as the lower garnet zone. As seen from Figure 4 of S & B, the garnet zone is very extensive in its eastward extension. Hence, there is a seesaw or "hinge-line effect" (approximately at the upper staurolite zone of M3), such that high-grade M2 metamorphic rocks to the west went up to a still higher grade, but high-grade M2 rocks to the east went down in grade. However, the hinge-line analogy is not exact in that during M2, rocks at the hinge were at slightly higher grade than during M3 (And + St + Bt assemblage *versus* St + Bt + Chl).

(3) In the rectangular area described above, andalusite was stable virtually everywhere during M2, but it was not stable in any part of the M3 overprint. The bathograd approach of Carmichael (1978) suggests that M3 occurred at somewhat higher pressure (*e.g.*, 0.5–1.0 kbar) than M2 (the assemblage Sil + St + Bt *versus* And + St + Bt), and hence, at slightly greater depth.

(4) Guidotti (1968, 1970a, 1974, 1989a), Guidotti & Holdaway (1993), and Guidotti *et al.* (1996) showed that development of various types of pseudomorph textures is a *key aspect* of M3 superposition on M2. The types and degrees of replacement found are very closely linked to where in the M3 metamorphic gradient a sample is collected. Foster (1977, 1981, 1994) has provided detailed discussions of the local diffusion-controlled reactions producing the pseudomorphs in the sillimanite-grade rocks; see also his discussion of pseudomorphs formed at lower grades in Guidotti *et al.* (1996). In all cases, the phases (mainly layer silicates) making up the pseudomorph are markedly more coarse-grained than they are in the groundmass. Typically, these coarse-grained layer silicates are randomly oriented and commonly, except for andalusite, the shape of the mineral that has been replaced is well preserved. S & B missed this *key aspect* as they tried to relate degree of pseudomorph development to HSZ *versus* LSZ. In the rectangular map-area described above, and all along the eastern side of the Mooselookmeguntic pluton, there is no evidence whatsoever of pseudomorph formation due to the M2 event. This is probably true throughout the whole area considered by S & B.

(5) Despite extensive development of various types of pseudomorphs throughout the area affected by M3, large amounts of highly systematic data on assemblages and mineral chemistry as a function of grade and assemblage, respectively, demonstrate a close approach to chemical equilibrium everywhere (Guidotti 1970a, b, 1973, 1974, 1978, Guidotti *et al.* 1975a, b, 1977, 1988, 1991). M2 andalusite is the only aspect of the mineral assemblage that did not re-equilibrate. Commonly, it persists as a metastable relic from M2. Excluding rare cases (*e.g.*, graphite-rich rocks), it is partially to largely replaced mostly by coarse-grained muscovite, regardless of the M3 grade. The degree of this replacement is more complete in the lowest-grade areas, and especially in the highest-grade portions of the M3 thermal gradient than in the intermediate portions.

The Coos Canyon Area: the Prototype Area of the HSZ of S & B

The strata at Coos Canyon (see the dots for b, c and d in Fig. 4 of S & B) are extremely well exposed and lithologically typical of the Perry Mountain Formation throughout its areal extent. This formation consists of interbeds on a 2- to 10-cm scale of moderately pure quartzites and greenish grey metapelites (Figs. 1a, b, 2a). Typically, the quartzite beds show a well-developed graded bedding relationship with the metapelites and commonly also display cross-beds and other sedimentary structures in their middle to upper portions (Figs. 4a, b; also, see Fig. 1.1a on p. 2 of Yardley 1989). In some outcrops, there is also evidence in the quartzites of internal deformation that might be due to either tectonic (Fig. 2b) or soft-sediment deformation.

Both periods of folding noted above can be seen at the Coos Canyon locality (Figs. 1a, b, 2a). Moreover, the relationship of the crenulation cleavage (S2) with the axial planes of the more open second-generation folds is also well displayed (Fig. 2b).

The metapelites have a fine-grained Ms + Qtz + Pl matrix with coarser platelets of biotite (generally at least subparallel to foliation) occurring on bedding or foliation surfaces. In some cases, biotite has a strong preferred orientation so that it shows the *only* unambiguous megascopically visible "stretching lineation" present in the rocks (Figs. 5a, b). Small euhedral, pink garnet porphyroblasts are also visible in hand sample (Fig. 6). Staurolite virtually always occurs as fresh, 1–1.5 cm twinned euhedral crystals (Fig. 6). Andalusite is usually visible only on bedding or foliation planes. With few exceptions, it is replaced by coarse muscovite, but the randomly oriented subhedral to euhedral shapes of the original crystals are retained (Figs. 7a, b). In the common case where the pseudomorph lies along the bedding interface between the top and bottom of adjacent graded beds, the coarse muscovite tends to be oriented subparallel with the interface. All of the Al-rich phases decrease modally as a given pelitic bed grades downward into the stratigraphically lower quartzite bed. Concomitantly, the grain size of biotite also decreases. At the tops of pelitic beds, abrupt truncation of staurolite is common where there is juxtaposition with the bottom of the overlying quartzite beds. This is well shown in Figure 1.1a of Yardley (1989).

Minor chlorite is commonly seen in thin section, typically oriented at very high angles to the main foliation. Not uncommonly, it has grown along and overprints the (at least weakly developed) crenulation cleavage present in many Coos Canyon samples. Guidotti *et al.* (1991) gave arguments based on the composition of chlorite and the coexisting phases to show that the chlorite formed in response to M3 staurolite-zone metamorphism being superimposed on M2 (St + And + Bt)-grade metamorphism. Moreover, this same metamorphic overprint caused the replacement of andalusite by coarse plates of muscovite.

New Observations on Coos Canyon Samples

Samples selected and studied in thin section over the years were collected largely for an assessment of mineralogical and petrological questions. They were collected long before it became "fashionable" to collect oriented samples in the field so that oriented thin sections could be prepared. However, they were routinely cut perpendicular to foliation so that with respect to the strain ellipsoid, some would have closely approximated XZ and YZ slices. Nonetheless, to assess more fully the assertions made by Solar (1996) and S & B, four new samples were collected from the Perry Mountain Formation at Coos Canyon, from essentially the same site as the three HSZ samples shown on Figure 4 of S & B as b, c, and d. All four involve the assemblage St + Grt

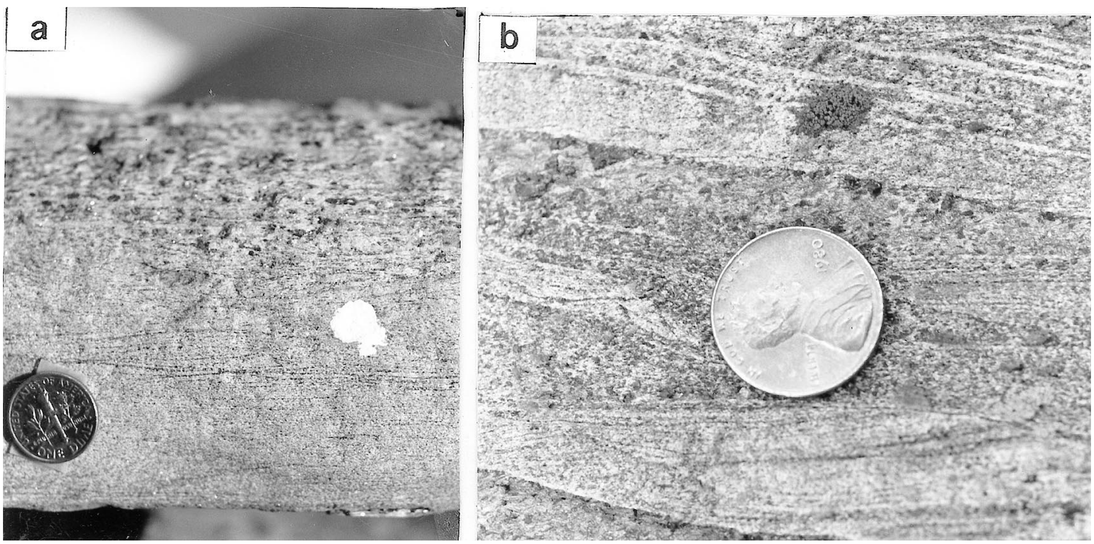

FIG. 4. Delicate sedimentary features in the Perry Mountain Formation preserved despite two periods of deformation and two episodes of metamorphism. (a) Graded bed with cross-beds associated with the gradation to pelite. (b) Details of the laminations associated with the cross-beds.

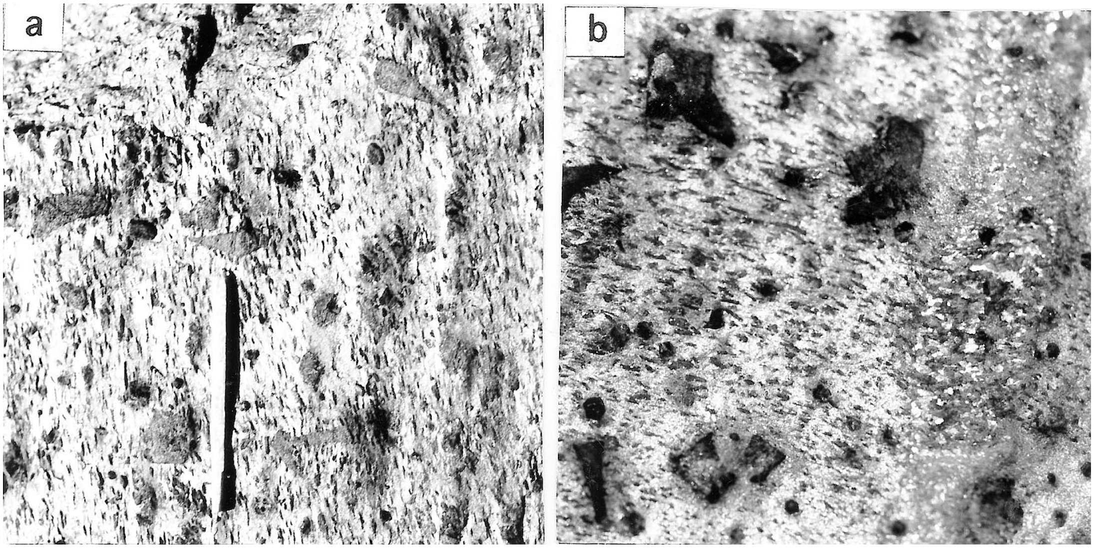

FIG. 5. Biotite "stretching" lineation. (a) Truncation of the lineation by staurolite porphyroblasts; tooth pick for scale. (b) Biotite lineation truncated by andalusite porphyroblast (subsequently replaced by coarse muscovite); same sample as (a).

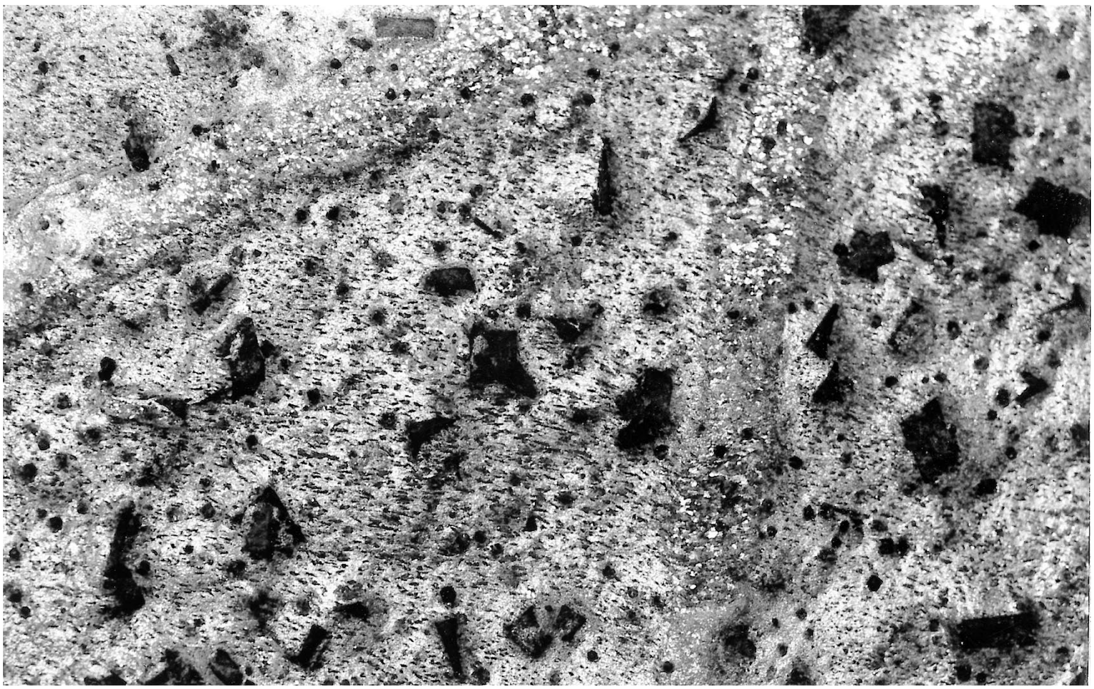

FIG. 6. Euhedral, 2-mm crystals of garnet distributed uniformly throughout the groundmass and aggregate of coarse muscovite that is a pseudomorphic replacement of andalusite. In contrast, note that staurolite tends not to occur as inclusions in the much larger pseudomorphs of andalusite, possibly suggesting nearly simultaneous nucleation at distinctly separate sites. The staurolite crystals are typically about 1–1.5 cm in length.

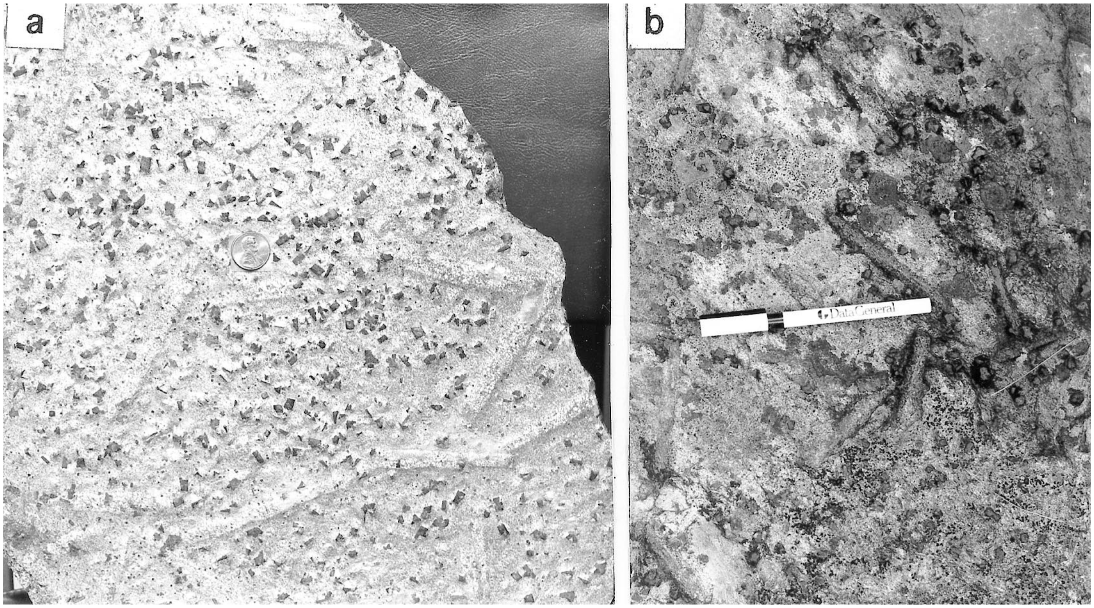

FIG. 7. Andalusite porphyroblasts. (a) View of randomly oriented, variably replaced andalusite porphyroblasts on a foliation surface. The generally random orientation aspect of staurolite is also apparent in this photo (penny for scale). The three pseudomorphs of andalusite at the center (immediately to the left of the penny) meet such that they outline an equilateral triangle. (b) Similar to (a), but in this case the andalusite is only partially replaced.

+ Bt +Ms + Qtz + Pl + Chl (due to M3) + accessories (ilmenite, tourmaline, and minor pyrrhotite being most prominent, with only very minor graphite). This assemblage typifies the Perry Mountain Formation at M3 staurolite grade as superimposed on M2. The only constraint employed in selecting four otherwise random samples was that they all displayed a strong, clear development of the above-noted biotite "stretching" lineation, which was later used to define the X direction, parallel to which most of my sections were cut. Although many exposures at Coos Canyon do not show any well-defined megascopic mineral lineation, it is not difficult to find samples that do display one by means of the aligned biotite.

For *each* of the four oriented samples, *four* thin sections were made parallel to the XZ plane of the strain ellipsoid (⊥ to Y). For purposes of comparison, one thin section cut parallel to the YZ direction (⊥ to X) also was made. These directional constraints duplicate those used by S & B with the exception that the X direction for our thin sections is probably more accurately located (see below).

For each thin section, observations were made to establish the relationships of S_i and S_e in garnet and staurolite porphyroblasts, and also to assess the presence and nature of any pressure shadows associated with these minerals. Observations also were made on the textural nature of the biotite plates. Below, a comparison is made between their observations and some of my new observations.

General Problems in S & B

Which classic metamorphic area?

Calling an area "classic" in a geological sense implies that it has been studied and documented in considerable detail. However, the area covered by their work represents only a portion of the area in western Maine in which detailed metamorphic petrology has been done. An idea of how much larger is the area covered by detailed studies can be seen in Guidotti & Holdaway (1993). Nonetheless, it is gratifying to have that portion of western Maine on which a significant portion of the work therein was done by me referred to as a "classic high-T, low-P area". However, it is dismaying that S & B failed to recognize and distinguish clearly the specific metamorphism on which work by myself and others may have helped make it into a so-called "classic high-T, low-P metamorphic area" in the sense noted above. The work in the area of specific concern would include many metamorphic mineralogy–petrology papers by my coworkers and me [*e.g.*, Guidotti (1968, 1970a, b, 1974, 1978), Guidotti *et al.* (1975a, b, 1977, 1988, 1991, 1996, *etc.*); twenty-seven papers dealing with this specific area], the thermal modeling papers of Lux *et al.* (1986), and DeYoreo *et al.* (1989a), and the papers on textural modeling by Foster (1977, 1981, 1994), and in relevant sections in Guidotti *et al.* (1996). Virtually all of this work has focused specifically on various aspects of the thermal pulse associated with the emplacement of the Mooselookmeguntic granitic pluton. This has been designated as M3 (as also used by S & B), and it has been argued that it was a static recrystallization event (as accepted by S & B also).

The S & B paper is wholly concerned with the high-*T*, low-*P* M2 event as designated by Guidotti (1970a) and in numerous subsequent papers, an event that occurred some 30 million years earlier and separated from M3 by a period of cooling to ambient temperatures. Only a few papers (four of 27) by the author that deal with metamorphism in western Maine (Guidotti 1970a, 1989a, Guidotti & Holdaway 1993, Guidotti *et al.* 1996) pertain to aspects of M2. Moreover, of these four papers, three were published as locally circulated New England Intercollegiate Geologic Conference reports. In no case was any detailed documentation provided on M2, especially with regard to textures and their implications for the relative timing of deformation and metamorphism. Hence, to the extent that the work of my colleagues and me in the relevant area involves establishment of a classic high-*T*, low-*P* terrane, it is clear that this designation applies wholly to M3, an event for which S & B apparently have views that closely match mine. It seems to be an unfortunate disservice to the metamorphic mineralogy–petrology research community that they have been so casual in the way they misidentified the so-called "classic" high-*T*, low-*P* terrane in western Maine, and in the process, misrepresented the vast bulk of the work over the years by my colleagues and me.

Some comments on the general methodology used by S & B

Several aspects of the general methodology used by S & B warrant comment, as they bear on the reliability of their more specific observations as discussed below.

(a) Most samples they use to illustrate textures are very graphite-rich (*at least* 20 of their 29 microphotographs). This is both very surprising and very peculiar because development of their arguments for HSZ is made largely in terms of the Perry Mountain Formation within which, owing to its particular lithologic features, they suggest such zones are mainly developed. [Ironically, they show the Madrid Formation (massive, calcareous, biotite granofels) and Carrabassett Formation (thick interbeds of pelites and impure quartzites on a scale varying from centimeters to meters) as largely within their HSZ]. The surprise and peculiarity arise because *very* few samples of the Perry Mountain Formation are at all graphite-rich. This is reflected by deposition in association with fairly pure quartzite beds, indicating markedly more mature sediments than is typical of western Maine strata (Cullers *et al.* 1974).

Discussions about the role of graphite are scattered in the literature [*e.g.*, Bell & Brothers (1985), Rubenach & Bell (1988), Burton (1986), Rice (1993), Rice & Mitchell (1991), Guidotti (1970a)]. Nonetheless, it is well recognized among experienced metamorphic petrographers that abundant graphite in samples can result in development of distinct textural differences relative to textures in adjacent rocks containing minor or no graphite. This is also readily apparent when closely proximal graphite-rich and graphite-poor samples from western Maine are compared texturally. It is highly unfortunate that S & B merged observations made on samples having minor graphite with those made on so many samples having very abundant graphite. Excluding the Smalls Falls Formation and a fairly small percent of the Rangeley Formation, their graphite-rich samples are highly atypical of units in western Maine.

(b) Equally surprising and peculiar is that S & B completely failed to recognize the presence of the platy ilmenite, and that it is *by far* the most prominent opaque phase in typical Perry Mountain Formation, and, excluding the Smalls Falls Formation and some of the Madrid Formation, in all other western Maine units. The orientation of ilmenite plates is usually strongly parallel with S1 (including its crenulation by S2), as defined by muscovite laths. It is highly visible as inclusions in staurolite, garnet and other silicates, and especially so in the Coos Canyon rocks. By far, ilmenite plates best show S_i *versus* S_e, being much better for this purpose than quartz inclusions as the latter tend to be irregular in shape.

(c) By inspecting hand sample and thin section fabrics, S & B chose their X directions as suggested by "bladed" muscovite plates and polycrystalline quartz in "elongate ribbons". Although this probably gave them a fairly good approximation of the X direction, it is likely that some of their slices may be a few tens of degrees off from parallelism with X, obviously adding some ambiguity to their observations. Because of selection of the X direction based on the clear, megascopically visible biotite "stretching" lineation, I believe that slices used herein are routinely within a few degrees of the true X-direction maximum. S & B recognized and discussed in some detail this biotite "stretching" lineation, but did not use it to choose the X direction.

Specific Illustrations Bearing on the Two Major Proposals of S & B

Aside from S & B not recognizing that it is M3 that "might" qualify as "a classic high-*T*, low-*P* metamorphism" as discussed above, I also have serious reservations regarding their assertions on the nature of the M2 metamorphic event. S & B use many textural features and examples to build their argument for zones of relatively higher and lower strain, plus syntectonic metamorphism, the bulk of which I find unconvincing.

Among the textural features they discuss are included foliations and S_i *versus* S_e, mineral and structural lineations, biotite "pull aparts" and "fish", pressure shadows, pseudomorphs, *etc.*

To keep this discussion reasonably short, I consider only some of the megascopic and microscopic textural features bearing on the two major proposals of S & B. The focus is on samples or outcrops from their proposed HSZ, as illustrated by exposures at Coos Canyon. Discussion of these should make evident the nature of my reservations about their assertions. Textural features are discussed first for the gross rock, and then for several specific minerals. I especially make use of the four carefully oriented new samples collected at Coos Canyon. Because these samples were cut specifically with respect to the biotite "stretching" lineation, slices perpendicular to Y should display to the maximum extent textures indicative of any strain associated with syntectonic recrystallization. All thin sections were studied with a standard petrographic microscope plus with a Zeiss Stemi SV 6 binocular petrographic microscope that enabled the entire thin section to be seen in a single view, as well as smaller portions at higher powers. This microscope permitted the use of a gypsum plate to assess the presence of any gross crystallographic orientation of quartz.

Gross Features of the Rocks

P and Q domains and the main foliation, S1

S & B interpreted mica-rich and quartz-rich laminae of S1 in the Perry Mountain Formation solely as P and Q domains formed in response to metamorphic differentiation associated with strain partitioning. Undoubtedly, this is partially true, but original sedimentary laminae also are commonly present. Well-preserved sedimentary structures (*e.g.*, delicate cross-beds) show a clear gradational zone, typically over a cm or more, between pelite and the stratigraphically lower beds of quartzite (Figs. 4a, b). A similar gradual transition can be seen in Figure 1.1a of Yardley (1989). The writer would interpret Figures 5a and 5b of S & B as good examples of these fine-scale sedimentary laminations, with the P domain on the right being the highly pelitic top of the next lower graded bed. Indeed, merely by switching the left and right hand sides, their Figure 5b is strikingly similar to the Coos Canyon sample shown on page 10 of Yardley *et al.* (1990).

Finally, the HSZ of S & B are largely defined *via* observations of the Perry Mountain Formation. The very nature of this unit emphasizes those sedimentary parallelisms, which could appear to be simple P and Q domains formed in conjunction with S1. In contrast, most of the "low-strain" zones involve the Rangeley Formation, which contains abundant thick beds of sandstone, conglomerate, *etc.*, which by their very nature produce more open folds and a less strongly developed S1.

Crenulation cleavage, S2

The discussion of the S2 crenulation cleavage by S & B (their p. 323) is quite unsatisfactory. They describe it as occurring in meter-scale, lens-like zones within the high-strain zone, parallel to and enclosed by meter-scale high-strain rocks. This is clearly a misstatement, as S2 occurs abundantly in samples from both their HSZ and LSZ rocks, ranging continuously from strong to very subtle or, occasionally, completely absent. Close inspection of several of their photos (Figs. 10c, d and e) suggests the presence of a very subtle S2 therein (trending northeast in the photos).

Moreover, it can be *observed* in many localities that S2 is related to superposition of later, open folds on the earlier isoclinal folds [*e.g.*, at the large outcrop at Coos Canyon, just south of the Route 17 bridge over the Swift River (Figs. 2a, b, 3a, b)], and many other localities throughout the area they considered. In some cases (*e.g.*, at Coos Canyon), the open folds are nearly in the same orientation as the isoclinal folds, but the plunges may be somewhat less steep. Elsewhere in western Maine, the F1 and F2 fold axes are markedly divergent. At any rate, S & B make no mention of an obvious example from within their prototype HSZ, for which the crenulation cleavage is demonstrably axial planar to a broad, open fold. Instead, they describe it as having some sort of lens-like pattern of occurrence.

S & B provide little discussion of the textural relationships between the porphyroblasts and S2 in either the HSZ or LSZ. However, it is readily demonstrable throughout much of the area *via* S_i /S_e relations that staurolite and andalusite commonly overprint S2 (Fig. 4 of Guidotti 1970b). Indeed, a case can be made that overprinting of this crenulation cleavage and crystallization in proximity with it may well explain most of the occasional, small angular divergence of S_i and S_e, especially in staurolite (*e.g.*, their Fig. 10e), and possibly even garnet.

Because they assert that in the HSZ there was a lesser amount of strain in the "lenses containing S2" than in the enclosing rocks, it is unsatisfying that they provide little discussion of when and how S2 was produced or how it fits into the broader aspects of the region. It raises a number of unanswered questions. For example, because it can be *observed* at Coos Canyon that the crenulation cleavage is axial planar to later, more open folds, how do these folds fit into their higher-strain-zone model?

Amount and timing of the proposed M2 strain effects

As discussed below, features associated with individual minerals, including those from new thin sections made from rigorously oriented samples in the type locality of their HSZ, provide support for *at most* only minor strain during the earliest stages of the M2 metamorphic event. By the time that staurolite and andalusite were crystallizing, there was little or no strain occurring in these rocks.

Several outcrop-scale observations strongly support this latter assertion. One involves the common occurrence of staurolite-rich veins cross-cutting bedding, S1, and S2 foliation (Fig. 8a). Such veins clearly formed at or near the peak of metamorphism. As seen in Figure 8a, they show no signs whatsoever of any offsetting or strain. The other observation is even more pronounced. It involves similar veins with andalusite (subsequently replaced by coarse muscovite due to M3) instead of staurolite (Figs. 8b, c). Clearly, they also formed at or very close to the thermal peak of the M2 metamorphism, but no indications of offsetting or strain are seen.

Another category of relevant outcrop-scale observations includes the above-noted well-preserved graded beds and delicate cross-beds (Figs. 4a, b) seen in many parts of the Perry Mountain Formation at Coos Canyon. Although there can be no doubt that strain would have been partitioned largely into the mica-rich beds, it "strains" credulity to assert that the partitioning would be so perfect that the delicate structures (*e.g.*, cross-beds and scour-and-fill structures) having *very close proximity with, and gradational into* the pelitic tops of beds would sufficiently escape any significant strain that they could still be so easily recognized!

Features of Specific Minerals

Quartz

In Q-domains, quartz shows only weak shape-preferred orientation and no crystallographic preferred orientation. In P-domains, quartz typically shows a well-developed shape-preferred orientation, but little or no crystallographic preferred orientation is apparent. This is especially evident from inspection of $S_i = S_e$ inclusions of quartz in staurolite. The impression of a seemingly stronger crystallographic preferred orientation in the P-domain in Figure 6b in S & B is misleading, probably owing to the color contribution from the abundant, fine-grained muscovite.

Biotite

Megascopic scale: Despite only minor discussion by S & B of a *megascopic* biotite "stretching" lineation, it is readily detected in Coos Canyon outcrops. Ironically, S & B show a photo illustrating this lineation (their Fig. 3a), but never use it further as a guide to optimize the directions of their thin section slices. Figures 5a and 5b illustrate clearly the degree to which this lineation is developed in some samples. Moreover, it is particularly revealing that in Figure 5b, the biotite lineation is abruptly truncated by a large, now-replaced andalusite crystal. Figure 5a shows the same sort of truncation of the biotite lineation by staurolite. Such truncations can be seen in many outcrops, and are certainly not expected if the St + And + Bt recrystallized during a syntectonic metamorphic event.

Microscopic scale: In the text and in the captions for their Figures 6e, 6f and 7, S & B assert that biotite "pull aparts" are common in LSZ samples, whereas biotite occurs as "fish" in HSZ samples. The new thin sections examined in this study show that biotite "pull aparts" also are common in the HSZ samples from Coos Can-

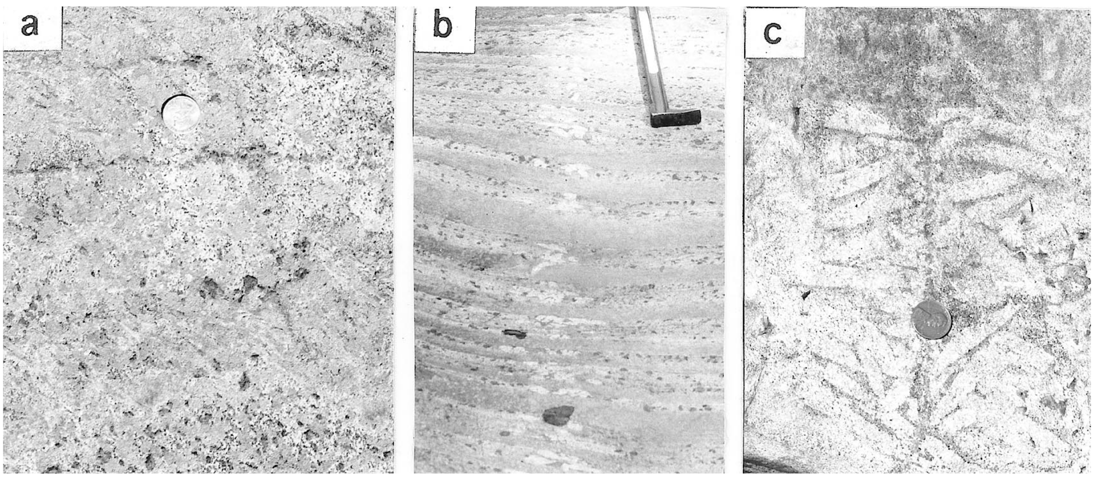

FIG. 8. Cross-cutting veins of staurolite and andalusite. (a) Veins of staurolite (on either side of the penny) associated with the broad open fold of Figure 2. The staurolite-filled veins sharply cross-cut bedding, S1, and the S2 crenulation cleavage. (b) Vein of now-replaced andalusite (left of chisel) cross-cutting vertical bedding. Note that, as expected, andalusite formation was concentrated in the pelitic beds. (c) View of an andalusite vein as seen on a foliation surface, essentially at 90° to the view seen in (b).

yon. Moreover, S & B claim that "biotite fish" are prominent in lineation-parallel thin sections of HSZ samples. The new thin sections confirm the biotite lineation, but only about 25% of my carefully oriented Coos Canyon samples display any development of "biotite fish", and then only sporadically in any given thin section.

Finally, S & B discuss kinking of biotite plates as being in some way related to their HSZ. This assertion is unacceptable for two reasons. (1) Any M2 high strain of significance for their arguments would have occurred at high T, and so would have annealed out quickly. (2) More importantly, all of the M2 metamorphic effects in their study area have been subsequently affected by at least garnet-grade M3 static metamorphism and closely approached a new equilibrium. Any M2 kinking would have been fully annealed by the M3 event. Owing to very late, localized brittle deformation, kinked biotite does occur, albeit only sporadically throughout the area. Typically, it shows partial alteration to Fe-enriched, clearly non-equilibrium chlorite; Guidotti *et al.* (1991) provided a full discussion.

Garnet

Megascopic scale: Garnet is common as 1–2 mm subhedral to euhedral crystals throughout the pelitic portions of the rocks at Coos Canyon. In relatively thick pelitic laminae, garnet appears to be randomly distributed throughout (Fig. 6). Apparently, when the large, now-replaced andalusite crystals grew, they merely overprinted the garnet in the groundmass, as suggested by the distribution and size of the relict crystals of garnet in the pseudomorphs (Fig. 6), *i.e.*, as expected if the andalusite crystals grew atectonically. As seen in thin section, staurolite envelops garnet in a similar fashion.

Microscopic scale: The abundance, distribution, and nature of garnet as seen in thin section are strongly compositionally controlled by the occurrence in some combination of both P and Q domains and mica-rich and mica-poor remnant sedimentary laminae. These domains and laminae clearly influence the amount of garnet and the various textural details of garnet such as external morphology, abundance and type of inclusions, and spatial distribution of inclusions.

In the majority of cases for the four newly studied samples, S_i in garnet is parallel to S_e. In some cases, the same *undeviating* $S_i = S_e$ passes completely through adjacent garnet and staurolite crystals, including cases in which garnet occurs as inclusions in the staurolite. Only about a third of the garnet crystals (in a given thin section, or for all sections in aggregate) show any angular difference between S_i and S_e, and then never more than 10–20° of deviation. The angular difference is best described as a *very* open "lazy s" shape. As noted above, these slight deviations may be a reflection of the garnet overgrowing weakly developed S2 crenulation cleavage. Indeed, the figures used by S & B (10c and 10d) to illustrate deviation of S_i and S_e are typical of the maximum deviations that I have observed, and could well be due to garnet overprinting a weakly developed S2 in these rocks, as suggested above.

For the four new samples studied herein, pressure shadows associated with garnet are nonexistent to only very weakly and sporadically developed. For even the best-developed pressure shadows, there is no consistent asymmetry from one shadow to another in a given sample. The one case of clear, asymmetric pressure shadows around garnet that S & B illustrate involves a highly graphitic rock. Hence, as noted above, its meaning may be ambiguous.

Staurolite

Megascopic scale: Simple visual inspection of the many slabby outcrop surfaces of Perry Mountain Formation in Coos Canyon reveals no obvious alignment of the staurolite crystals. However, S & B claimed that statistical measurement of the long dimension of many crystals on a slab reveals greater alignment of staurolite on slabs located in a HSZ. Unfortunately, their diagrams purporting to support this assertion (their Fig. 4) are unconvincing. Inspection of their contoured diagrams may even suggest better alignment of staurolite in some LSZ samples. Moreover, if alignment of elongate porphyroblasts is only evident in the context of detailed statistical analysis, one might question its tectonic significance. The alignment could be due to some other control, such as an earlier fabric inherent in the rock. For example, I have noted some tendency for staurolite to grow as overprinting porphyroblasts in an elongate fashion parallel with the S2 crenulation cleavage. Figure 3b from Coos Canyon shows a case in which there is a clear megascopic alignment of staurolite in the direction of the axial planar S2 cleavage of a later, open fold. Finally, S & B ignore the almost universal cruciform twinning of the staurolite crystals [on the (231) plane, so that two crystals cross at ~ 60°] and how this would factor into and possibly undermine their proposal of a staurolite lineation.

Microscopic scale: For the vast majority of staurolite crystals in the new thin sections (in a given thin section, or for all sections in aggregate), S_i passes through staurolite crystals with no deviation whatsoever from S_e. In the few cases in which there is deviation by S_i from S_e by as much as 30°, it seems that it can just as easily be explained by the staurolite crystal growing along the S2 direction and partially overprinting a Q domain of the S2 crenulation cleavage. Figure 10e of S & B illustrates this possibility quite well.

Pressure shadows associated with staurolite are virtually nonexistent in the new thin sections considered herein. This fact is evident even in the hand specimen as seen in Figure 5a. The photos in S & B purporting to show pressure shadows associated with staurolite involve very graphite-rich rocks, and so their true significance is, at best, ambiguous.

Andalusite

Megascopic scale: The suggestion of a lineation of andalusite crystals (or of products of their replacement) by S & B is considered incorrect. Their one photo (Fig. 3c) purporting to show the staurolite and andalusite crystals in a mutual alignment is completely misleading. Figures 7a and 7b illustrate the typical non-alignment of andalusite from the HSZ at Coos Canyon. Moreover, such andalusite crystals (now variably replaced by coarse muscovite due to superposition of M3) are commonly at high angles to the biotite lineation (see Fig. 5b), the only clear, unambiguous megascopic mineral lineation developed in these rocks.

In summary, excluding cases like that of Figure 3b, there is little convincing evidence for widespread alignment of porphyroblasts in *any* rocks in the area considered. Indeed, in the case of andalusite, simple inspection of foliation surfaces in the field shows an essentially random orientation of andalusite crystals within the plane of the foliation. Ironically, over the years, I have informally described the andalusite pseudomorphs as seen on foliation surfaces as "turkey tracks", because they convey an impression much like that of tracks made by turkeys walking about in a muddy barnyard, hardly an aligned pattern. The presence or absence of such lineations is important with regard to the existence of any HSZ and with regard to the M2 metamorphism being syntectonic during or even near the peak of the heating event.

Ilmenite

Microscopic scale: Ilmenite plates are especially useful in the metamorphic rocks of western Maine for displaying features of the fabrics. Such plates record both the superposition of S2 on S1 and the angular relations between S_i in porphyroblasts and S_e of the groundmass foliation. In the new samples from Coos Canyon studied herein, it is clear from ilmenite plates (and quartz) that, with only rare exceptions, S_e and S_i in staurolite are parallel, with no angular divergence whatsoever. The same is largely true with regard to S_i and S_e in garnet, but as with quartz inclusions, in about a third of the cases there are weak divergences of up to 10–20°.

Figure 6c, and possibly 6d, of S & B illustrate nicely how the ilmenite plates (not affected by staurolite growth in contrast to the graphite platelets) go through the staurolite so that S_i and S_e are parallel. In contrast, the distribution of graphite in the same staurolite is crystallographically controlled. The biotite in that sample behaves as they state because biotite does form a "stretching" lineation in a moderate proportion of M2 rocks.

Conclusion

Other questions and criticisms can be raised regarding the observations and assertions by S & B. However, those discussed above should suffice to caution readers lacking detailed familiarity with the geology of western Maine that it may be unwise to accept S & B uncritically regarding the tectonometamorphic aspects of M2. Based upon the above discussion of the purely "observational" aspects of S & B, my conclusion is quite simply put: the observations and data they present are sufficiently flawed and questionable that their general conclusions or assertions should be accepted only with reservation. In my opinion, it seems that their subdivision into HS and LS zones may basically be an *a priori* assertion needed to provide a mechanism to facilitate their model for pluton emplacement, *e.g.*, Brown & Solar (1998a). Moreover, the textural features they present show little supporting evidence for a synkinematic M2, especially during the medium- and higher-T portions of the event.

If feasible, I urge readers for whom it is important in terms of their own research to assess the pros and cons of the questions I raise about the two main proposals in S & B, to go to see the rocks in the field. The rocks at Coos Canyon are extremely well exposed, and the locality is very scenic.

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