Maine Geological Survey
Studies in Maine Geology: Volume 2
1989

Hurricane Mountain Formation Mélange: Description and Tectonic Significance of a Penobscottian Accretionary Complex

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ABSTRACT

The Hurricane Mountain Formation, which crops out nearly continuously for more than 160 km (100 mi) along the entire length of the Lobster Mountain anticlinorium, is described and interpreted as a polymictic, tectonic mélange that contains olistostromal antecedents. It is believed to be mainly Middle to Upper Cambrian in age, based on sparse paleontologic evidence. An isotopic apparent age of 540 Ma, determined for an amphibolite megaclast, sets an approximate maximum age limit for the accumulation of the mélange in the Indian Pond area, southwest of Moosehead Lake. Metagabbro of intrusive origin yields a preliminary isotopic apparent age of 485 Ma on calcic amphiboles of its metamorphic assemblage. This indicates an Early Ordovician minimum age for the mélange and the Penobscottian metamorphic event. The formation is interpreted from structural relationships at regional and small scales to be overlain unconformably by formations as old as Middle Ordovician, which are much more simply deformed. The Hurricane Mountain Formation, although it is polydeformed and regionally metamorphosed to low

metamorphic rank, nevertheless preserves many accretionary tectonic features akin to modern examples in fore-arcs of active plate margins.

The mélange exhibits a tectonic fabric throughout much of its semipelitic to pelitic matrix. Those parts of the formation containing abundant clasts of sedimentary parentage show evidence of an early olistostromal history. Stratal disruption is moderate to extreme. Boulder-in-matrix (argille-à-blocs) fabrics are also documented. Metabasaltic and metagabbroic rocks were emplaced both by magmatic intrusion, as well as by faulting and disruption of volcanic rocks. Small phacoidal lenses of felsic volcanic ash protolith form a minor but pervasive component of the matrix. Clasts of endogenous and exotic origins range in size from the microscopic to examples that exceed 1.5 km in length. Metabasite blocks show a range of metamorphism from lower greenschist to middle amphibolite facies. Those of higher grade than the pervasive, white mica - chlorite grade of the matrix indicate by their sharp structural and metamorphic discontinuities at their contacts that they attained their higher grade assemblages prior to final tectonic emplacement. A medium-pressure, low- to medium-temperature P/T trajectory is inferred for this phase of Penobscottian metamorphism. Compositions of sodic-calcic amphibole in one megaclast, however, indicate metamorphism at high pressure and low temperature.

The Hurricane Mountain Formation is tectono-stratigraphically correlated with other units containing mélange characteristics in the Caucomgomoc inlier, Chesuncook dome, and Munsungun anticlinorium. It is considered to be a major component of a suture zone between two amalgamated exotic terranes, the Boundary Mountains terrane to the northwest, and the Gander to the southeast. As such, it is a key to the underlying cause of the Penobscottian orogeny.

INTRODUCTION

The purposes of this contribution are twofold: first, to describe the overall characteristics of a Cambrian to Lower Ordovician (?) olistostromal and tectonic mélange that is characteristic of most of the Hurricane Mountain Formation; and second, to focus in detail on some of its structural and petrologic characteristics that give clues to the tectonic environment in which it formed. In its descriptive aspects, this paper forms what may be considered the first of a two-part discussion of pre-Middle Ordovician, accretionary tectonics as developed from geologic mapping in Maine. The second part emphasizes the regional geologic framework, and proposed tectonic kinematics of pre-Taconian amalgamation of a suspect exotic terrane, the Boundary Mountains Terrane (floored by sialic basement that is believed to be composed of granofels and gneiss as exposed in the Chain Lakes massif), with another, believed to be the Gander (Boone and Boudette, 1989). This orogenic event, which is restricted to supracrustal cover rocks of Late Precambrian(?), Cambrian, and Early Ordovician age, is assigned to the Penobscottian orogeny (first named the Penobscot disturbance by Neuman, in Neuman and Rankin, 1966; Neuman, 1967). The interpretive accretionary tectonic model is herein referred to and refined.

The Hurricane Mountain Formation is a polydeformed tectonite, and of low metamorphic rank. Structures within it are believed to record two orogenies, the Penobscottian, in late Cambrian to earliest Ordovician time, and, more than 100 million years later, the Acadian. In contrast, along the belt of the St. Daniel mélange (Baie Verte - Brompton line; Williams and St-Julien, 1982) that is believed to delineate the northwest margin of the Boundary Mountains/Gander composite terrane (Boone and Boudette, 1989), orogenic expression in penetrative deformation is *Taconian* and Acadian. Whereas the Taconian is considered to record arc - continent collision in central and southern New England (e.g., Stanley and Ratcliffe, 1985), it may more fundamentally represent collision involving the Early Ordovician Laurentian continental margin and a sial-floored terrane or composite terrane (Boone and Boudette, 1989), upon part of which, the Bronson Hill arc (Stanley and Ratcliffe, 1985; Aleinikoff, 1977), and possibly the Ascot - Weedon arc (cf. discussion *in* Cousineau, 1987), were constructed.

Observations are presented in succeeding sections and in Boone and Boudette (1989) to support the argument that Taconian deformation in the pre-Silurian anticlinoria of central-western, and north-central Maine produced neither a regional, penetrative deformational fabric nor a distinctive and widespread fold geometry. This study concurs with the views earlier put forth by Neuman (1967) and Hall (1970), that the dominant deformation is pre-Taconian, i.e., pre-Middle Ordovician, and that Taconian deformation is relegated to broad warping, and possibly localized open folding and high-angle faulting. The view that Taconian penetrative deformation is absent in this area, however, stands mainly on negative evidence, for there are no isotopic dates on micas in cleavages, especially as they relate to the polydeformed, pre-Silurian strata of this region. Field structural and stratigraphic determination of the age of penetrative deformation in these rocks is further hampered by the presence of at least two generations of cleavage within the western and south-central tracts of Silurian and Devonian strata of the Kearsarge - central Maine synclinorium (e.g., Moench and Zartman, 1976, and Osberg, 1974, respectively).

Along the northwestern margin of the synclinorium, however, as well as in the Moose River synclinorium, there is a striking contrast in penetrative fabric between the Silurian and Devonian strata, on the one hand, and the pronounced polydeformed, pre-Middle Ordovician strata of the Lobster Mountain anticlinorium (Fig. 1), on the other. Middle to Upper Ordovician metavolcanics, metavolcaniclastic rocks, and slate in the anticlinorium are deformed and cleaved as if they were subjected to the same deformational regime as imprinted upon the Silurian and Devonian strata. The absence of deformation in dated post-Acadian, Devonian plutons in western and northern Maine (e.g., Boone and Gaudette, in prep.; Loiselle et al., 1983; Hubacher and Lux, 1985) indicates that the younger regime in this part of Maine must be the Acadian, and therefore the only deformational regime to have affected the Middle and Upper Ordovician strata is, likewise, probably Acadian.

If widespread Taconian folds and cleavage lurk undetected amidst the Penobscottian and Acadian structures of the Lobster Mountain anticlinorium, the Taconian structures would be essentially coaxial and coplanar to those of the Acadian. The essentials, however, of the argument to follow would not be invalidated. The belt of intense Taconian orogenic deformation appears to be confined to several tens of kilometers astride the Baie Verte - Brompton line, as documented in the internal and external zones of the Quebec Appalachians by St-Julien and Hubert (1975). This structural zone probably extends deeper into the Cambrian - Ordovician cover sequences above Grenvillian basement (St-Julien et al., 1983) to the north and west of (structurally below) the St. Daniel belt, than it does into the cover sequences to the south and east, overlying the Chain Lakes basement of the Boundary Mountains terrane. This is believed to be so, not only from mapping referred to in this report, but because interpretation of the Quebec - western Maine seismic profile (Stewart et al., 1986) strongly indicates that Chain Lakes basement is thrust over Grenvillian basement; this carries the implication, adopted in this paper and in Boone and Boudette (1989), that the covering, pre-Middle Ordovician formations of the Boundary Mountains and Lobster Mountain anticlinoria were transported with the Chain Lakes as a structural unit, i.e., terrane. If Taconian penetrative deformation extends farther southeastward, at least into the western and north-central Maine anticlinoria, however, an alternative model would be rendered more viable: Osberg (pers. commun., 1987) has proposed that the St. Daniel and Hurricane Mountain belts of ophiolite and mélange represent a single suture zone, broadly of Taconian age, structurally repeated by Acadian fold and thrust tectonics. Difference in ages of mélanges, ophiolitic rocks, and cover sequences would, according to his model, apparently reflect different portions of pre-Taconian oceanic crust and Taconian fore-arc elements that now appear as segments in fold - thrust sequences.

Boone and Boudette (1989) present evidence in favor of the western and central Maine orthotectonic zones of mélange as having marked a lithospheric plate boundary distinct, in time and location of suturing, from the Baie Verte - Brompton line. This boundary, termed the Hurricane Mountain belt, extends northeastward from the Lobster Mountain anticlinorium and Chesuncook dome (Fig. 1), to include belts of mélange of broadly similar age, in the Caucomgomoc inlier, the Munsungun anticlinorium, and the Lunksoos[1] anticlinorium (Boone and Boudette, 1989). The Hurricane Mountain belt is interpreted as a suture zone between the sial-floored Boundary Mountains terrane, to the present-day northwest, and another terrane, also initially having a sialic basement, probably the Gander, to the southeast.

The geometry of the Hurricane Mountain Formation probably is not stratiform; furthermore, if its identity as an ancient accretionary complex is correct, the minimum age of the Hurricane Mountain Formation would be based on its cover of fore-arc basin deposits over those portions of mélange that had become tectonically inactive. Assuming present-day southeastward polarity of subduction, the oldest part of the accretionary complex would be found southeast of the Lobster Mountain anticlinorium, and thus would lie buried beneath younger strata of the Kearsarge - central Maine synclinorium. The exposed part of the complex in the Lobster Mountain anticlinorium, from which virtually all information on the Hurricane Mountain Formation has come, is probably but a small fraction of the whole, if modern analogs are appropriate. Although the Hurricane Mountain Formation has been mapped as essentially stratiform within the 5 to 10 km of cross-strike exposure, it is believed to have originated as an accretionary wedge, or prism. The geology of the mélange holds intrinsic interest if only from the point of view of its antiquity within the Appalachian tectonic framework.

One of the aims of microstructural study of drill core samples of the Hurricane Mountain Formation taken from the anticlinorium in the Brassua Lake and The Forks quadrangles (Fig. 1) was to learn whether the tectonic environment of mélange formation involved mainly dip-slip thrust motion, or whether a strike-slip component, which might signify oblique subduction, could also be recognized. This depends entirely on recognition of earliest incremental strain patterns and their orientations. Earliest microstructures and their original orientations can be identified only if younger strain geometries can be recognized and analytically retrodeformed. Without isotopic dating of individual foliation sets, this problem has been approached using the usual geometric criteria of superimposed structural elements. Obtaining knowledge of net slip, and inferring the tectonic environment of this early Paleozoic mélange-forming event depend heavily on comparison with microstructural elements formed in modern tectonic environments of active plate margins. Comparison with modern accretionary complexes is remarkable for the similarities encountered. This implies, but does not prove, that all Hurricane mélange microstructures thus

[1] Cf. Boone and Boudette (1989) in which the name, Weeksboro - Lunksoos Lake anticlinorium is abbreviated to Lunksoos anticlinorium.

Figure 1. Geologic map of Lobster Mountain anticlinorium and Chesuncook dome. Patterned areas represent pre-Middle Ordovician formations of the Lobster Mountain anticlinorium, and those subjacent to Saw Mill and Southeast Cove Formations of the Chesuncook dome, and show relationship of Hurricane Mountain Formation to the following pre-Silurian formations: Boil Mountain Ophiolite, Jim Pond Fm., Dead River Fm., Kennebec Fm., Lobster Mountain volcanics (modified from Osberg et al., 1985). Silurian and Devonian formations northwest of the Lobster Mountain anticlinorium occupy the Moose River synclinorium; those east of 69°45' and south of ~45°55' occupy the Roach River synclinorium; the remainder, south of 45°30', occupy the Kearsarge - central Maine synclinorium.

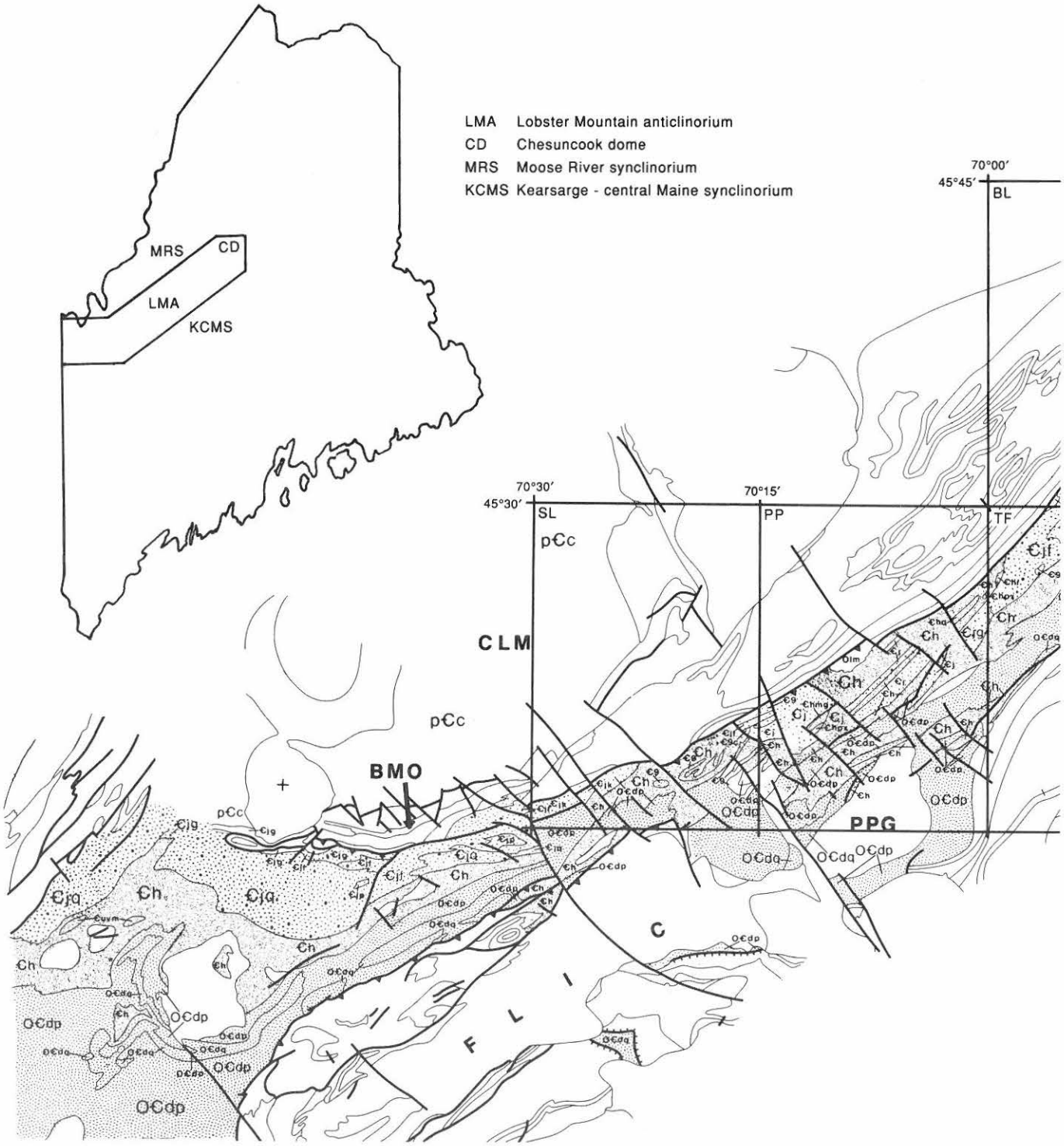
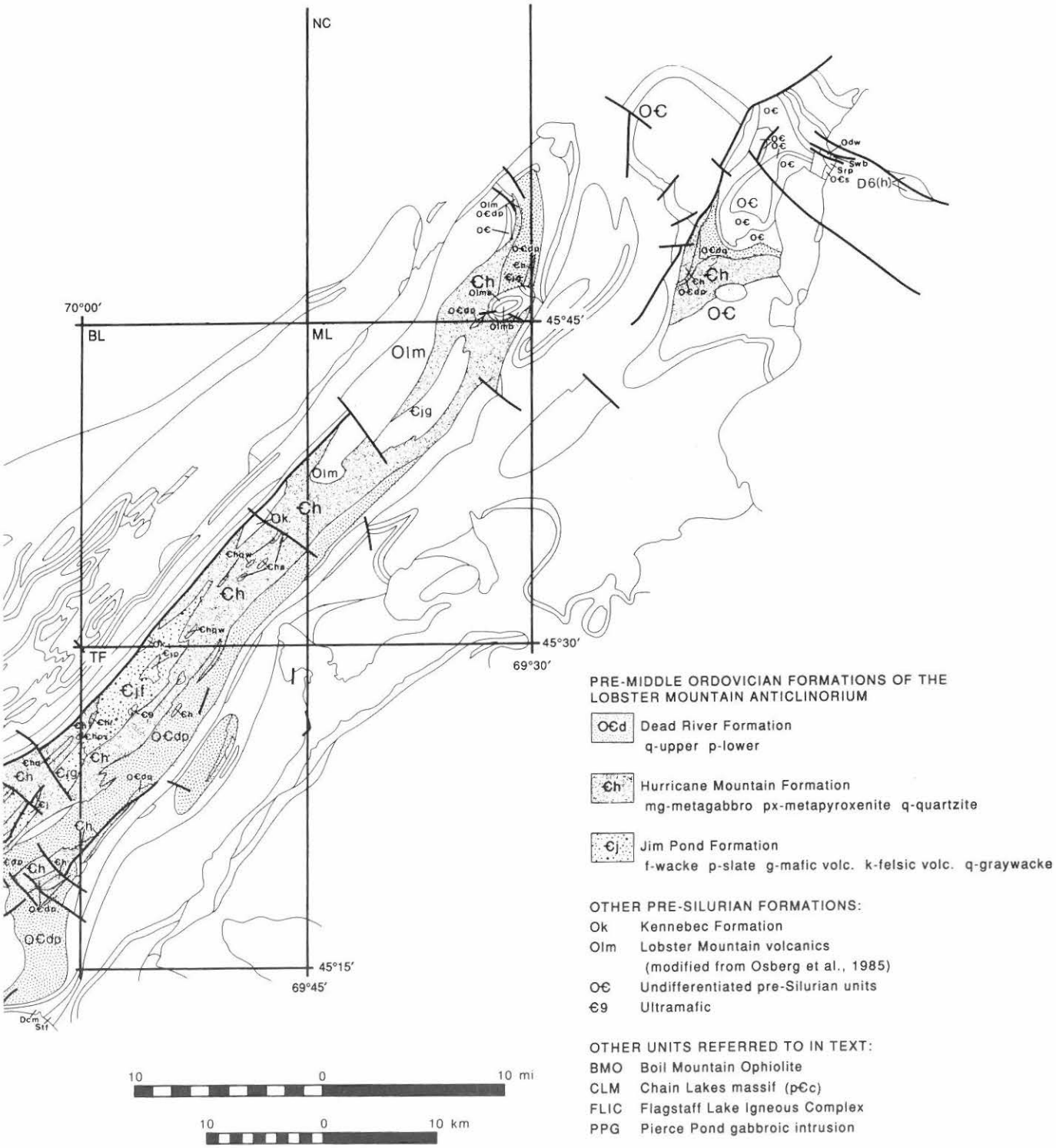


Figure 1. Continued.



compared originated in one tectonic episode, i.e., the Penobscot event.

To recognize whether or not a penetrative Acadian cleavage or foliation is superimposed and thus modifies earlier foliations in the Hurricane Mountain Formation depends on: (a) similar orientations of analogous structural features in the Hurricane Mountain Formation and in younger, post-Penobscot, pre-Acadian formations, (b) comparable lithic heterogeneity of the affected layered metasedimentary successions, and (c) to what extent earlier fabric anisotropy has affected the orientations of later microstructural features. Furthermore, recognizing Penobscottian structural elements depends on whether it can be demonstrated that the Taconian orogeny as a pervasive cleavage-forming event had been confined mainly to the region northwest of the Boundary Mountains anticlinorium.

Latest folds in the polydeformed rocks of the Lobster Mountain anticlinorium and Chesuncook dome (Fig. 1) are upright and contain an axial surface, spaced cleavage that has transposed earlier cleavage elements. The axes and associated axial surface cleavage of these folds are approximately colinear and coplanar, respectively, to those elements in Acadian folds in Middle to Upper Silurian and Devonian strata flanking these major uplifts. These similarities provide a point of departure in sorting out identities and relative ages of foliations. Based on comparison of structural elements and their orientations, the present study suggests that both dip slip and strike slip components of displacement in the Hurricane Mountain mélange are present; if both were formed in the Penobscot event, the net effect may be interpreted as recording transpressional strain in the accretion of the mélange.

Three formations comprise the pre-Middle Ordovician rocks in the Lobster Mountain anticlinorium. In tectonostratigraphic order, from oldest to youngest, they are the Jim Pond (Boudette, 1978, 1982), the Hurricane Mountain (Boone, 1983, 1985) and the Dead River Formations (Boone, 1973). Each is composed of distinctly different bulk compositions that responded differently to development and modification of foliations. The Jim Pond Formation, which contains abundant mafic and felsic metavolcanic rocks, exhibits tight to open folds, and apparently was the most competent of the three during folding. A predominant axial planar cleavage to mesoscopic folds, of unknown age, in metasedimentary and meta-volcaniclastic rocks of the Jim Pond Formation, is locally folded and mildly overprinted by a second, presumably Acadian cleavage. In order of decreasing competency are the remaining two formations: the Hurricane Mountain Formation, composed largely of metasiltstone, quartzwacke, with slate and phyllite in much subordinate proportion, and the Dead River Formation, a flysch sequence composed of roughly equal proportions of slate or phyllite, and feldspathic, chlorite-rich arenite. In the order given, polydeformation is most evident in the Dead River Formation, in which an Acadian component of refolding and cleavage transposition is well documented (Burroughs, 1979). This unit is extensively polydeformed, displaying a strong transposition of S_1 cleavage and refolding of F_1 folds into tight to isoclinal, F_2 upright folds. These folds range in scale from millimeters to several meters (Burroughs, 1979). They are interpreted as drag folds, satellitic to major, Acadian F_2 folds that produce much of the structural repetition of formations at quadrangle map scale as, for example, in the Pierce Pond quadrangle (Boone, 1985). Counter to impressions gained from study of the Dead River Formation, penetrative strain caused by Penobscottian deformation in the predominantly metasiltstone matrix lithology of the Hurricane Mountain Formation is believed from this study to be much more intense than that produced by the Acadian. If this interpretation is correct, the Hurricane Mountain Formation, in bulk, responded more effectively to strain hardening prior to the Acadian than did the Dead River Formation. On the other hand, beds of metapelite in the Dead River flysch succession may show greater response to polyphase deformation in terms of striking examples of refolded folds at micro- and mesoscopic scales, owing to a more pervasive contrast in competency (P.H. Osberg, pers. commun., 1987) between the interbedded pelitic and chloritic wacke lithologies characteristic of this flysch unit. The view that most of the foliations that form a penetrative fabric in the Hurricane Mountain Formation are Penobscottian, therefore, depends heavily on the close correspondance of this fabric with examples from geologically younger mélanges in present-day accretionary complexes.

Anastomosing shear cleavages in the Hurricane mélange truncate very fine-grained compositional laminations and curve into a quasi-layer-parallel, shear foliation. These microstructures, so prevalent in the Hurricane mélange, are interpreted as having begun to evolve within the growing volume of melange while deposition of sediment and olistostromal transport were occurring at, and near the sediment - water interface. Most of these microstructures are assigned to the Penobscot event, rather than to younger Taconian or Acadian events, because locally they are variously recrystallized in relict hornfels of a narrow contact aureole against a metagabbro sill-like body of intrusive origin. A preliminary $^{40}Ar/^{39}Ar$ minimum metamorphic age of approximately 485 Ma for the metagabbro has been determined (see section on isotopic dating). Evidence is cited in the section on metamorphism to support the interpretation that the age of gabbro intrusion, and maximum age of its polythermal, retrograde metamorphism, may be significantly older. Kennebec Formation feeder dikes that cut the Hurricane mélange show a single, rough cleavage that can be seen in core specimens to extend into the Hurricane mélange on a scale of millimeters to centimeters. If the Kennebec cleavage is Acadian, as proposed, this view also would support the contention that most of the microstructures in the mélange were formed prior to Middle Ordovician time, based on the stratigraphic age of the Kennebec Formation. In the central part of the Brassua Lake quadrangle, a spaced fracture- and transposition (crenulation) cleavage, believed to be Acadian, modifies only slightly the earlier Pennobscottian structures (Doty, 1987). Except near late fault zones, localized overprints of kink-banding have not

obscured a wide variety of early, accretion-related structures in the mélange of the Hurricane Mountain Formation. These are discussed in succeeding sections.

Throughout the Lobster Mountain anticlinorium, the pre-Silurian rocks are metamorphosed to regional metamorphic grades ranging from prehnite-pumpellyite to lowermost greenschist facies. Acadian regional metamorphism, as recorded in the Silurian and Devonian strata surrounding the anticlinorium, is isofacial with the pre-Silurian rocks south of about 45°40' (Fig. 1), but northward, it decreases such that glauconite is found in Silurian sandstone of the Ripogenus Formation. Absence of higher-grade, *regional* relict assemblages within the polydeformed matrix of the Hurricane Mountain mélange, suggests that its pre-Acadian, i.e., Penobscottian, metamorphic history involved similarly low temperatures, and sub-blueschist confining pressures. Relict cordierite porphyroblasts and deformed, pinite pseudomorphs are preserved in relict hornfels of mélange matrix where intruded by feeder dikes of the Middle to Late Ordovician Kennebec and Lobster Mountain volcanic formations. High-grade amphibolite facies assemblages attributed to pre-Penobscottian, oceanic fracture zone metamorphism, or to early Penobscottian metamorphism are also preserved in exotic blocks of metavolcanic origin in the Hurricane mélange (Frost and Boone, 1978; Boone, 1983). Other than rare porphyroclasts of garnet, evidence is lacking that the mélange *matrix* was subjected to regional metamorphic grades higher than greenschist.

An Acadian metamorphic overprint is interpreted for the low temperature portions of $^{40}Ar/^{39}Ar$ release spectra of hornblendes in amphibolites within the mélange. Chlorite grains in the mélange matrix show both anomalous blue, as well as brown interference colors, which indicate disequilibrium assemblages. Thus far, textural evidence on which to assign the different chlorites to stages of a single, polythermal event, or to polymetamorphic events, has not been recognized.

Previous Work

Boucot et al. (1959) mapped and described a section of rusty metasiltstone and slate, now assigned to the Hurricane Mountain Formation, on Spencer Stream. In 1969, I and Syracuse University students began inch-to-the-mile mapping of the pre-Silurian rocks in the Boundary Mountains and Lobster Mountain anticlinoria. Serra (1973) mapped and interpreted the structure of the pre-Silurian strata in the Spencer Lake, Maine, 15' quadrangle, while I was engaged in mapping the same rocks in the neighboring Pierce Pond quadrangle (Boone, 1985). We both recognized a prevalence of flaser structure in the Hurricane Mountain Formation, but interpreted it mainly as a depositional feature. Clasts of massive gray limestone, quartzite, and sparse metavolcanic rocks were noted, but the full impact of mélange characteristics of the Hurricane Mountain Formation remained elusive in streambed and forest outcrops until the mid-'70's when large rafts of quartzite and ultramafic rocks in the Pierce Pond quadrangle, and exotic blocks of greenschist and amphibolite (Frost, 1977; Frost and Boone, 1978) were recognized in the Hurricane Mountain Formation in the Brassua Lake 15' quadrangle, where the mélange is best exposed, drilled, and its polymict and exotic aspects of clasts best displayed. Remapping of selected parts of the Hurricane Mountain Formation in the Pierce Pond quadrangle revealed ophiolitic and quartz-rich metasedimentary exotic blocks that previously had been interpreted as intrusives and autochonous bedded successions, respectively. The following description of mélange of the Hurricane Mountain Formation expands upon that in Boone and Boudette (1989), with the addition of new data and observations.

LITHOLOGY OF THE HURRICANE MOUNTAIN FORMATION MÉLANGE

Reference is made in this section and the following, to mélange types defined by Cowan (1985). In brief, they are: progressive stratal disruption of sandstone and mudstone (type I; see Fig. 2a, and drill-core sample, 2c), and mudstone, tuff, chert, and sandstone (type II) successions (Fig. 2c upper photo, d, e, f; Fig. 6b). Type III includes polymictic, chaotically deformed (or "churned") masses (Fig. 3d) in which the blocks, or clasts, record multi-stage tectonic events, the entire assemblage being "ready made" (Cowan, 1985) by the time of final emplacement, as opposed, evidently, to subsequent deformation following assembly of the enclosing part of the accretionary complex. Type IV comprises brittly faulted mudstone (Cowan, 1985) and presumably siltstone. Much of the Hurricane Mountain mélange is believed to strongly resemble the Franciscan mélange of the Pacheco Pass area, California, described by Cowan (1974). In the Hurricane Mountain mélange, commonly there are gradations between types I and II into penetratively sheared and faulted type IV. Boulder-in-matrix varieties (type III) are found locally throughout the strike belt of the formation.

The lithology of the fine-grained, most pervasive part of the formation is discussed first, followed by description of the categories of clasts.

Matrix Lithology of the Hurricane Mountain Formation

The term *matrix* refers to metasiltstone, slate, or phyllite, both in parts of the formation in which exotic or endogenous clasts abound, as well as in those parts in which clasts are microscopic, or nearly so. The matrix is mostly micaceous metasiltstone. In addition to quartz, common mineral constituents are fine-grained white mica giving a diffraction pattern of a 3T polytype (phengite?), chlorites, commonly showing both anomalous blue, as well as brown interference colors, and less commonly, smears and streaks of very fine-grained rutile and sphene. Tourmaline is a common, very fine-grained accessory mineral. Garnet is rare; it has been noted in the Indian Pond area of the Brassua Lake quadrangle, where it is clearly porphyroclastic, and may be a relict contact metamorphic mineral. Inter-

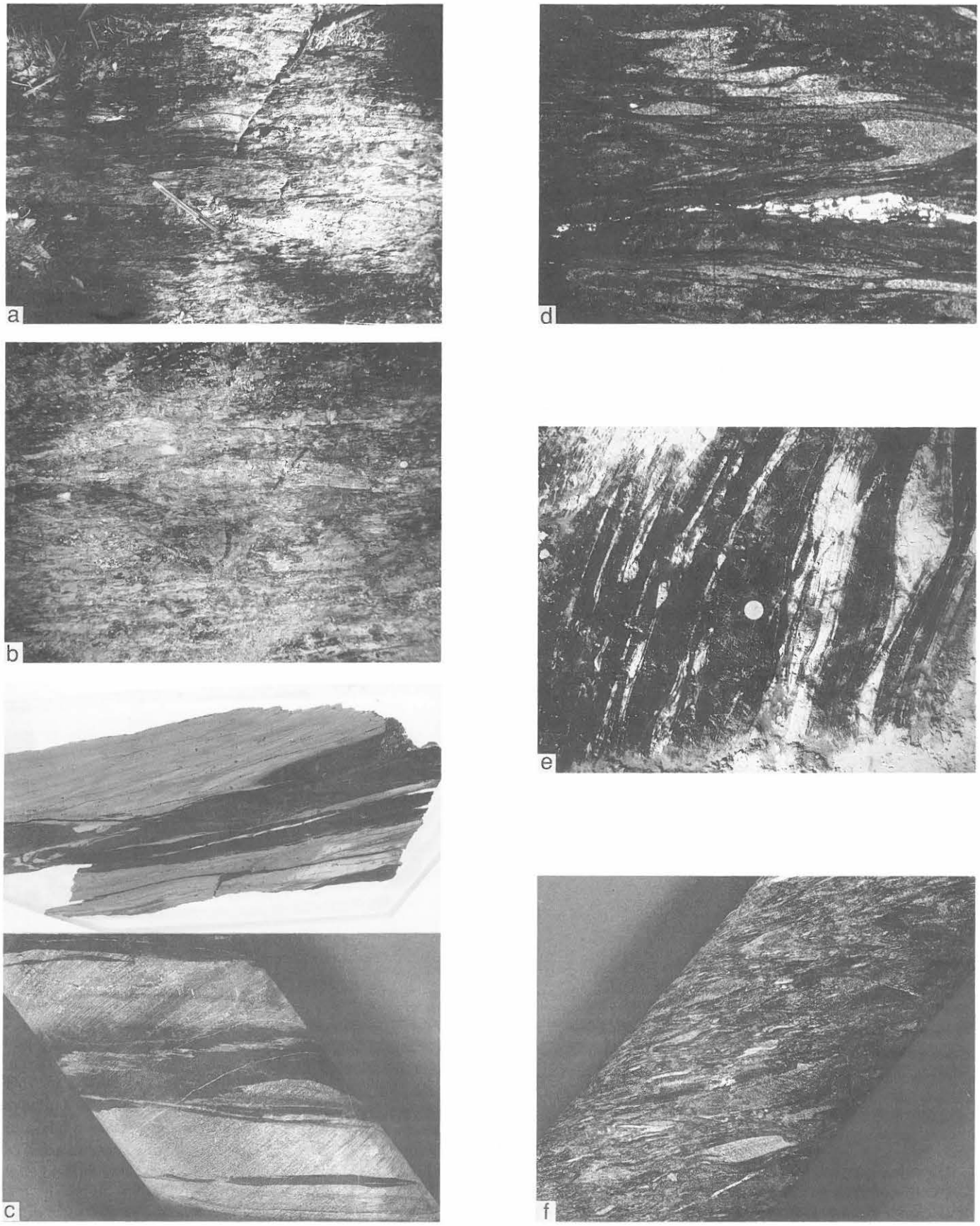


Figure 2.

TABLE 1. CHEMICAL ANALYSES OF MATRIX, HURRICANE MOUNTAIN FORMATION, COMPARED TO METAPELITES OF DEAD RIVER FORMATION

	Hurricane Mountain Formation		Dead River Formation Average of 10 analyses[a]
	1[b]	2[b]	3
SiO_2	66.45	62.82	60.00 wt. %
TiO_2	0.84	0.93	0.99
Al_2O_3	14.04	16.91	18.5
Fe_2O_3	4.84[c]	3.00	2.49
FeO	---	3.54	5.13
MnO	0.03	0.06	0.37
MgO	2.82	2.51	2.48
CaO	0.23	0.11	0.87
Na_2O	1.27	0.75	2.13
K_2O	3.84	4.38	3.67
H_2O	5.33	5.53	<4.18
CO_2	n.a.	n.a.	0.03
TOTAL	99.69	100.54	100.86

[a]Analyses from Boone (1973)
[b]Analyses from P. T. Lyttle (1976)
[c]Total Fe reported as Fe_2O_3

Sample 1 (=no. 65 of Lyttle) from ~1430' elev., NW slope of Otter Pond Mountain ~0.4 mi east of Bowtown/Pierce Ponds township line. Andalusite zone of Pierce Pond gabbro contact metamorphic aureole.

Sample 2 (=no. 349 of Lyttle) from ~1420' elev., south slope of Hurricane Mountain, ~1.2 mi west of Bowtown/Pierce Ponds township line. Cordierite zone of Pierce Pond gabbro contact metamorphic aureole.

The averaged analyses of Dead River Formation metapelites represent samples from chlorite-muscovite, to K-feldspar-cordierite grades of metamorphism, northern Little Bigelow Mountain 15' quadrangle. Locations shown in Boone (1973).

laminated slate (or phyllite) is common, but distinctly subordinate to metasiltstone. Chemical analyses of typical matrix are given in Table 1. Metasiltstone is almost exclusively carbonate free; metapelitic matrix from outcrops is also typically carbonate free, but locally, lenses are calcareous or dolomitic. These carbonate-bearing varieties appear to be much more common in drill core samples. Rarely, fault-bounded lenses of metasedimentary rock, in which stratal disruption is minimal, exhibit depositional structures and parallel bedding. Laminations and tiny phacoidal lenses of light buff, very fine-grained, white mica and unidentified zeolitic or feldspathic minerals (relict, felsic ash protolith?) are a common and characteristic feature of the matrix in many areas. In most outcrop exposures, bedding and bedding laminations (identified by small-scale mineralogical gradation across the layering) are truncated by low-angle shear surfaces, and only rarely can they be traced for more than a meter. Small-scale fold-hooks are common (Fig. 2d). Systematic structural repetition of layering has not been recognized in the matrix. These structures, taken singly and in combination, produce flaser-like laminae, and also thin, tapering lenses or pseudobeds, with lengths ranging from millimeters to several centimeters, but rarely more than a meter (Fig. 2b,c).

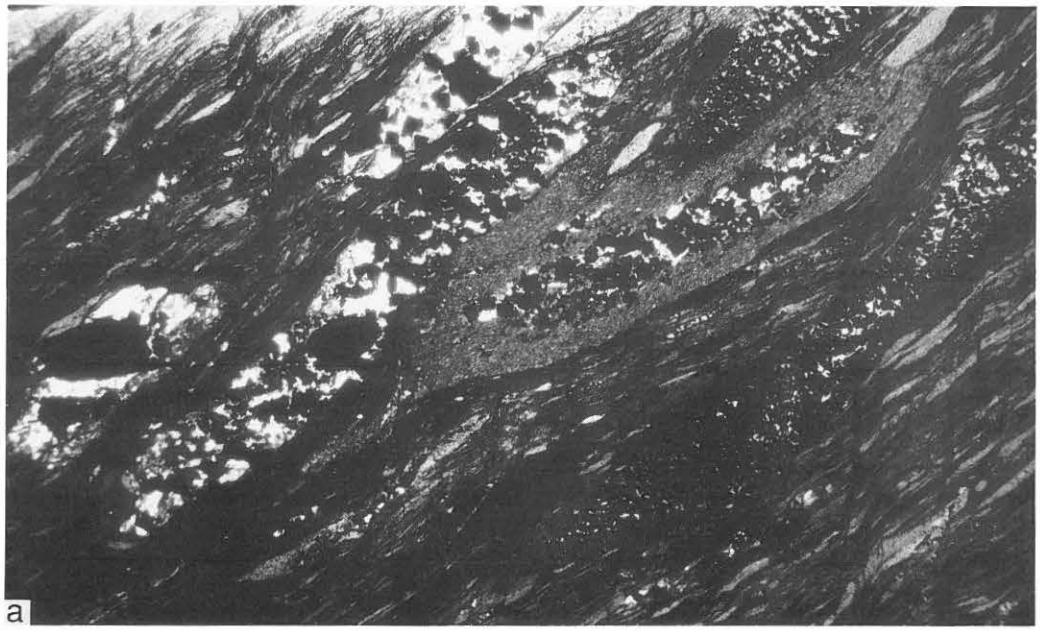
The matrix is color-variegated, but most commonly is dark gray or gray-green, and rusty, owing to the weathering of dispersed, fine-grained sulfides. Less commonly, the matrix is carbonaceous and darker gray, but rarely totally black. In some outcrop areas, the matrix is light or medium gray where sulfides and carbonaceous material are lacking. In many areas throughout the Lobster Mountain anticlinorium, the matrix is of typical "tiger-stripe" aspect, a pattern produced by flaser-shaped lenses of rusty metasiltstone alternating with dark, greenish-black chloritic lenses and light buff felsic laminae (Fig. 2a,e).

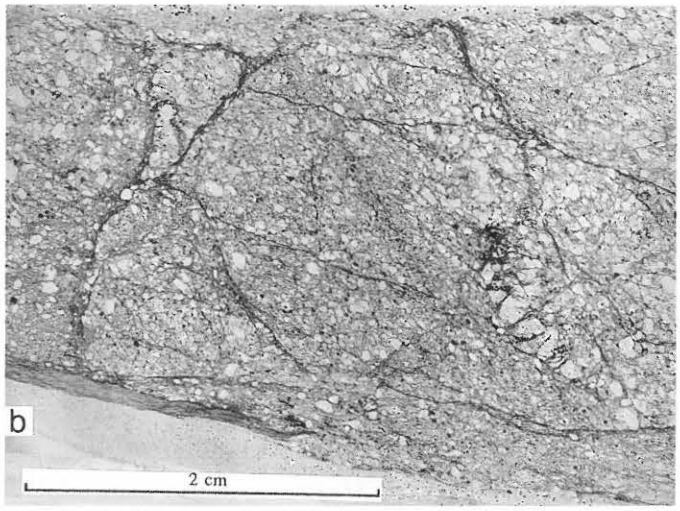
Encountered in drill-core, but to date not in outcrop, is a lithologic association marked by quartz-pyrite-dolomite "salt-and-pepper"-textured lenses, surrounded by carbonaceous, pyrite-rich, calcareous pelite, with sparse, wispy laminae of pyrrhotite (Doty, 1987). Locally in thin section the lenses are surrounded by a multicrystalline shell of carbonate (Fig. 3a). X-ray diffraction study indicates the carbonate shells consist of a slightly greater than 1:1 proportion of magnesian calcite ($Mg/Ca + Mg = 0.1 - 0.2$) to dolomite. These compositions are approximate, as it is not known if Fe, Mn, or Zn are major components (cf. Reeder, 1983; Anovitz and Essene, 1987).

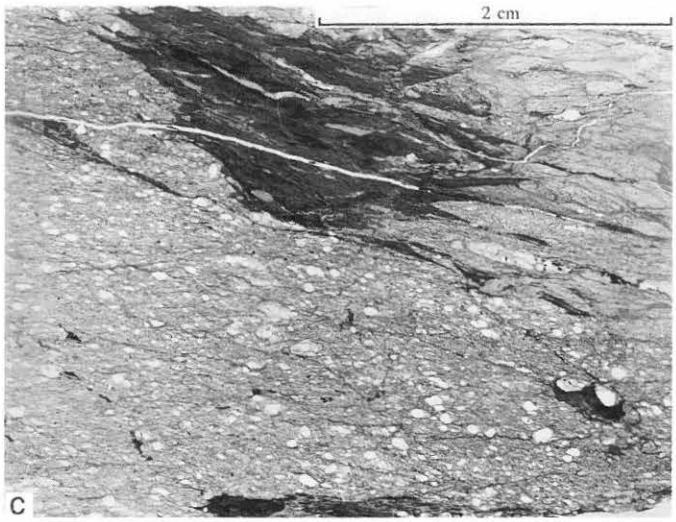
Two chlorite species - Fe-richer and Mg-richer - occur in separate bands within the matrix surrounding the lenses, giving an indication of the localized scale of Fe/Mg disequilibrium throughout much of the matrix of the Hurricane mélange.

Locally in outcrop, as well as in drill core, sparse zones of cleanly foliated slate and well-layered laminite occur. Those composed of slate commonly range in thickness from 1 to 3 m in drill core, and from several tens of meters to a maximum of about 150 m as mapped in surface exposures. The outcrop areas extend a few hundreds of meters along strike. Their contacts with surrounding matrix are sharp with no evidence of shear, as seen in drill core, but outcrops showing contacts are not exposed. Color within each of the slate bodies is uniform, and is either light gray, brown or black. Some of the laminites strongly resemble *chert-laminites* (Yoshida, 1983). Less deformed examples show layering that ranges from 1 to 5 mm thick, commonly with wavy, irregular surfaces. The laminae consist of

Figure 2. (a) and (b) Flaser structure produced by shearing at low angles to layering in metasiltstone - slate matrix of Hurricane Mountain Formation. Brassua Lake and Pierce Pond quadrangles, respectively. Pen and coin indicate approximate scale. (c) Stratal disruption evidenced by flaser structure in layered felsic ash and dark slate (top) and in graded, fine- grained, feldspathic meta-arenite and slate in core sample (bottom; Doty, 1987, pl.3). Width of each photo represents 8 cm. Brassua Lake quadrangle. (d) Sheared F1 microfolds of metatuff in matrix of metasiltstone, slate and metatuff (Doty, 1987, pl. 16). Width of photo represents 6 mm. (e) "Tiger-stripe" matrix showing incipient to moderate stratal disruption of dark green to black, chlorite-rich layers, cherty laminite and buff to white, feldspathic meta-arenite (felsic ash ?). Coin is 2.5 cm in diameter. (f) Flaser structure and polymict tectonic clasts in core sample, Brassua Lake quadrangle. Scale as in (c).







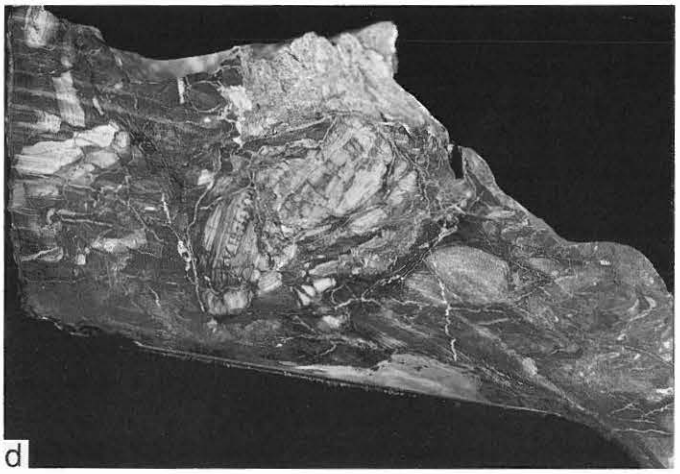


Figure 3. (a) "Salt-and-pepper" texture of quartz-pyrite lenses in matrix of drill-core sample, as seen in thin section (transmitted light). Carbonate-mantled lens, center right, is 5.5 mm long. Streaks of pyrrhotite, not visible in photo, occur sporadically throughout matrix. Lenses are pre-S_2 in age, as these and many other examples are bent in same sense of offset across S_2 (nearly vertical in photo) as are other lenses and planar features in surrounding matrix. (b) Anastomosing cataclastic shears in feldspathic meta-arenite clast. Shears are outlined by concentrations of opaque minerals and by diminution of quartz and feldspar grain-size. Pierce Pond 15' quadrangle. (c) Intercalation of feldspathic meta-arenite and black slate along shear surfaces. Larger grains of clastic origin are flattened in plane of predominant foliation, and cataclastic shears intersect in acute angles that are roughly bisected by foliation. These features are interpreted as a later deformational modification, by flattening, of the relict sedimentary fabric and the cataclastic shears shown in (b). Brassua Lake 15' quadrangle. (d) Monomictic slump-breccia of siltstone in black slate matrix. Moosehead Lake 15' quadrangle.

alternations of dark gray, chlorite-bearing pelite and gray to white, fine-grained quartz. In drill-core examples, some are calcareous.

Provenance of the Matrix Sediment

The predominance of lithologies comprising a spectrum between metasiltstone, aluminous metapelite, and minor feldspathic quartzite and felsic metavolcanic rock suggests a terriginous source, or sources, close to active volcanism. Sparse lenses of fine-grained, chlorite-rich calcareous phyllite may have been derived from immature, mafic volcanic detritus.

The interpretation of matrix mineralogical differences, upon which color and other bulk physical properties depend, is as follows. The different varieties of matrix probably owe their origin to pre- or early accretionary stratigraphic horizons, but the low density of outcrops in relation to the common change of color from outcrop to outcrop precluded the attempt to subdivide the matrix into lithotectonic or lithostratigraphic facies. In surface exposures, weathering, to varying degrees, has modified matrix mineralogy, and therefore color. The combined and varied effect of Holocene weathering, as well as of probably several episodes of pre-Holocene weathering, has only come to light after acquiring drill core samples of the Hurricane Mountain Formation, through the courtesy of Noranda Exploration Incorporated. At depths greater than about 6 m, the mélange matrix is noticeably more calcareous (ranging from a few tenths to several percent of carbonate minerals), more graphitic, and unoxidized. Drill core of matrix taken from below the zone of oxidation is consistently a display of black, greenish black, gray to light gray, and white. The pronounced friability of the matrix in surface exposures, therefore, results not only from its structural complexity, but surely also from volume changes that occurred during oxidation of graphite and iron sulfides, dissolution of carbonates, and precipitation of goethite.

The origin of the bodies of slate, regardless of thickness, is postulated, first, to be controlled by deposition of fine silt and clays intervening in space or time between episodes of both olistostromal slumping and down-slope, mass-movement of sediment (cf. Underwood and Bachman, 1982). Second, well-bedded shale and siltstone could then be isolated as structural units by thrust faults, followed by transfer of these structural units from lower, to upper plate by fault migration within structurally evolving accretionary complexes (Moore et al., 1981; McCarthy and Scholl, 1985). Alternatively, the formation and preservation of slaty cleavage may have been due to tight to isoclinal, early folding within the accretionary complex, followed by shearing out of hinge zones, and tectonic isolation between main sequence (thrust) faults.

The association of chert-laminites with mafic volcanic rocks, slump-breccias, and distal turbidites in many circum-Pacific, arc-related environments cited by Yoshida (1983) describe well the lithologic associations seen in the Hurricane Mountain mélange.

The origin of the quartz-pyrite-dolomite lenses is ascribed to a modern, possible analog developed by Ritger et al. (1987), for processes occurring near the toe of the accretionary complex that forms the lower continental slope off Oregon and Washington. They describe pyrite-bearing, concretionary deposits sampled from the water-sediment interface of this tectonically active accretionary prism. These deposits are thought to represent loci of methane-rich fluid expulsion caused by the dewatering of sediments within the tectonically active prism. The concretions consist of Mg-calcite + dolomite + aragonite-cemented sand, silt, and clay among which silt and clay apparently predominate. They comment that "In mud-rich samples pyrite is generally disseminated, whereas in coarser samples, it occurs more frequently in localized concentrations..." (Ritger et al., 1987, p. 148-149), an apt description of the pyrite distribution in the Hurricane Mountain mélange matrix lithology. In the Hurricane Mountain mélange, however, concretionary structures are not found. Either the "salt-and-pepper" lenses were formed as such, or they conceivably could represent tectonically formed lenses of disrupted concretionary deposits. A quasi-primary, diagenetic origin seems more likely, because the lens shapes appear to be largely independent of shear bands in the enclosing matrix. Unlike the mineralogy of the lower continental slope deposits, however, biogenic aragonite would not have endured the subsequent accretionary tectonics in the Hurricane Mountain Formation. Metamorphic aragonite is absent.

Clasts

The mélange is polymictic. Clasts consist of a variety of lithologies that are designated as endogenous or exotic. Those classified as endogenous include the products of sedimentary and volcanic stratal disruption, whether by olistostromal, or by post-burial tectonic processes. Their lithologies are widespread throughout the length and breadth of the Hurricane Mountain Formation. Locally, these lithologies can be seen and reasonably interpreted to be *in situ*, undisrupted beds, as remnants of stratigraphic successions, in gradational contact with surrounding matrix. This class also includes tectonically disrupted mafic dikes or sills, where structural relations in outcrop give reasonable assurance that they were intruded locally. Those termed exotic have no apparent *local* source. In some examples, they cannot be ascribed to depositional, intrusive, or metamorphic origins within the mélange as exposed in the anticlinoria of west-central, and northern Maine. Clast sizes range from microphacoidal, lithic fragments to blocks and rafts mappable at quadrangle scale (Fig. 4). Clasts may or may not be foliated. Metabasites in some of the exotic blocks were deformed and metamorphosed prior to their fragmentation and incorporation in the mélange. Many blocks of wacke display a rough cleavage

DEVONIAN - MIDDLE ORDOVICIAN AGE

Dgr Devonian(?) granite

Dc Carrabassett Formation (slate)

DScs Silurian or Devonian(?) calcareous slate

Sul Unnamed Silurian cleaved limestone and calcareous slate

Ok Kennebec Formation of Middle Ordovician (Llanvirn to Llandeilo) age, felsic metavolcanic and metavolcaniclastic rocks.

PRE-MIDDLE ORDOVICIAN AGE

O€d Dead River Formation (polydeformed, volcanogenic flysch)

€h Hurricane Mountain Formation mélange

€j Jim Pond Formation, "quartzwacke"-rich, volcaniclastic rocks, poorly to massively bedded, and showing a rough cleavage.

mg Polymetamorphosed metagabbro

CLASTS

qw "Quartzwacke" (feldspathic arenite)

pb Pillowed metabasalt

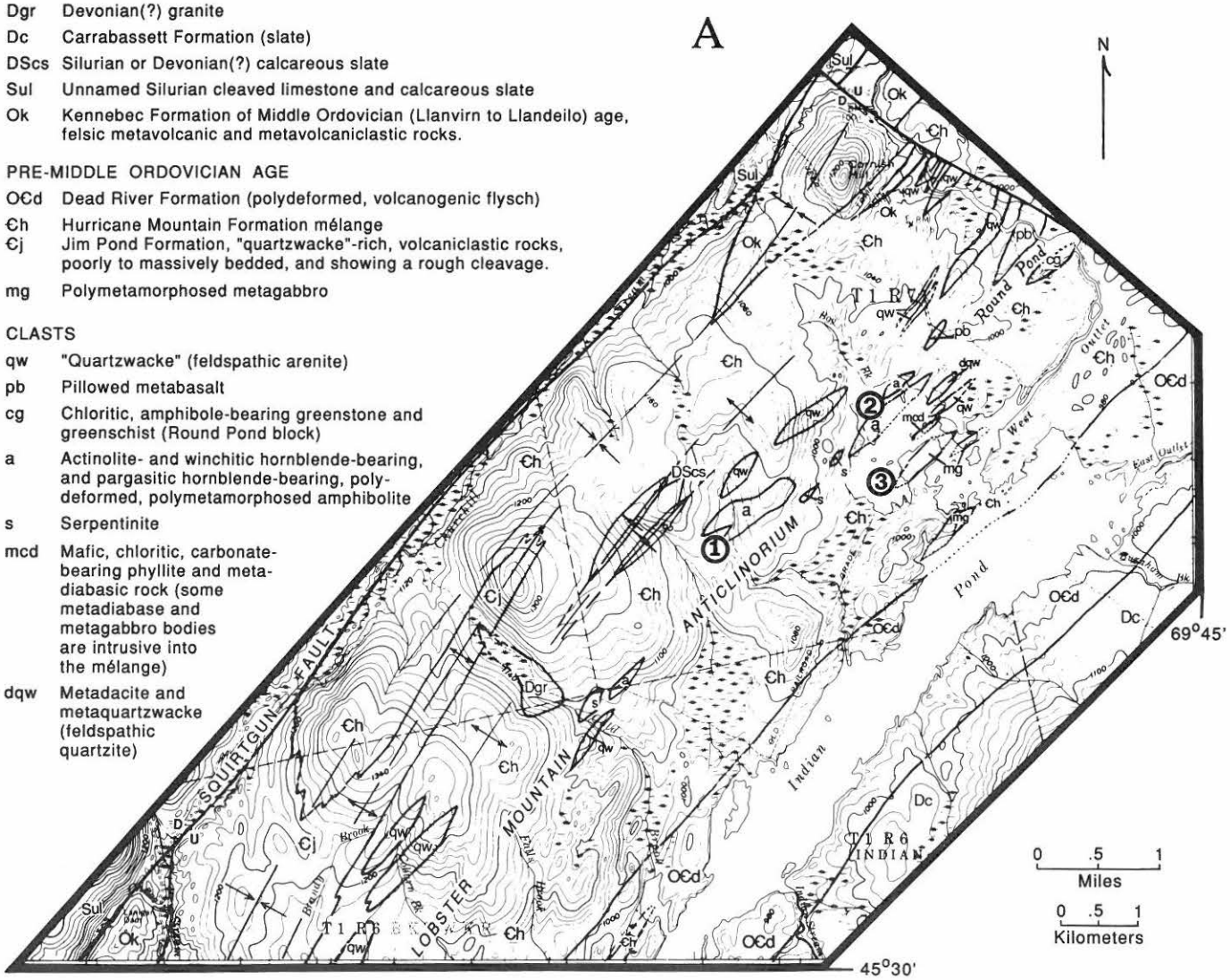
cg Chloritic, amphibole-bearing greenstone and greenschist (Round Pond block)

a Actinolite- and winchitic hornblende-bearing, and pargasitic hornblende-bearing, polydeformed, polymetamorphosed amphibolite

s Serpentinite

mcd Mafic, chloritic, carbonate-bearing phyllite and metadiabasic rock (some metadiabase and metagabbro bodies are intrusive into the mélange)

dqw Metadacite and metaquartzwacke (feldspathic quartzite)



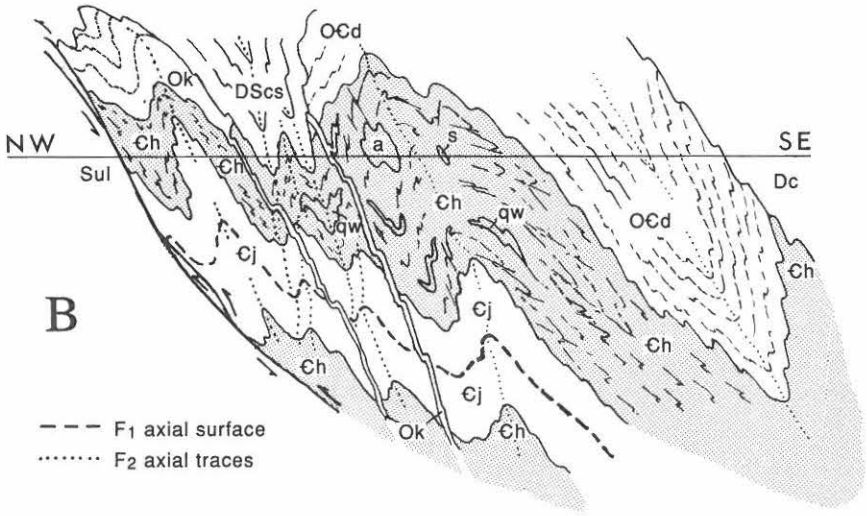


Figure 4. (a) Geologic outline map of the Indian Pond area, Brassua Lake 15' quadrangle (cf. Fig. 1 for location), showing distribution of large clasts in the mélange of the Hurricane Mountain Formation (modified from Boone, 1983; Boone and Boudette, 1989). Numbers refer to locations and informal names of other megaclasts and intrusives discussed in text: (1) M-17 high rank amphibolite; (2) "China Island" epidote amphibolite; (3) "Gabbro Point" intrusive.
(b) Composite cross section shows relationship of axial-plane folding of early F_1 folds to tight, upright (Acadian?) F_2 folds, and presence of two unconformities: one beneath the Middle Ordovician Kennebec Formation, the other, beneath the Silurian and Devonian strata. All units truncated by the Squirtgun fault (heavy line symbol with reverse motion indicated).

(Gray, 1978) that parallels the dominant foliation in the enclosing matrix. Endogenous clasts of wacke and mafic volcaniclastic origins may show variously sharp to diffuse margins, even in single examples. The following description of clasts augments that of earlier reports (Boone, 1983; Boone and Boudette, 1989) and describes in detail certain lithologic types that are useful in reconstructing tectonic environment, and other types of enigmatic source that may have future value in provenance or terrane evaluations.

Endogenous Clasts. Endogenous clasts comprise the following rock types, listed in order of decreasing abundance:

- feldspathic wacke
- feldspathic meta-arenite (metasandstone)
- feldspathic granule-metaconglomerate, of wacke or arenite bulk composition
- quartz-rich semi-pelite, commonly graphitic
- massive to foliated, chlorite- and carbonate-rich greenstone (metatuff?)
- metabasalt, metadiabase (locally derived, fragmented dikes, sills, or thin flows)
- pillowed metabasalt

Feldspathic metasandstone and wacke make up the bulk of the endogenous clasts. Modal analyses of stained thin sections of these clasts indicate the most common ones are feldspathic wacke, referred to in earlier field terminology (Boone, 1983) as quartzwacke and graywacke. Quartz, both as coarse, angular to augen-shaped grains and as finer, sheared grains, amounts to 30-35 volume percent; feldspar (almost exclusively as plagioclase, medium to coarse grains showing twinned, checkerboard domainal structure), commonly amounts to 35-40 percent. Very fine-grained, chlorite - ferric oxide-rich patches and wispy lenses amount to 15-20 percent. Coarse-grained opaque oxide and pyrite constitute about 5 percent. In some specimens, fine-grained clusters of stilpnomelane and white mica surround plagioclase grains. Lithic fragments are rare.

The origins of the blocks of impure metasandstone and meta-arenite are believed to be endogenous because of the following observations and interpretations: (1) Many appear to have formed as olistoliths of initially semi-consolidated, lumpy fragments; gradations can be seen from clast mineralogy and grain-size to those of the matrix, across several millimeters to a few centimeters around the ends of clasts (Fig. 5c). (2) Others appear to have formed as tectonic inclusions, because their phacoidal shapes apparently were largely controlled by boudinage and extensional shear at moderate or low angles to previous layering. Least commonly, (3) those on a "multiple-outcrop" scale appear to have formed as thick, fault-bounded, tabular clasts ("rafts") which are well bedded internally. Commonly, the beds are a meter to 4 or 5 m thick and probably less than 200 m long. Rarely, undisrupted, medium to thick beds can be recognized by gradation of bedding into increasingly thinner laminations into the matrix. Angular to rounded, phacoidally shaped metasandstone fragments range up to about a meter in length. These are common in types I and II mélange. Many of the phacoidal clasts of metasandstone contain web-like arrays of very thin veins that do not appear to extend into the enclosing matrix. Microscopically, the veins consist of very fine grains of brown oxide (goethite?), comminuted quartz, and feldspar. Their features appear to precisely fit the description of cataclastic shears, described by Lucas and Moore (1986), that occur within sandstones of the Sitkalidak Formation on Kodiak Island, Alaska, and within other sandstone units of modern accretionary complexes. An example of these endogenous clast features in feldspathic wacke of the Hurricane Mountain mélange is shown in Figure 3b & c.

The outcrop areas characterized by well-cleaved slate, referred to earlier in the discussion of mélange matrix lithology, are interpreted as fault-bounded lenses that escaped penetrative shearing.

Coarse-grained debris flow deposits were encountered in drill core. The clasts are supported by siltstone matrix in matrix-supported breccia with a calculated thickness of approximately 1 m. The clasts are rounded to angular, randomly oriented, and are composed of carbonate-bearing greenstone, siliceous laminite, and poorly foliated micaceous quartzite. Upper and lower contacts are sharp and apparently unsheared. The massive matrix indicates that locally, breccias are not subsequently deformed. As Doty (1987, p. 8) has noted for one example, "The contact with underlying, sheared type II is sharp, and may be erosional...," lending substance to the likelihood "that the clast breccia was deposited in situ..." as an olistolith. Figure 5 shows examples of a range of clast dimensions.

Some of the meta-basaltic and meta-diabasic blocks within the mélange are classified as endogenous because from field relationships, the blocks can be readily ascribed to dismembered, locally intruded dikes and sills. Those identified were apparently not more than a meter in width. Some fragments show a relict fine grained selvage on remnants of the wall, or contact surfaces. These small intrusive bodies were either brittly fragmented, or in other examples, boudinaged to form tectonic clasts strung out along the direction of foliation in the enclosing matrix. They are much less abundant than the endogenous metasedimentary clasts. Examples of metabasites that were initially intrusive into the Hurricane matrix have been noted in The Forks quadrangle (W. A. Burroughs, pers. commun., 1980) and in southern Brassua Lake quadrangle (M. Donnelly and W. Lynch, pers. commun., 1985).

Where roughly tabular, mafic, metaigneous rock bodies are large enough to be mappable, for example, at 1:10,000 or at quadrangle scale, it becomes a matter of arbitration, where outcrop control is lacking, in deciding if these are large clasts or purely intrusive bodies. The rule of thumb was adopted that, if the mappable body in question exhibits a relict, finer-grained, marginal facies and is in direct contact (with or without superimposed cataclasis) with a relict contact metamorphic aureole in the surrounding mélange, it is regarded as an intrusive rock body and not as a tectonic clast. Metadiabasic and metagabbroic rocks in some parts of the mélange in the Spencer Lake quadrangle

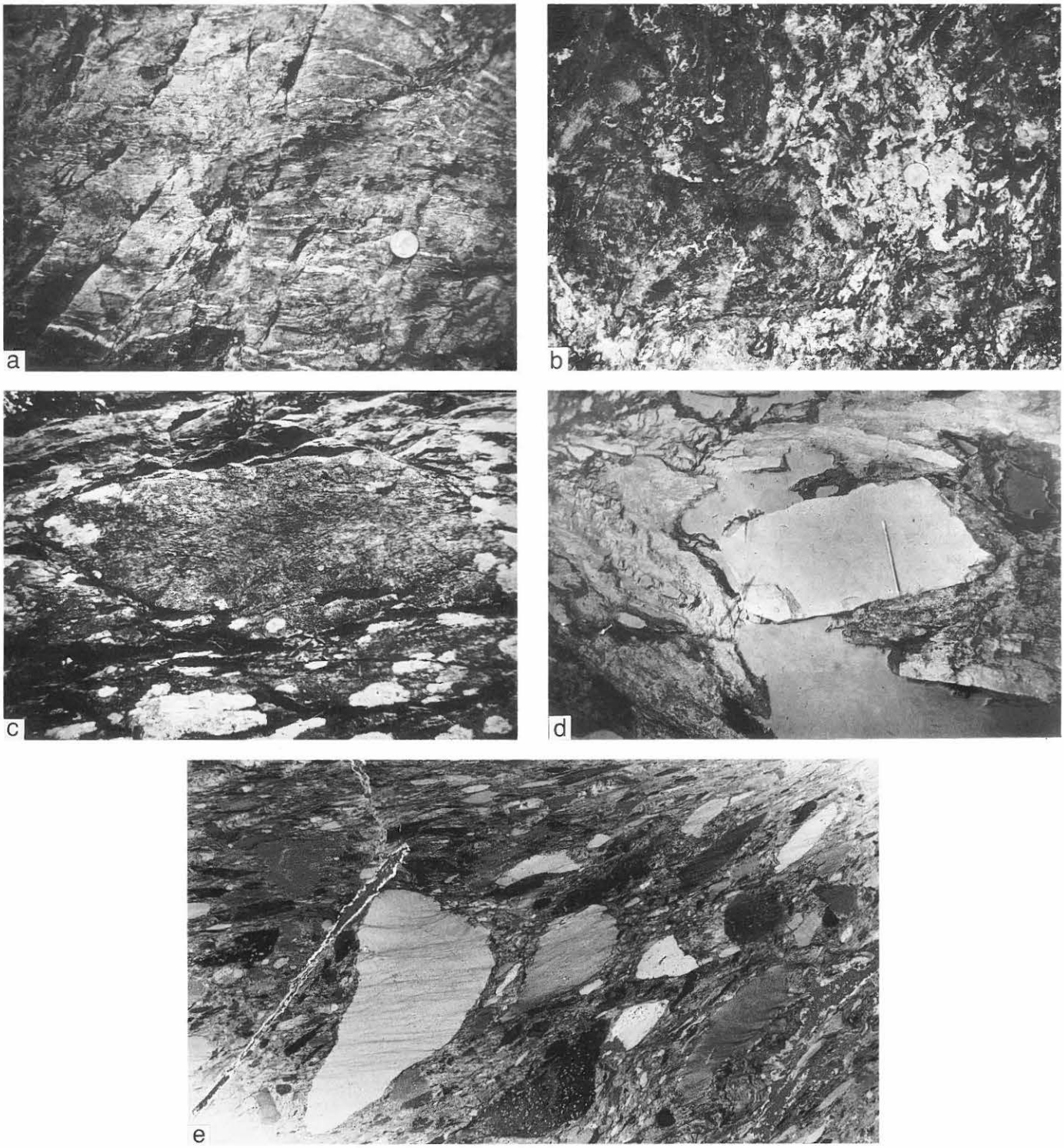


Figure 5. Mega-, meso- and micro-scale clasts in Hurricane Mountain Formation mélange. (a) and (b) Amphibolite gneiss showing wavy foliation and swirled pegmatitic structure. Coins, ca. 1 in. (2.5 cm) in diameter, give scale. From 1.37 km (0.85 mi)-long block west of Bog Brook and northwest cove of Indian Pond, Brassua Lake 15' quadrangle (Fig. 4). (c) and (d) Feldspathic arenite ("quartzwacke") and gray quartzite clasts. Pencil in (d) gives scale. In (c), left margin of clast is sharply defined against matrix; right margin is gradational into matrix across several centimeters. Moosehead Lake 15' quadrangle. (d) is from channel of Dead River above Grand Falls, Pierce Pond 15' quadrangle. (e) Photomacrograph of thin section: matrix-supported, polymict, granule metaconglomerate (debris flow?). Length of photo represents 3.8 cm. Crenulation cleavage (horizontal in photo) cuts across mudstone and siltstone clasts. Quartz-bordered pyrite vein (left) is also offset by cleavage. From drill core, Brassua Lake 15' quadrangle.

mapped by Serra (1973) and in the Indian Pond area of the Brassua Lake quadrangle (this report) are thus described as intrusive, when judged by these criteria.

Massive, carbonate-rich greenstone and foliated equivalents exhibiting thin relict beds or laminations are locally common, and are composed of chlorite, pyrite, calcite, and ankerite. These rock types also may be endogenous, but not in a primary, depositional sense. Where they crop out on islands in Indian Pond, they can be seen to grade into massive, rusty-weathering, chlorite-richer calc-greenstone, which I interpret to be a product of hydration and CO_2-metasomatic alteration of mafic tuff. The Ca-Mg carbonate-bearing greenstones can be seen as clasts locally throughout the entire belt. The thinly bedded to laminated derivatives, then, would imply brief exposure of the altered, tuffaceous mafic protolith to winnowing action of sea-floor currents, but without significant transport or incorporation of detrital quartz or feldspar. Subsequent flattening and development of foliation has probably enhanced their laminated appearance. Discussion with Bradford A. Hall (pers. commun., 1984) leads to the view that this lithology is commoner in the Chase Brook Formation than it is in the Hurricane Mountain Formation.

Exotic Clasts. Clasts of exotic origin occur throughout the Hurricane Mountain belt. In the Lobster Mountain anticlinorium, they consist of the following, listed in order of decreasing abundance:

- volcaniclastic, feldspathic wacke
- metagabbroic and metadiabasic rocks (apparently not derived from locally disrupted, intrusive or extrusive sources)
- chloritic and pyritic, massive, carbonate-bearing greenstone, amphibolite, and greenschist
- gray, massive, fine-grained metalimestone
- light gray, faintly bioturbidic, thickly bedded orthoquartzite
- black, carbonaceous, feldspathic quartzite and metaconglomerate
- serpentinite
- metapyroxenite
- felsic, aphyric metavolcanic rocks
- gray to buff, weakly banded, very fine-grained quartzite (metachert?)
- metamorphosed chert-laminite
- alkali granite (only one occurrence)

The first five clast lithologies are scattered widely throughout the entire belt. Some of the clast types, on the other hand, are locally concentrated. Gray quartzite, for example, is restricted to the Hurricane Mountain type area, whereas rafts of black, feldspathic quartzite, are locally common at Grand Falls of the Dead River (both localities in southern Pierce Pond quadrangle). Mafic metavolcanic and intrusive rocks appear to be concentrated in the three areas mentioned in previous paragraphs. Amphibolite rafts are concentrated only in the central Brassua Lake quadrangle, in the vicinity of Indian Pond.

Two types of sandstone are distinctly dissimilar to the common feldspathic meta-arenite and wacke. One is clearly volcaniclastic, or derived from detritus of immaturely weathered intrusive rock, inasmuch as it is rich in medium to coarse, angular grains of white-weathering plagioclase. The upper part of the Jim Pond Formation may be a possible source for these. The other is light gray orthoquartzite on Hurricane Mountain. There, a succession of half-meter to meter-thick beds without apparent grading or internal laminations is approximately 20 m thick and extends along the strike of the formation approximately 50 m. It thus appears to be a discrete block. Bedding attitude is parallel to foliation in surrounding mélange matrix. If it is olistostromal in origin, one would expect several, if not abundant, occurrences locally. Sparse, curvilinear, half-centimeter-wide structures composed of white quartz resemble worm burrows; their origin is unclear. The provenance of this lithology is unknown, but similar, though thinner-bedded, metasandstone is observed in the Grand Pitch Formation of late Precambrian to Cambrian age, in the Lunksoos anticlinorium (Robt. B. Neuman, pers. commun., *in* Boone and Boudette, 1989).

Three large raft-shaped blocks of dark bluish gray to black, thickly bedded, carbonaceous feldspathic quartzite, roughly 10 to 15 m thick and at least 100 m long, are exposed near the top of Grand Falls, Dead River, in the southwestern ninth of the Pierce Pond quadrangle. The rafts are composed of graded beds of quartzite that grade sharply downward into thin, dark gray, matrix-supported, saussuritized plagioclase-rich, granule-metaconglomerate bases of a few centimeters thickness. Cross-bedding and channel-fills are common in the upper, laminated parts of thick beds. Cataclastic shear zones within the quartzite are pervasive and range up to a centimeter in thickness; they are mostly parallel to bedding. Detailed petrographic observations are presented in Appendix I with the objective that discovery of similar quartzite elsewhere will lead to its provenance in terms of source rock and source terrane. Apparently, its mineralogy and petrography are unique with respect to other pre-Silurian rocks of Maine.

Two bodies of metapyroxenite, and layered metapyroxenite in the Pierce Pond quadrangle (central part of Fig. 1), are interpreted to be exotic and tectonically emplaced. Regarding the layered rocks, on Stony Brook Mountain in the southwest part of the quadrangle, meta-orthopyroxenite and metagabbroic rocks crop out in close proximity to one another (Boone, 1985). They are believed to constitute a block more than 1.6 km (1 mi) long in tectonic contact with gray quartzite and mélange matrix. Relict orthopyroxene of the metapyroxenite is partially replaced by cummingtonite and green calciferous clinoamphibole, and is host to fine-grained opaque oxides aligned as sagenitic inclusions along the pyroxene cleavages. The metagabbroic rocks show relict layering of metagabbro, gabbroic anorthosite, and volumetrically minor anorthositic varieties. Plagioclase is clouded, and mafic minerals are replaced by chlorite and green calciferous clinoamphibole. This mafic and ultramafic lithic assemblage may have been derived from the Boil Mountain

Ophiolite (Boudette, 1982), which crops out 32 km (20 mi) to the west-southwest.

Metabasite blocks, ranging from massive to well foliated, and showing different degrees of metamorphism, are common in the northwest Indian Pond area. The Round Pond block (Fig. 4), displays pumpellyite-actinolite grade greenstone with relict tuffaceous and accretionary lapilli textures at its southwest end. The block is 0.8 km (0.5 mi) long, and the features just described grade into foliated greenstone and greenschist containing a higher pressure assemblage (lacking pumpellyite, but containing sodic-calcic amphibole near winchite in composition; cf. section on metamorphism of metabasite blocks) at the northeast end. The foliation conforms to the regional northeast strike and steep dip of the surrounding matrix foliation. In contrast to the gradation in metamorphic intensity within the block, there is no discernible difference in the low metamorphic grade and fine grained texture of the mélange matrix in contact with the block at its southwestern and northeastern ends. Similar blocks, but with contorted foliation marked by an actinolite-rich, epidote, chlorite, rutile-bearing mineral assemblage, crop out on islands in northwestern Indian Pond (Fig. 4). Thoroughly recrystallized, retrograde metamorphosed, coarse-grained metagabbro is common in the same area. These bodies, at least one of which is clearly intrusive, contain polythermal mineral assemblages ranging from upper greenschist to lower amphibolite facies. In the lowlands to the west, blocks of coarse-grained, high-rank amphibolite have been mapped (Frost, 1977; Frost and Boone, 1978) which display a highly contorted, polydeformed fabric. Their metamorphic grade, as well as their textural and structural elements, are in sharp contrast to the typically low-rank, fine-grained mélange matrix in which they are enclosed. The petrology of the metabasite blocks is discussed in a succeeding section.

TECTONIC HISTORY OF THE HURRICANE MOUNTAIN FORMATION

Until recently, all observations concerning lithology, petrography, and structural geology of the mélange have been obtained from outcrop during geologic mapping in several 15' quadrangles. Extreme friability and lack of coherence of the mélange at the surface impeded structural analysis. Cores obtained from Noranda Exploration, Incorporated, have provided a wealth of new structural data from which a model of microstructural evolution can be constructed. This section draws upon, and modifies, structural observations and interpretations in a study of drill core samples of the mélange (Doty, 1987). The interpretive part of this section explores a working hypothesis in which a continuity of deformation during the Penobscottian mélange-forming event is proposed, and to assess to what extent younger deformations (here ascribed to the Acadian orogeny) have modified it.

Study of drill core samples suggests that the mélange matrix underwent shearing repeatedly from the time it was unconsolidated, progressing from the stage of dewatering and volume loss, to brittle shear and mylonitization. The processes of slip, ductile shear (Tchalenko, 1968) and cataclastic shear (Lucas and Moore, 1986), small-scale folding, and faulting all contributed to strain-hardening of the matrix. As Lucas and Moore (1986), Moore et al. (1986), and Karig (1986) have documented in detail, once sediment has become strain-hardened along a shear zone, further deformation will take place in adjacent, unsheared or less sheared parts of the sediment mass. The S-surfaces discussed in succeeding sections are postulated to be preserved examples, involving mimetic recrystallization, of some of these features. To pursue the working hypothesis, it would not be a surprising consequence that final stages of Penobscot deformation, within the suture zone between amalgamating terranes, would achieve further strain-hardening and flattening of the mélange en masse. It is not known if the final, Penobscottian evolution of major structure produced strongly overturned, or recumbent fault-fold geometries, as seems a likely interpretation from regional mapping, or if layers, other enclosing S-surfaces, and earlier faults were thrown into tight, upright or overturned folds that became more tightly appressed during the Acadian orogeny.

Lagging in time and space behind the actively accreting and deforming mélange, one would also expect folding to commence in an overlying, time-transgressive carapace of flysch, which the Dead River Formation is interpreted to be. This formation also is polyphase-deformed, but exhibits a much more ductile style, as evidenced by the common occurrence of refolded folds, and a greater regularity of structural attitudes of these folds and of related cleavages (Boone, 1973; Burroughs, 1979). Conversely, flaser structure, hackly, anastomosing foliations, and mylonitized main shears, as in Hurricane matrix, and web-like, cataclastic shear zones, as in metasandstone rafts and blocks, are not observed in the Dead River Formation. These contrasts suggest that the Dead River Formation, in aggregate, behaved less competently during the polyphase events than did the Hurricane mélange. Compared to the relative simplicity of fold geometries and cleavage in unconformably overlying, Middle Ordovician, and younger metavolcanic and metasedimentary rocks, the structural responses - each being different in the mélange and flysch - get at the question of assignment of *penetrative* deformational structures in these rocks to Penobscottian, versus later (chiefly Acadian?) events (cf. Fig. 6f). Evidence is cited to support the viewpoint that Acadian deformation modified only slightly the microstructures typically encountered in the Hurricane Mountain mélange. Localized development of kink bands are largely attributed to Acadian or post-Acadian deformation, based on orientations similar to those observed in Silurian and Devonian rocks.

Microstructure of Mélange Matrix

Figures 2, 3a & c, and 6 show typical examples of mélange matrix in outcrop, hand specimens, drill-core samples, and thin section. In polished, sawed surfaces and thin sections, but only

rarely in outcrop, different styles and orientations of foliations can be seen. In terms of microgeometry and, to a lesser extent mineralogy, they are defined as follows: S_1 comprises (a) the flaser structure along which slices of layered sedimentary protoliths are juxtaposed, commonly at very shallow angles to original bedding. The surfaces of juxtaposition are shears, along which commonly occur laminae (veins) of quartz in metasiltstone lithologies, and less commonly, of carbonate in more calcareous examples (Fig. 6a). It also comprises (b) a "main cleavage" as observed in outcrop, and seen in thin section to be manifested by a slaty cleavage in metapelitic layers, becoming more akin to a rough cleavage in siltier and coarser arenaceous protoliths. At outcrop scale, "S_1" in metasiltstone or phyllite may be a visually estimated average of S_1 and conjugate S_2 surfaces that lie at shallow angles to S_1. S_2 foliations are commonly as pervasive as S_1. They are defined as microshears (main displacement shears) that lie in two, or possibly three different orientations, illustrated in Figure 6b, and identified in lower hemisphere equal area plots (see below). Figure 6b shows pervasive, curvilinear sets of S_2 that are commonly sigmoid, losing their identity where they merge into parallelism with S_1. These foliation surfaces are commonly lined with smears of graphitic material (as judged by reflectivity in reflected light microscopy) and, within lenses that are chlorite-rich, the shears are lined with opaque oxide and very fine-grained TiO_2 (rutile or brookite), a mineral assemblage that reflects a mafic volcanic source. S_2 shear surfaces in typical matrix materials are notably quartz poor, suggesting concentration of the minerals lining shear surfaces by removal of SiO_2 and perhaps phyllosilicates. S_3 is assigned to non-pervasive, localized zones of crenulation cleavage and kink-bands (Fig. 6c, d, e). These zones range in width from a few millimeters to several centimeters, and are commonly separated from one another by a few centimeters to a meter or more.

Methods

A description of the methodology for determining orientations of structural features from drill core samples is appended to Table 2. More than 100 thin sections of Hurricane mélange matrix lithologies were made from the cores. Others were made to study metaigneous rocks and their contacts with the mélange. Several thin sections were polished to identify oxides, sulfides, and graphite. The majority were oriented, and sets of mutually perpendicular sections (Fig. 7) were studied on the universal stage to obtain the data on which Figure 8 is based. Orientations were (1) perpendicular to strike (St). St slabs and thin sections, thus, are viewed looking along strike either to the north-northeast or south-southwest. Most long dimensions of St thin sections are parallel to the trace of S_1 as viewed on the vertical, longitudinal sawed surface of the core. Gently plunging microfolds and S-intersections were observed to advantage in these sections. (2) Dp sections (nearly perpendicular to dip) were taken from surfaces cut perpendicularly to St slabs, and are close to horizontal. They were oriented as to azimuth within this plane (Fig. 7). Dp sections were used to observe steeply plunging microfolds and S-intersections. Conjugate sets of St and Dp were required for the three-dimensional analysis of core sections. Sections parallel to foliation (F) yielded little microstructural information.

Attitudes of S_1, S_2, and S_3 in core samples, determined from these sets, are summarized in the equal area stereographic projections of Figure 8. A contoured lower hemisphere diagram of poles to S_1 cleavage and lithologic planar elements (Fig. 8a) gives an indication of the *within-core sample* variation of strike from the visual average used in alignment, and the predominance of a near-vertical dip. Inasmuch as S_1 has lens-like geometry, strike and dip both are visually estimated averages for each plot. A visually estimated error of $\pm 5^{\circ}$ is assigned to both strike and dip of S_1.

The S_2 and S_3 surfaces were the least tractable to analyze, and involved laborious correlation between St and Dp thin sections, as studied on a universal stage, with their parent slabs from the core samples. S_3 surfaces are commonly planar to curviplanar, and tend to fan slightly in dip. Estimated error for S_2 and S_3 is $\pm 10^{\circ}$ for both strike and dip.

The lower hemisphere projections show, as expected, that S_1 , the principal, or main cleavage, is steeply dipping and more or less fixed in strike by the artifice of orientation of core samples. S_2, together with superimposed structural elements, forms three groups of broadly different orientations (Fig. 8 b, c, and d). One group is close to S_1 in strike, but gentler in dip to the northwest. The second dips steeply to the southeast, but is more variable in its northeast strike. The third strikes east-northeast, with steep to moderate southerly dips. Figure 8b shows that if the S_1 poles labeled *d* through *h* were rotated so as to plot within the maximum shown in Figure 8a, the first set would group more closely to the S_3 pole labeled *b*; the second, the poles of which lie in the northwest part of the projection, would still diverge widely in strike, though they would group more closely in a 65°-85° range of inclination. To test the possibility that core samples *d* through *h* may have been incorrectly oriented in their rotation around the core axis (by virtue of the "S_1 strike criterion, summarized in the comments to Table 2), small circles, and arcs thereof, were drawn coaxially around the average inclination of the drill holes (Fig. 8b). These show that if one were to carry out appropriate rotations around the axis of cores, they would concentrate the strikes of *d* through *h* of the second group, while doing little to increase the scatter in bearing and inclination of poles to S_1, the first group of S_2, and related planar elements. It is likely that the first two sets of S_2 may have a similar *variation* in orientation. Whether this is valid or not, one may note that the total variation in dip of the S-planes of the first two sets of S_2 is close to that of S_1 (Table 2), which is about 45°. The "S_1 strike criterion" is probably valid for the volumes of rock that are host to the two drill holes, and coincidentally the strikes of foliation in surface exposures around the drilling sites are nearly the same (see methodology, Table 2).

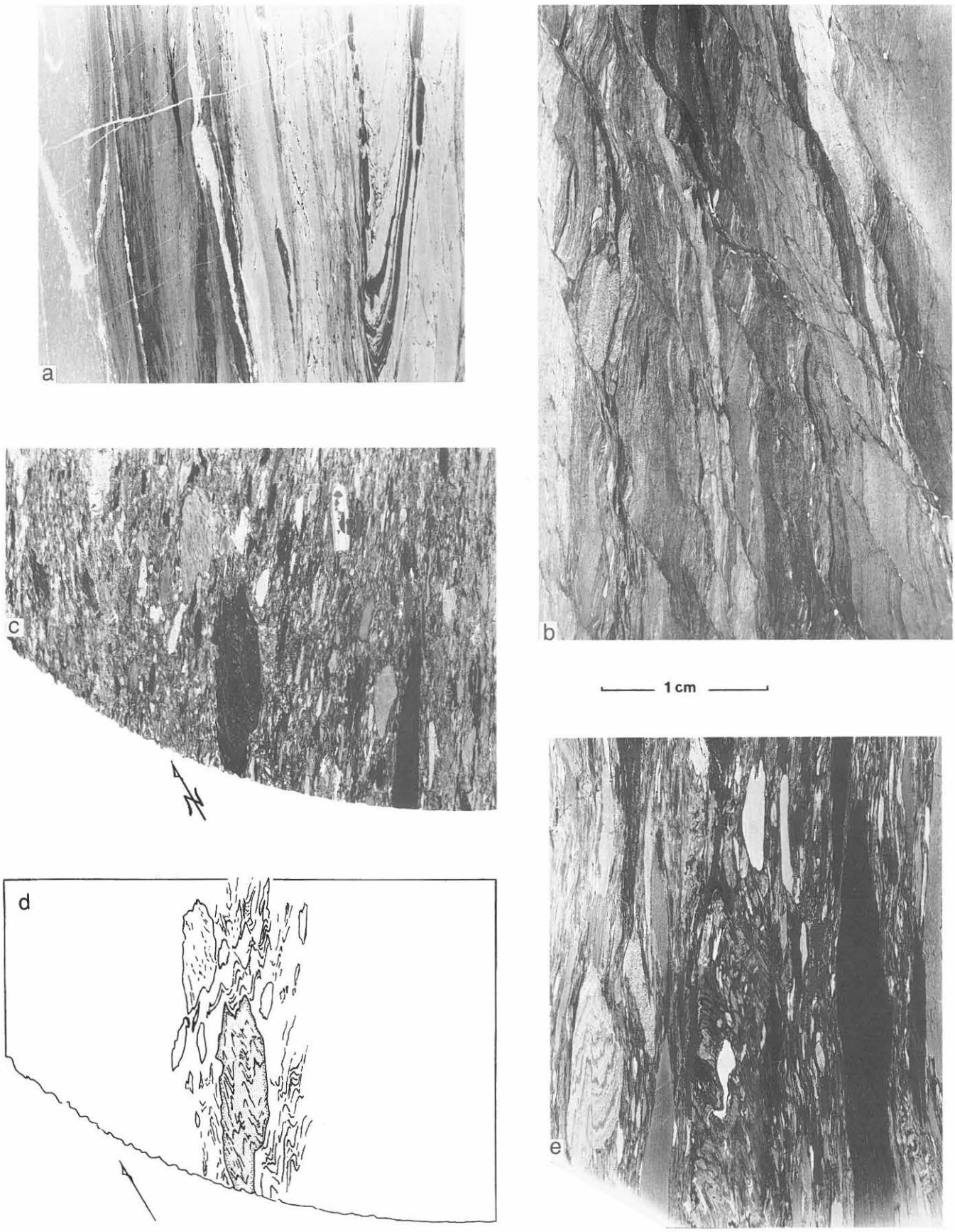


Figure 6.

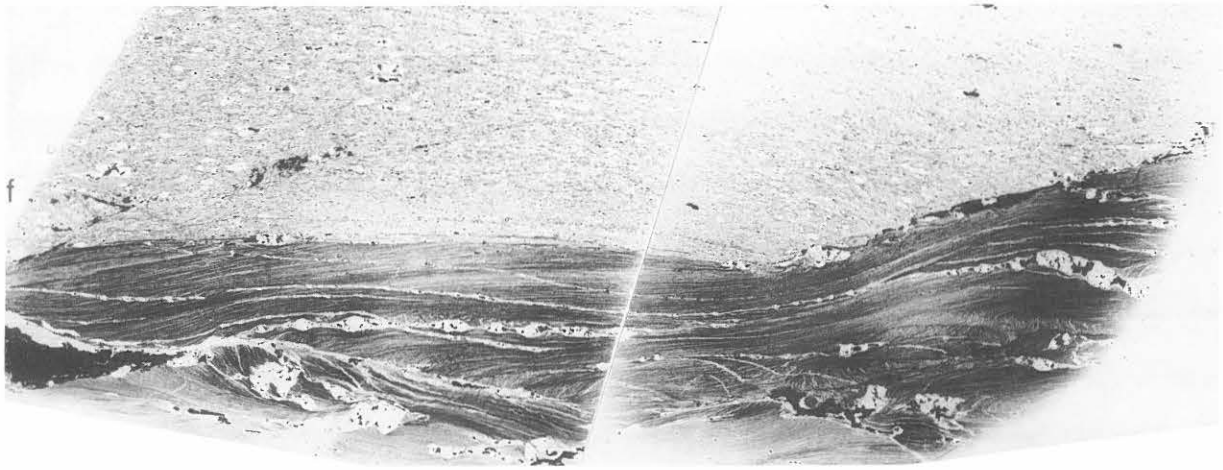


Figure 6. Photomacrographs of microstructures in Hurricane Mountain Formation mélange matrix. All are from drill cores, Brassua Lake 15' quadrangle, and shown at same scale. (a) Incipient stratal disruption and flaser structure (S_1) and sheared microfold in calcareous phyllite and black slate. Veins (white) are calcite. Dp section (cf. Fig. 7) cut in horizontal plane. Serial cuts show that the synformal fold plunges gently NNE. (b) St section showing typical development of S_2 microshears. Viewed NNE along strike; ESE toward right. S_1 is sigmoidally bent between and sheared by main displacement shears (dipping steeply to ESE) and less abundant riedel-like and thrust shears (cf. Fig. 10, which is constructed on this and other examples). Shear surfaces are commonly lined with graphite, and pyrite or pyrrhotite, and much less commonly by quartz. South and SE-dipping S_2's (cf. Fig. 8) show reverse fault sense of displacement. Microboudinage of siltstone layers (light gray) and segmentation of quartz veins parallel to S_1 are interpreted to be pre-S_2. (c) Dp section of strongly disrupted matrix. Some clasts (e.g., rounded white quartz) may be depositional; most, however, show phacoidal outlines and are probably tectonic. (d) Tracing of central part of (c) to illustrate post-depositional (and post-stratal disruptive, post-S_1) origin of microfolds in dark, pelite-rich clast. Microfolds can be followed with continuity from matrix into clast along the northerly strike of the microcrenulations. (e) Light clast, lower left, shows pre-disruptive formation of microfolds. Central band shows discrete microcrenulations and kinks. (f) Composite photomacrograph of 2 thin sections showing intrusive contact of quartz-phyric metafelsite dike, believed to be typical of Kennebec Formation, with polydeformed, Hurricane Mountain Formation wall-rock. Metafelsite shows a single, slightly wavy foliation. Note microboudinage of quartz veins,in wall-rock, that parallel the contact.

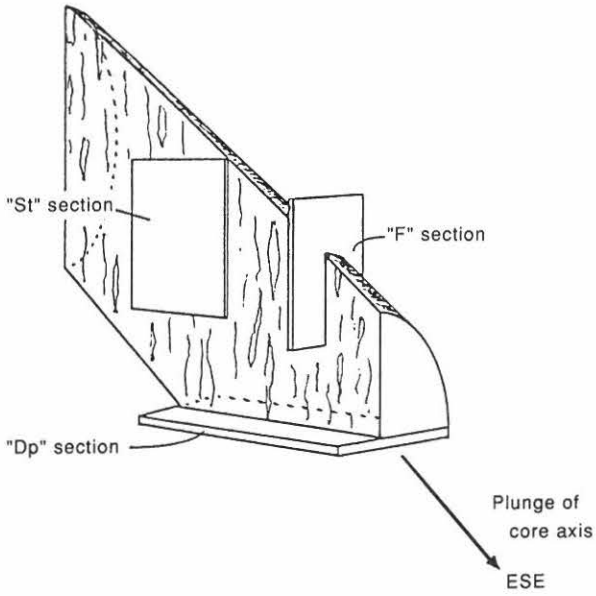


Figure 7. Relationship of oriented thin sections to core sample orientation. See text.

The tight clustering, particularly in strike, of S_1 poles in Figure 8a, however, should not be viewed as applicable to the entire strike belt of the mélange in the Lobster Mountain anticlinorium. Strikes of foliation as measured in outcrop, from the Pierce Pond, to the northern part of the Moosehead Lake quadrangle (Fig. 1) range from approximately N30°E to N65°E, where not perturbed near transverse faults and post-Acadian intrusions. This variation is not regionally systematic, but forms local, curvilinear bends in strike, as may be visualized from Figure 9. This 35° variation falls within an approximately 50° range of strike of Acadian slaty cleavage in Silurian and Devonian strata in The Forks (Fig. 8d), Brassua Lake, and Moosehead Lake quadrangles. Variation in dip of S_1 and related planar features in the Hurricane Mountain Formation, however, is greater than in the Silurian and Devonian strata. The data sets are about equal (~100 readings) and the same exclusions apply.

Interpretation

The comparison of variations in strike of foliations - Acadian slaty cleavage in strata of Middle Silurian and younger ages, and the predominant foliation in pre-Middle Ordovician rocks - together with steep dips common to both, strongly implies

TABLE 2. FOLIATION DATA, HURRICANE MOUNTAIN FORMATION AND RELATED STRUCTURAL UNITS, FROM DRILL CORES IN BRASSUA LAKE QUADRANGLE. All dips are given with reference to a SE or SW declination.

Depth (in ft.) in drill hole, at top of core sample	Mélange type or lithic name in 10 to 30 cm lengths of core (Cf. appendix III for lithologic descriptions)	S_1 strike	S_1 dip	Pole bearing	Pole plunge	Sense of shear (x/y = "x over y") U-stage observations unless otherwise noted	S_{2+3} strike	S_{2+3} dip	Pole bearing	Pole plunge
Core 5B, 85-2										
17	phyllite									
36	type I (Fig. 5f)									
42	type I									
80	:ype I	34	106	124	16		40	73	310	17
85	type II	30	97	120	7	NW side down	30	117	120	27*
94	type I									
105	phyllite									
121	type II	30	86	300	4		-	-		
140	black slate	28	114	118	24		-	-		
197	cherty laminite									
201	type I(fig. 6c,d)	26	96	116	6		-	-		
234	type II (fig. 3a)	30	98	120	8	major;	86	46	356	38
						S side up;	86	52	356	44
						dextral minor	89	115	179	25*
							89	95	179	5
237	type I									
295	type I									
318	type II; undistributed, 3-4 cm graded beds, wispy S_{0+1} (Fig. 2c)	29	90	119	0		-	-		
321	type II	28	90	118	0	from	45	76	315	14*
						core	40	115	130	25
344	type I (Fig. 2f)	30	112	120	12		-	-		
380	"	30	85	300	5	SE/NW, sinistral	10	46	280	44*
380	type II	27	90	117	0		-	-		
418	"	27	90	117	0		-	-		
Core WCS-1										
28	gray slate									
40	black slate	30	97	120	7		-	-		
56	phyllite w/ quartzite phacoidal clasts									
68	type III									
82	type I w/ Ord. (?) metafelsite showing discordant, intrusive contact									
88	black slate	30	114	120	24		-	-		
90	type II	28	114	118	24		-	-		
125	type III	34	114	124	24		-	-		
130	type I	30	110	120	20	NW/SE	18	138	108	48
143	type II	28	98	118	8		-	-		
208	type II	36	105	126	15		-	-		
216	"	30	94	120	4		-	-		
230	"	28	114	118	24		-	-		
234	type II w/ black slate above	30	100	120	10		-	-		
250	type II	28	92	118	2		-	-		
272	black slate	30	108	120	18		-	-		
290	types I & II	30	106	120	16		-	-		
302	type III ?									
323	type II in mylonitic contact w/ Kennebec or Lobster Mtn. metavolcanic feeder dike									
326	Middle to Upper Ordovician (?) diatreme on type I									
337	cherty laminite	30	85	300	5		-	-		

* identifies sharply defined crenulations and kink bands

TABLE 2. CONTINUED.

Depth (in ft.) in drill hole, at top of core sample	Mélange type or lithic name in 10 to 30 cm lengths of core (Cf. appendix III for lithologic descriptions)	S_1 strike	S_1 dip	Pole bearing	Pole plunge	Sense of shear (x/y = "x over y") U-stage observations unless otherwise noted	S_{2+3} strike	S_{2+3} dip	Pole bearing	Pole plunge
351	black slate on type I	26	96	116	4		-	-		
372	type I	28	88	298	2		-	-		
409	type I									
437	type I	30	95	120	5		-	-		
453	calc. phyllite lens/type I	28	104	118	14		-	-		
480	calc. phyllite									
503	type II /calc. phyllite /type I (Fig. 6a,b)	30	124	120	34		55	74	325	16
						major crenulation and fracture cleavage: (major 55°E set shows SE over NW reverse (thrust) motion, w/ dextral shear component)	55	79	325	11
							55	85	325	5
						minor E/W, but sinistral	10	94	100	4*
	plunge of F_1 fold:			50	32NE					
518	type I									
530	type I									
538	sheared lenses of metatuff(?) in type I	30	104	120	14		-	-		
541	type II in sheared contact w/ meta-andesite dike of Lobster Mtn. Volcanics									
544	Meta-andesite									
588	type II	30	95	120	5		-	-		
624	types I & II	30	126	120	36	NW/SE	12	3NW	102	87*
							12	29NW	102	61
							30	80	300	10*
637	type II									
656	type II & calc. phyllite/felsic to intermediate metatuff									
703	type I	34	100	124	10	core only	-	-		
704	graded bedded metasiltstone & gray slate; core only									
713	type I	30	114	120	24		-	-		
726	tuffisite breccia (Olm) in sheared contact w/ type I	32	92	122	2		50	76	320	14
729	type II	30	92	120	2		50	95	320	5
730	type II	28	109	118	19		-	-		
732	type I									
734	type I	32	117	122	27		-	-		
736	type I (Fig. 6e)	26	96	11	66	dextral	30	77	300	13
						N side	90	131	180	41*
						down	96	139	186	59*
737	type I	30	102	120	12		-	-		
761	type I above metatuff									
764	metatuffaceous breccia/cataclastic S_3? shear zone									
773	metatuff above type I									
774	type I									
776	type I (Fig. 2d)									
780	type I	30	95	120	5		-	-		
781	type I	27	87	297	3		-	-		
790	type I/gray slate	30	98	120	8		-	-		
800	gray slate/type I	30	93	120	3		-	-		

* identifies sharply defined crenulations and kink bands

ADDENDUM TO TABLE 2: METHODS OF DETERMINING ORIENTATIONS OF FOLIATION SURFACES

The approximate bearing and plunge of the drill holes is perpendicular to strike and 50° to the southeast. One core, labeled 5B-85-2, is believed to have a trend and plunge of the axis of 120°, 52° into bedrock with average strike of foliation of N30°E, while that for the other, WCS-1, is believed to be 130°, 55°, in bedrock of average strike of foliation of about N35°E. Although core retrieval at the time of drilling did not permit orientation with respect to the core axis, it turned out that in a practical way this was possible, owing to the constancy of strike and near-vertical dip of the major planar structures in the Hurricane Mountain Formation throughout the central part of the Lobster Mountain anticlinorium from which the cores came. Core specimens, thus, were rotated so that the predominant S_1 foliation and layering (conventional S_0 is generally absent) were brought into alignment with, firstly, the local strike and, secondly, the overall steep dip of foliation. The accuracy of the method may be wanting, but for purposes of distinguishing the differences in orientation between the predominating, earlier structures and later crenulation cleavage, the method has practical value and is reasonably precise. The accompanying table gives a summary of mélange type, other lithologies, contact relationships, and attitudes of microstructural features of the mélange matrix. The data from the table record about 70 readings of S_1 and S_2 across more than 366 meters (1200 feet) of drill core. The core samples were retieved from holes drilled about 13 km (8 mi) apart and more or less on strike within the formation. From these data, means and standard deviations (1 σ: $\pm 10°$) of the mean for dip of S_1 features are within two degrees of one another for each drill hole location.

an Acadian control on the orientations found in the older formations. Overturned, refolded beds in the Dead River Formation have been noted in the Chesuncook dome (Fig. 1; Jahrling, 1981; Boone, unpubl. mapping) and in the The Forks quadrangle (Burroughs, 1979; Marvinney et al., 1981). The repetition of strike belts of pre-Middle Ordovician formations across upright, tight to isoclinal folds in The Forks (Burroughs, 1979) and Pierce Pond (Boone, 1985) 15' quadrangles suggests that in both areas, earlier overturned or recumbent folds have been refolded. Overturned strata and refolded folds have not been found, however, in the Kennebec Formation or Lobster Mountain volcanics, of Middle and Upper Ordovician ages. Fold styles and cleavage orientations in these strata are similar to those observed in nearby Silurian and Devonian formations of the Moose River, and Kearsarge - central Maine synclinoria.

The presumed structural imprint of Acadian age on the pre-Middle Ordovician formations implies that the penetrative fabric and foliations in the Hurricane Mountain Formation mélange may be modified, at least in part, by Acadian deformation. The task of sorting out ages of foliations in a complexly foliated and sheared mélange is approached in a comparative way, by applying experimental structural data, and observations of geologically recent mélanges as analogs to the features recorded here from the Hurricane Mountain Formation. Many of these observations from the literature seem to apply. In addition, rare observations of cleavage relations across contacts between the mélange and younger rock identified as Kennebec feeder dikes, as seen in drill core (Fig. 6f), supports the view that many of the microstructural features in the mélange are pre-Middle Ordovician.

Doty (1987, p. 13) proposed that foliations superimposed on S_1, that he grouped together as S_2, are expressed "as two forms of transposed structure." While carrying out the exercise just described, the core samples and thin sections were reexamined to see if "the two forms of S_2" were distinguishable by difference in orientation on the lower hemisphere projections of Figures 8b and c. As can be seen, there is not a unique distinction between the *orientations* of the three types of foliation observed (only one set of late kink-bands are thus); furthermore, transposition (as commonly referred to in the formation of crenulation cleavage and kink-banding) does not apply to the three clusters of S_2, as shown on Figures 8b and c. The large open circles of Figure 8c, identifying S_2, denote microscopic main shears, many of which result in sigmoidal warping of S_1. S_2 of this report is restricted to these features (Figs. 6b, 8b and c). The S_2 surfaces are broadly curvilinear and of irregular radius of curvature in profile. They show a more pronounced anastomosing network in St (vertical) sections than they do in Dp sections. They do not form axial planar cleavages to microfolds. The S_2 surfaces enclose sheared, phacoidal microlithons ranging up to 3 or 4 mm in thickness.

Figure 8. Equal area, lower hemisphere projections of structural elements in matrix of Hurricane Mountain Formation mélange (cf. notes in Table 2 for methods of analysis). (a) Contour diagram of poles to sheared layering and "main cleavage" (S_1 and subparallel orientations of S_2 microshears). Bearing and plunge of one well documented F_1 fold hinge is shown. (b) Poles to S_2 and S_3 related to corresponding S_1 in 9 of the samples. Star denotes average bearing and plunge of two drill holes from which analyzed core samples came; small circles labelled 10° to 110° of conical angle are concentric to that axis. Note that the northwesterly plunging poles are roughly concentric to the 90°-110° segments, possibly caused by inaccurate orientation of cores about their axes (see methods, Table 2). Arrows toward little circles indicate how most of the S_2 and S_3 poles would be relocated if all S_1 poles were clustered in area of maximum concentration shown in (a). (c) Orientations of main displacement shears, S_2. Localized crenulation cleavage and kinks, S_3, involve transposition of, and have similar strike to S_1. (d) Scatter plot of poles to cleavage in Silurian and Devonian slates from The Forks (Marvinney, 1982), Moosehead Lake (Simmons Major, 1988, and Boone, unpubl. mapping), and Brassua Lake, 15' quadrangles (cf. locations, Fig. 1). Large dot shows pole to foliation in Kennebec Formation welded tuff, West Outlet, south of Somerset Junction, Brassua Lake 15' quadrangle. Shaded areas show concentration of poles to late, N-S striking, transposed foliations in W- to NW-striking kink bands; area with open dotted pattern, E-W transposed foliation in NE-striking kink bands. Schematic map insets show typical orientations of kink bands, believed to be of late- or post-Acadian age, in Cambrian to Lower Devonian metapelitic rocks (lower left), and in Cambrian to Lower Ordovician metapelites of Dead River Formation (upper right), in the Brassua Lake and Moosehead Lake 15' quadrangles.

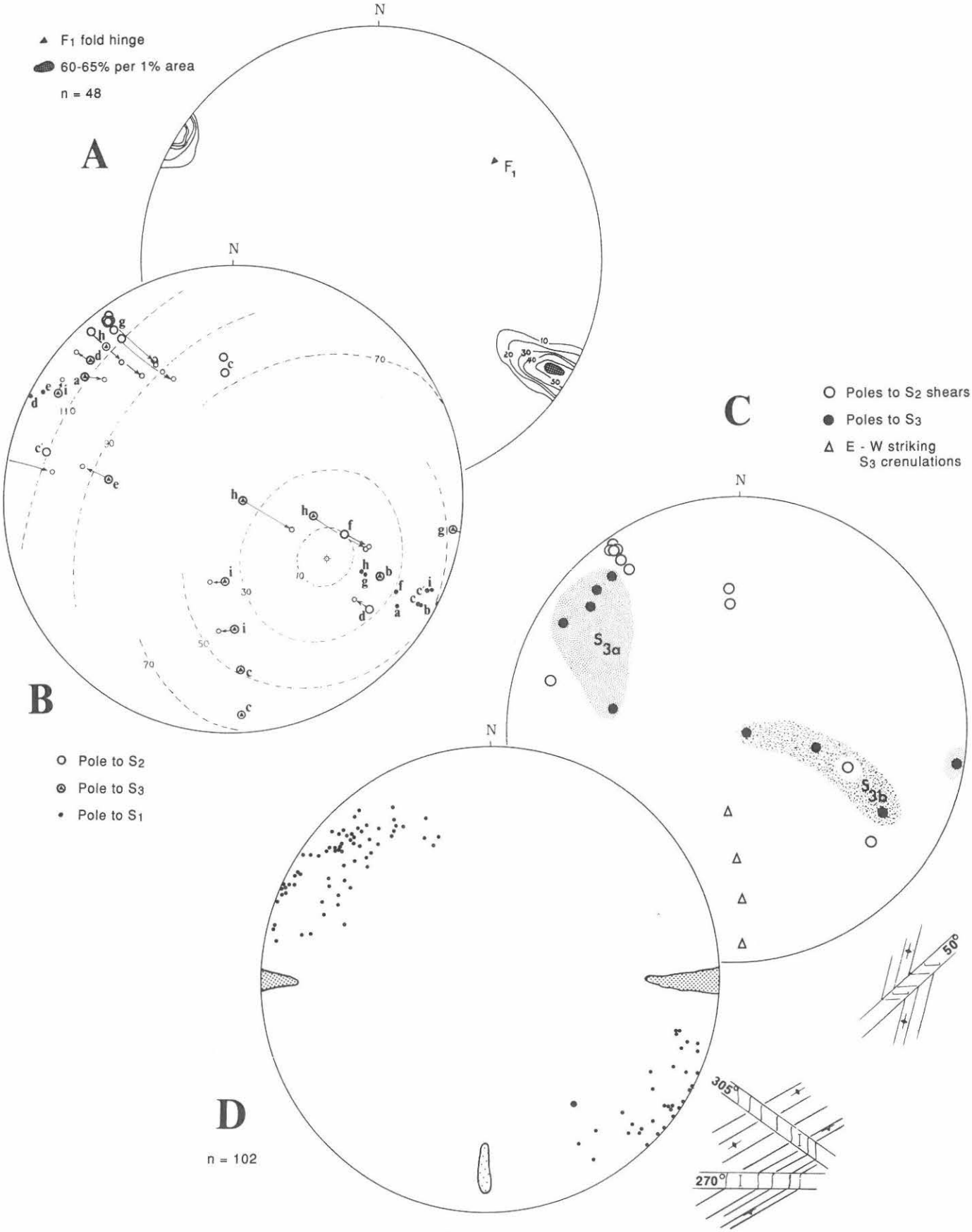

F1 fold hinge
60-65% per 1% area
n = 48
A
N
F1
10
20
30
40
50
B
Pole to S2
Pole to S3
Pole to S1
C
Poles to S2 shears
Poles to S3
E - W striking S3 crenulations
S3a
S3b
D
n = 102
50°
305°
270°

Figure 8.

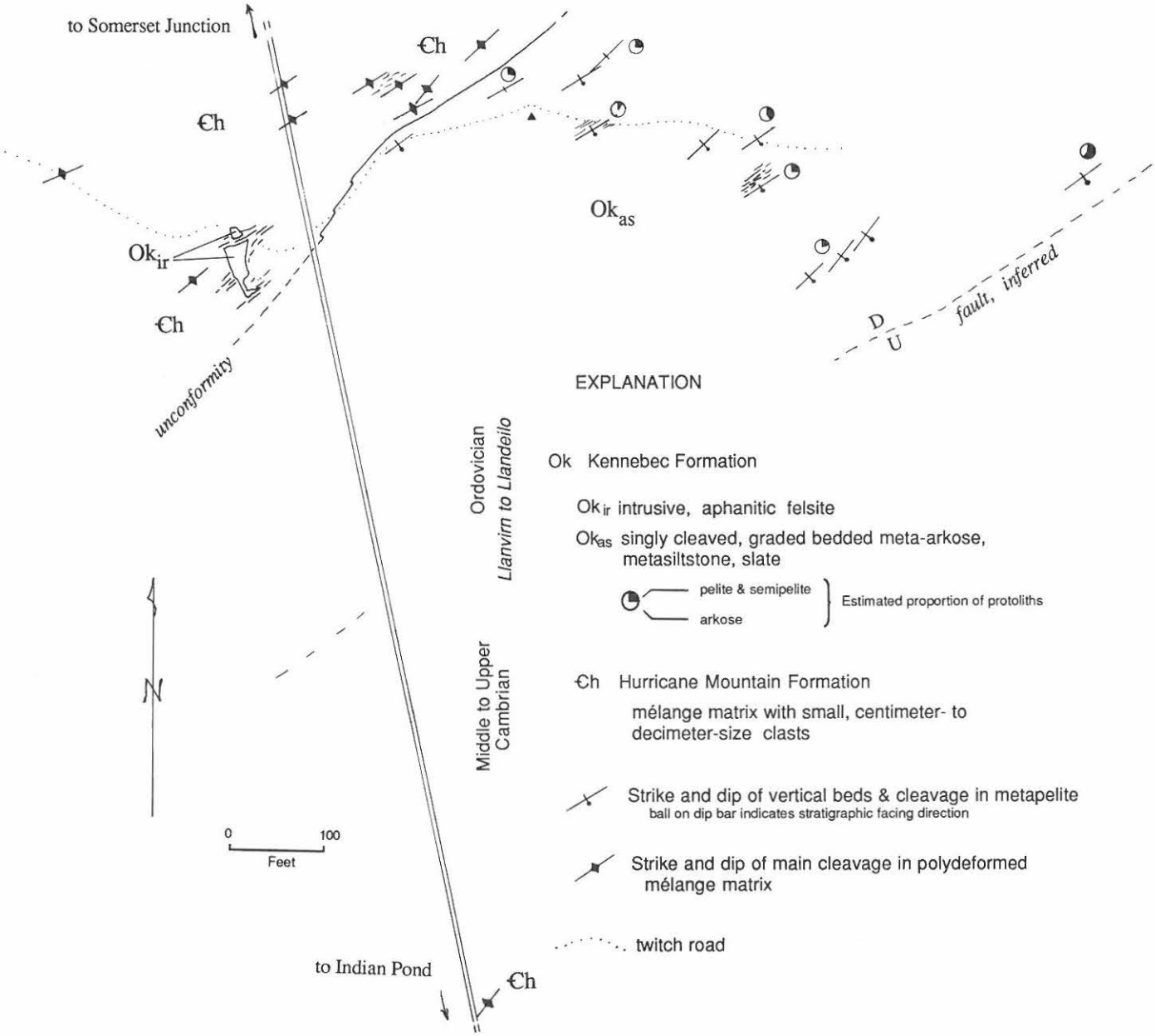


Figure 9. Pace and compass map of Hurricane Mountain Formation - Kennebec Formation contact relationships, ca. 3.9 km (2.4 mi) south of Somerset Junction, Brassua Lake quadrangle. These cleavage orientations may be compared with the microstructures shown in Figure 6f.

These microphacoids, or tectonic clasts, are pervasive in much of the Hurricane matrix. Together with the wavy shear foliations that bound them, they form, in effect, a penetrative fabric in the mélange, which the microshearing process apparently creates. This structure may relate commonly to tectono-metamorphic differentiation along shear surfaces (Hammond, 1987). This structure evidently produces the characteristic, hackly, or scaly cleavage throughout much of the Hurricane mélange. Those examined in detail show opposing senses of shear: those belonging to southeast- to south-dipping sets show a southeast over northwest sense of shear (Fig. 6b). In one sample, a dextral component of shear was observed in Dp section. Those belonging to northwest-dipping sets show opposing senses of shear.

The second "S_2" structure recognized by Doty (1987) consists of sharply defined kink-bands and crenulation cleavage in which zones of transposition range in width from roughly 20 to 30 mm up to a few centimeters, but are widely spaced, from several centimeters to more than a meter, throughout the core samples. They are such pronounced structures that they are easily recognized on drill-core surfaces as well as in outcrop.

They are grouped as S_3 structures in this report, and are shown by the triangle-filled circles on Figure 8b. They commonly appear in thin section to be axial planar to small microfolds involving S_1 and S_2, but as plotted, most of their poles do not lie in a great circle band common to S_1 poles.

Orientations of S_3 suggest three sub-sets. The most common are southeast-dipping crenulation cleavages (S_{3a}) which exhibit a southeast over northwest thrust sense of shear (Fig. 8c). Less common, northwest-dipping examples (S_{3b}) show both thrust and normal senses of shear. The east-west striking, north dipping set (open triangles) shows a north side down, normal sense of displacement. Intersecting S_3 subsets were not found. All of these involve subsequent deformation of earlier-formed cleavage. The set showing east-west strike is similar to that of many northwest striking, steeply dipping kink bands commonly observed in slate and phyllite of the Dead River Formation, and also in the Lower Devonian, Carrabassett Formation and other units of the Seboomook Group in western and north-central Maine. The kink bands in the Seboomook Group, at least, cannot predate the Acadian.

Origin of Foliations

The descriptions of matrix lithology, flaser structure of layering, and microstructures, lead to the interpretation that most of the planar features represent facets of a continuum of deformation within an accreting mélange. Structural mapping of on-land exposures of geologically young mélanges in modern fore-arcs, as well as descriptions of cores retrieved from Deep Sea Drilling Project sites over submerged, active trench and fore-arc settings (cf. Moore and Allwardt, 1980; the contributions *in* Moore, 1986; Aalto, 1982; and Cowan, 1982) provide a comparative basis, or criterion, from which an interpetation of structures in the Hurricane Mountain Formation mélange may be formulated. The resulting interpretation is cognizant of some superposed structures (map-scale folds as well as microstructures) originating in younger orogenic (e.g., Acadian) events.

The matrix structures in the Hurricane Mountain mélange, as described in the foregoing section, are strikingly similar to those observed in (1) mélanges of modern accretionary complexes (Karig, 1986; Lucas and Moore, 1986; Moore et al., 1986), (2) fault zones in clay-rich sediment masses, and (3) laboratory experiments of shearing in silt- and clay-rich sediment (Tchalenko, 1968).

The inferred sequence of events and processes leading to formation and modification of foliations in these examples, could just as well apply to the matrix of the Hurricane Mountain Formation in the early Paleozoic. The spectrum of structures is virtually the same. One may envision a deformation path to be followed by a given volume of matrix silt and clay, as progressing from listric faulting and slumping of unlithified or semiconsolidated sediment near the depositional interface, where initial break up of sedimentologic continuity occurs and extensional shearing within semilithified strata begins, to eventual burial to deeper levels where sediment masses may be thrust-fault bounded (Cowan, 1982, 1985). The photographs in Figures 2, 3, 5, and 6 might be arranged in a number of permutations of sequence, but for example, Figures 2c and d, Figures 3b-d, and Figures 5c-e might relate to one or another of these processes, as sediment progressed toward penetratively deformed rock. Gradations range from preservation of coherent stratification (Figs. 2c, 6a) to complete stratal disruption (Figs. 2a, b, and e, f; Fig. 3c, Fig. 5d, and Figs. 6b - e) as seen in outcrop and drill core, and these examples indicate that the disruption ranged from macroscopic to microscopic scales. The gradations suggest that disruption progressed inhomogeneously in neighboring rock volumes of various size at any given point in time. Different examples of disruption are seen at random in outcrop, just as they appear to be, along the 390 meters (1280 ft) of core from the two drill hole sites.

The flaser structure into which lenses of bedded segments were juxtaposed is postulated to have been initiated by layer-parallel extension and flattening accompanied by low-angle extensional shear. Strain and relative timing criteria are lacking in the Hurricane matrix to indicate whether this began in gravitationally unstable semiconsolidated layers, but the common occurrence of olistostromal blocks of arenite and wacke throughout the mélange suggest that it did. Layer-parallel extension could also occur by tectonic flattening under higher load pressure deeper in an accretionary complex. However, by analogy with modern examples, as thrust faults propagated into the sediment mass (probably with continued burial to shallow depths), the axis of maximum compressional stress (σ_1) within the fault zone would have to rotate into a shallow angle with respect to the main layering, resulting in compressional shear approximately parallel to earlier formed extensional shear surfaces (see Moore et al. (1986) for a rock mechanical discussion of modern shear cleavage formation). Folds of high amplitude but of short, millimeter-scale wavelength were formed in thin carbonate-bearing layers, presumably unconsolidated and therefore possessing lesser competency. Shearing along axial surfaces of outcrop-scale folds in metasiltstone, and shearing out of limbs to produce tectonic clasts of hinge-zone remnants (fold hooks) of thin metachert and metasandstone layers and quartz veins was commonplace. The microstructures permit the interpretation that this process occurred simultaneously with compressional shear in clay-rich layers.

Many examples of matrix suggest, by comparison with modern analogs, that shearing in unconsolidated or semiconsolidated clay-rich layers was responsible for the onset of the S_2 shear-foliation. The geometry of the intersecting shears is remarkably similar to that shown in examples, illustrated by Tchalenko (1968), of natural and experimentally produced shear zones in clay. Anastomosing surfaces in clay, on the same millimeter to centimeter scale as seen in Hurricane matrix, result from the intersection of main shear surfaces with subsidiary thrust- and riedel shears (cf. Fig. 6b and Fig. 10 for possible analogs in Hurricane matrix). In the Hurricane matrix, it appears

that the microshears, once formed in clay-rich layers, may have propagated short distances, on a sub-millimeter scale, into silty and tuffaceous layers as a consequence of continued deformation. In contrast, carbonate-rich, metapelite matrix (seen only in cores: Fig. 6a) is conspicuous by the near absence of anastomosing cleavage and microphacoidal clasts. Moore et al. (1986) cite a lower porosity and higher shear strength of calcareous mudstone, compared to smectitic mudstone, as lithologic and hydrodynamic causes producing this same contrast in Barbados core samples.

The pervasiveness of these shear zones suggests that once a shear zone is formed, dewatering within the zone leads to greater cohesion. Subsequent strain is taken up by development of new shear zones in less deformed material adjacent to existing shears (Moore et al., 1986). This is believed to be the repetitive process by which a nearly penetrative S_2 fabric was formed. If, however, S_2 began as thrust and riedel shears in clayey matrix, crystallization of new chlorite and white mica would have had to commence soon after the formation of the shears. Otherwise, it is doubtful that shear surfaces, initially formed in unconsolidated sediment, would survive subsequent deformation and low-grade metamorphism. If the thrust and riedel shears were initially preserved thus, many might become small S-surfaces, depending on their orientations within a stress field, in the further development of small-scale C and S fabrics, (Fig. 2e, f; Fig. 6b) as strain hardening, recrystallization, and metamorphism ensued. Early cleavage, S_1, (commonly parallel to, or at a small angle to flaser structure, and to long axes of phacoidal or ellipsoidal clasts) is interpreted to have begun during the stages of extensional shear accompanied by homogeneous flattening within the flaser-shaped lithons. Relicts of S_1 may later have behaved as C (cisaillement) shear surfaces (Berthé et al., 1979), if the mélange matrix continued to develop a high strain, shear zone fabric, replete with S_2 and S_3 foliations. Mimetic crystallization on this fabric during regional metamorphism, either Penobscottian or Acadian, may only have served to enhance these foliations. The *geometries* of the microstructures as now preserved at regional chlorite - muscovite grade, and the common occurrence of chlorites of varied Mg/Fe ratio (indicating disequilibrium between these solid solutions) that in part constitute these fabrics, suggest that this has occurred.

The model proposed here apparently does not conform in one respect to the observations of Moore et al. (1986). Their correlation of scaly fabric with fault zones suggests that its formation is confined to a structural thickness of about 40 m from a master fault. Either (a) major faults controlling the formation of S_2 shear fabric in the Hurricane Mountain Formation have been overlooked, or (b) the continuation of the proposed process toward an ultimate, pervasive, penetrative character causes the earlier major faults, now inactive, to be masked, or (c) the timing of formation of the S_2 surfaces is unrelated to the mélange-forming processes. The lack of marker horizons is an obvious hindrance to solving this dilemma. Karig (1986) noted with respect to the Nankai wedge, ".. the significant thickness of these shear zones and early deactivation of some thrusts....suggest that sheared strata may also become *strengthened*" (italics mine).."with continued strain, and deformations thus migrate elsewhere or diffuse..." (p. 130).

This postulated continuum of deformation, leading from the initial, extensional shear stage of formation of S_1 folia, accompanied by continued grain rotation and recrystallization with flattening, followed by the formation and propagation of S_2 anastomosing shear foliations, implies that both S_1 and S_2 should show generally similar orientations with respect to one another, and consistent senses of shear, if their orientations with respect to ambient stress fields were controlled by near-surface gravitational instability, burial, and deeper thrusting, as suggested in the foregoing part of this discussion. These orientations and directions of shear are approximated by the southeast-dipping S_2's and S_{3a}. As previously mentioned, the northwest-dipping S_2's show opposing senses of shear. Their anastomosing patterns and open curvature are similar to the southeast-dipping sets. Opposing senses of shear could have developed around lens-shaped clasts by inhomogeneous flattening on the scale of the lenses, as proposed by Hammond (1987) to explain microshear directions around clasts in an Australian mélange. Alternatively, the Hurricane Mountain mélange S_2's showing northwest over southeast thrust shear, indicate, in restored orientation, low-angle thrust shearing antithetic to the more commonly observed northwest-directed shears. In modern examples of backthrusting in sediments (cf. analysis of fault mechanics, Aleutian Trench: Davis and von Huene, 1987), backthrusts are steeper in dip and make a steeper angle with the main décollement than do the seaward-vergent thrusts. Even though examples of the Hurricane mélange serve as a possible geometric analog, it is doubtful if the process of backthrusting would generate pervasive, antithetical microshears in regional-scale volumes of an enclosing mélange. Hammond's interpretation for opposing senses of microshear (Hammond, 1987) appears to be much more applicable to the observed shear senses on the S-surfaces of the Hurricane mélange.

One of the plots, S_2 *c* (Fig. 8b), appears to have been rotated on an axis random to the core axis. Its orientation is unaccounted for.

The Hurricane matrix, already multiply deformed on S_2, was thereby evolving toward a structurally competent lithology, as the S_3 foliations indicate. S_{3a+3b} foliations may represent either late-stage Penobscottian, or Acadian deformation. The zones of discrete crenulations and kinks, assigned to S_{3a} (triangle-filled circles, Fig. 8b), show a shear sense of southeast side up, or reverse faulting of southeast side over northwest. S_{3a} clearly truncates all other structures and in some examples is axial planar to microfolds involving those structures. This displacement sense is the same as for the majority of the S_2's. It is also in accord with field determination of Acadian reverse faulting along part of the Squirtgun fault, farther southwestward in the Pierce Pond quadrangle (Boone, 1985), where the northwest side of the Lobster Mountain anticlinorium is faulted against the

overturned southeast limb of the Moose River synclinorium. It is also in accord with the *regional* sense of Acadian thrusting or reverse faulting, which extends from the northwestern side of the Kearsarge-central Maine synclinorium, southeastward to the Maine coast (Osberg et al., 1985). S_{3a} therefore, if this assessment is correct, is the only evident main-phase Acadian (as opposed to late- or post-Acadian kink band formation) *microstructural* modification - localized and non-pervasive - of the mélange matrix. If some of the foliations, such as here ascribed to the mélange-forming S_1 and S_2 foliations, originated in the Acadian, then they should produce structures characteristic of the Hurricane matrix *pervasively* in other, post-Lower Ordovician, pre-Acadian formations of similar bulk composition to the Hurricane matrix, rather than being confined as a penetrative fabric distinctive to the Hurricane Mountain Formation. Given the premise that S_1 and S_2 were integral to the mélange-forming process, the likelihood cannot be dismissed, however, that Acadian shear occurred along preexisting foliations in the Hurricane Mountain mélange.

Acadian deformation apparently was not thoroughly penetrative in the Hurricane Mountain Formation and certain of the younger pre-Silurian formations: this is demonstrated in several areas where Kennebec Formation feeder dikes intrude the Hurricane Mountain Formation. These can be seen in outcrop as well as in drill core, and are confined to the areas close to contacts with the unconformably overlying Kennebec Formation. Pelitic zones of mélange against some of the dikes preserve small relicts of porphyroblastic cordierite, but they are elongated parallel to one or another of the S_{3a} or S_{3b} sets. The distinctive fabric formed by S_1 and S_2 is apparently much modified by recrystallization and further deformation along these contacts. The dike margins are weakly foliated parallel to the S_3 orientations in their wall rocks (Fig. 6f). The foliations distinctive to the bulk of the mélange, S_1 and S_2, therefore probably originated prior to the Middle Ordovician Kennebec volcanic episode.

The pace and compass map (Fig. 9) of an inferred half-graben structure, showing Hurricane matrix in contact with much less deformed strata of Kennebec volcaniclastic rocks, illustrates a common pseudoconformity of strike and steep dip of principal planar elements in both the Hurricane Mountain Formation and overlying younger strata. It is only in larger, quadrangle-scale perspective (e.g., Fig. 1) that the stratigraphic aspects of unconformity are evident. Figure 9, and other local examples of pseudoconformity (Boone, 1973) and unconformity (Marvinney, 1982, 1984) involving the Dead River and The Forks Formations, suggest the prevalence of gentle dips of pre-Middle Ordovician stratification and foliations when the Kennebec Formation, Lobster Mountain Volcanic Complex, and The Forks Formation were deposited. The times of their deposition range from Llandeilo in the Middle Ordovician, to probably Early Silurian (late Llandovery; cf. Marvinney, 1982, 1984).

The postulated Acadian rotation of Penobscottian structures in the Lobster Mountain anticlinorium was nearly coaxial with, and roughly of the same magnitude as the steeply dipping, southeast-facing, Silurian and Devonian strata which bound the anticlinorium on its southeast side. This implies that a structural "rind" of pre-Silurian rocks of unknown thickness below the unconformity, and an undetermined thickness of Silurian and Devonian covering strata above that surface, underwent coherent Acadian fold-rotations. The basal strata above the pre-Silurian unconformity are mainly calcareous phyllite, siltstone and limestone. If most of the pore fluids in these rocks had been expelled before Acadian folding, they may have attained shearing strength great enough to behave structurally coherent with the strata beneath, instead of acting as a décollement zone.

Figure 10 shows in diagrammatic form the commonest present-day structural attitude of S-surfaces in the matrix of the mélange. The divergence in strike and dip of S_2 and S_{3a} in the Hurricane matrix of the core samples (Fig. 8b,c) is virtually the same as that of Acadian cleavage in younger, Silurian and Devonian strata. This indicates that the postulated imprecise orientation of core samples with respect to plunge of the core axes, as questioned earlier, probably does not contribute much to the dispersion of S_2 and S_3.

To summarize, Figures 10 and 11 show diagrammatically that the sense of shear and microfold geometry belonging to S_1, S_2, and most of the S_{3a}'s and S_{3b}'s of the Hurricane Mountain mélange matrix would conform to a thrust orientation with

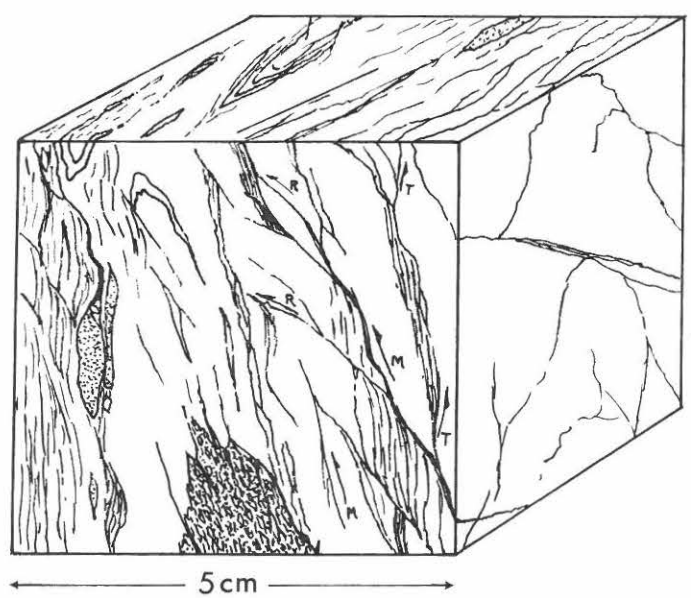


Figure 10. Block diagram showing relationship of steeply dipping S_1 cleavage oriented at very shallow angles to sheared layering (lower left) and S_2 main shears (M), thrust shears (T) and riedel-like shears (R) at shallow angles to S_1. Shear separations and sheared margins of metasiltstone in fold crest (bottom center) and quartz arenite microclasts (dotted pattern in clasts, left) conform to same shear sense. Late kink folds and discrete crenulation cleavages not shown. View is toward north, and is in approximately the same orientation as Figure 11.

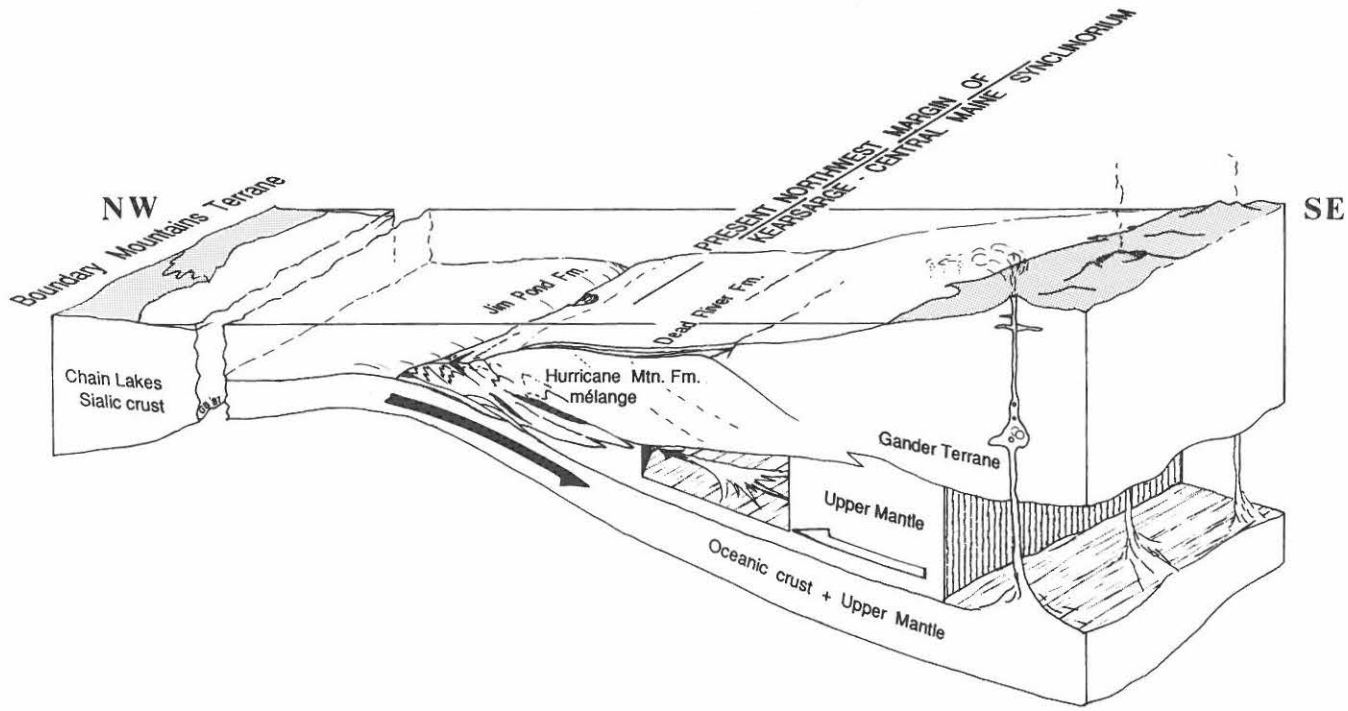


Figure 11. Perspective diagram showing interpretation of tectonic setting of Hurricane Mountain Formation accretionary complex in Late Cambrian to earliest Ordovician time. With subduction of oceanic crust (Jim Pond Formation and underlying mantle), the Hurricane Mountain mélange will mark the suture zone between the Boundary Mountains and Gander terranes. The southeast margin of the Boundary Mountains terrane is a passive margin. Cut-away in mantle wedge above subducted oceanic lithosphere shows arrow to indicate possible location and direction of transport of Mid- to Late Cambrian felsic lavas of the upper part of the Jim Pond Formation. Dead River Formation is deposited as volcanogenic flysch on the fore-arc upper slope, upon tectonically inactive, older Hurricane Mountain Formation. View is toward the north.

regard to the interpretation of restored geometry of an accretionary complex and its relationship to a present-day southeast polarity of late Cambrian subduction.

Time of Deformation

The evolution of ideas about the early assembly of the northern Appalachians in Maine has been strongly influenced by the belief that the Taconian orogeny produced folds and associated penetrative fabrics in rocks well to the east and southeast of the classic Taconic fold belt of western New England and Quebec. Pavlides et al. (1968) summarized prevalent opinion in the 1960's on the role of the Taconian orogeny in this area. Deformed (and polydeformed) rocks beneath unconformities covered by Silurian strata in central New England, Maine, and into western New Brunswick were logically interpreted as expressing Taconian deformation, uplift and erosion. Only in the apparent continuity of stratigraphy from Middle Ordovician (now considered as Llandeilo to Caradoc; cf. Osberg et al., 1985) to Silurian rocks (cf. Rickards and Riva, 1981) of the Aroostook - Matapedia belt of northeastern Maine did there seem to be an exception to the broad coverage of Taconian deformation.

Subsequent work along, and southeast of, the axis of the Boundary Mountains anticlinorium showed that Taconian deformation is muted, apparently being expressed by broad warping, local faulting, and moderate magmatic activity. Moench (1969) recorded a conformable contact between strata of Middle to Upper Ordovician age and overlying Ordovician(?) to Devonian strata in the Rangeley area. The Taconic unconformity, expressed by uplift of the anticlinorium, thus gives way to a conformable sequence on its southeast flank; the region of onlap was termed a tectonic hinge line (Boone et al., 1970).

Recent mapping by Cousineau (1987) in the region of l'Estrie - Beauce, Quebec, shows that the predominantly volcaniclastic strata of the Magog Group contain only one cleavage. The Magog Group is Middle Ordovician (Llandeilian, or possibly pre-Llandeilian, to Caradocian; Cousineau, 1987) and crops out in the St. Victor synclinorium, which is in thrust contact with the St. Daniel belt. Petrographic and chemical comparison of clasts in the St. Daniel belt with strata of similar lithologies in the Frontière Formation, basal to the Magog Group, implies the thrusting was not of regional dimensions. Comparison of

cleavage in the Magog strata with that in the Famine Formation of the St. Francis Group, across the Guadalupe thrust fault in the neighboring Connecticut Valley - Gaspé trough, indicates the cleavage is Acadian (Cousineau, 1987) because the Famine Formation contains an Eifelian (lower Middle Devonian) fauna (Boucot and Drapeau, 1968). It is therefore of more than passing interest that in this area just to the southeast of the Baie Verte Brompton line in southeastern Quebec, the Taconian orogeny folded the Magog strata, but apparently did not produce a penetrative cleavage in them (Cousineau, 1987).

A pre-Middle Ordovician unconformity in the Lobster Mountain anticlinorium (Boone, 1983) separates moderately folded and cleaved volcanic and volcaniclastic rocks of the Kennebec Formation from the polydeformed strata of the Jim Pond, Hurricane Mountain, and Dead River Formations below. The oldest strata (Kennebec Formation) above the unconformity contain a Middle Ordovician (Boucot and Heath, 1969), Llanvirn to Llandeilo (cf. Ross et al., 1982) fossil assemblage. Recent mapping (Simmons, 1987, 1988 (Simmons Major)) has shown that the Lobster Mountain Volcanic Complex (Boucot and Heath, 1969), which contains a shelly fauna of Ashgillian age (Neuman, 1973) near the top of the succession, is probably in gradational lower contact with the Kennebec Formation. Therefore, a Taconian unconformity in its classical sense is apparently absent. The pre-Middle Ordovician unconformity could be considered Taconian only if viewed as an extremely early phase of the Taconian. Although Rodgers (1971) likened the orogenic events broadly categorizing the Taconian in the type Taconic belt to a bullish stock market cycle, he aptly cautioned (Rodgers, 1971, p. 1170): "Above all, let us be wary.....of extending the term Taconic orogeny...beyond the region where Ordovician activity was in fact considerably greater than either Cambrian or Silurian." To this may be added the caveat of linking orogenies across major terrane boundaries.

The indication of a pre-Taconian, Early Paleozoic orogenic event along the Lobster Mountain - Lunksoos anticlinoria was first cited by Neuman (in Neuman and Rankin, 1966) to account for polydeformed strata of the Grand Pitch Formation, then considered to be of *probable* Lower Cambrian age, in the vicinity of the type locality on the East Branch of the Penobscot River, within the Lunksoos anticlinorium (cf. Neuman, 1962). Neuman demonstrated that these rocks lie unconformably beneath strata containing Early to Middle Ordovician fossils. He termed the intervening folding and cleavage-forming event the Penobscottian disturbance (Neuman and Rankin, 1966, p. 8-17; Neuman, 1967, p. 32-33). A pre-Middle Ordovician event was also recognized by Hall (1969). Hall (1970) assigned this event to the Penobscottian in the Munsungun anticlinorium. Both Neuman and Hall assigned tilting, and broad, open folding, as well as magmatic activity to the Taconian in their respective areas, but neither in the Lunksoos nor in the Munsungun was a Taconian cleavage-forming event recognized. As Hall (1970, p. 44) noted, the "Penobscot deformation appears to have been considerably more intense than the Taconic and probably the Acadian." Continued mapping and age refinements of rocks in the central and northern parts of the Lobster Mountain anticlinorium lead to the view that the Penobscottian, probably to the exclusion of the Taconian, was the major pre-Acadian cleavage-forming orogenic event in this region. This follows from the cited stratigraphic ages and from the observation that the moderately folded rocks of the Kennebec Formation and Lobster Mountain Volcanic Complex are simply deformed, and contain fold- and cleavage geometries that are colinear and coplanar with Acadian counterparts in nearby Silurian and Devonian strata.

The origin of highly contorted foliation in exotic blocks of high-grade amphibolite gneiss in the Indian Pond area, Brassua Lake 15' quadrangle (Figs. 4 and 12) clearly predates their incorporation in the mélange matrix, as their contacts with matrix mark a profound structural, as well as metamorphic discontinuity. The blocks are considered remnants of the earliest known Penobscottian dynamothermal metamorphism, as amphibolites of similar age and structure are unknown elsewhere. Their origin and age are discussed in following sections on petrology and isotopic apparent age.

Boone and Boudette (1989) summarize the evidence for the timing and regional extent of the Penobscottian orogeny in Maine, Quebec, and northwestern New Brunswick, and propose that the Penobscottian resulted from the collision and amalgamation of the Boundary Mountains terrane, northwest of the Lobster Mountain anticlinorium, and a second terrane, probably the Gander (Basement C of Osberg, 1978), to the southeast. The Hurricane Mountain Formation mélange is interpreted to be the suture zone along which terrane-accretion took place. This zone is termed the Hurricane Mountain belt and is inferred to extend from the Lobster Mountain anticlinorium northeastward across Maine, linking the mélanges of the Caucomgomoc inlier (Pollock, 1985, 1989), the Chesuncook dome, and the Munsungun anticlinorium (Hall, 1970; Boone et al., 1984) with the Elmtree inlier in New Brunswick. The reader is referred to Boone and Boudette (1989) to pursue this tectonic model.

METAMORPHIC HISTORY

Five metamorphic events, summarized in Table 3, are recognized in the rocks of the Lobster Mountain anticlinorium. Late- to post-Acadian, M_2 and M_3 metamorphism (Acadian designation) is locally dominant around the Pierce Pond gabbroic intrusion and around the Flagstaff Lake Igneous Complex (PPG and FLIC, Fig. 1) in the central and southwestern part of the Lobster Mountain anticlinorium. Fortunately, for the purpose of documenting Penobscottian events, the mélange matrix, as well as clasts and fault-bounded mafic intrusive rocks in the Indian Pond area of the anticlinorium, have the least of Acadian regional overprint, and apparently have no overprint of Acadian contact metamorphism. Farther north, around the volcanic center of Lobster Mountain, late Ordovician contact metamorphism local-

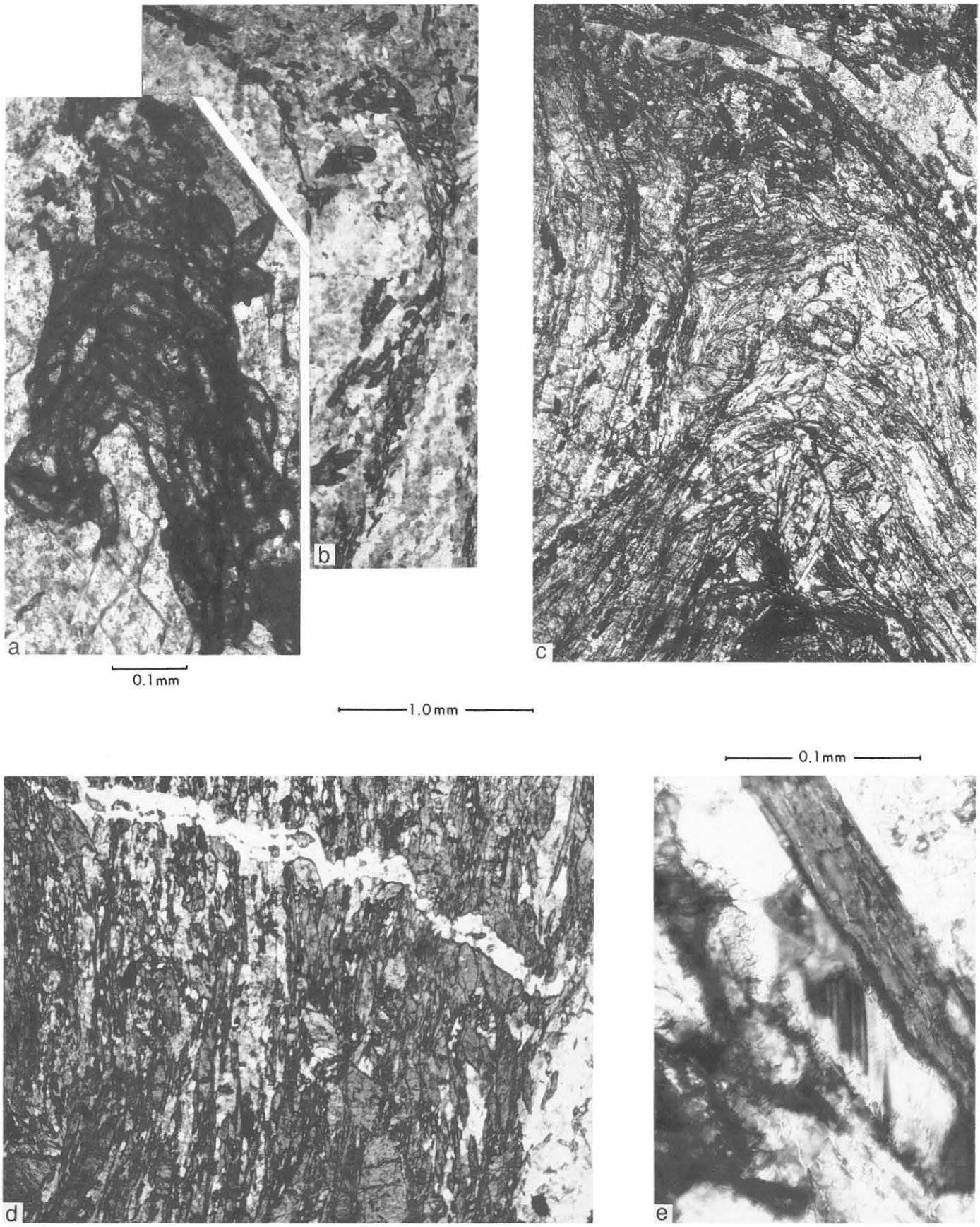


Figure 12.

TABLE 3. METAMORPHIC EVENTS RECOGNIZED IN THE ROCKS OF THE LOBSTER MOUNTAIN ANTICLINORIUM.

Event		Mineral Assemblage
Late- or post-Acadian contact metamorphism		
$M_{2/3}$		Biotite-muscovite to K-feldspar-cordierite
Acadian regional metamorphism		
M_1		Chlorite-white mica
Late Ordovician (Ashgill) contact metamorphism		
$M_{o.c.}$		Spotted slate (pinitized cordierite porphyroblasts) Chlorite-stilpnomelane-actinolite-epidote-Ab(lowest greenschist) in metabasites
Penobscottian metamorphism		
M_{p2}	(a) regional	Anchimetamorphic to chlorite-white mica
	(b) contact & fault zone	Biotite-ilmenite±garnet(?)±andalusite(?) at contact with gabbro sill; biotite-ilmenite in protomylonitic shear zones
M_{p1}		Pumpellyite-actinolite to amphibolite; local preservation of hi-P assemblage (only in exotic metabasite boulders and blocks in M_{p2}-metamorphosed mélange)

ly took the wall rocks up to lowest-greenschist rank in analyzed metabasites (Helsel, 1986; Helsel and Boone, 1987). Cordierite is common as small porphyroblasts in metapelites, and epidote in felsic tuffs. Milder contact effects, related to Kennebec volcanism in the Indian Pond area, and Lobster Mountain volcanism in the Northeast Carry 15' quadrangle, are seen where relict cordierite porphyroblasts are streaked out along Acadian cleavages in narrow selvages of Hurricane matrix where it forms host-rock to feeder dikes. These effects do not pervade the rocks beyond distances of a few decimeters from the dike contacts, as studied in core samples and in outcrop.

At the north end of Indian Pond, however, sparse garnet and possibly relict andalusite occur in the matrix of the mélange. The garnet was found only by probe scanning, and is of extremely fine grain size. The core and rim analyses (Table 4) on one of the larger, 10-μm-long grains, shows a zonation of composition from an almandine-pyrope-rich core to spessartine-rich rim. The grain is lens-shaped parallel to the S_1 foliation, and the zoning is apparently concentric to that shape. It is weakly birefringent, but does not match the optical characteristics of its compositionally closest anisotropic analog, carpholite. These observations suggest that the garnet is porphyroclastic. If so, it is an unusually sparse relict of an earlier, higher-grade metamorphic event in the mélange here, or it originally was introduced as a clastic component during sedimentation. The chlorite - white mica-rich assemblage gives no hint of an earlier, higher grade event. Of the several grains identified, none has porphyroblastic fabric relationships to the matrix that would be typical of garnet.

Microprobe analyses of the extremely fine-grained white micas and chlorites, so common to the matrix, thus far have not yielded single-mineral stoichiometries. From optical characteristics as well as the microprobe results, it appears the chlorites are ripidolitic, and have a wide range of atomic ratios of Mg/Mg + Fe + Mn from ~ 0.2 to 0.8.

Metamorphism of Amphibole-Bearing Exotic Blocks and Intrusive Metagabbro, Indian Pond Area

Description. The metabasite blocks range from chlorite-actinolite-pumpellyite-epidote-bearing metatuffs with well-preserved, primary pyroclastic textures, to actinolite-edenitic winchite-albite-epidote-bearing, fine-grained greenschists, to (in three of the largest rafts) pargasitic hornblende-zoisite-Mg chlorite-albite-bearing, strongly foliated amphibolite. Other blocks of high-temperature origin are fault-bounded metagabbro of intrusive origin in the mélange, and metadiabase sills and dikes.

Metagabbroic rocks within the Hurricane Mountain Formation are generally medium-grained, with local patches of relict gabbroic pegmatite. Metagabbro is commonly massive in outcrop, but relict igneous layering occurs in layered metagabbro of the Stony Mountain block, SW quarter of the Pierce Pond quadrangle (Fig. 1). The metagabbros of the Indian Pond area (Fig. 4, locality 3; photomicrographs shown in Fig. 13) show, by virtue of their chalky plagioclase laths and dark green, amphibole pseudomorphs of pyroxene, a relict massive fabric and texture. In most outcrops, it can be seen that the metagabbros are transected by thin, chlorite-rich shears. Many of these are planar to broadly curvilinear and may be several decimeters long. Others are of millimeter to centimeter scale, and form

Figure 12. Photomicrographs of amphibolite from "M-17" megaclast, west of northwest cove of Indian Pond, T1R7 township (cf. Fig. 4, and Fig. 5a, b). (a), (b), and (c) Microfolded foliation outlined by sphene swarms in (a) and (b), and by pargasitic hornblende in (c). The 1.0 mm scale bar applies to (b), (c) and (d). Light gray areas in (a) are hornblende (lower left) and altered plagioclase; light gray areas in (b) are altered plagioclase. (c) Altered plagioclase of intermediate composition (see text) is found as layers along fold limbs (upper right). Small patches of clear albite occur in hinge zone of disharmonic fold. (d) and (e) Common textural relations of albite. In (d), crenulated albite-rich vein cuts older foliation defined by hornblende and altered intermediate plagioclase. Part of lens of older plagioclase shown in lower right. At high magnification (e), twinned albite (center) is separated from hornblende prisms by thin selvages of magnesian chlorite decorating their margins. Dark patch, lower left, consists of polygranular sphene, chlorite, and epidote. Light area, upper right, is older, altered plagioclase of hornblende + Ca-richer plagioclase earlier assemblage.

TABLE 4. ELECTRON MICROPROBE ANALYSES OF SELECTED METAMORPHIC MINERALS, HURRICANE MOUNTAIN FORMATION MÉLANGE, INDIAN POND AREA.

		CALCIFEROUS AMPHIBOLES				
		Round Pond Block M-25.5		Amphibolite Block, W of NW cove, Indian Pond M-17		
		1	2	3	4	5
	SiO_2	49.05	50.92	43.79	46.17	45.09
	Al_2O_3	6.21	5.95	15.05	11.07	14.49
	Fe_2O_3†	3.25	3.11	2.83	2.23	2.76
	TiO_2	0.10	0.11	0.41	0.37	0.45
	MgO	13.23	12.88	10.69	13.04	11.79
	FeO	13.02	12.58	11.46	10.51	10.53
	MnO	0.23	0.35	0.23	0.13	0.23
	ZnO	0.05	0.16	0.05	0.00	0.00
	CaO	8.40	8.37	10.00	11.01	10.19
	Na_2O	3.31	2.69	2.00	1.53	2.06
	K_2O	0.15	0.16	0.21	0.20	0.21
	Cl	0.00	0.18	0.07	0.00	0.04
	Total	97.00	97.57	96.91	96.73	97.84
T	Si	7.08	7.28	6.30	6.69	6.41
	Al^{iv}	0.92	0.72	1.70	1.31	1.59
M_{1-3}	Al^{vi}	0.14	0.28	0.85	0.58	0.84
	Fe^{3+}	0.37	0.36	0.33	0.26	0.31
	Ti	0.01	0.01	0.04	0.04	0.05
	Mg	2.85	2.74	2.29	2.82	2.50
	Fe^{2+}	1.60	1.52	1.39	1.29	1.29
	Mn	0.03	0.04	0.03	0.02	0.03
	Zn	0.01	0.02	0.01	0.00	0.00
	Σ	5.01	4.97	4.99	5.01	5.02
M_4	Ca	1.33	1.31	1.58	1.71	1.55
	Na	0.67	0.74	0.44	0.29	0.45
	Σ	2.00	2.05	2.02	2.00	2.00
A	Na	0.28	0.02	0.14	0.14	0.12
	K	0.03	0.03	0.04	0.04	0.04
	Σ	0.31	0.05	0.18	0.18	0.16
MgO/FMO (molecular)		0.63	0.63	0.62	0.68	0.66
		(A)	(A)	(B)	(B)	(B)

(A): Sodic-calcic amphibole (ferric, edenitic to actinolitic winchite).
(B): Calcic amphibole (barroisitic, tschermakitic pargasite).

†Fe_2O_3: from Fe^{3+} calculated from Laird and Albee (1981a) normalization 3.

irregular, intersecting arrays. Quartz veins and irregular, lens-like knots of quartz are less common. In thin section, relict plagioclase exhibits stout idiomorphic laths (Fig. 13a); relict pyroxene (augite?) occurs as irregular, subidiomorphic, large prisms (Fig. 13d) that are less abundant than the plagioclase laths. These constitute the relict texture of the rock. They are surrounded by radiating splays of sodic-calcic amphibole (Fig. 13b) showing a range of compositions (Table 4). The amphiboles within these clusters, in turn, may be partly surrounded by small patches of clear albite (Fig. 13b,c). Accessory apatite occurs as stout prisms. Ilmenite (Fig. 13c), as irregular, rounded, xenomorphic grains, and sparse pyrite, make up the accessory opaque minerals. The plagioclase laths have a pronounced granular appearance owing to clots of very fine-grained sphene and epidote set amidst cloudy plagioclase of varied, intermediate composition (optically oligoclase to andesine). The relict pyroxene prisms contain a patchwork of edenitic hornblende within subcalcic augite (Table 4).

Metabasite blocks range from pillowed metabasalt, poorly foliated greenstone, well layered to well foliated metatuff and green phyllite (Fig. 13g), to fine-grained greenschist (Fig. 13e,f), and coarse-grained, well foliated amphibolite in which irregular lenses of coarse metamorphic pegmatite may occur (Fig. 5a,b). Greenschist and amphibolite commonly display a highly con-

TABLE 4. CONTINUED.

		CALCIFEROUS AMPHIBOLES (CONTINUED) Gabbro Point, Indian Pond							
		6	7	8	9	10	11	12	13
	SiO_2	47.11	45.82	43.22	48.04	40.61	48.46	41.34	42.47
	Al_2O_3	5.68	6.10	8.49	5.06	13.55	4.37	10.75	9.30
	Cr_2O_3	0.00	0.06	0.00	0.00	0.00	0.02	0.00	0.05
	Fe_2O_3†	2.92	2.94	3.96	3.56	2.44	2.01	2.71	2.79
	TiO_2	1.43	0.06	0.18	0.07	0.00	0.11	0.00	0.80
	MgO	10.97	5.95	5.47	7.76	3.31	6.55	3.39	4.60
	FeO	17.20	24.43	24.20	22.64	24.82	24.99	26.81	25.70
	MnO	0.58	0.66	0.47	0.83	0.51	0.57	0.35	0.58
	CaO	10.31	10.40	9.86	9.47	10.54	11.50	10.51	10.65
	Na_2O	1.82	1.50	2.09	1.49	2.39	0.58	2.49	2.18
	K_2O	0.49	0.20	0.15	0.15	0.21	0.23	0.25	0.34
	Total	99.34	99.05	98.09	99.07	98.38	99.39	98.61	99.47
T	Si	6.92	6.97	6.57	7.12	6.23	7.28	6.39	6.48
	Al^{iv}	1.08	1.03	1.43	0.88	1.77	0.72	1.61	1.52
M_{1-3}	Al^{vi}	--	0.07	0.10	--	0.68	0.54	0.35	0.15
	Fe^{3+}	0.34	0.36	0.48	0.42	0.29	0.24	0.32	0.30
	Cr^{3+}	--	0.01	--	--	--	0.02	--	0.06
	Ti	0.16	0.01	0.02	0.01	--	0.01	--	0.09
	Mg	2.40	1.35	1.24	1.71	0.76	1.47	0.78	1.05
	Fe^{2+}	2.13	3.13	3.11	2.82	3.21	3.15	3.49	3.30
	Mn	0.07	0.09	0.06	0.10	0.07	0.07	0.05	0.08
	Σ	5.10	5.02	5.01	5.06	5.01	5.50	4.99	5.07
M_4	Ca	1.62	1.70	1.61	1.50	1.73	1.85	1.74	1.74
	Na	0.28	0.30	0.39	0.43	0.27	0.15	0.26	0.26
	Σ	1.90	2.00	2.00	1.93	2.00	2.00	2.00	2.00
A	Na	0.24	0.14	0.22	--	0.44	0.02	0.49	0.38
	K	0.09	0.04	0.04	0.03	0.04	0.04	0.05	0.07
	Σ	0.33	0.18	0.26	0.03	0.48	0.06	0.54	0.45
		Brown	Pale Bl-Grn	Deep Blue	Deep Bl-Grn	Green-Blue	Dark Blue	Dark Blue	Dark Blue
MgO/FMO (molecular)		0.52	0.30	0.28	0.37	0.19	0.31	0.18	0.24
		(C)	(C)	(D)	(E)	(D)	(E)	(D)	(D)

Calcic amphiboles: (C), ferri-barroisitic edenite; (D), ferric to low-Fe^{3+}, barroisitic ferro-tschermakite; (E), barroisitic ferro-actinolite.

†Fe_2O_3: from Fe^{3+} calculated from Laird and Albee (1981a) normalization 3.

torted, multiply-folded foliation (Fig. 5; Fig. 12c,d). The metabasites of lower metamorphic grade suggest they were formed either as flows in a marine environment, (where they show flattened, indistinct pillows or well preserved pillow structure), or as aquagene tuffs. Most of the relict flow-rocks are aphyric, and contain carbonate minerals in lenses or in small, relict vesicles. In thin section, they are observed to contain pumpellyite and epidote (Frost, 1977), commonly with actinolite, but in one example, with a sodic-calcic amphibole close to winchite in composition (Table 4). They are very fine-grained, but epidote commonly is subidioblastic, and may show zoning from pistacite-rich cores to clinozoisite-richer rims (Fig. 13e,f). All contain abundant sphene, rutile, and locally, hematite. (Sphene-, epidote-, and rutile-rich shear bands in mélange matrix may represent metatuff layers or clasts that have been extensively drawn out and attenuated.) Metatuffs and mafic, volcaniclastic metasedimentary rocks may show gradations between them on the scale of outcrop or hand specimen, which commonly imbues the rock with a wispy, undulose layering that appears to be structurally independent of a rough, but more or less planar foliation where present. They are commonly fine-grained and granulose, and variously dark green or pale yellowish green, depending on variations in chlorite and epidote. Blocks derived by segmentation or boudinage of small sills or dikes are gray, fine-grained, and commonly massive. Locally they may show small, relict plagioclase phenocrysts.

TABLE 4. CONTINUED.

SUBCALCIC AUGITE[1]

	Gabbro Point		China Island Block					
	1		2		3		4	
SiO_2	53.11		54.99		53.54		56.88	
Al_2O_3	0.60		3.22		4.44		1.96	
Cr_2O_3	0.09		0.11		0.03		0.01	
TiO_2	0.04		0.00		0.09		0.04	
MgO	11.67		16.85		15.16		18.57	
FeO	20.93		12.22		13.52		9.78	
MnO	0.26		0.35		0.28		0.19	
CaO	11.05		11.09		10.57		11.80	
Na_2O	0.19		0.73		1.22		0.55	
K_2O	0.00		0.09		0.10		0.03	
Total	97.94		99.64		98.95		99.82	
Si	2.10		2.04		2.00		2.09	
Al^{iv}	--		--		--		--	
Al^{vi}	0.03		0.14		0.20		0.08	
Cr^{3+}	tr		tr		tr		tr	
Ti	tr		--		tr		tr	
Mg	0.69		0.93		0.85		1.02	
Fe^{2+}	0.69		0.38		0.42		0.30	
Mn	0.01		0.01		0.01		0.01	
Ca	0.47		0.44		0.42		0.46	
Na	0.01		0.05		0.09		0.04	
K	--		tr		0.01		tr	
Jd	0.4		2.8		0.1		2.2	
Cats	0.5		2.5		2.8		1.1	
Wo	25.2	26	21.8	23	20.5	22	24.1	25
En	36.9	37	51.3	54	47.2	52	55.7	58
Fs*	37.0	37	21.6	23	23.9	26	16.9	17
MgO/FMO(moles)	0.50		0.70		0.67		0.77	

[1]Fe^{3+} not required in Essene-Fyffe (1967) normalization of these analyses.
*Includes $MnSiO_3$

EPIDOTE, PUMPELLYITE, AND SPHENE

	Round Pond	China Island				
	E1	E2	E3	P1		S
SiO_2	35.68	38.41	36.60	37.10	SiO_2	30.72
Al_2O_3	22.38	24.64	26.28	23.89	Al_2O_3	1.75
Cr_2O_3	0.00	0.20	0.03	0.08	TiO_2	37.80
Fe_2O_3[2]	15.00	10.81	9.57	12.87	MgO	0.67
TiO_2	0.06	0.17	0.00	0.08	FeO^t	1.22
MgO	0.00	0.13	0.13	2.46	MnO	0.05
Mn_2O_3[2]	0.38	0.33	0.13	0.00	CaO	27.75
CaO	22.80	23.01	23.26	20.08	Na_2O	0.04
Na_2O	0.01	0.00	0.02	0.11	K_2O	0.05
K_2O	0.00	0.05	0.00	0.00		
Total	97.01	97.72	97.01	96.68		100.04
Si	2.91	3.02	2.94	5.91	Si	0.99
Al^{iv}	0.09	--	0.06	0.09	Al	0.07
Al^{vi}	2.06	2.30	2.42	4.40	Ti	0.92
Cr^{3+}	--	0.20	0.03	0.01	Mg	0.03
Ti	tr	0.01	--	0.01	Fe	0.03
Mg	0.00	0.02	0.02	0.59	Mn	tr
Fe^{2+}	--	--	--	--	Ca	0.96
Fe^{3+}	0.92	0.64	0.58	1.54	Na	tr
Mn^{3+}	0.02	0.02	0.01	--	K	tr
Ca	1.99	1.94	2.00	3.43		
Na	0.05	--	tr	0.04		
K	--	tr	--	--		
$\frac{(Fe+Cr+Mn)}{(Al+Fe+Cr+Mn)}$	0.30	0.23	0.20	0.26		
CZ	54	67	70			
PC	45	32	29			
PM (mole %)	1	1	1			

[1]Compared to published analyses (cf. Deer et al., 1962) FeO^t is anomalously high by ca. 4%, and the anhydrous total, by ca. 2%.
[2]Fe and Mn treated as trivalent.

TABLE 4. CONTINUED.

	PLAGIOCLASE					
	Gabbro Point		Round Pond	M-17 Amphibolite		
	1	2	3	4	5	6
SiO_2	56.74	61.81	68.21	68.36	67.84	66.66
Al_2O_3	21.67	23.66	19.84	20.27	20.02	21.36
Fe_2O_3[1]	7.98	0.00	0.00	0.00	0.16	0.00
TiO_2	0.02	0.01	0.02	0.00	0.00	0.04
MgO	0.04	0.24	0.00	0.00	0.02	0.05
FeO	0.36	1.21	0.18	0.03	0.00	0.19
MnO	0.00	0.00	0.00	0.00	0.00	0.01
CaO	4.83	1.42	0.09	1.25	1.04	1.18
Na_2O	7.83	8.43	11.54	10.41	10.80	9.93
K_2O	0.31	2.46	0.02	0.22	0.92	0.00
Total	99.79	99.25	99.90	100.53	100.79	99.42
Si	2.58	2.76	2.99	2.99	2.95	2.96
Al^{iv}	1.16	1.24	1.01	1.01	1.03	1.04
Al^{xs}	--	--	--	0.03	--	0.08
Fe^{3+}	0.26	--	--	--	0.01	--
Ti	tr	tr	tr	--	--	tr
Mg	tr	0.02	--	--	tr	tr
Fe^{2+}	0.06	0.05	0.01	tr	--	0.01
Mn	--	--	--	--	--	tr
Ca	0.24	0.07	tr	0.06	0.05	0.06
Na	0.69	0.73	0.98	0.89	0.91	0.86
K	0.02	0.14	tr	0.01	0.05	--
Or	2.0	15.0	0.1	1.0	4.9	0.0
Ab	73.0	78.0	99.5	92.7	90.3	93.9
An (mole %)	25.0	7.0	0.4	6.3	4.8	6.1

[1]Fe^{3+} assigned to fill T-site deficiency in Si + Al.

	GARNET		
	Porphyroclast (?) in Ti-Fe-rich, semipelitic mélange matrix, Indian Pond		
	Core	Rim, inner portion,	Rim, edge
	1	2	3
SiO_2	36.91	37.75	36.82
Al_2O_3	23.34	21.91	22.16
Cr_2O_3	0.03	0.00	0.00
TiO_2	0.03	0.01	0.06
MgO	4.09	1.99	1.49
FeO	28.99	19.24	15.37
MnO	2.71	14.37	18.42
CaO	4.62	4.28	4.03
Na_2O	0.05	0.11	0.06
K_2O	0.04	0.07	0.04
Total	100.81	99.70	98.48
Si	2.90	3.04	3.01
Al^{vi}	2.16	2.08	2.13
Cr^{3+}	tr	--	--
Ti	0.002	0.005	0.004
Mg	0.48	0.24	0.18
Fe^{2+}	1.90	1.29	1.05
Mn	0.18	0.98	1.27
Ca	0.39	0.37	0.35
Σ VIII*	2.95	2.88	2.85
Almandine	64	45	37
Spessartine	6	34	45
Pyrope	16	8	6
Grossular (mole %)	13	13	12

*Alkalies omitted in normalization to eight cations.

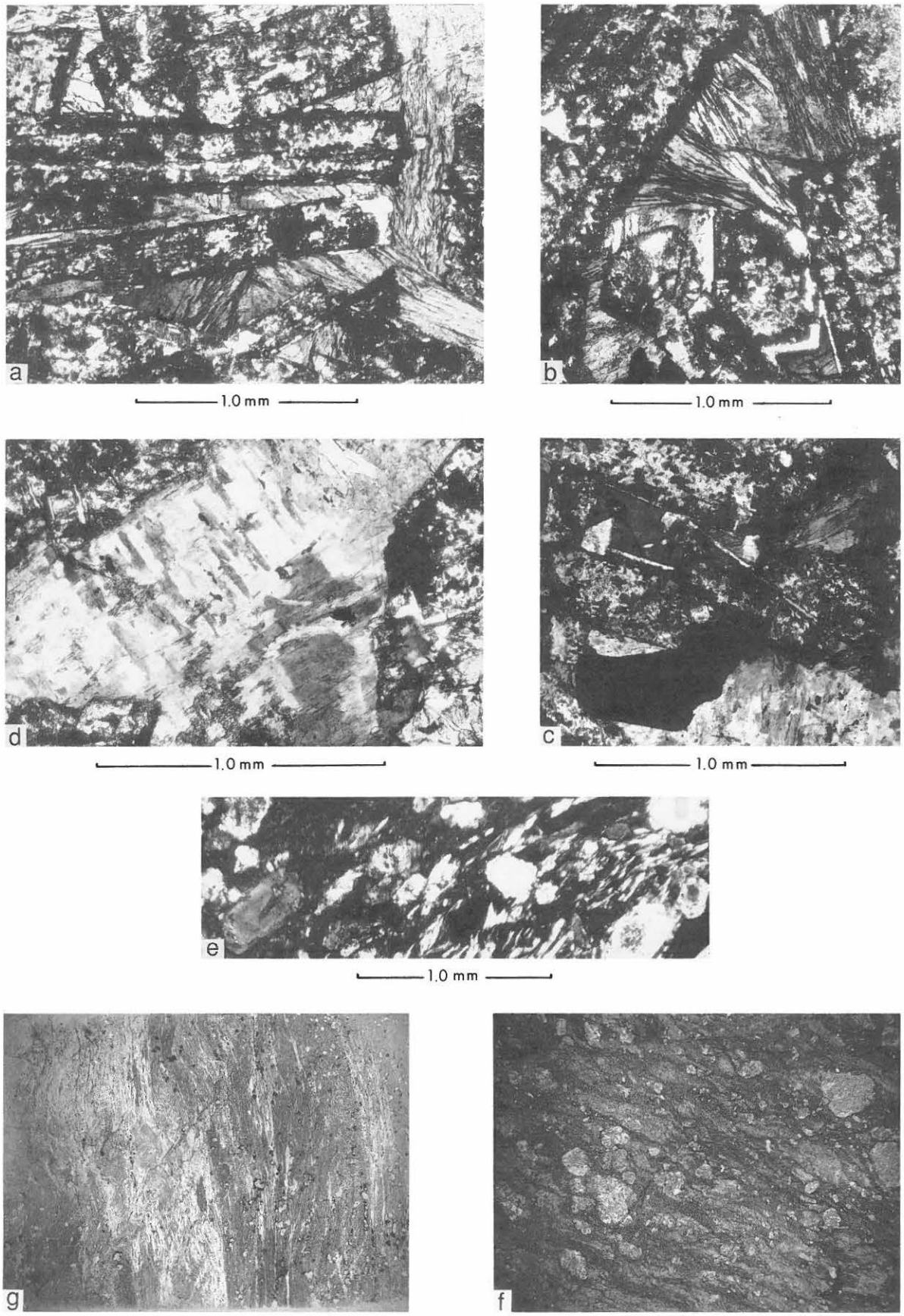


Figure 13.

The pargasitic hornblende-rich amphibolite tectonites of the largest of the megaclasts (see Fig. 4) are surprisingly coarse-grained and attain locally a gneissic fabric, owing to the presence of plagioclase-rich, quartz-bearing, irregular veins and pods (Fig. 5a,b). A swirled, chaotic foliation is common. The foliation, clearly outlined by hornblende, can also be traced in thin section by swarms of sphene crystals (Fig. 12a,b) and in other samples, by anhedral rutile grains. Hornblende crystals are not bent or fractured where they form the hinge-zones of small folds (Fig. 12c). As shown in Figure 12b, the sphene swarms are commonly embedded in patches of densely clouded plagioclase. Zoisite is locally present in these patches. Locally, very coarse, clouded-plagioclase-rich patches, some as large as 30 cm across, resemble anatectic or metamorphic pegmatites. On a localized scale in thin section, small anhedral lenses of clear albite of An_{5-6} in composition (Table 4) are tucked between hornblende prisms. Clouded plagioclase inclusions *within* hornblende, and in the patchy, irregular lenses, range in composition between An_{24} and An_{31}, based on extinction angles in a-normal sections. Around the clear albite grains intergranular to hornblende, locally some of the margins of the hornblendes are minutely corroded and incompletely mantled by tiny plates of chlorite. Ptygmatically folded veins of albite cut across the amphibolite foliation (Fig. 12d). Apatite and hematite are accessories.

Interpretation. The collective history experienced by these metabasites is explored first in those of higher temperature initial origin. The metagabbros and amphibolites contain polymetamorphic mineral assemblages. Higher temperature relicts stand out amid assemblages of successively lower temperature conditions, either at low pressure, or medium-high pressure. The origin of amphibole in metagabbro, and in amphibolite and greenschist blocks in otherwise subgreenschist to lowest greenschist facies mélange matrix can be ascribed to several possible tectono-metamorphic environments. In descending order (a crude lithospheric analogy) from spreading ridges to consuming plate boundaries, they are: (1) burial metamorphism under low pressure along the flanks of an actively spreading, accretionary plate boundary (Miyashiro et al., 1971); (2) contact dynamothermal metamorphism by dike- and sill-swarms in the same tectonic setting; and, as summarized by Malpas et al. (1973): (3) preserved mantle tectonite; (4) accretionary plate boundary magmatism; (5) dynamothermal metamorphism along transform faults; (6) contact dynamothermal or static metamorphism within an evolving island arc; (7) dynamothermal metamorphism, commonly high pressure, during ophiolite obduction; and (8) subduction-related, green- to blueschist facies metamorphism. None of the eight hypothetical petrogeneses can be dismissed categorically for the origin of the exotic metabasites in the Hurricane Mountain Formation.

The metamorphic history of the metagabbros is discussed first. The gabbroic protoliths, where studied extensively in samples from Indian Pond, originated as clinopyroxene-rich, olivine-free, low-titanium ferrogabbros. Vestiges of orthopyroxene are not found, but as Ferry (1985) has documented for the Skye gabbros, clinopyroxene, as opposed to orthopyroxene, can remain remarkably resistant to retrograde alteration. It is not yet known if fluid pressure, fluid flow, or oxygen fugacities in the Indian Pond metagabbros progressed during metamorphism as they did in the Skye examples, nor is it clear as to whether the pyroxenes found at Indian Pond are magmatic relicts, or are metamorphic. Because the Indian Pond metagabbros are strongly amphibolitized, and because actinolitic and common calciferous hornblendes occupy a niche intermediate in Ca-content to clino- and orthopyroxenes, these gabbroic protoliths could well have had compositions of normal two-pyroxene (tholeiitic) gabbros. The preservation of small percentages of clinopyroxene enhances this compositionally-based argument. Detracting from this argument, however, is that microprobe analysis shows the clinopyroxene to be subcalcic augite (augite analysis 1, Table 4); this has a Ca/Ca + Mg + Fe atomic ratio not much removed from that of the calcic and sodic-calcic amphiboles (amphibole analyses 6-13) coexisting with it. Similar subcalcic augite, but with higher Al-contents (augite analyses 2-4) occurs in an epidote amphibolite megaclast ("China Island" of Fig. 4) about 1 km (0.6 mi) northwestward across strike. Textural relations here suggest the augite is metamorphic, which implies it owes its origin to crystallization in an H_2O-deficient environment. Although the same could apply to the metamorphic environment of the metagabbro of "Gabbro Point", Indian Pond (Fig. 4), the relict igneous interpretation of the subcalcic augite there analyzed is favored on the basis of textural relations and its lower Al-content.

Figure 13. Photomicrographs of metagabbro, epidote amphibolite, and mafic, aquagene metatuff. All from Brassua Lake 15' quadrangle. (a), (b), and (c) Laths of strongly clouded primary igneous plagioclase (mottled) set amid radiating splays of Fe-rich, edenitic to pargasitic hornblende. Albite and sodic oligoclase (clear white areas) form partial mantles on clouded plagioclase. The sodic-calcic amphibole splays are bordered by Fe-rich actinolite at their contacts with sodic plagioclase. (d) Ferri-edenite (gray bands; cf. Table 4, anal. 6) within subcalcic augite (white; augite anal. 1) oriented ~ 90° to trace of clinopyroxene c-axis. Based on textural relationships, the subcalcic augite is assumed to be relict igneous, but see text discussion. Anhedral black grains in (c) and (d) are ilmenite with submicroscopic sphene and rutile inclusions. (a) through (d) from "Gabbro Point" (Fig. 4, location #3), northwest cove of Indian Pond. (e) Epidote-amphibolite, "China Island", northwest cove of Indian Pond (Fig. 4, location #2). Epidote is zoned from pistacite-rich cores to Al-richer rims. Many cores of crystals are clouded by inclusions of fine-grained sphene (e.g., upper left and lower right). Lower right half of photo shows actinolite-rich matrix; upper left is chlorite-rich (black to dark gray). (f) Epidote- and pumpellyite-rich, relict pyroclasts in chlorite-rich matrix showing lenses and layers typical of aquagene tuff. Round Pond block (Fig. 4). (g) Fine-grained greenschist composed of chlorite, talc, ankeritic carbonate, and pyrite, northwest cove, Indian Pond. Protolith was probably aquagene, mafic tuff.

A visually estimated, ca. 1.5 volume percentage of ilmenite[2] together with the moderate Ti-contents of analyzed amphiboles (Table 4), suggest a relatively low Ti-content of the parent gabbroic rocks.

Common textural relationships (Fig. 13a,d) suggest that an early stage of amphibolitization resulted in the partial replacement by brown hornblende (Table 4, amphibole analysis no. 6) of orthopyroxene lamellae in clinopyroxene hosts (augite analysis no. 1). Destruction of calcic igneous plagioclase resulted in an almost opaque clouding by very fine-grained sphene and epidote. Granoblastic zoisite crystallized as intergranular mosaics around the primary plagioclase relicts. Sodic plagioclase, determined by microprobe analyses (Table 4) and by extinction-angle measurements as ranging from nearly pure, clear albite to variously clouded calcic oligoclase, appears as epitaxial, partial rims on the extremely clouded parental pseudomorphs. Clear albite and ferroactinolitic to ferro-winchite-bearing, aluminous actinolites appear to be in stable textural equilibrium (Fig. 13b,c). These textural aspects indicate a static, hydrothermal retrograde event, spurred by brittle deformation that allowed ingress of H_2O-rich fluids.

Hornblendes intermediate in composition between ferroactinolite, pargasite, tschermakite, and winchite, all of varied Na, Al, and Fe contents (Table 3, amphibole analyses 6-13) appear to signify a post-magmatic-emplacement, polythermal event that was characterized by a continuum of decreasing temperature. Brittle, non-penetrative formation of intersecting shears and localized foliation may have been coeval. Actinolites of lower Na and ^{IV}Al form rims upon, and radiating splays between, those with higher percentages of these elements (textures illustrated in Fig. 13). Gradational zoning toward actinolitic rims, lack of exsolution structure, and lack of bimodal clustering of compositions in Mg - (Fe^{2+}, Mn) - ^{IV}Al (Oba and Yagi, 1987) and in (^{A}Na + K) - ^{IV}Al and Ca - Na (Ernst, 1979) are compatible with the interpretation of polythermal retrograde metamorphism. Zoisite and albite fill microscopic shears with poorly defined margins.

These textural and mineral compositional relationships in metagabbro of intrusive origin reflect retrograde metamorphism of the primary igneous assemblage. This is viewed as promoted by initial shrinkage due to subsolidus cooling which produced fractures on a meso- and micro-scale, thereby allowing penetration of (connate, oceanic?) H_2O-rich fluid. In its essentials, this is the prevailing theme inferred by Ito and Anderson (1983) for the amphibolitization of gabbro in the mid-Cayman Rise. Mafic magmatism within an evolving accretionary complex, however, such as is believed to be the history recorded at "Gabbro Point" (locality 3, Fig. 4) is just as viable, and could yield similar textures, structures, and mineral assemblages.

The later, profuse development of actinolitic hornblende and chlorite-rich shears could have been produced in response to renewed magmatism or tectonism along a transform fault, or to the same sequence of events in a tectonically active fore-arc environment. Compressive deformation and faulting of the metagabbro during disruption of its initially intrusive structural geometry within the tectonically evolving mélange is not only likely, but expectable (cf. Echeverria, 1980). At Indian Pond, quartz-rich, protoclastic and mylonitic lenses and seams are concentrated within the sheared contact zone between the metagabbro and relict, biotite- (and andalusite ?) bearing hornfels in the Hurricane matrix. Metamorphic P/T inferences are discussed below.

The metabasite blocks of low metamorphic rank in the mélange of the Indian Pond area are characterized by moderately Fe-rich epidote, pumpellyite and sphene (Table 4), and very fine-grained albite and weakly pleochroic actinolite. The zonal pattern of epidote, first documented by Frost (1977) in the Round Pond block, has since been noted as common to all the low-grade metabasite clasts. The epidote zonation, from pistacitic cores to clinozoisite-richer rims, may imply increasing temperature during its formation (Liou et al., 1985), or greater nucleation rates for Fe-richer compositions. The Round Pond block is of interest because sodic-calcic amphibole close to winchite in composition has the highest atomic ratio of Na/Na + Ca, and calculated Na (M_4), suggesting that these rocks may have experienced the highest metamorphic pressures of the sampled metabasites. Sphene, albite, epidote, actinolite, and minor pumpellyite, rutile, and hematite form a common pumpellyite-actinolite facies assemblage in these blocks.

The metamorphic history of the exotic, meso-scale clasts and megaclasts of amphibolite are discussed with reference to the large blocks of amphibolite (near locality 1, Indian Pond area, Fig. 4). Analytical data from two blocks near locality 1, grouped together here as M-17, are used to interpret the metamorphic textural evolution and mineral assemblages. Hornblende compositions in M-17 (Table 4, analyses 3, 4, and 5) are compositionally intermediate between aluminous actinolite ("common hornblende"), pargasite, and winchite. They are unzoned and relatively free of fine-grained alteration products along cleavages and fractures. The fact that hornblende crystals are not bent or fractured in hinge zones of folds, and that hornblende and clouded plagioclase crystals enclose similarly folded swarms, or trains, of sphene or rutile, indicates that folding preceded final (annealing?) recrystallization. Small patches of chloritic alteration are found at contacts with albite (Figure 12e), rather than against relict, clouded plagioclase. They appear at random with regard to fold geometry. These textural and compositional relationships demonstrate a polymetamorphic, retrograde thermal overprint on an original, pargasitic hornblende - Ca-richer plagioclase assemblage. The sharp rimming of albite on clouded plagioclase, diffuse lenses of zoisite that appear to have replaced the foliation, and albite-rich veins that in turn have been folded, indicate that the overprinting was

[2]Microprobe analyses of ilmenite in metagabbro and actinolitic greenschist blocks gave unsatisfactory totals between 101 and 103 wt. %. Excess Ca and Ti over stoichiometric ilmenite indicates ~0.5% sphene and ~4.3% rutile (mole %) admixed with host ilmenite in metagabbro. The ilmenite solid solution in the "China Island" greenschist block (Fig. 4) is a manganoilmenite with ~40% $MnTiO_3$ with ~1.5% sphene and ~0.7% rutile admixed. These interpretations assume all Fe is ferrous.

not simply due to polythermal recrystallization during a single cooling event. The final, perhaps stable, assemblage in the M-17 amphibolites would therefore seem to be: hornblende + Mg-rich chlorite + albite + zoisite (+ minor epidote) + sphene + hematite.

Origin of Albite-Quartz Veins in M-17 Amphibolite. Recently, Sorensen and Barton (1987) described migmatites and veins of albitic plagioclase-quartz-muscovite in amphibolite blocks within the Catalina Schist subduction complex, California, and ascribed their origin to crystallization from a melt at moderately shallow levels within a subduction zone. The composition of the migmatites and their relationships to enclosing blocks within the schist are similar to the M-17 amphibolites of the Hurricane Mountain Formation in the area west of Indian Pond. The M-17 amphiboles are similar in some respects to those in the Catalina blocks, but the M-17 mineral assemblages differ in the following: (a) lack of fresh plagioclase more calcic than An_6, (b) absence of garnet and discrete grains of white mica (but not epidote), (c) macroscopic, but not microscopic structural conformity of the M-17 veins to the pronounced foliation of the host amphibolite, and probably most importantly, (d) the sparse content of quartz. Estimated modes of quartz in outcrop examples and in thin section range from about 2 to 30%. The textures are lepidoblastic rather than igneous, and there is no hint of a pre-amphibolite facies igneous fabric.

Ellis and Thompson (1986), in their analysis of the partial melting of amphibolites, predicted that the liquid field would be expanded to lower temperatures by the addition of Na to amphibole-liquid phase relations in CMASH, bringing the solidus closer to that of Ab - Qtz - H_2O. This would bring temperatures of initial partial melting into the 700°C range (Johannes, 1985), but probably not without a pyroxene solidus phase at pressures less than 8 to 10 kilobars (Ellis and Thompson, 1986).

There is no pyroxene, relict igneous or metamorphic, in the analyzed M-17 amphibolites, and mineral assemblages indicative of high pressure *and* high temperature are lacking here and elsewhere throughout the mélange. The veins in M-17 amphibolite, furthermore, appear to be compositionally quite dissimilar to mid-ocean ridge plagiogranites (cf. Spulber and Rutherford, 1983, for a compilation). On the basis of the similarity, however, of albite composition in the veins and locally within the amphibolite host (as detailed in a previous paragraph) the albite, and probably zoisite, in both of these structural relationships is probably part of the same stable mineral assemblage.

Significance of Changes of Plagioclase An-Content in Amphibolite. The compositional and textural relationships summarized in the preceding paragraphs suggest that the earlier, Ca-richer plagioclase-hornblende assemblage was incompletely recrystallized at higher pressure, and possibly lower temperature. Maximum fluid pressure was probably not greater than 4 kb, if the fluid was predominantly H_2O (Maruyama et al., 1986). It is not clear from textural and structural relations within and surrounding the M-17 clasts, whether the higher pressure metamorphism predated the emplacement of the clasts at their present sites in the mélange, or whether this occurred following emplacement and is therefore to be ascribed to late Penobscottian, M_{p2} metamorphism.

The composition of the earlier, An-richer plagioclase is estimated from extinction-angle measurements to be ~ An_{32}. Based on the more aluminous of the M-17 hornblende compositions, the conditions of earlier metamorphism of the M-17 megaclast were probably within a low pressure, garnet-andesine zone (Fig. 14; see also Laird and Albee, 1981b; Laird et al., 1984). From this, the speculation can be made that the *porphyroclastic* garnet, analyzed in the semipelitic matrix, may have been derived from the breakup of *initially* similarly metamorphosed rock.

If zoisite were initially absent from the high-grade assemblage, as seems likely from textural relationships, the pressure of amphibolite metamorphism probably began at not more than 1 to 1.5 kb, based on the P_{fluid}-T petrogenetic grid of Liou et al. (1985). The temperature range of formation of the pargasitic hornblende assemblage was probably in the 450° to 500°C range. The succeeding, higher pressure metamorphism, however, probably occurred at lower temperatures. This is suggested by the prevalence of rutile, sphene, and hematite (as opposed to ilmenite and magnetite) in the mélange matrix, indicating a low-temperature metamorphism (Mielke and Schreyer, 1972) at high fO_2.

The varied metamorphic mineral assemblages of the metabasite clasts, indicating a range of metamorphic grade from prehnite-pumpellyite(?) to pumpellyite-actinolite, to greenschist and amphibolite facies, do not find counterparts in the consistently low grade, white mica-chlorite-bearing assemblage of regional extent in the mélange matrix. The structural disharmony that the polydeformed metabasite clasts exhibit against the regionally northeast-striking fabric of the enclosing mélange suggests that the blocks were metamorphosed and deformed to their present states before becoming incorporated in the matrix. Both they, as well as the metagabbro of intrusive origin at Indian Pond, are polymetamorphic. The common occurrence of anomalously pleochroic, blue and brown chlorites in the matrix, indicates that it also is polymetamorphic, as well as being polydeformed. The sequence of change in chlorite composition, however, cannot be discerned. Much of the metamorphism of the mélange matrix, like much of its polydeformation, probably postdates the high temperature phases of metamorphism recorded in the clasts, as judged from the contrasts in structure and fabric previously discussed. Although the relict, sheared, contact aureole in mélange matrix against metagabbro dates from the time of intrusion, it is unclear as to whether the matrix was previously metamorphosed to the approximate grade which it now exhibits, even though its sheared fabric was apparently healed and overprinted by the contact metamorphic event.

Acadian metamorphism of the Hurricane Mountain Formation, if present, is difficult to detect, much less, to prove. Low-temperature portions of thermal release steps in $^{40}Ar/^{39}Ar$ spectra of amphibolite and metagabbro, discussed in the follow-

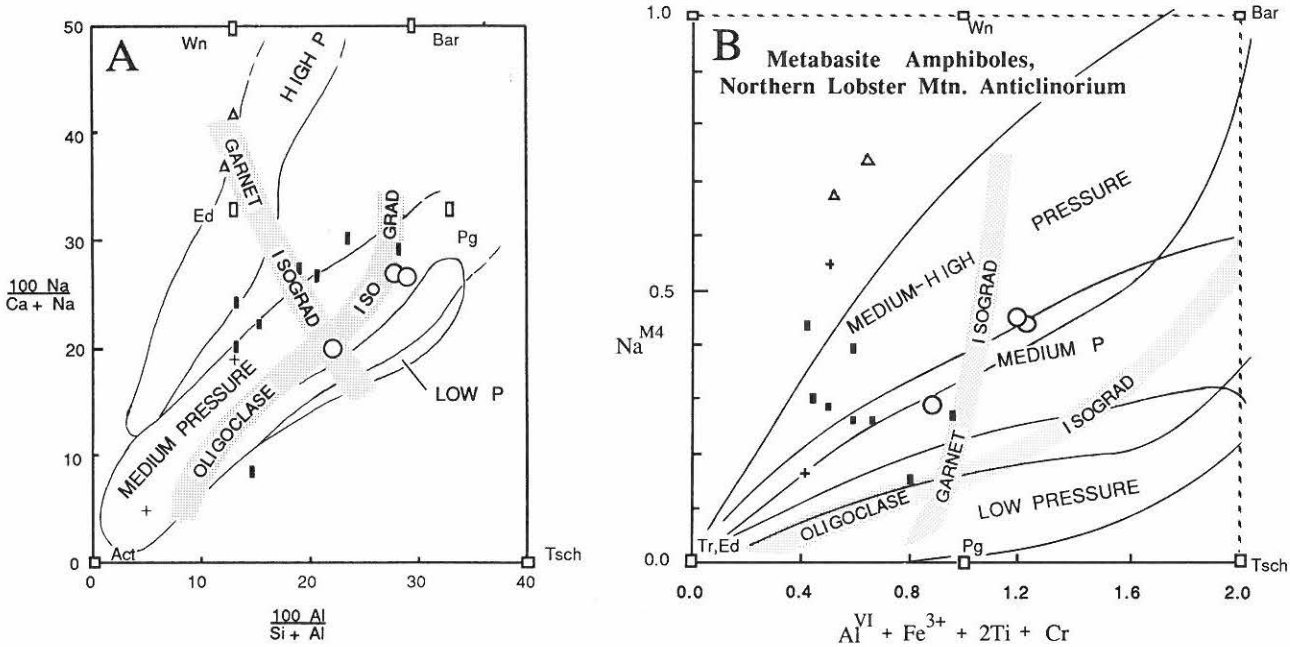


Figure 14. Compositions of calcic and sodic-calcic amphiboles in metabasite megaclasts and intrusive metagabbro of the Indian Pond area, Brassua Lake 15' quadrangle, plotted with reference to low-, medium-, and high-pressure paths of metamorphism (in (a), boundaries adapted from Laird and Albee, 1981b; in (b) from Laird et al., 1984). (a) Atomic proportions in percent; (b) formula proportions, dependent on normalization procedure (cf. Table 4). Garnet and oligoclase isograds refer, respectively, to amphibole compositions correlated with the garnet isograd in interlayered metapelites and metabasites, and with coexisting albite (above the band) and with An-contents ≥10 (below) in Vermont (Laird and Albee, 1981b; Laird et al., 1984). Circles: hornblendes in M-17 megaclast; triangles: edenitic winchite, Round Pond; black rectangles: sodic-calcic amphiboles, intrusive metagabbro ("Gabbro Point"; all localities shown in Fig. 4); crosses: very fine-grained edenitic ferroactinolite in Upper Ordovician contact metamorphosed Lobster Mountain volcanic rocks (Helsel and Boone, 1987) added for comparison.

ing section, may signify an Acadian overprint, at least for the metagabbro spectrum.

A possible explanation for the lack of a distinct Acadian metamorphic overprint in the mélange may be drawn from metamorphic characteristics observed in rocks of the Kennebec Formation and Lobster Mountain Volcanic Complex overlying the Hurricane Mountain Formation, for these do not show any evidence of polymetamorphism. Metabasalts of the Lobster Mountain Volcanic Complex show a lowest greenschist facies overprint on their volcanic textures and fabrics (Helsel and Boone, 1987). Volcanic mineralogies and textures are widely preserved in basaltic, andesitic, and rhyodacitic flows of this formation. Pelitic beds within the Lobster Mountain volcaniclcastic succession developed porphyroblastic cordierite where contact metamorphosed close to feeder dikes of the Middle to Late Ordovician volcanic succession. The cordierite is now largely pinitized and occurs as ellipsoidal spots flattened in the plane of a single slaty cleavage. The pinite pseudomorphs and the cleavage are interpreted to be of Acadian age. A regional Acadian metamorphism of chlorite - white mica grade would be essentially indistinguishable from an earlier metamorphic event, or events, associated with the formation and time of major deformation of the mélange.

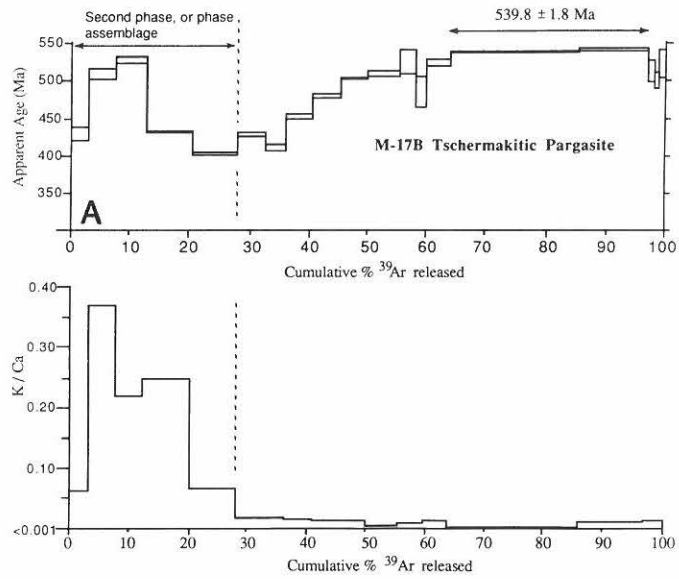
ISOTOPIC AGE OF AMPHIBOLITE MEGACLAST AND METAGABBRO, INDIAN POND AREA

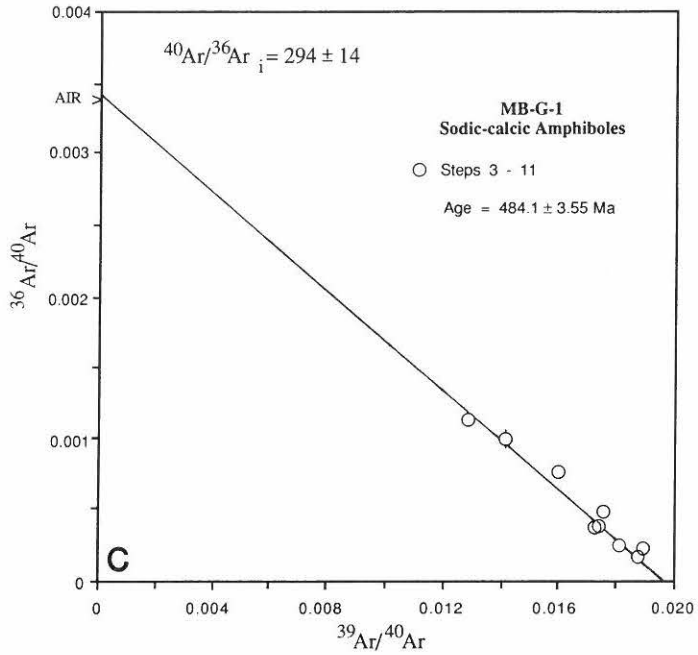
Description

The M-17 megaclasts, and metagabbro of "Gabbro Point" (Fig. 4) from which the dated samples come, are described in the preceding section. The analyzed sample of amphibolite is somewhat coarser grained than is typical. The texture and mineralogy of the metagabbro are typical of that exposed across the entire point.

Analytical Techniques

A high purity (~99.5%) pargasitic hornblende in sample M-17B was separated from clear and altered plagioclase, sphene, and minor epidote and chlorite; the calcic amphiboles of the metagabbro were separated to a similar degree of purity from a similar mineral assemblage, but with the addition of minor clinopyroxene, zoisite, and ilmenite. Standard heavy liquid and magnetic techniques were used, and then the separated amphiboles were sized between 150 and 250 μm. The samples were





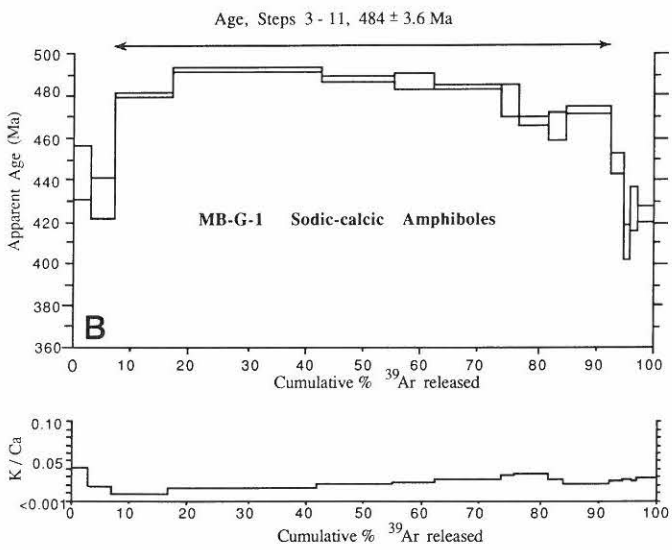


Figure 15. Stepwise argon release spectra for amphiboles of metabasites, Indian Pond area, Brassua Lake 15' quadrangle. (a) Pargasitic hornblende in megablock of amphibolite. Plateau age, based on ~ 35% of ^{39}Ar released, is 540 Ma. (b) Release spectrum of calcic amphiboles, of varied composition, in intrusive metagabbro. (c) Three-isotope plot of heating steps 3-11 (Table 5), metagabbro. Least squares regressed fit (York, 1969) of line to these steps yields a preliminary age of 484 ± 3.6 Ma (see text).

irradiated at the University of Michigan Ford reactor in the H-5 position. Neutron flux was monitored using Fe-mica, which has an age of 307.3 Ma. Correction factors for interfering reactions of Ca and K were determined by irradiation of K_2SO_4 and CaF_2. These salts revealed correction factors of: $(^{36}Ar/^{37}Ar)_{Ca}$ = 0.000222, $(^{39}Ar/^{37}Ar)_{Ca}$ = 0.000825, and $(^{40}Ar/^{39}Ar)$ = 0.033. Argon extraction was carried out in a double-vacuum tantalum furnace and temperature was monitored with a thermocouple placed within 2 mm of the sample. The system blank was 2 x 10^{-14} moles of ^{40}Ar at temperatures below 1300°C. Isotopic abundances of argon were measured on a Nuclide 4.5 - 60 RSS mass spectrometer. Age calculations and uncertainty estimates (± 1 σ) follow procedures described by Dalrymple et al. (1981).

Results

The ages and structural settings of the samples were first reported on by Boone and Heizler (1988). The $^{40}Ar/^{39}Ar$ release spectrum for the M-17B pargasitic hornblende is shown in Figure 15a, that for the amphiboles of the metagabbro, in Figures 15b and 15c; the data are compiled in Table 5. The relatively large analytical uncertainties are due to the low K_2O contents of the samples (~0.2 and 0.15-0.50 wt. %, respectively; cf. Table 4).

The spectrum for the hornblende of the amphibolite exotic block shows initial excess ^{40}Ar followed by an age gradient between ~ 20 to 65% of the total ^{39}Ar released. A plateau portion, defined by heating steps 1180°C and 1210°C, comprises approximately 35% of the total ^{39}Ar released and has a calculated mean age of 539.8 ± 1.8 Ma. The apparent age gradient is attributed to argon loss from a relatively non-retentive site or phase, superimposed with a phase which has not experienced argon loss since 540 Ma. The multiple phases are evidenced by varied K/Ca ratios (Fig. 15a, lower graph). The first 30% of argon released exhibits relatively high K/Ca ratios, followed by a more homogeneous portion of the release steps showing values

TABLE 5. K/Ar DATA FOR HORNBLENDE IN AMPHIBOLITE MEGACLAST, AND IN ACTINOLITIC AMPHIBOLE AND HORNBLENDE METAGABBRO, HURRICANE MOUNTAIN FORMATION MÉLANGE, INDIAN POND AREA, BRASSUA LAKE 15' QUADRANGLE

TEMP °C	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$ (E-3)	^{39}Ar (E-13 mol)	$\%^{39}Ar$ released	$^{40}Ar^*$ %	$^{40}Ar^*/^{39}Ar_K$	Age ± s.d. Ma
MB-17 B Amphibole (J = 0.005977; wt = 0.37598 g)								
650	88.36	8.200	149.7	0.318	3.15	50.2	44.94	429.2 ± 7.9
730	95.80	1.376	139.9	0.460	7.69	56.7	54.59	509.4 ± 6.9
800	71.56	2.381	50.57	0.491	12.5	78.8	56.85	527.7 ± 3.7
850	54.16	1.968	30.46	0.791	20.4	83.2	45.33	432.5 ± 1.5
900	53.11	7.342	40.44	0.771	28.0	78.0	41.86	402.9 ± 2.5
930	52.12	26.09	33.27	0.451	32.4	83.6	44.93	429.2 ± 3.1
950	61.73	29.48	74.21	0.374	36.1	67.0	42.75	410.5 ± 4.0
980	59.87	35.57	53.61	0.461	40.7	76.8	47.73	452.8 ± 3.1
1000	60.39	38.65	45.50	0.459	45.2	81.3	51.08	480.7 ± 3.3
1020	58.89	42.21	32.35	0.508	50.2	87.8	53.94	504.2 ± 1.2
1040	58.21	43.95	28.41	0.511	55.3	89.9	54.64	509.9 ± 3.1
1060	57.90	43.31	21.24	0.277	58.0	92.9	56.45	524.5 ± 16.0
1100	62.98	41.70	53.55	0.155	59.6	78.8	51.64	485.3 ± 20.2
1130	59.87	46.39	29.35	0.423	63.7	89.8	56.36	523.8 ± 4.6
1180	59.46	41.03	19.95	2.22	85.7	94.4	58.20	538.5 ± 0.8
1210	59.78	40.49	19.74	1.14	97.0	94.4	58.52	541.1 ± 1.9
1240	59.23	38.92	28.76	0.119	98.2	87.4	55.02	512.9 ± 13.7
1280	61.50	39.31	41.94	0.075	98.9	80.5	53.38	499.6 ± 10.3
1450	117.4	38.19	221.3	0.112	100	45.7	56.26	522.9 ± 18.3
MB-G-1 Hornblende (J = 0.006052; wt = 0.37500 g)								
750	147.8	11.46	348.2	0.259	3.00	30.5	46.02	443.3 ± 12.5
820	108.5	27.08	225.5	0.362	7.18	39.7	44.63	431.3 ± 9.8
870	74.99	43.03	98.74	0.818	16.6	64.3	50.39	480.2 ± 1.5
920	56.78	28.34	27.17	2.22	42.3	88.7	51.79	491.9 ± 1.0
940	54.35	23.26	18.76	1.10	55.0	91.8	51.28	487.6 ± 1.4
950	56.62	20.73	25.99	0.634	62.4	87.6	51.14	486.5 ± 3.8
970	52.58	17.57	12.24	0.997	73.9	94.4	50.82	483.8 ± 1.0
990	69.72	15.62	72.23	0.239	76.6	68.8	50.02	477.1 ± 7.8
1020	56.35	14.68	30.40	0.461	82.0	84.1	48.89	467.6 ± 1.9
1060	61.61	18.20	50.46	0.248	84.8	75.3	48.59	465.1 ± 6.5
1120	51.97	23.04	16.61	0.642	92.3	92.1	49.48	472.6 ± 2.1
1150	53.31	21.38	30.36	0.212	94.7	82.2	46.53	447.6 ± 4.8
1180	55.59	19.20	51.79	0.094	95.8	68.2	42.18	410.1 ± 8.6
1220	58.85	20.57	57.24	0.110	97.1	68.3	44.00	425.9 ± 10.4
1400	63.76	18.68	74.16	0.254	100	65.5	43.71	423.5 ± 3.8

typical of the analyzed hornblende (Table 4). The high K/Ca ratios may reflect K-rich domains such as rims of zoned crystals, exsolution phases, or inclusions. Harrison and FitzGerald (1986) have suggested that low ^{40}Ar retentivity in a metamorphic amphibole exhibiting varied K/Ca ratios may be due to exsolution structure within the host crystals.

The ambient, or regional metamorphic grade in the Indian Pond area precludes the heating of the M-17 hornblende to temperatures greater than 350-375°C since the time of its initial cooling. These temperatures would be insufficient to cause argon loss from a homogeneous hornblende phase (Harrison, 1981). The plateau portion therefore is thought to represent the minimum age, i.e., cooling below ~ 500°C, of amphibolite facies metamorphism of the body of rock from which the megaclast was derived. The complex release spectrum of the first 20% of ^{39}Ar released may result from K-rich inclusions or exsolution phases with different argon retentivities.

The 540 Ma plateau age thus places a *minimal* value on the maximum age of accumulation of the Hurricane Mountain Formation in this area. The numerical age corresponds approximately to a Middle Cambrian stratigraphic age (Snelling, 1985) if one assumes that the older of the permissible range of ages of the Cambrian-Precambrian boundary (~530 - ≥570 Ma) is the more accurate (Cowie and Johnson, 1985).

The spectrum for the metagabbro amphiboles shows a broader, but less definitive, "plateau" showing convex-upward curvature between ~ 8 to 78% of the total ^{39}Ar released (Fig. 15b). The spectrum is thus characterized by younger apparent ages for low- and high-temperature extractions, with older ages being indicated for intermediate steps. The K/Ca ratios are

variable over the entire spectrum. This variation is thought to result from a mixture, in this rock, of calcic amphiboles of different compositions (cf. previous descriptions and also Table 4), and therefore, perhaps of somewhat differing ages. The calculated age, regarded as preliminary, is 484±3.6 Ma, assuming an atmospheric component of trapped argon.

Figure 15c shows a three-isotope plot for incremental heating steps 3-11 (870-1120°C) comprising 85% of the total argon released, in which the regressed data are weighted in regard to the percentage of ^{39}Ar released (York, 1969). Plots of the data form a linear array which, when projected to zero on the $^{36}Ar/^{40}Ar$ axis, yields an apparent age of 484.1 ± 3.55 Ma from the inverse of the $^{39}Ar/^{40}Ar$ ratio on the x-axis. Similarly, extrapolation on the y-axis shows that the initial trapped argon composition, calculated as $^{40}Ar/^{36}Ar_i = 294 \pm 14$, is essentially equal to atmospheric, or 295.5. Thus the "plateau" age and the three-isotope array effectively yield the same result. The weighted sum of residuals, however, is greater than an acceptable value for an isochron (n-2) by a factor close to 4. The age of ~485 Ma is interpreted to represent a minimum age for the argon closure temperature of these amphiboles.

The 485 Ma age is roughly equatable to an Arenig stratigraphic age in the Lower Ordovician (Palmer, 1983; Ross et al., 1982; McKerrow et al., 1985; Gale, 1985). Ross (1984), however, would place this closer to the Llanvirn/Arenig boundary. This preliminary isotopic age is considered to place a minimum age on the accretionary tectonothermal events affecting the Hurricane Mountain Formation mélange in this area. The metagabbro contact with the matrix of the mélange, although sheared, is considered to have been initially intrusive, based on relict coarser texture of metapelitic lenses of mélange matrix within several centimeters of the contact that carry rare, probable relicts of andalusite and biotite (observed in thin section). Following its crystallization, the gabbro was retrograded in a polythermal, and possibly polybaric metamorphic event. If the maximum temperature of this event that began with the crystallization of pargasitic hornblende was greater than ~500°C, retention of radiogenic ^{40}Ar would have begun following cooling below that temperature; if the thermal maximum was below that value, then radiogenic ^{40}Ar retentivity would have commenced from the time of crystallization. Thus, for example, if any of the amphiboles in this metagabbro, such as the ferroactinolites, formed below the temperature of argon retentivity, as opposed to the higher-temperature, pargasite-richer hornblendes, they would have begun to accumulate ^{40}Ar from the time of their later, lower-temperature crystallization. A spectrum of geologic ages of 485 Ma and older, therefore, may lie concealed in the data presented here.

The bracketing ages are consistent with local and regional structural relationships of the Hurricane Mountain Formation and other formations unconformably overlying it, as discussed in foregoing sections. These isotopic ages are the first to place tentative brackets on the time of Penobscottian deformation and metamorphism.

EPILOGUE

Initial restudy of the Grand Pitch Formation in the Lunksoos anticlinorium shows that mélange is present there, and that similarities to the Hurricane Mountain mélange outweigh differences. Tectono-stratigraphic correlation with the Hurricane is a distinct probability, because the mélange is apparently infolded with formations resembling those in the Chesuncook dome with which the Hurricane Mountain mélange there is associated. It is also infolded with metavolcanic rocks resembling the Jim Pond Formation, as is the Hurricane Mountain Formation in the Lobster Mountain anticlinorium. There are other strata within the Grand Pitch Formation, however, which do not resemble those associated with the Hurricane Mountain Formation west-southwest of the Katahdin batholith, but which may prove to be correlatives of strata in the Miramichi anticlinorium. We may anticipate, therefore, that the terrane (Gander?) southeast of the suture zone may be identified in the Lunksoos anticlinorium, based on lithologic comparisons, on the age assignment of the *Oldhamia*-bearing portions of the Grand Pitch, and on the interpretation of the fore-arc geometry presented in this contribution and in Boone and Boudette (1989), as set forth in the introduction.

ACKNOWLEDGMENTS

I am most grateful to Walter A. Anderson, State Geologist, for his support, patience, and warm hospitality over many years of travel to and from the Maine Woods. I also wish to thank Michael E. Donnelly, Senior Geologist, Noranda Exploration, Incorporated, and Willy Lynch, then also of Noranda, for their interest, lively discussions, and cooperation in making available specimens of drill core taken in the Hurricane Mountain Formation. These yielded much new structural information scarcely attainable in weathered, surface material. I thank John S. Dickey, Jr., for his support while chairman of the Department of Geology, Syracuse University, in providing funds for some of the microprobe analyses; John Hunt, Cornell University, provided inspired assistance during the analytical sessions on the microprobe. Peter Jones, of the Department of Geology, Syracuse, made many superior thin sections of the mélange rocks; I also thank him for excellent preparation of photographs. I am also grateful to Syracuse University for the opportunity to participate in the 1984 Penrose Conference on mélanges of the Appalachians, convened in Newfoundland.

Discussions with other participants of that conference, and with Robert H. Moench, Eugene Boudette, Pierre St-Julien, Walter Trzcienski, Bradford A. Hall, Stephen Pollock, Peter Plumley, and Bryce Hand helped to clarify many of my hypotheses concerning the evolution of the Hurricane. I am also grateful to Robert B. Neuman for his critique of an early draft of the manuscript. Syracuse students who over the years have mapped with me in the Hurricane Mountain belt, or adjacent to

it, have contributed much to the store of knowledge about it; I am especially grateful thus, to Sandy Serra, Ken Frost, and Ruth Simmons Major. Without the collaborative, pioneering efforts of Dave Doty on the cores, the initial study of microstructures might not have been accomplished. I am grateful to Matthew Heizler, State University of New York at Albany, for his collaborative work in separating and analyzing the amphiboles.

The manuscript has benefited from the thoughtful and detailed reviews of Philip Osberg, Stephen Pollock, and Jim Hibbard. Their comments and suggestions are much appreciated. I am especially grateful to Phil for prodding me toward a more rigorous analysis of the ages of foliations. If there are remaining shortfalls, they are mine. I also thank the editors of these volumes, Robert Marvinney and Robert Tucker, for their suggestions and help. Andrew MacL. Boone assisted during the '75, '77 and '78 field seasons. For many years of support while the mapping and the ideas for this paper took shape, Susanne MacL. Boone is deeply thanked.

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APPENDIX I. PETROGRAPHIC DESCRIPTION OF CARBONACEOUS, FELDSPATHIC QUARTZITE BLOCKS IN HURRICANE MOUNTAIN FORMATION.

Quartz is preserved as well rounded, large grains in tabular portions of the rock (roughly parallel to bedding) that were unaffected by flattening and cataclasis. Wavy, lens-like bands of domainal extinction are prominent in some grains. About 1.5% of the undeformed, large grains are coarsely rutilated, reminiscent of pegmatitic quartz. Sparse grains show inclusions of stubby prisms of rutile, zircon(?), and tourmaline. Stained thin sections reveal that the feldspar is almost exclusively plagioclase. It, like the quartz grains, occurs in bimodal size distribution: large clasts surrounded by distinctly finer grains in the matrix. Sparse grains are well rounded, but most are angular and show ragged edges. Extinction-angle measurements across albite twins indicate most grains in both size distributions are in the oligoclase range of composition. Patchy areas within large grains are replaced by albite. Many of the larger grains show a checkerboard domainal structure. At least half of the larger grains show a crudely zonal clouding by nearly opaque rods and filaments, roughly 5 to 10 μm thick, and aligned approximately 75° to the basal cleavage. Their abundance decreases noticeably near the margins. The inclusions are deep brown or brownish red, and are isotropic. In polished section, they are scarcely distinguishable from host feldspar in reflected light. These characteristics resemble aluminous spinel commonly seen as inclusions in plagioclase of anorthosites and mafic layered intrusions (Whitney, 1972), and in which a zonal distribution is also common. The gradation toward the rims commonly is concentric to the angular, often highly irregular grain margins. Since there is no detectable zoning of plagioclase composition toward the rims or apparent overgrowths of new plagioclase, a selective replacement of inclusions, postdating the time of clast formation, is suggested. A post-lithification, or metamorphic age of removal of these inclusions from grain margins is likely. Modal analysis gives the following:

Quartz	59 volume percent
Plagioclase	14
Carbonaceous material (graphite?)	18
Chlorite	8
White mica	0.5
Pyrite & pyrrhotite	0.5

APPENDIX II. DESCRIPTION OF THE TYPE SECTION AND REFERENCE SECTION OF THE HURRICANE MOUNTAIN FORMATION

TYPE SECTION

Typical outcrops of the Hurricane Mountain Formation are found on the upper slopes of Hurricane Mountain, located in the northern part of the south central ninth of the Pierce Pond, Maine, 15' quadrangle (Fig. 1). The mountain, approximately 1300 feet in relief, is elongated parallel to local strike and forms the south valley wall of the Dead River in this part of the quadrangle. It and neighboring mountains owe their topography to erosionally more resistant hornfelses that formed by contact metamorphism of the Hurricane Mountain and Dead River Formations around the northern margin of the Pierce Pond gabbroic intrusion, of Lower Devonian age (Boone, 1973; Lyttle, 1976; Boone and Gaudette, in prep.).

The type section is bounded by outcrop belts of the overlying Dead River Formation (Boone, 1973) on the southeast flank of the mountain and, to the northwest, along the axis of the Dead River (Boone, 1985). The Hurricane Mountain Formation here forms the core of an F_2 anticline that trends east-northeast and is transected by three steeply dipping transverse faults. The southwest boundary is defined by one of the transverse faults, located at the southwest end of Hurricane Mountain. The northeast boundary is defined by the transverse fault approximately 1.6 km (1 mi) east-northeast of the summit of Hurricane Mountain. The strike length of the type section is 3.3 km (2.05 mi). A narrow belt of overlying Dead River Formation defines the trough zone of an adjacent syncline to the northwest, and the Hurricane Mountain/Dead River contact here, on the northwest slope of Hurricane Mountain, is taken as the northwest boundary. The width is thus approximately 2 km (1 to 1.3 mi). The Hurricane Mountain Formation and other pre-Silurian units within this part of the Lobster Mountain anticlinorium were previously designated as unnamed, undivided units of probable Cambrian and Ordovician age (Hussey, 1967).

UNIT DESCRIPTION

In the area of the type section, the Hurricane Mountain Formation is composed of metasiltstone and subordinate metapelite, as observed along the upper part of the northwest slope, and close to the summit ridge of Hurricane Mountain. Locally, light gray, thickly bedded quartzite interrupts the uniformity of metasiltstone and metapelite, as for example, in outcrops extending 15 to 20 m perpendicular to strike on the southwest end of the summit ridge (Boone, 1985). The quartzite here and in other localities occurs as exotic clasts within the matrix of metasiltstone. Elsewhere in this area, clasts are either too small to be shown at conventional map scales, or are absent.

The Hurricane Mountain Formation is distinguishable from other arenaceous and pelitic formations on the basis of microstructure and diamictic tectono-stratigraphic zones. Its predominant lithology consists typically of interlamination of metasiltstone and subordinate slate and phyllite, variously sulfidic to non-sulfidic, and of varied, but generally low, graphitic content. The laminations, with subordinate thicker layers and lenses, display flaser-like pseudobedding produced by closely spaced, pervasive shear-surfaces which truncate depositional layering at shallow angles. In most outcrops, the unit is also marked by thoroughly penetrative, anastomosing, hackly fracture cleavage surfaces. Small (millimeter- to centimeter-length) lenses and phacoidal clasts of felsic, fine-grained metatuff are volumetrically subordinate, but are observed in most outcrops and are regionally of widespread occurrence. Larger lenses and layers of metatuff are extremely sparse. Combination of these features produces a lenticular appearance in which the pseudobedding generally cannot be traced with continuity for more than a meter or two. Layering is made visible by color variegation ranging from light to dark shades of gray, brown, and green, in which small-scale, light buff to white felsic lenses are interspersed. Weathering produces a varied degree of limonitic staining. These lithologies, in varied proportions, also form the *matrix* of olistostromal and tectonic clast-bearing parts of the formation.

Sparse zones of thick lenses and beds of light gray weathering, pale greenish gray quartzose wacke are encountered generally toward the structurally lower part of the formation. Commonly, this rock type is preserved as olistoliths and tectonic clasts. Clasts form an important aspect of the formation and are described in the main body of the text in further detail than previously (Boone and Boudette, 1989). They are not, however, prominent on Hurricane Mountain other than the quartzite cited in the previous paragraph.

The name and the type area were selected informally[1] during the early stages of mapping in the Lobster Mountain anticlinorium. Although clasts had been observed early in the mapping of the unit, the name became fixed in regional parlance before further mapping to the north, and also to the northeast in the Brassua Lake quadrangle, revealed spectacular occurrences of map-scale clasts of varied lithology in the formation (cf. foregoing text; also Frost and Boone, 1978; Boone, 1983). The "lithologic constant" of the formation is its matrix, however, and therefore the type area, and the name, are retained as being stratigraphically suitable.

INDIAN POND REFERENCE SECTION

A variety of metasedimentary and metaigneous (metabasite) clasts, many that are mappable at inch to the mile scale (Fig. 4), crop out on islands in the northwest cove of Indian Pond and in surrounding forested lowlands in a radius

[1]Name placed on file with Geologic Names Committee, U.S. Geological Survey, in 1971.

of 3 to 4 km to the west and north, in the Brassua Lake 15' quadrangle. The formation here is also host to sills and dikes of metadolerite and metagabbro. Clast dimensions range in length from 1.4 km (0.75 mi) to those that are mesoscopic and microscopic. Locations and lithologies of the larger, mapped clasts are detailed in Figure 4, and are described at length in the foregoing text.

THICKNESS

The Hurricane Mountain Formation is approximately 1200 m thick. This is a minimum estimate, measured on nearly continuous exposures across a demonstrably homoclinal section on the SE limb of the same F_2 anticline, 2 km southwestward on Basin Mountain. This is a structural thickness because depositional units may have been repeated by thrusting (duplexing) at various scales and also because of the documentation in the foregoing text that layers have undergone attenuation by extensional shear at shallow angles to layering during the Penobscottian orogeny, with perhaps further tectonic thinning during the Acadian. Despite foliation attitudes that are close to vertical, most map widths are greater than this minimum thickness estimate owing to drag, or parasitic folds related to the F_2 (mainly Acadian) folds.

In regard to regional thickness, the geometry of the formation probably was never tabular. If the interpretation is correct that the formation was accreted above a subduction zone, it may have been thinly wedge-shaped, by analogy with the geometries of modern accretionary complexes. Its thickness may have increased to the southeast in the direction of inferred polarity of subduction, but this remains speculative because it is covered by younger formations in that direction.

LOWER CONTACT

The structural relationship of the Hurricane Mountain Formation to the underlying, less deformed, volcanogenic Jim Pond Formation of Cambrian age is tectonic. In the type area, and probably throughout the Pierce Pond 15' quadrangle, it is interpreted to be a thrust or reverse fault. In the southwest part of the Lobster Mountain anticlinorium, in the Kennebago Lake quadrangle, the contact zone is expressed by olistoliths of Jim Pond wacke, quartzite, and volcanogenic rocks in a wacke matrix that becomes increasingly fine grained and quartz-rich structurally upward into the Hurricane Mountain Formation (Boone and Boudette, 1989). The base of the Hurricane Mountain Formation in the type area, as well as throughout the Lobster Mountain anticlinorium, is defined by matrix that is predominantly metasiltstone, commonly rusty, owing to disseminated pyrite and pyrrhotite. In the Spencer Lake quadrangle, and elsewhere northeastward along strike, a sharp structural discontinuity separates the Hurricane Mountain Formation from felsic volcanics, or from graded beds of wacke and volcanogenic, bedded pseudochert and lenses of ferromanganese oxide of the upper part (estimated to be the upper one-third) of the Jim Pond Formation (Serra, 1973). In the Pierce Pond quadrangle, the Hurricane Mountain Formation is in tectonic contact with the underlying Jim Pond Formation, based on extreme contrast in penetrative deformation which is best observed along the east valley wall of Enchanted Stream in the central ninth of the Pierce Pond quadrangle (Fig. 1), about 2 km (1.3 mi) upstream from the confluence with the Dead River (Boone, 1985).

At Enchanted Stream, volcanogenic wacke, mafic metatuff, and slate are exposed on the southeast limb of an asymmetrical, upright anticline, in which minor folds are moderately tight and inclined, and show an early S_1 axial planar cleavage. These exposures are separated from the structurally lowermost exposures of highly sheared Hurricane Mountain Formation to the southeast by a 5 m wide zone lacking bedrock exposure.

The age of the presumed fault-juxtaposition here is unknown. It is inferred to have occurred early in the tectonic history of the two units, as discussed in the main body of the paper, reflecting the same event which (1) triggered the olistostromal deposition of Jim Pond Formation debris into the Hurricane Mountain Formation, as noted previously, and (2) caused the deposition of thick, massive quartzwacke deposits structurally below demonstrable Hurricane matrix in The Forks and southwestern part of the Brassua Lake quadrangles. These observations collectively suggest that the initial fault motion which was responsible for the juxtaposition of the two formations was normal and created a submarine scarp along which Jim Pond material was fragmented and then transported into proto-Hurricane fine-grained sediment. This implies localized extension or transtension near the upper surface of the growing accretionary prism. The relations described in the contact zone on Enchanted Stream suggest juxtaposition by thrusting, possibly utilizing the same fault surface or zone. Pollock (1985, 1989) and Hall (1970, and pers. commun., 1984) also have mapped fault contacts between volcanics and mélange, which are considered to be correlative with the Jim Pond and Hurricane Mountain Formations, in the Caucomgomoc inlier and Munsungun anticlinorium, respectively.

UPPER CONTACT

Regionally, all three pre-Middle Ordovician formations, the Jim Pond, the Hurricane Mountain, and the Dead River, are unconformably overlain by the Kennebec Formation and the Lobster Mountain Volcanic Complex, the ages of which range from Middle to Upper Ordovician. At most localities where the Hurricane Mountain Formation can be seen in contact with the directly overlying Dead River Formation, the contact is disconformable or mildly unconformable, as shown by abrupt change in composition, color, and microstructure. At a few localities in the Pierce Pond and Spencer Lake quadrangles, this contact is apparently gradational, as viewed in stream and woods exposures of small lateral extent. The gradation is expressed by loss of the flaser structure of pseudobedding, loss of the predominantly silty protolith, increase of parallel bedding, with or without grading, and increase in green wacke and slate, upward into the Dead River Formation. The localities are as follows: in road-side exposures along a lumbering access road on the hill slope south of Poplar Hill Falls, near the east edge of the Pierce Pond quadrangle; on Enchanted Stream, approximately 1.3 km (0.8 mi) north of its confluence with the Dead River (and about 0.8 km, or 0.5 mi, south of the lower contact described in the previous section; see Boone, 1985); and on Otter Pond Mountain and Black Nubble in the southeast ninth of the quadrangle (Lyttle, 1976). At each of these localities, the gradation spans a thickness of approximately a meter, just beneath the well bedded volcanogenic flysch of the overlying Dead River Formation of Late Cambrian to Early Ordovician age (Boone, 1973). Serra (1973) described the contact as gradational by means of interbedded alternation of lithologies across a thickness two orders of magnitude greater than bedding thickness in exposures that are ~13 km (8 mi) west of the type area, in the Spencer Lake 15' quadrangle. An alternative explanation is that this may be an expression of structural repetition across tight, minor folds in the contact zone. The upper contact is not well exposed on Hurricane Mountain.

AGE

The age of the Hurricane Mountain Formation probably ranges from Middle Cambrian to Early Ordovician (Tremodocian?). Depositional age estimates of the metasiltstone/metapelite 'matrix' are based upon meager paleontological evidence. The age of exotic blocks of metabasites is based upon preliminary isotopic dating. Structural relationships with formations which bound its lower and upper contacts are interpreted to bracket the age of the mélange-forming events. Fossils collected by Harwood (1973) in the Cupsuptic quadrangle were described by Robert M. Finks, Jr. as *Protospongia* sp. or *Diagoniella* sp. These sponges are elsewhere associated with brachiopod faunas ranging in age from Middle Cambrian to Early Ordovician (Robert M. Finks, Jr., pers. commun., 1986). Inasmuch as exotic blocks of Jim Pond Formation are incorporated within the basal Hurricane, the Hurricane Mountain Formation matrix must, for the most part, be syndepositional with, or postdate the Jim Pond Formation. Evidence of the Cambrian age of the Jim Pond Formation is summarized at length elsewhere (Boone and Boudette, 1989). Recent reassessment (J. N. Aleinikoff, pers. commun., *in* Boone and Boudette, 1989) of zircon U-Pb isotopic data (Aleinikoff and Moench, 1985) suggests that felsic volcanic rocks of the upper part of the Jim Pond Formation yield apparent ages of 520 - 542 Ma. The lower part of the Hurricane Mountain Formation is interpreted to be about the same age. A similar apparent age, 540 Ma, has been determined for an exotic megaclast of high-rank amphibolite in the Hurricane Mountain Forma-

tion in the Brassua Lake quadrangle (cf. foregoing text). Metagabbro intrusives into the Hurricane Mountain Formation in the same area, yielded an apparent age of ~485 Ma (Tremadoc to early Arenig). The isotopic ages and their implications are discussed in detail in the main body of this paper.

Locally, in the Brassua Lake quadrangle, the Hurricane Mountain Formation is unconformably overlain by openly folded felsic volcanic rocks of the Kennebec Formation of early to middle, Middle Ordovician age (Boucot and Heath, 1969), (Llandeilo to earliest Caradoc age; cf. discussion in main body of text). Feeder dikes of the Kennebec volcanic rocks intrude the Hurricane Mountain Formation in that area. Structural details across contacts of Kennebec Formation feeder dikes with the polydeformed Hurricane Mountain Formation are discussed under the heading *Tectonic History* in the main body of this paper. In the Chesuncook dome, the Jim Pond Formation is not exposed, but the Hurricane Mountain, the Dead River, and overlying pre-Silurian (probably pre-Middle Ordovician) formations are intruded by the Bean Brook gabbro, for which Faul et al. (1963) reported a K/Ar apparent age of 464 Ma. Satellitic sills and dikes of the Bean Brook gabbro also truncate polydeformational structures within the host stratigraphic units.

REGIONAL EXTENT

The unit has been traced from the vicinity of the Maine - New Hampshire border (Osberg et al., 1985; Boudette et al., in press) to the pre-Silurian core rocks of the Chesuncook dome, approximately 100 mi (~160 km) to the northeast. Possible correlatives include the undated Hurd Mountain and Avery Brook Formations of inferred Cambrian or Ordovician age (Pollock, 1985), in the Caucomgomoc inlier, mélange of the Chase Brook Formation (Hall, 1970) of Arenig age (J. E. Repetski, *in* Neuman, 1984) in the Munsungun anticlinorium, unnamed mélange unconformably underlying the Shin Brook Formation of Mid- to Late Arenig age (Neuman, 1984) in the Lunksoos[2] anticlinorium, and the Devereaux Formation of the Fournier Group, Elmtree inlier, northeastern New Brunswick (Fyffe and Noble, 1985). If the mélanges of the Hurricane Mountain and Chase Brook Formations are (or were) physically part of the same accretionary complex, at least some degree of diachroneity, or duration of accretionary processes, would be established.

[2]Name shortened in Boone and Boudette (1989).

APPENDIX III. COMMENTS ON LITHOLOGY OF CORE SAMPLES.

5B - 85 - 2 Drill Core

ft

17 Thinly layered to laminated, pyrite-bearing, gray metasiltstone, minor pyrite-carbonate rock, and dark gray phyllite, showing well developed flaser structure, layer-parallel cleavage, and phacoidal microclasts of graphitic metasiltstone. Layering (S_1 and S_2) open to tightly folded by S_{3a}, with a transposed shallowly dipping, axial surface cleavage. Tight, isoclinal, early (F_1?) microfolds are complexly refolded and sheared.

36 to 62 Dark gray, phyllitic matrix-supported, polymictic granule metaconglomerate (debris flow?), showing rounded and flattened clasts of light to dark gray metasiltstone, graphite-rich phyllite, phyllitic granule-conglomerate, and sheared, relict microporphyritic metavolcanic (?) rock, all clasts ranging from fractions of a mm to 3 cm in length (Fig. 5e). Bedding laminations, S_1 foliation, and wispy pyritic lenses show convolute, open folds. Some of the lenses comprising the flaser-structure in the matrix show truncated tight to isoclinal microfolds.

80 Light and dark gray metasiltstone, black phyllite, and fine-grained pyrite - quartz lenses, collectively showing small-scale flaser ("tiger stripe") microstructure.

85 Thinly bedded to laminated, graphite-free and graphitic phyllite. Microboudinaged, prehnite-chlorite-quartz veins. Sheared isoclines within flaser-shaped microlithons.

94 Strongly crenulated dark gray phyllite with interlayered, ptygmatically folded, cherty laminite.

105 Strongly sheared, phacoidally cleaved phyllite. Deformed quartz veins cutting quasi-brittly folded, quartz-pumpellyite veins.

121 Isoclinally shear-folded, light to dark gray, slate and metasiltstone. Ptygmatically folded, quartz-filled extension fractures.

197 Cherty laminite and gray phyllite, showing openly folded foliation parallel to laminations. Extensional shears in cherty laminite.

201 Interlaminated gray, hackly cleaved, phyllitic metasiltstone and dark gray phyllite, showing flaser structure and polymict, meso- and microphacoids of depositional and tectonic clasts of fine-grained metasiltstone, black slate, and carbonate bearing metasiltstone. Laminations within the clasts and matrix show same generation (F_2 or F_3) of crenulation microfolds (Fig. 6d).

234 Strongly sheared phyllite and black slate showing small-scale flaser-shaped laminations. Rounded, disk-shaped lenses of polygranular, subhedral pyrite + quartz, some mantled by polygranular, fine-grained carbonate rims (Fig. 3a). Quartz of the lenses commonly shows beard structure at high angles to lens surfaces.

237 Hackly cleaved, pyritic phyllite showing small-scale flaser structure. Lenses and folded, cross-cutting veins of pyrite, carbonate, and chlorite.

295 Cf. description of 201' core sample.

318 Cf. description of 121' core sample, but without isoclines. Grades into thin to medium, graded bedded, gray, quartz-rich phyllite and black phyllite (Fig. 2c). Flaser-shaped laminations within gray to black phyllite.

321 Strongly shear-folded, thin- to medium-bedded, light gray metasiltstone and dark gray phyllite. Transposed S_1 forms axial planar "slip" cleavage (S_2).

344 & 380 Light and dark gray metasiltstone, black phyllite, and fine-grained pyrite lenses, all collectively showing small-scale flaser ("tiger stripe") structure. Rounded, flattened disk-shaped clasts of metasiltstone and metatuff localized in thin structural zones (Fig. 2f).

381 & 418 Cf. lithology of 318' and 121' samples; in addition, relict graded, thin to medium beds.

WCS- 1 Drill Core

28 Gray slate; S_1 modified by widely spaced fracture cleavage (S_3?).

40 Black slate; S_1 modified by widely spaced fracture cleavage (S_3?).

56 Dark gray phyllite, S_1 sheared at shallow angles by S_2; in sharp contact with quartzite containing web-like, anastomosing cataclastic shears.

68 Highly sheared, quartz-pyrite veined, tectonic breccia with tectonic inclusion of metasiltstone and phyllite showing flaser structure and swirled, broken ("churned") microclasts of light gray metasiltstone.

82 Graphitic phyllite, S_1 sheared at low angles to form flaser-shaped lithons, and locally transposed along crenulation-limbs (both forming, in sum, S_2). Small-scale discordant igneous contact with meta - quartz porphyry that shows a single, slightly wavy, rough cleavage (a feeder dike to Kennebec Formation felsic metavolcanic rocks?) (Fig. 6f)

88 Graphitic black slate, S_1 cut at shallow angles by S_2 shear surfaces that are lined by chlorite + graphite.

90 Brittle to quasi-brittle deformation of black and gray metasiltstone and phyllite, showing well developed flaser structure. Small isoclines within lenses show sheared out limbs. Quartz veins in cross-cutting veins show highly strained fabrics and microbrecciation. Spaced cleavage (S_2) formed by localized transposition of S_1 along low-angle shears.

125 Strongly sheared, sericite-chlorite-oxide-bearing, fine-grained andesitic (?) metatuff, in ductile-fault contact with mylonitized, siliceous semi-pelite and sheared phyllite (beyond 2 cm from the contact, host rock is similar to core sample 130').

130 Finely laminated, graphitic and non-graphitic sericitic phyllite interlayered with thicker laminae and lenses of sericite phyllite (derived from felsic ash ?). S_2 shears transect an earlier flaser structure ($S_0 + S_1$) in the dark gray phyllite, which locally shows complex microfolds cut by an axial planar, spaced transposition-cleavage parallel to the predominant S_2 shears. Well developed c and s fabric in thick lenses of sericite phyllite.

143 Light and dark gray metasiltstone, black phyllite, and fine-grained pyrite lenses, all collectively showing small-scale flaser ("tiger stripe") structure. Rounded, flattened disk-shaped metasiltstone clasts confined to ~8 cm-thick structural horizon.

208 Isoclinally shear-folded, light to dark gray, slate and metasiltstone. Ptygmatically folded, quartz-filled extension fractures. Small-scale isoclines are absent. Grades into thin to medium, graded bedded, gray, quartz-rich phyllite and black phyllite. Flaser-shaped laminations within gray to black phyllite.

216 to 230 Similar to description of 208' core sample.

234 Strongly sheared black phyllite, with thin pyrite lens intersecting in S_1 and S_2 to form thickened crest and troughs, giving the composite lenses a barbed, wispy profile.

250 Strongly shear-folded, thin- to medium-bedded, light gray metasiltstone and dark gray phyllite. Transposed S_1 forms axial planar "slip" cleavage (S_2).

272 Roughly cleaved, metavolcanic rock. Anastomosing stilpnomelane folia diverge around angular to sheared, titanomagnetite pseudomorphs, and augen and lenses of fine-grained feldspar which is variously altered to very fine-grained micaceous and chloritic pseudomorphs (this sheared metavolcanic rock is interpreted to be from a feeder dike to the Kennebec or Lobster Mountain volcanic rocks). This rock is in sheared, mylonitic contact with graphitic metasiltstone in which phyllitic cleavage is cut at very shallow angles by S_1 main shears and, variably at steeper angles, by spaced S_2 subsidiary shears that merge sigmoidally into cleavage and S_1 shear surfaces. The metasiltstone and its structure is typical of, and is assigned to the Hurricane Mountain Formation.

290 Polymict debris flow (cf. description of samples 5B - 36 to 42) in sheared contact with quasi-brittly deformed, sedimentary breccia of light gray micaceous metasiltstone and dark gray mudstone.

302 Swirled, complexly sheared and brecciated ("churned") microfolds and small-scale flaser-shaped lenses of black phyllite and light gray to white metasiltstone.

323 Very similar to the two fault-bounded lithologies of core sample 272'.

326 Polymict, clast-supported breccia, with incipiently cleaved, very fine-grained matrix. Clasts are angular to rounded, felsic to intermediate, altered porphyritic volcanic rocks, metasandstone, and metasiltstone. This rock is interpreted to have originated from release of over-pressured volatiles, and may belong to a diatreme structure (of Ordovician [Kennebec or Lobster Mountain] or younger age). It is in sharply discordant contact with sheared, laminated, dark gray metasiltstone that is assigned to the Hurricane Mountain Formation.

337 Microfaulted and sheared, cherty laminite of Hurricane Mountain Formation, in contact with altered, unfoliated, carbonate-metasomatized, coarse-grained, quartz-altered plagioclase rock that is probably of Late Ordovician or younger age.

351 Black phyllite, brecciate and veined with quartz and pyrite, otherwise similar to core sample 234'.

372 Gray to light gray, flaser-laminated and microfaulted phyllite and subordinated metasiltstone. Lenses of fine-grained pyrite are mantled by calcite. Web-like networks of very thin, cross-cutting, monomineralic veins of quartz, calcite, and pyrite.

409 Interlaminated, chlorite-rich, and sericite-rich phyllite showing very small-scale flaser structure. Medium grained, Fe-rich chlorite-quartz-pyrite segregations along some of the main shears. Lath-shaped porphyroclasts of relict volcanic plagioclase in shear-band marking contact of Hurricane Mountain Formation with altered, medium-grained, metagabbro sill that intersects 6.7 m (~22ft) of core. Metagabbro is of probable Lobster Mountain Volcanic Complex affinity, based on textural similarity of relict plagioclase and titanomagnetite, localized, incipient, protoclastic deformation, and lack of foliation.

437 to 453 Thick flaser lenses of black, pyritic phyllite and pale gray to yellowish, greenish-gray, carbonate-bearing, sericitic phyllite (metatuff?). Small-scale flaser-lenses within the 1 to 2 cm-thick, host lenses. Core sample 437' is phyllonitized, relict hornfels from within contact metamorphic margin of metagabbro sill (cf. 409'), and contains abundant, flattened ovoids of cordierite pseudomorphs.

480 Phacoidally and roughly cleaved, pale yellowish green, Fe-rich chlorite-epidote-calcite-brookite-quartz phyllite. Main shear foliation and subsidiary shears outlined by Ti-oxide concentrations. Quartz grains in some of the cross-cutting quartz-carbonate veins show pronounced high-strain fabrics (very fine-grained mosaic (polygonal) texture, and coarser-grained, banded structure parallel to main shears in host phyllite.

503 to 530 Gray to dark gray, finely laminated, sericite-rich, and quartz-sericite phyllite showing phacoidal cleavage and flaser lenses and laminations. Rare S_1 fold-hooks preserved within lenses (Fig. 6a). Very fine-grained cherty lenses show well developed, graphite-filled sigmoidal shear-bands. Single and multiple fold-hooks of pyrite concentrated at intersections of shear-surfaces (Fig. 6b). This assemblage in sheared contact with flaser-laminated, Fe-chlorite-epidote-carbonate Ti-oxide phyllite containing epidote-rich pseudomorphs of blocky plagioclase (relict, plagioclase-phyric, mafic tuff).

538 Similar to core samples in the interval 503' to 530', but in addition, shows sheared lenses of fine-grained, sericite-rich, metatuff.

541 Quartz-rich and quartz-poor phyllite, showing well developed, main and subsidiary shears (S_2), with S_1 mainly at shallow angles to, and tangential to subsidiary (thrust) shears. Phacoids of polygranular quartz are larger (1-3 mm thick) in quartzose phyllite than in sericite-rich phyllite. Poorly cleaved, plagioclase-phyric, meta-andesite with Ti-oxide-sphene pseudomorphs of relict, skeletal titanomagnetite (assigned to Lobster Mountain Volcanic Complex) in strongly sheared contact with Hurricane Mountain Formation mélange.

544 Meta-andesite: ~An_{20}-richterite(?)-chlorite-sphene-minor quartz, with zoisite bands outlining foliation. Interpreted as a feeder dike of Late Ordovician Lobster Mountain Volcanic Complex.

588 Interbedded light gray metasiltstone and dark gray phyllite. Metasiltstone layers show pull-apart structure along medium- to low-angle extensional shears. Wispy relict flame structure and channelling. Phyllite and metasiltstone both show locally well developed flaser laminations bounded by low-angle shears.

624 Similar to core sample 503'.

637 Extensively sheared, sericite-rich, brookite-magnetite-bearing, felsic metatuff in sheared contact with black, gray, and light gray metasiltstone showing openly folded flaser structure. Tightly chevron-folded locally. Phacoidal cleavage locally well developed.

656 to 678 Similar to core samples 480' and felsic portions of 637'. The felsic samples 637' and 656' are from the margins of a 5.5 m-wide dike that is believed to be broadly contemporaneous with the Hurricane Mountain Formation accretionary structural events.

703 Metasiltstone and phyllite showing fine-scale laminations and S_1 cleavage cut by S_2 main and subsidiary shears to form flaser lenses and phacoidally shaped, tectonic clasts. Very thin, wispy pyrite lenses along some of the shear surfaces.

704 Thin to medium graded beds of metasiltstone and slate showing poorly developed S_2 main and subsidiary shears. Amoeboid pyrite lenses on cleavage and shear surfaces.

713 Sub-millimeter- to centimeter-thick flaser lenses of light and dark gray metasiltstone and gray phyllite, forming a typical "tiger-stripe" appearance. Spidery arrays of microscopic, cataclastic shears in dark gray metasiltstone.

726 Polymict, matrix-supported, tuffisite meta-breccia (assigned to Lobster Mountain Volcanic Complex) in mylonitic, sheared contact with tiger-striped metasiltstone and phyllite similar to core sample 713'. Breccia consists of clasts of angular to rounded, 1 mm- to 3 cm-long clasts of relict, plagioclase-phyric metabasalt and multiply cleaved and sheared, quartz-rich and quartz-poor phyllite (Hurricane Mountain Formation mélange), showing long dimensions and foliations at random angles to a single, rough cleavage of the volcaniclastic matrix.

729 Thick flaser lenses of light gray, sericite-rich phyllite and dark greenish gray, thoroughly sheared, chlorite-brookite sericitic greenschist. Two-cm-wide fault zone marked by microbreccia and disharmonically folded flaser lenses, within which chevron microfolds pass into a transposed foliation along their axial surfaces, roughly parallel to the fault zone.

730 Thin flaser laminae and lenses of sericitic phyllite, Ti-oxide-chlorite-sericite phyllite, and multiply cleaved, metadacitic(?) phyllite showing equant, angular, quartz and plagioclase porphyroclasts. Varied concentrations of wispy plagioclase porphyroclasts. Varied concentrations of wispy pyrite veins, and quartz-pyrite segregations. Pronounced c and s fabric (S_2) developed in thin structural zones; in others, lenses and laminae are moderately to tightly isoclinally folded, with axial surfaces (S_{3b}?) oppositely inclined (and out of sequence?) to the transposed foliation in c-surfaces. Some flaser lenses show black phyllite and gray metasiltstone laminae tightly chevron-folded, forming a transposed foliation (S_{3a}?) parallel to main shears that bound the lenses. Neighboring structural zones show well preserved, extensional shears outlined by graphite.

732 to 734 Disharmonic, openly folded, flaser lenses and laminae of gray metasiltstone and phyllite. Concordant, centimeter-thick, quartzite lenses showing irregular, pinch-and-swell structure, and thin, tapering, extensions that cross-cut surrounding flaser lenses. Metasiltstone lenses range from <1 mm to 2 cm in thickness. Smaller lenses of metasiltstone and phyllite are truncated by shear surfaces that bound the thicker lenses of metasiltstone. Wispy pyrite veins show thickened wedges at tapering intersections of main and subsidiary shears.

736 Polymict, tectonic, phacoidally shaped clasts of metasiltstone, laminated quartzite (metachert?), and phyllite, some showing folds that predate formation of the clasts (Fig. 6e). Clasts range in length from ~ 0.1 mm to ~ 5 cm.

737 Similar to core sample 732' but with 3 cm-thick quartzite lens, broken along moderately high-angle shears into irregular, nested, phacoidal clasts.

761 to 764 Metatuff (assigned to Hurricane Mountain Formation) composed of epidote-Ti-oxide-sericite-quartz, showing sheared, indistinct, thick wavy lenses.

773 Openly folded, flaser laminated, gray metasiltstone and phyllite.

774 to 790 Flaser lenses and laminae of gray metasiltstone and phyllite, showing localized kink-bands and *shear folds* (Fig. 2d), the short limbs of which are quartz-rich, and the long limbs, sericite-rich. Rounded, flattened, sericitic, quartz-bearing lenses (felsic metavolcanic protolith?) are preserved within less sheared lithons in which chevron (kink) folds are absent.

800 Gray slate, and minor, interlaminated, light gray metasiltstone, showing incipiently developed, flaser laminations and lenses. Widely spaced, high-angle, extensional shears.