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Stratigraphy and metamorphism of the Silurian and Lower Devonian rocks of the western part of the Merrimack Synclinorium, Pinkham Notch area, east-central New Hampshire

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TRIP B-3

STRATIGRAPHY AND METAMORPHISM OF THE SILURIAN AND LOWER DEVONIAN ROCKS OF THE WESTERN PART OF THE MERRIMACK SYNCLINORIUM, PINKHAM NOTCH AREA, EAST-CENTRAL NEW HAMPSHIRE

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ACKNOWLEDGMENT

At the outset we would like to point out the fundamental and critical role of Professor M. P. Billings in deciphering the geology of the Pinkham Notch area. Although we were not able to find a copy of his road log for it, Billings led an NEIGC field trip to the Pinkham Notch area in 1946, and it is probable that some of the exposures to be visited on the present trip were included on Billings′ trip of 40 years ago. Our map of the area differs from those of Billings primarily in the names and ages of some of the units. The differences are readily explained, however, by the fact that the work in Maine, which developed the Merrimack synclinorium stratigraphic sequence and tied many of the units to fossils, was not done until years after Billings′ maps of the Pinkham Notch area were published. Billings′ study of the stratigraphy, structure, and metamorphism of the Pinkham Notch area is a classic upon which this field trip is thoroughly dependent.

GEOLOGIC SETTING

The Merrimack synclinorium forms a broad belt of Silurian and Lower Devonian strata east of the Bronson Hill-Boundary Mountain anticlinorium across eastern Maine, central New Hampshire, and central Massachusetts and Connecticut (Williams, 1978; Osberg and others, 1985; Billings, 1956; Zen and others, 1983; Rodgers, 1985) (fig. 1). Moench (1971) defined and mapped a distinctive sequence of stratigraphic units in the west part of the synclinorium in the Rangeley area of western Maine. Hatch and others (1983) extended this Rangeley area sequence southwest across eastern and south-central New Hampshire. Thompson (1984), Robinson (1981), and Berry (1985), among others, have extended all or parts of this sequence across southernmost New Hampshire and central Massachusetts into northern Connecticut. Eusden and others (1986) have reported this same sequence of units further east in the synclinorium in southeastern New Hampshire and adjacent southwestern Maine. These Silurian and Lower Devonian strata are interpreted to have been deposited at or near the eastern margin of continental North America in the time interval after the Taconian collision between North America and the Bronson Hill island arc and before the Acadian collisional (?) orogeny.

The Silurian and Lower Devonian rocks of this sequence in east-central New Hampshire are divided into the formations indicated in table 1. All are metamorphosed sedimentary rocks; no metavolcanic rocks have been recognized in the belt in eastern New Hampshire and they are very rare or absent throughout the belt.

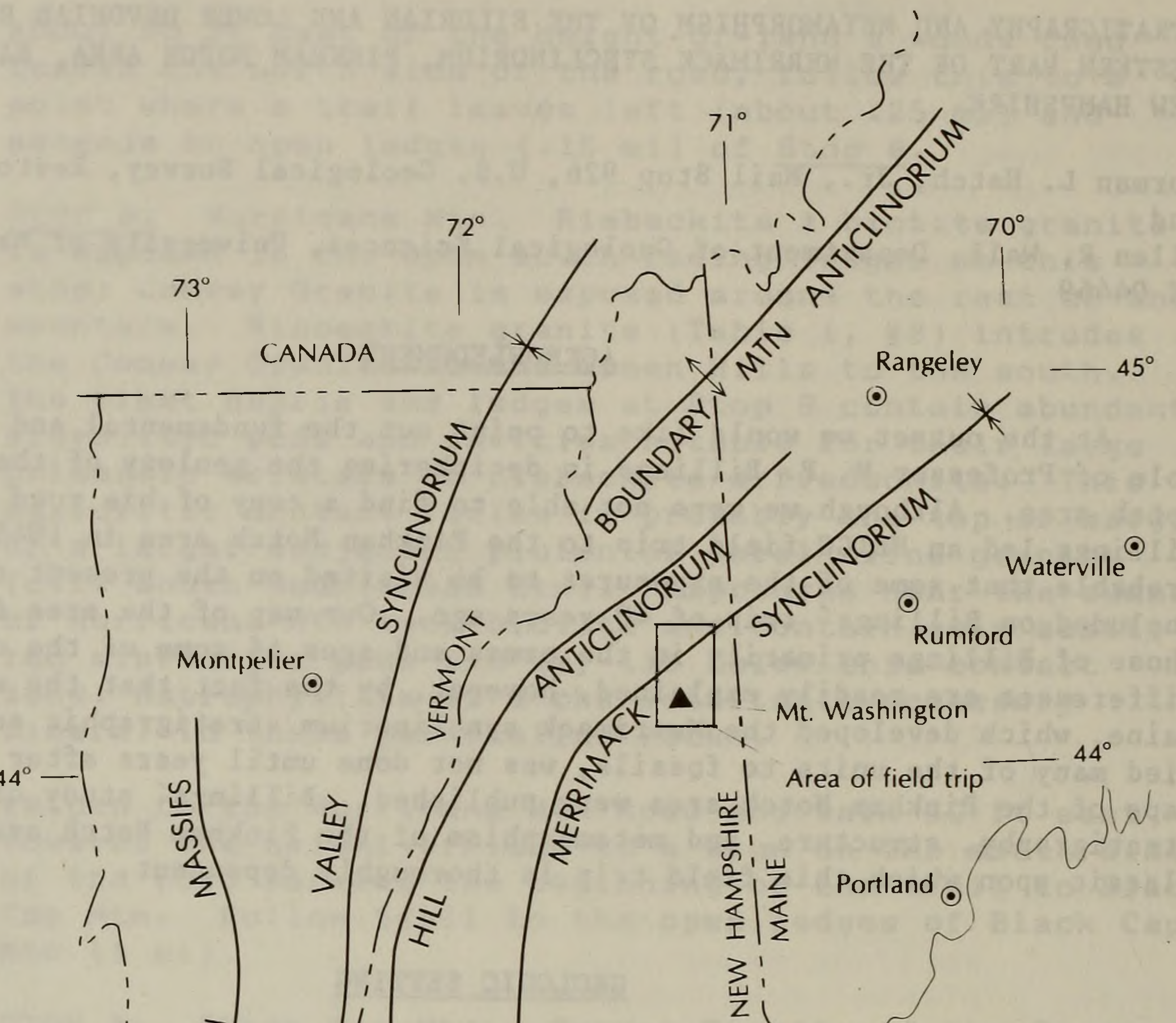


Figure 1. Map showing location of the field trip area in the geologic framework of western New England.

TABLE 1. STRATIGRAPHIC UNITS OF THE MERRIMACK SYNCLINORIUM IN EAST-CENTRAL NEW HAMPSHIRE.

AGE	FORMATION	LITHOLOGY
Early Devonian	Littleton	Mica schist and granulite
Silurian	Madrid, upper	Plagioclase-quartz-biotite granulite
	Madrid, lower	Layered calc-silicate granulite
	Smalls Falls	Sulfidic schist and quartzite
	Perry Mtn.	Quartzite and mica schist
	Rangeley	Mica schist, quartzite, grit

The model advanced by Moench and others (1982) and by Hatch and others (1983) is that the Silurian rocks of the Merrimack synclinorium are an eastern, more distal, deeper water facies of the shelf-facies Silurian Clough Quartzite and Fitch Formation of the Bronson Hill anticlinorium (figs. 1 and 2). The axis of the Bronson Hill anticlinorium is about 15 miles west or northwest of the area to be visited on this field trip. The Silurian sequence to be seen on the trip is intermediate in both thickness and number of units between the Silurian of the Bronson Hill (Billings, 1937, 1956) and of the Merrimack synclinorium east of Rangeley, Maine (Moench, 1971). The on-strike continuation of the Lower Devonian Littleton Formation in north-central Maine, the Seboomook Formation, has been interpreted by Hall and others (1976) to have been derived from the east in contrast to the underlying westerly-derived Silurian rocks. The Littleton forms a thick blanket across both the shelf (Bronson Hill) and basin (Merrimack) Silurian sequences in New Hampshire (fig. 2).

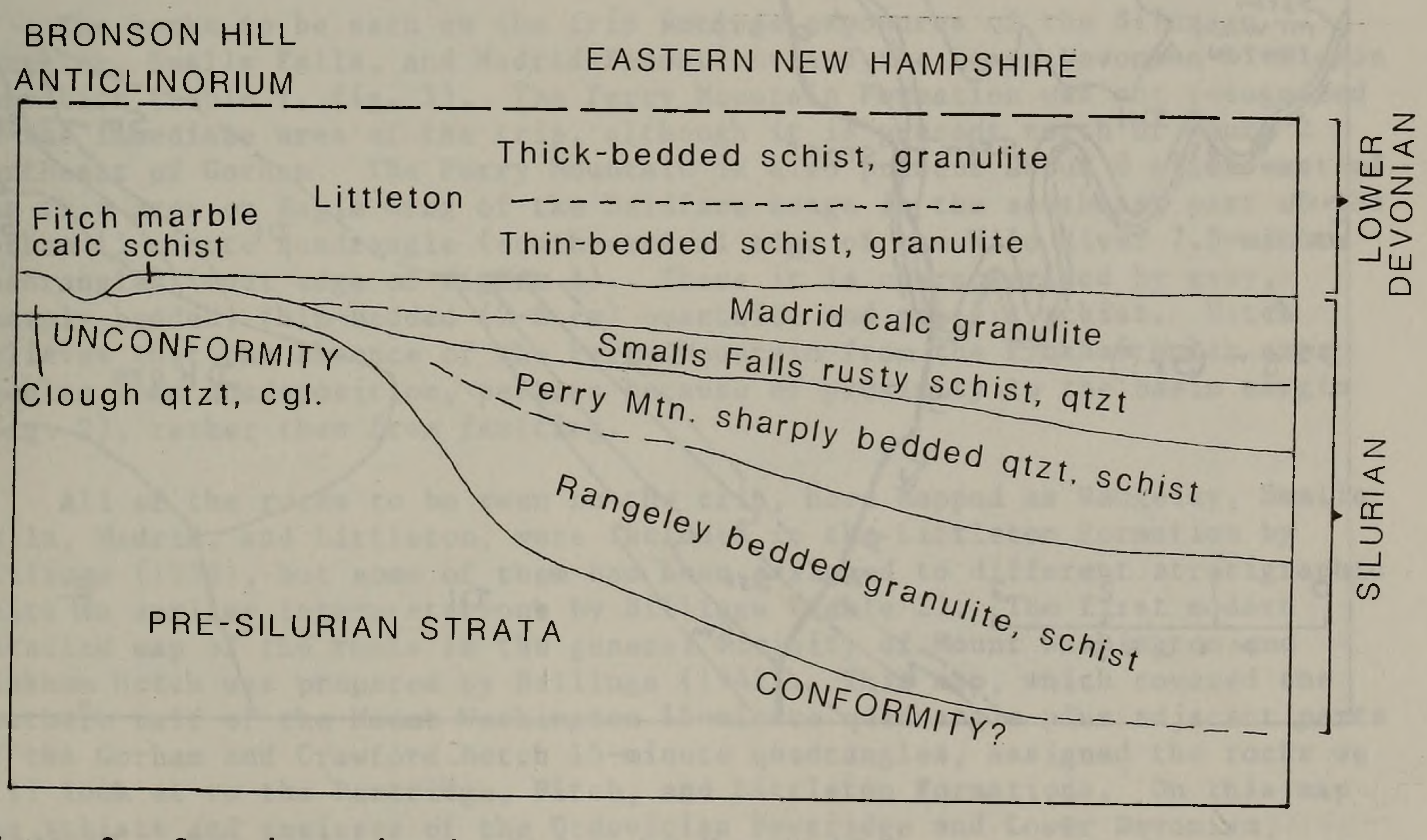


Figure 2. Stratigraphic diagram showing the relation between the thin Silurian shelf facies on the Bronson Hill anticlinorium and the much thicker Silurian basin facies of the Merrimack synclinorium to the east. Both are blanketed by roughly comparable thicknesses of easterly derived (?) Lower Devonian Littleton Formation.

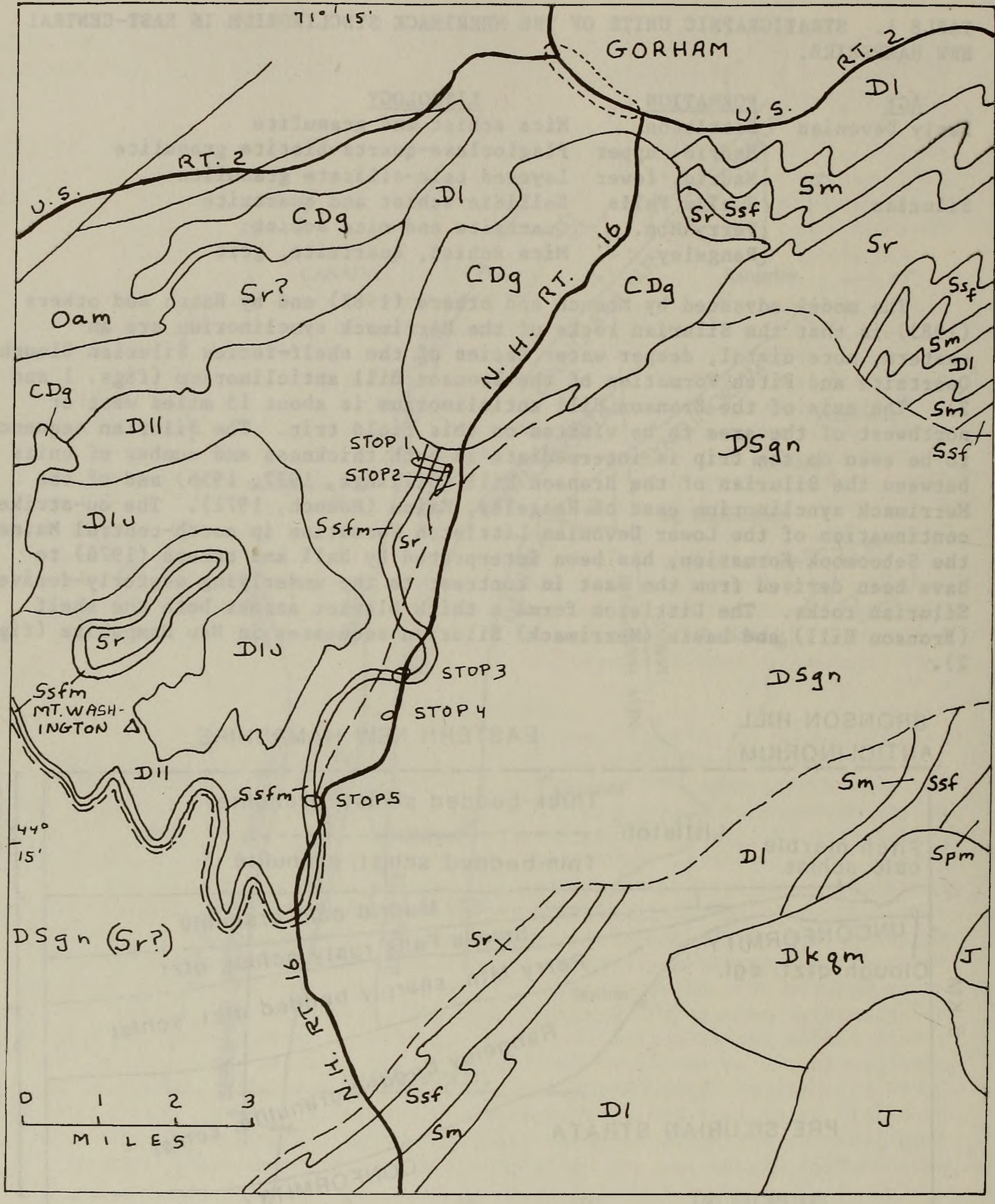


Figure 3. Geologic map of Pinkham Notch and the surrounding area. Modified from Billings and others (1946), Billings and Fowler-Billings (1975), Billings (1928), and Hatch and Moench (1984).

EXPLANATION FOR FIGURE 3

J	Jurassic to Cretaceous plutonic rocks
CDg	Devonian to Carboniferous granitic rocks
Dkqm	Devonian Kinsman Quartz Monzonite
DSgn	Undifferentiated Silurian and Devonian paragneiss
Dl	Undivided Lower Devonian Littleton Formation
Dlu	Upper member of the Littleton Formation
Dll	Lower member of the Littleton Formation
Ssfm	Undivided Smalls Falls and Madrid Formations
Sm	Silurian Madrid Formation
Ssf	Silurian Smalls Falls Formation
Spm	Silurian Perry Mountain Formation
Sr	Silurian Rangeley Formation
Oam	Ordovician Ammonoosuc Volcanics
	Contact, approximately located
	Approximate location of gradational boundary between undifferentiated paragneiss and recognizable formations

The field trip will examine exposures in the southwest part of the old Gorham 15-minute quadrangle (Billings and Fowler-Billings, 1975) and the southeast corner of the Mount Washington 15-minute quadrangle (Billings, 1941; Billings and others, 1946) (fig. 3). More modern topographic maps of these areas are the Carter Dome 7.5-minute quadrangle (southwest quarter of the Gorham 15-minute), and the Mount Washington 7.5- X 15-minute quadrangle (south half of the Mount Washington 15-minute).

The rocks to be seen on the trip include exposures of the Silurian Rangeley, Smalls Falls, and Madrid Formations and the Lower Devonian Littleton Formation (table 1, fig. 3). The Perry Mountain Formation was not recognized in the immediate area of the trip, although it is present north of Route 2 northeast of Gorham. The Perry Mountain is also present about 8 miles east of the trip area on Eagle Crag of the Baldface Range in the southeast part of the Gorham 15-minute quadrangle (south-central edge of the Wild River 7.5-minute quadrangle) (east edge of figure 3). There it is characterized by gray, sharply bedded, thin-bedded (2-8 cm) quartzite and pelitic schist. Hatch believes that the absence of the Perry Mountain from the Pinkham Notch area results from nondeposition, perhaps because of proximity to the basin margin (fig. 2), rather than from faulting.

All of the rocks to be seen on the trip, here mapped as Rangeley, Smalls Falls, Madrid, and Littleton, were included in the Littleton Formation by Billings (1956), but some of them had been assigned to different stratigraphic units in earlier interpretations by Billings (table 2). The first modern detailed map of the rocks in the general vicinity of Mount Washington and Pinkham Notch was prepared by Billings (1941). This map, which covered the southern half of the Mount Washington 15-minute quadrangle plus adjacent parts of the Gorham and Crawford Notch 15-minute quadrangles, assigned the rocks we will look at to the Partridge, Fitch, and Littleton Formations. On this map the schists and gneisses of the Ordovician Partridge and Lower Devonian Littleton Formations were separated from each other by a very narrow belt of calc-silicate rocks assigned to the Silurian Fitch Formation. Five years later, Billings and others (1946) published a map of the entire Mount

Washington 15-minute quadrangle, which included most of the area of the 1941 map. On this map, and in the accompanying report, all of the schists and gneisses previously assigned to the Partridge Formation were reassigned to the Littleton Formation, and the thin calc-silicate unit previously assigned to the Fitch was named the Boott Member of the Littleton from exposures on Boott Spur on the south ridge of Mount Washington. Thus, all of the stratified rocks were reinterpreted to be within the Lower Devonian Littleton Formation, and only the Boott was separately mapped. This same stratigraphic system was followed by Billings (1956) on the statewide report and map and by Billings and Fowler-Billings (1975) on their map of the Gorham 15-minute quadrangle.

TABLE 2 STRATIGRAPHIC ASSIGNMENTS OF THE ROCKS IN THE PINKHAM NOTCH AREA SHOWING CHANGES IN INTERPRETATION, NOMENCLATURE, AND AGE THROUGH TIME.

Billings (1941)		Billings et al.,(1946)		This report	
Littleton	(Dev)	Littleton	(Dev)	Littleton	(Dev)
Fitch	(Sil)	Boott Member	(Dev)	Madrid	(Sil)
				{Smalls Falls	(Sil)
Partridge	(Ord)	Littleton	(Dev)	{Rangeley	(Sil)

The rocks Billings and others (1946) assigned to the Boott are a very distinctive light- and dark-green layered calc-silicate granulite not reported from the Littleton in the Bronson Hill anticlinorium (Billings, 1937, 1956). Many students of New England geology have pondered at length, although little has been written, over whether the Boott was really a calc-silicate member stratigraphically within the Littleton, or was Fitch Formation below the Littleton as originally assigned, or possibly neither. During a quick trip to exposures on the West Branch of the Peabody River (figs. 6, 10) in the fall of 1977, Robert Moench first introduced Hatch to the possibility that the Boott might be the Madrid Formation of the Rangeley, Maine, sequence. Subsequent re-study of the metamorphic rocks of the southern part of the Mount Washington and Gorham 15-minute quadrangles and of the northern part of the Crawford Notch and North Conway 15-minute quadrangles supports this interpretation. The strongly layered green calc-silicate granulite (fig. 4) is identical in thickness, bedding style, and composition to the lower part of the Madrid Formation of western Maine (Moench, 1971). Furthermore, at virtually every locality of this unit in eastern New Hampshire it adjoins deeply rusted, pyrrhotite-rich, graphitic, flaggy quartzite and schist typical of the Smalls Falls Formation, which underlies the Madrid in western Maine. These graphitic and sulfidic rocks may have influenced Billings in his original (1941) assignment of the rocks below the calc-silicate unit to the Partridge Formation.

The lithology of the rocks on both sides of the layered calc-silicate and sulfidic schist units is also compatible with the correlation with the Rangeley, Maine sequence. The layered calc-silicate granulite grades, over about 10 meters, into thick-bedded to massive plagioclase-quartz-biotite, "salt and pepper" granulite with local minor calc-silicate beds and pods. This salt and pepper granulite in turn grades into well-bedded, light-gray aluminous pelitic schist and granulite. Within about 10 meters of the contact, the aluminous schist and granulite (quartzite) unit is characterized by cyclically graded beds 5 to 10 cm thick that consistently indicate that the sequence is topping up from the pyrrhotitic rocks (Smalls Falls) into the layered calc-silicate (lower Madrid) into the massive plagioclase-quartz-

Figure 4. Photograph of the well-layered calc-silicate granulite of the lower part of the Madrid Formation. West Branch of the Peabody River.

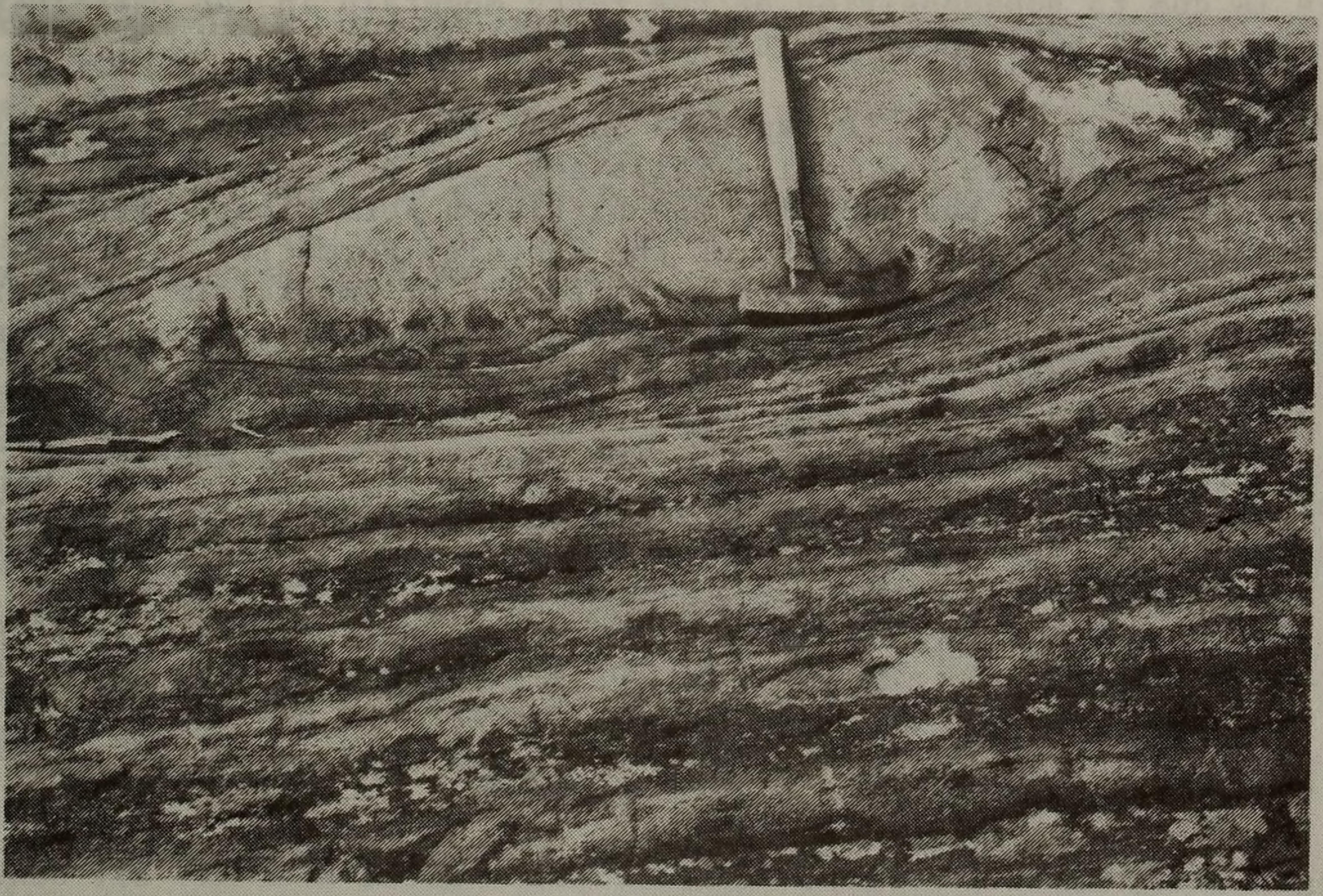


Figure 5. Photograph of well-bedded schist and granulite of the Rangeley Formation with calc-silicate "football". Stop 2A, Peabody River.

biotite "salt and pepper" granulite (upper Madrid), and finally into the aluminous schist and granulite with graded bedding (Littleton).

Stratigraphically below the deeply rusted pyrrhotitic rocks of the Smalls Falls are generally well bedded schist and quartzite that are broadly similar to the aluminous schist and granulite of the Littleton Formation. These rocks differ from the Littleton rocks, however, in the following subtle ways. 1) The rocks below the Smalls Falls contain abundant pods, generally 15 to 30 cm thick and 30 cm to 1 m long, of calc-silicate granulite (fig. 5). In order to side-step the question of whether these pods are concretions or boudins, they are commonly referred to as "footballs". 2) Local beds preserve primary grading and indicate that this unit underlies the Smalls Falls. More typically, however, the progression from granulite to schist is abrupt on both sides of a given granulite bed, and primary tops are indeterminate. The Littleton Formation has a significantly higher percentage of graded beds. 3) Many exposures of this unit are slightly rusty weathered, and commonly this rustiness has a distinctive reddish cast unlike that in either the Smalls Falls or the Littleton. 4) The granulites of this unit are locally more quartz rich than those of the Littleton. 5) Locally the granulites are gritty or pebbly. Because all of these features are characteristic of the well-bedded schist and granulite parts of the Rangeley Formation in western Maine, we have made that correlation (Hatch and others, 1983; Hatch and Moench, 1984). The only argument against this correlation is the local absence in the Pinkham Notch area of the Perry Mountain Formation, which in Maine occurs between the Smalls Falls and the Rangeley. As noted above, we feel this absence is due to nondeposition of the Perry Mountain in the western part of the depositional basin near the (Bronson Hill) shelf.

Present stratigraphic thicknesses in the Pinkham Notch area can be accurately measured for the Smalls Falls and Madrid Formations but can only be roughly estimated for the Rangeley and Littleton Formations. Because bedding is no longer recognizable in most of the Rangeley Formation in the Pinkham Notch area, its internal structure is difficult or impossible to determine. For this reason the stratigraphic thickness can only be estimated from the large areas of exposure to be at least a kilometer. In contrast, the Smalls Falls Formation can be accurately measured to range from about 6 meters thick at Lakes of the Clouds, just south of the summit of Mount Washington, to possibly 100 meters thick near Pinkham Notch. The lower, layered calc-silicate part of the Madrid Formation similarly can be accurately measured to be only about 10 meters thick. The upper, plagioclase-quartz-biotite granulite part of the Madrid ranges up to a few hundred meters in thickness, although its gradational contact with the overlying Littleton makes precise measurement difficult. The Littleton was reported by Billings (1941, p. 895) to be about 4000 feet (1220 meters) thick in the area immediately north of Mount Washington, and we agree with that figure.

Ages assigned to the units in the Pinkham Notch area are all based on fossil control from outside the area (Hatch and others, 1983). The Silurian age of the Rangeley derives from late Llandoverian fossils from the Blanchard Ponds belt of the formation in western Maine northwest of Rangeley (Moench and Boudette, 1970). The age of the Smalls Falls depends upon correlation with the fossiliferous Parkman Hill of central Maine (Pankiwskyj and others, 1976). No fossils have been reported from the Madrid, and its Silurian age is dependent upon correlation with the latest Silurian (Pridolian) (Harris and others, 1983) Fitch Formation in the Bronson Hill anticlinorium. The Early Devonian age of the Littleton Formation is based on fossils from the type area (Billings and Cleaves, 1934).

METAMORPHISM

All of the rocks to be seen on the trip have been metamorphosed to sillimanite grade. A small area immediately southwest of the Dolly Copp campground is staurolite-andalusite grade (fig. 6; Billings, 1941, p. 888) but will not be seen on the trip. The most striking difference in the sillimanite-grade rocks is textural, between schist and granulite sequences that preserve primary compositional layering (bedding), to be seen at Stops 1 and 2A, and comparable rocks of the same formation that have been changed to gneiss and in which bedding has been obliterated, to be seen at Stops 2D and 4. Of interest is the fact that the two types coexist in very close proximity across a moderately sharp boundary. On Stop 2 we will see exposures that show the transition between the two types.

As shown by both Billings (1941, fig. 3) and by Hatch and Moench (1984), the gneiss-schist metamorphic boundary approximately, but not precisely, follows the stratigraphic contact between the Rangeley and Smalls Falls Formations in the field trip area (fig. 3). Regardless of the orientation of that stratigraphic boundary surface at the time of metamorphism, it is difficult to believe that the closely coincident gneiss-schist boundary surface is truly isogradic. Rather, it seems probable that the close geographic coincidence of these two boundaries, which are unrelated in origin, must result at least in part from a greater inherent propensity of the Rangeley schist, relative to the Littleton schist, to be converted into gneiss. This propensity may be a function of subtle differences between the chemical composition of the Rangeley schist and that of the outwardly similar Littleton schist, but this question has yet to be studied in detail. The reluctance of the Smalls Falls and lower Madrid rocks to be converted to gneiss will be shown at Stop 3.

Although irregular in detail, the boundary separating the gneissic rocks from bedded schists and granulites roughly parallels the regional trend of isograds through this part of central New England, where the grade increases eastward from a low in the Connecticut valley into easternmost New Hampshire and adjacent Maine. Taken by themselves, these relations suggest a prograde metamorphic control on the transformation to gneiss. In the vicinity of the field trip stops, the gneiss boundary drawn on figure 3 is, although gradational over a few hundred meters, a fairly sharp boundary. The rocks to the west, around Mount Washington, are well-bedded metasedimentary rocks, whereas the rocks to the east of Route 16 are gneisses. The gneiss boundary shown in the northeast and southeast parts of figure 3 is much less precise. It essentially bounds areas in which enough exposures of the distinctive Madrid and Smalls Falls lithologies were present to enable mapping them and assigning the adjoining rocks to either the Rangeley or the Littleton, from areas in which this was not possible. Most of the rocks presumed to be either Rangeley or Littleton on both sides of the boundary are gneisses. Although too few exposures of distinctive Madrid or Smalls Falls rocks were seen in the large area of DSgn on figure 3 to enable mapping them, most of the gneisses contained calc-silicate "footballs", or had the distinctive red-rusty cast, or both, suggestive of the Rangeley Formation. This interpretation is

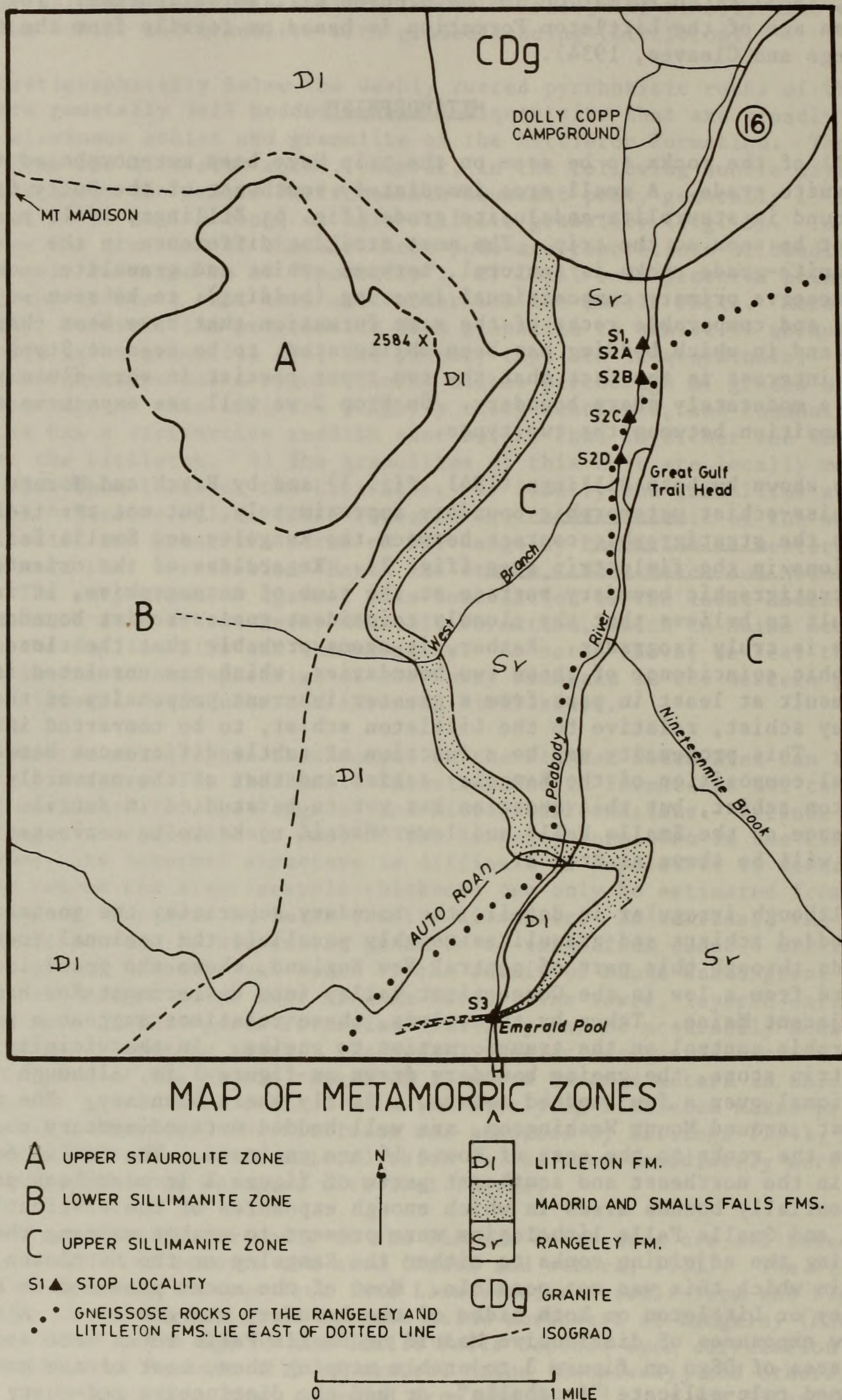


Figure 6. Map showing metamorphic zones in the vicinity of Stops 1 through 3.

significantly different from that of Billings and Fowler-Billings (1975) in which three separate pre-"Boott" calc-silicate units extend northeasterly across the area of DSgn on figure 3. Although we are very uncertain about their continuity across the area of DSgn, most of the exposures of these calc-silicate rocks seen by Hatch impressed him as being lower Madrid.

A detailed study of the metamorphism in a 12 square mile area roughly centered around the 2584 foot knob on the eastern slope of Mt. Madison (figs. 6 and 10) reveals evidence for polymetamorphism in the Pinkham Notch area (Wall and Guidotti, 1986). The first metamorphic event, M1, is shown by the presence of abundant pseudomorphs of muscovite, quartz, and sillimanite after andalusite. The second event, M2, was at sillimanite grade and formed the pseudomorphs. Three metamorphic zones are mapped in this area: an upper staurolite zone, a lower sillimanite zone, and an upper sillimanite zone (fig. 6). Figure 7 shows the AFM and the AKNa topologies indicating the observed assemblages in each of the three metamorphic zones.

The boundary between the upper staurolite and the lower sillimanite zones is defined by the appearance of the sillimanite + biotite join in the AFM topology for the lower sillimanite zone. In many metapelites elsewhere, sillimanite is brought in by a discontinuous reaction: Staur + Chl + NaMusc + Qtz $\rightleftharpoons$ Bio + Sill + K-richer Musc + Ab + H_2O. This specific tie line flip is not observed in the present study because the transition to the lower sillimanite zone occurs within the Littleton Formation, which has a relatively iron-rich bulk composition (compared to the more Mg-rich Rangeley). Hence, primary chlorite is absent. Had the transition to the lower sillimanite zone occurred in the Rangeley Formation (as it does in western Maine), the tie line flip probably could have been documented in terms of observed assemblages. Because of fairly abundant Fe-sulfides, the "silicate bulk composition" of the Rangeley Formation is relatively richer in Mg, thereby enabling the occurrence of Mg-rich phases like chlorite.

Within the lower sillimanite zone, a systematic decrease in the modal percent of staurolite is observed as the upper boundary of this zone is approached. The complete disappearance of staurolite by the reaction Staur + NaMusc + Qtz $\rightleftharpoons$ Bio + Sill + K-richer Musc + Ab + Gar + H_2O (Guidotti, 1970) defines the boundary between the lower and upper sillimanite zones. The breakdown of staurolite results in the formation of the three-phase field Sill + Bio + Gar on the AFM topology for the upper sillimanite zone (fig. 7). Mineral assemblages observed in the upper sillimanite grade schists include Sill + Bio + Gar, Bio + Gar, and Sill + Bio. In the Littleton Formation all of the observed assemblages include ilmenite $\pm$ graphite. In the Rangeley Formation, pyrrhotite is present in addition to ilmenite and graphite.

The metamorphism that produced the present pattern of zones (M2) overprints an earlier metamorphism of at least staurolite + andalusite + biotite grade. The evidence for the earlier metamorphic event (M1) lies in the numerous euhedral prograde pseudomorphs after staurolite and andalusite present in the pelitic schists of the Rangeley and Littleton Formations throughout the area. The pseudomorphs were formed during M2. Both of these events are static in nature and are considered to be Acadian in age, but the recent report by Lux and Guidotti (1985) of Carboniferous metamorphism in western Maine invites speculation on this point.

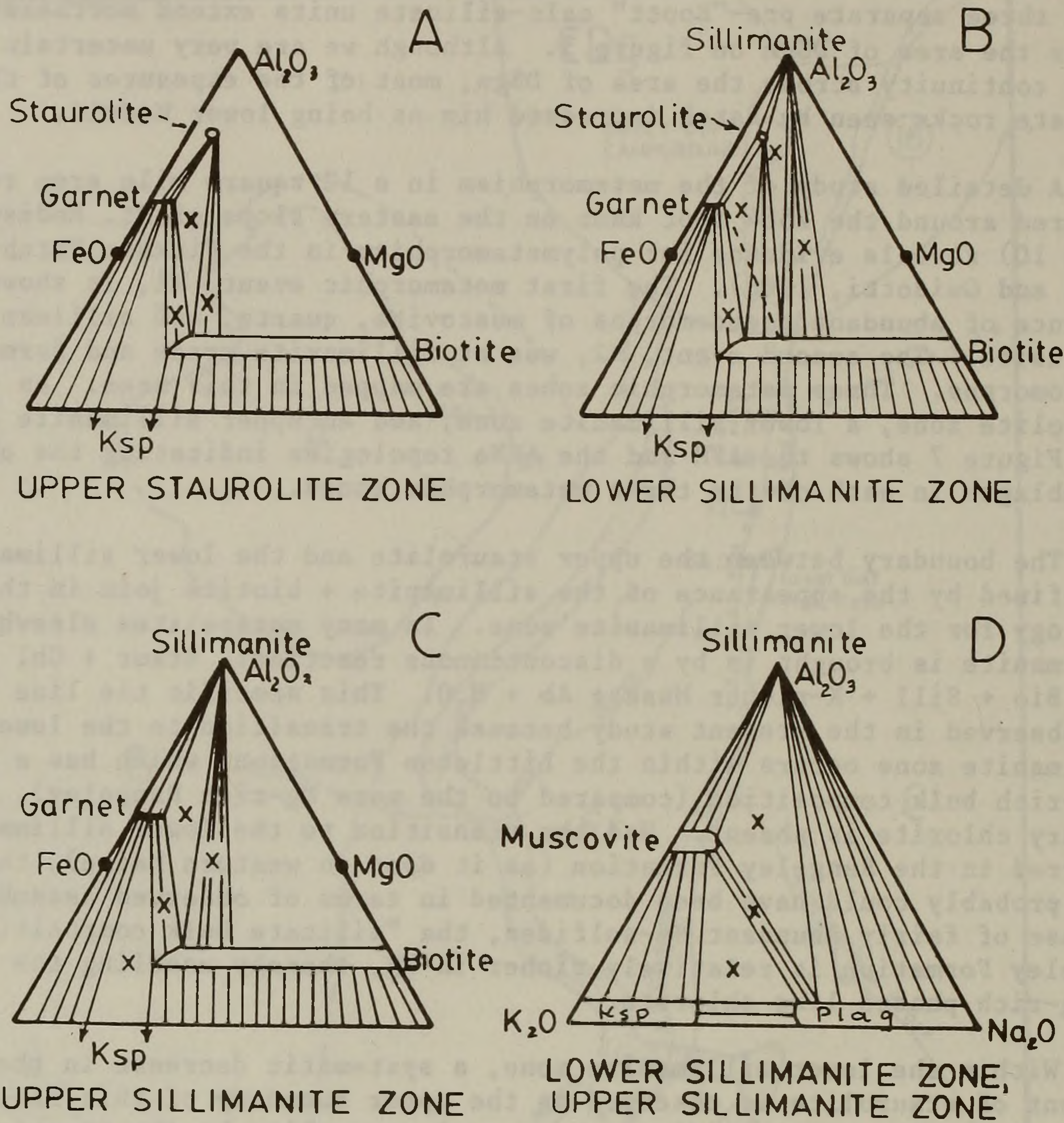


Figure 7. Schematic AFM (A,B,C) and AKNa (D) projections of assemblages (observed assemblages shown by x) for the upper staurolite through upper sillimanite zones. Diagrams A, B, and C correspond to the assemblages observed in areas marked A, B, and C respectively on figure 6.

The progressive transition from well-bedded Rangeley schist and granulite to Rangeley gneiss will be seen on Stop 2. All of the exposures examined on Stop 2 are within the upper sillimanite zone (fig. 6). At Stop 2A bedding, some with grading, is still well preserved. At Stops 2B, 2C, and 2D, over a distance of less than a kilometer south of Stop 2A along the Peabody River and essentially parallel to the strike of bedding, the well-bedded schists and granulites of the Rangeley Formation gradually change to moderately rusty-weathering, foliated, spangled gneisses (fig. 8). This textural change occurs over an even shorter distance (about 500 meters) east of Stop 2A across Route 16. In the first stage of this process the bedding becomes less well defined and grading is no longer recognizable. Pseudomorphs become less abundant and some muscovite spangles as much as 1 cm in diameter are present (Stop 2C, fig. 8). Further south up the Peabody River at Stop 2D, the rock becomes distinctly gneissose with alternating thin layers 0.5 to 2 cm thick of lighter

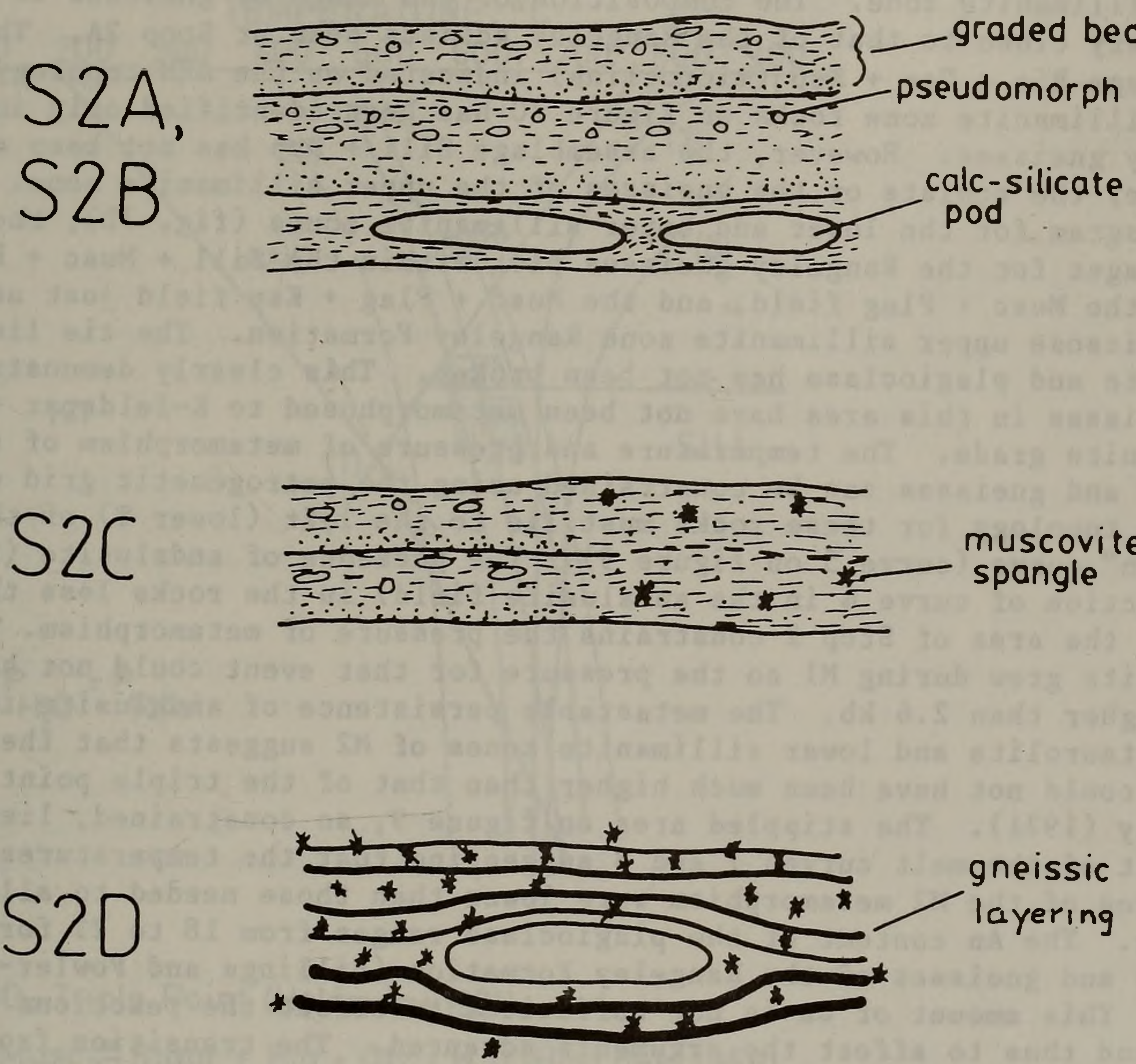


Figure 8. Schematic diagram illustrating the transition from well-bedded schist and granulite to gneiss in the Rangeley Formation at Stop 2. See text for discussion.

quartzofeldspathic and darker biotite-rich material, suggestive of incipient anatexis (Stop 2D on fig. 8). No hint of the original bedding remains, and the pseudomorphs have disappeared. Clots of coarse-grained quartz, plagioclase, and muscovite 10 to 15 cm in length are oriented both parallel and transverse to the foliation, which is defined by parallel biotite plates. Muscovite spangles as much as 2 cm across are more abundant in these gneissose rocks. Calc-silicate pods, present in horizons parallel to bedding in the bedded Rangeley schists and granulites, persist in the gneissose rocks where they are generally oriented parallel to the foliation.

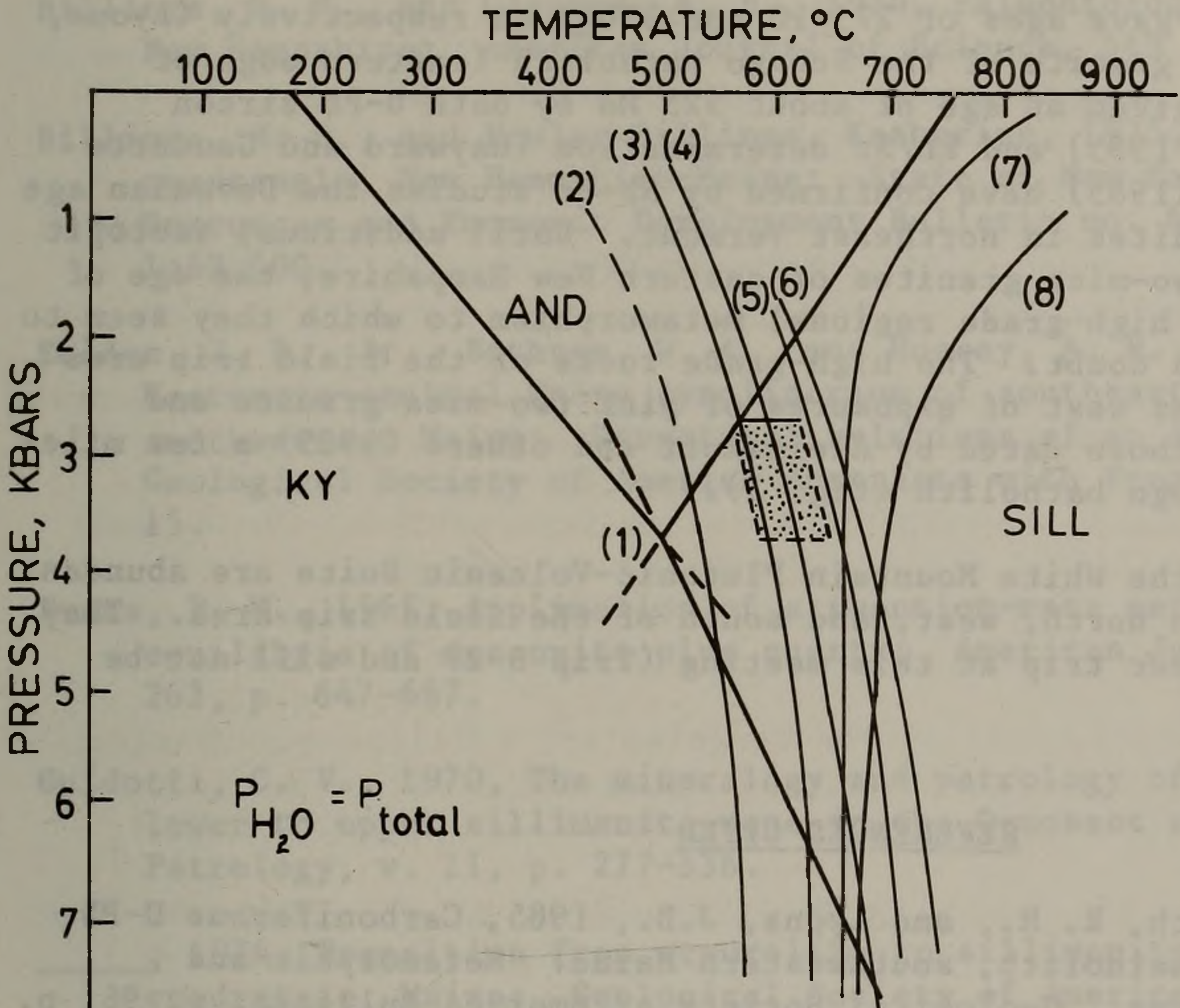
Available outcrop data indicate that the gneiss exposed along Route 16 between the Mt. Washington Auto Road and Emerald Pool is Littleton Formation stratigraphically above the Madrid Formation. This gneiss differs from that of the Rangelely Formation in that calc-silicate pods ("footballs") are rare to absent, muscovite spangles up to 8 cm in length appear to have replaced muscovite pseudomorphs after andalusite, and its color is gray rather than rusty red-brown.

The gneisses of both the Rangeley and Littleton Formations lie within the upper sillimanite zone. The composition of the Rangeley gneisses is believed to be very close to that of the Rangeley schists seen at Stop 2A. The assemblage Bio + Gar + Ksp (microcline) indicated on the AFM topology for the upper sillimanite zone rocks on figure 7C has been identified only in the Rangeley gneisses. However, the assemblage Sill + Ksp has not been observed in either the schists or the gneisses of the upper sillimanite zone. On an AKNa diagram for the lower and upper sillimanite zones (fig. 7D), the mineral assemblages for the Rangeley gneisses plot within the Sill + Musc + Plag field, the Musc + Plag field, and the Musc + Plag + Ksp field just as for the non-gneissose upper sillimanite zone Rangeley Formation. The tie line between muscovite and plagioclase has not been broken. This clearly demonstrates that the gneisses in this area have not been metamorphosed to K-feldspar + sillimanite grade. The temperature and pressure of metamorphism of the schists and gneisses can be constrained using the petrogenetic grid of figure 9. The topology for these rocks must lie to the left (lower T) of the Ksp + Sill "in" curve (curve 5 on figure 9). The presence of andalusite (formed by the reaction of curve 4 in the andalusite field) in the rocks less than a mile west of the area of Stop 2 constrains the pressure of metamorphism. The andalusite grew during M1 so the pressure for that event could not have been much higher than 2.6 kb. The metastable persistence of andalusite in the upper staurolite and lower sillimanite zones of M2 suggests that the pressure for M2 could not have been much higher than that of the triple point of Holdaway (1971). The stippled area on figure 9, so constrained, lies well to the left of the melt curves 7 and 8 suggesting that the temperatures and pressures of the M2 metamorphism were lower than those needed to allow melting. The An content of the plagioclase ranges from 18 to 22 for both the schists and gneisses of the Rangeley Formation (Billings and Fowler-Billings, 1975). This amount of Ca is not sufficient to offset the reactions described above and thus to affect the arguments advanced. The transition from schist and granulite to gneiss may simply be due to metamorphic differentiation resulting in the formation of leucosomes of quartz + plagioclase + muscovite. Further discussion of this process will take place on the outcrop at Stop 2.

STRUCTURE

All of the stratified rocks of the area are variably deformed. The structural analysis by Billings (1941) is excellent, and his maps (1941, pl. 10; Billings and others, 1946, pl. 1) clearly show the nature of folds by the outcrop pattern of the Fitch (Boott). This pattern is very similar to that shown by Hatch and Moench (1984) and on figure 3 for the Smalls Falls and Madrid. Bedding generally dips moderately to steeply and strikes predominantly to the north or northeast. Schistosity most commonly is roughly parallel to bedding. Most observed minor folds fold both bedding and schistosity and generally have axial surfaces that strike north and dip steeply. These folds are tight to open and have axes that typically plunge gently to the north or south.

In addition to the more obvious folds, which fold both bedding and early schistosity, isoclinal folds that predate them are present. These isoclines are most readily documented by reversals in topping direction of graded beds and thus are most recognized in the well-graded rocks of the lower part of the Littleton Formation. Other than a few minor folds, these structures will not be emphasized on this field trip.



(1) Al_2SiO_5 Triple Point (Holdaway, 1971)

(2) Chl + Musc ⇌ Staur + Bio + Qtz + H_2O (Hoschek, 1969)

(3) Staur + Chl + NaMusc + Qtz ⇌ Bio + Sill + KricherMusc + Ab + H_2O (see Guidotti, 1974)

(4) Staur + NaMusc + Qtz ⇌ Sill + Bio + Kricher Musc + Ab + Garn + H_2O (Guidotti, 1970)

(5) NaMusc + Plag + Qtz ⇌ Al_2SiO_5 + NaKsp + H_2O (Thompson, 1974)

(6) Musc + Qtz ⇌ Sill + Ksp + H_2O (Evans 1965)

(7) H_2O Saturated Granitic Melt (Tuttle and Bowen, 1958)

(8) H_2O Saturated Melt without K-feldspar (see Thompson, 1974)

Figure 9. P-T curves relevant to the upper staurolite through upper sillimanite zones. The stippled area indicates the interpreted approximate range of pressures and temperatures for the M2 metamorphism.

PLUTONIC ROCKS

The principal plutonic rock in the field trip area is the body of light-gray two-mica granite that underlies and extends north and northeast from the Dolly Copp Campground (body of CDg between Gorham and Stop 1 on fig. 3). Small dikes and sills of similar granite and pegmatite are common throughout the area and will be seen on the trip. This granite is similar to other Two-mica granites throughout western, central, and northern New Hampshire that have long been considered to be Devonian (Acadian) in age and assigned to the New Hampshire Plutonic Suite (New Hampshire plutonic series of Billings, 1956). Recent Rb/Sr studies of two such bodies in southern and southwestern

New Hampshire, however, gave ages of 275±10 and 330±3 Ma respectively (Lyons, 1979), and the two-mica granite of the Sebago batholith (eastern edge of figure 3) has recently given an age of about 325 Ma by both U-Pb zircon (Aleinikoff and others, 1985) and Rb/Sr determination (Hayward and Gaudette 1984). Arth and Ayuso (1985) have confirmed by Rb-Sr studies the Devonian age of similar two-mica granites in northeast Vermont. Until additional isotopic dating is done on the two-mica granites of eastern New Hampshire, the age of these bodies and of the high-grade regional metamorphism to which they seem to be closely related is in doubt. The high-grade rocks of the field trip area are only about nine miles west of exposures of pink two-mica granite and pegmatite identical to those dated by Aleinikoff and others (1985) a few miles further east in the Sebago batholith (fig. 3).

Plutonic rocks of the White Mountain Plutonic-Volcanic Suite are abundant in eastern New Hampshire north, west, and south of the field trip area. They are the subject of another trip at this meeting (Trip B-2) and will not be covered on this trip.

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ROAD LOG FOR TRIP B-3

Pertinent maps:
Topographic maps:
Carter Dome, N. H. 7.5-minute (1:24,000)
Mt. Washington, N. H. 7.5-minute x 15-minute (1:25,000)
or Mt. Washington, N. H. 15-minute (1:62,500)
Crawford Notch, N. H. 15-minute (1:62,500)
North Conway, N. H. 15-minute (1:62,500)
Geologic maps:
Gorham 15-minute (Billings and Fowler-Billings, 1975)
Crawford Notch 15-minute (Henderson and others, 1977)
Mt. Washington 15-minute (Billings and others, 1946)
North Conway 15-minute (Billings, 1928)
White Mtn. region (Hatch and Moench, 1984)
New Hampshire (Billings, 1956)

Trip will assemble at the south end of the Dolly Copp Campground west of Route 16, south of Gorham. To reach the assembly point turn west off N.H. Route 16 onto the Dolly Copp Road (paved) about 4.3 miles south of Gorham, N.H., or about 2.5 miles north of the entrance to the Mount Washington Auto Road. Turn at U.S.F.S. sign for Dolly Copp National Forest Campground. After 0.3 mile turn left (south) into the entrance to the Campground. Proceed south on paved road through the campground about 0.9 mile to the assembly point at the south end of the campground.

From assembly point walk south along the Great Gulf Link Trail (marked simply Great Gulf Trail on both the Gorham 15-minute and the Carter Dome 7.5-minute quadrangles) about 1700 feet (520 meters) to outcrops in the Peabody River immediately east (left) of the trail (fig. 10).

STOP 1 Rangeley, Smalls Falls, Madrid, and Littleton Formations (fig. 10). This first exposure in the river is Rangeley Formation. Rocks are well-bedded, gray, slightly rusty weathering mica schist and granulite in which schist beds are 2-10 cm thick and granulite beds are 1-3 cm thick (fig. 5). Some beds are graded and consistently indicate tops are to the west. Small knots of muscovite are interpreted to be pseudomorphs after both staurolite and andalusite. Lenticular pods ("footballs") of calcareous granulite 15-30 cm thick and 0.5-1 meter long are common (fig. 5). Whether they represent concretions or boudinaged beds is a question that can be debated.

From this exposure of Rangeley in the river proceed west through the woods up the slope of hill 2584 (fig. 10). At about elevation 1600 feet, after passing over exposures of well-bedded Rangeley Formation, we will look at an exposure of metamorphosed grit in which the individual clasts are 2-4 mm across (some are slightly larger). Channels of this grit into underlying schist are locally exposed (fig. 11), and all indicate that the section youngs to the west. This grit is shown on Billings and Fowler-Billings' (1975) map as a horizon of quartz conglomerate. We suggest that it supports our correlation of this group of rocks with the Rangeley Formation.

At about elevation 1670 feet in a small gulley are exposures of about 25 meters of section of deeply rusted, slabby, flaggy sulfidic gray quartzite and minor schist. These rocks are typical of the Smalls Falls Formation, to which we assign them.

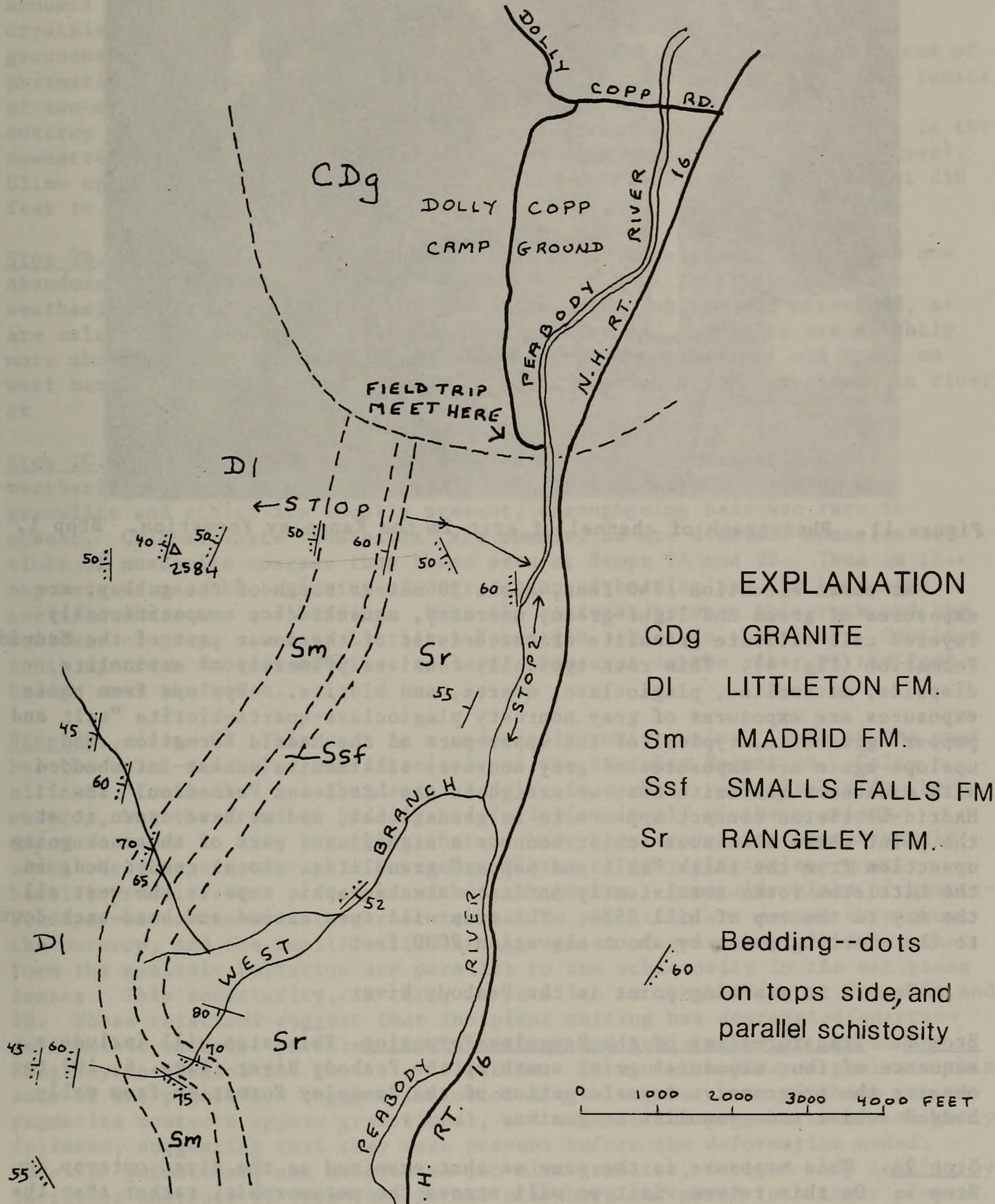

Figure 10. Geologic map of the rocks in the vicinity of Stops 1 and 2.

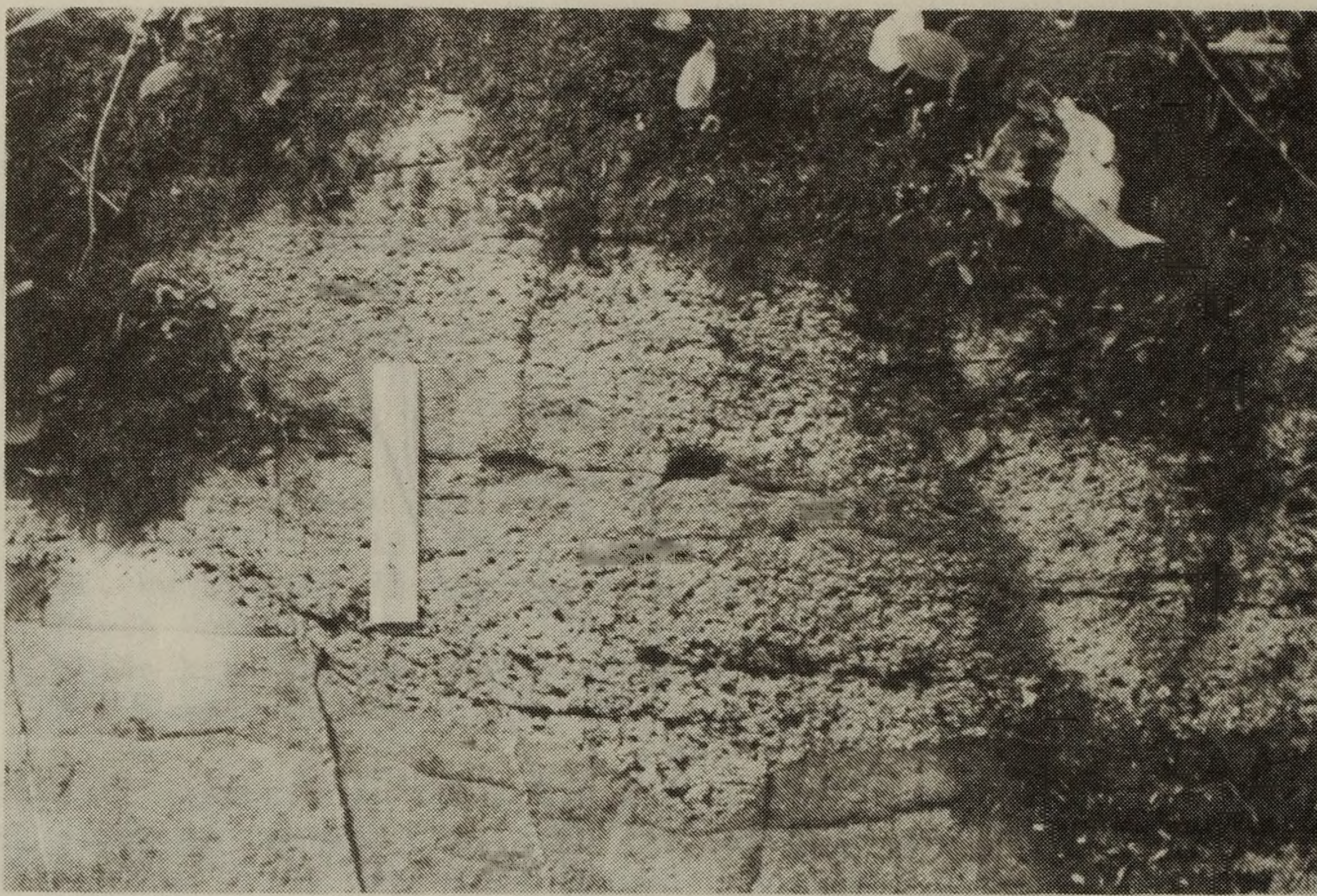

Figure 11. Photograph of channel of grit in the Rangeley Formation. Stop 1.

At about elevation 1740 feet, about 70 meters south of the gulley, are exposures of green and light-green, nonrusty, nonsulfidic, compositionally layered calc-silicate granulite characteristic of the lower part of the Madrid Formation (fig. 4). This rock typically consists primarily of actinolite, diopside, microcline, plagioclase, quartz, and biotite. Upslope from these exposures are exposures of gray nonrusty plagioclase-quartz-biotite "salt and pepper" granulite, typical of the upper part of the Madrid Formation, and upslope again are exposures of gray nonrusty sillimanite schist interbedded with micaceous quartzite that we assign to the Littleton Formation. The Madrid-Littleton contact appears to be gradational, and we have drawn it at the point where aluminous schist becomes a significant part of the rock going upsection from the thick "salt and pepper" granulites. Local graded beds in the Littleton rocks consistently indicate stratigraphic tops to the west all the way to the top of hill 2584. The trip will turn around and head back down to the starting point by about elevation 2000 feet.

Return to starting point in the Peabody River.

<u>Stop 2</u>. <u>Transformation of the Rangeley Formation</u>. This stop will include a sequence of four exposures going south up the Peabody River (figs. 6, 10) to observe the progressive transformation of the Rangeley Formation from well-bedded schist and granulite to gneiss.

<u>Stop 2A</u>. This exposure is the same as that examined as the first outcrop in Stop 1. On this return visit we will stress the metamorphic, rather than the stratigraphic, aspects of the rock. Note particularly the well-preserved nature of the bedding, local graded beds, and the calc-silicate footballs, even though these rocks are sufficiently high in the sillimanite zone that staurolite has gone. Abundant pseudomorphs after staurolite and andalusite range from 1 to 4 cm in length and are composed of muscovite and lesser

amounts of quartz, plagioclase, biotite, and sillimanite. Sillimanite crystals 0.1-0.8 mm long are common in the pseudomorphs, whereas in the groundmass mats of fibrolite have nucleated on biotite grains. Aggregates of prismatic sillimanite are also present in the groundmass. A few small lenses of two-mica granite and pegmatite are present. Walk upstream along the outcrop about 200 feet to a point where the stream forks (actually this is the downstream end of a long thin island in the main body of the Peabody River). Climb up onto the west bank of the river and continue upstream for about 250 feet to

Stop 2B. (fig. 6) Outcrop in the Peabody River immediately beside the now abandoned trail on the west side of the river. Rock is slightly rusty-weathering sillimanite schist and granulite. Bedding is well preserved, as are calc-silicate "footballs". Two-mica granite and pegmatite are slightly more abundant than at Stop 2A. Continue south upstream along old trail on west bank of river about 1350 feet south of Stop 2A to next exposures in river at

Stop 2C. (fig. 6) Rock is again sillimanite rich and slightly rusty weathering, but here it is relatively massive and, although lenses of granulite and schist are locally present, throughgoing beds are rare to absent. Calc-silicate "footballs" are common, as are distinct spangles or clots of muscovite coarser than those seen at Stops 2A and 2B. Thus in this exposure we see the beginning of degradation of bedding and the beginning of gneissic character and banding. Note the contrast between this rock and the boulders of gray, nonrusty Littleton Formation schist in the river. Continue south upstream another 400 feet to large exposures in the river at the foot bridge over the river.

Stop 2D. (fig. 6) This rock is a moderately rusty gneiss. Much of the rust has the brick-red color characteristic of the Rangeley Formation. Calc-silicate "footballs" are abundant. Bedding is nowhere recognizable in the outcrop, but the trend of bedding and foliation in all of the previous exposures seen in Stop 2 suggest that we have been traversing approximately along the same stratigraphic horizon. Blocks of gray plagioclase-quartz-biotite granulite are preserved within the gneiss. Irregular blobs of quartz-feldspar-muscovite-biotite-garnet-tourmaline pegmatite are common throughout the outcrop, and the small lenticular aggregates of quartz and feldspar that form the gneissic foliation are parallel to the schistosity in the schistose lenses. This schistosity, in turn, is parallel to the bedding at Stops 2A and 2B. These relations suggest that incipient melting has segregated quartzo-feldspathic material parallel to the bedding and schistosity of the bedded Rangeley to produce the gneissic foliation. Irregular bodies of gneiss within some of the pegmatites suggest inclusion of gneiss, but some of these gneiss-pegmatite contacts appear gradational, and some of the pegmatites are slightly foliated, suggesting that they were present before the deformation ended. Were the pegmatites, and associated two-mica granites, derived very locally by incipient anatexis or were they formed elsewhere and moved into their present site? And finally, were the metamorphism and granite/pegmatite formation Acadian or Alleghanian events? When we have resolved these interesting questions, we will return to the cars via the Great Gulf Link Trail.

From the original assembly point (mileage 0.0) drive back north out of the campground.

Mileage

0.9 Turn right (east) onto Dolly Copp Road.

1.3 Turn right (south) onto Route 16.

2.1 Entrance to Dolly Copp Picnic Area on right. Continue south on Route 16.

2.9 Outcrop on left (east) side of road at Greens Grant/Martins Location town line is slightly rusty muscovite-spangled gneiss assigned to the Rangeley Formation.

3.8 Small outcrops on right (west) and in river below it are moderately rusty gneiss with calc-silicate "footballs" assigned to the Rangeley, plus pegmatite and binary granite.

4.7 Entrance to Mount Washington Auto Road on right. Continue south on Route 16.

4.8 Small outcrops on left of nonrusty gneiss assigned to the Littleton Formation.

5.1 Enter Pinkhams Grant.

5.2 Outcrop on left of slightly rusty to nonrusty gray gneiss assigned to the Littleton Formation, with much pegmatite and two-mica granite.

5.4 Pull into paved parking on right and park. From a point 130 feet north of the south end of the parking area climb down to the Peabody River for

Stop 3A. Smalls Falls, Madrid, and bounding gneisses at Emerald Pool. The exposures to be examined are on both sides of a small beach about 20 feet wide on the east side of the river. At the south edge of the beach is about 10-15 feet of deeply rusty, sulfidic, flaggy quartzite and schist characteristic of and assigned to the Smalls Falls Formation. South of this rusty quartzite and schist is decreasingly rusty weathering gneiss containing calc-silicate "footballs". At the north side of the beach is about 10 feet of nonrusty, well-banded, light- and dark-green calc-silicate granulite characteristic of the basal part of the Madrid Formation, bounded on the north by nonrusty, gray, muscovite-rich gneiss. The difference between the rusty "football"-bearing gneiss to the south and the nonrusty nonfootball-bearing gneiss to the north is very obvious here. We conclude that the rusty "football"-bearing gneiss is Rangeley and that the nonrusty gneiss is either upper Madrid or lower Littleton. On the basis of the high muscovite content we lean toward lower Littleton. If these interpretations are correct, both the Smalls Falls and the Madrid are less than 20 feet thick at this locality, in contrast to the much thicker sections of both formations seen at Stop 1. Does this mean that Stop 3 was originally closer to the shore (more proximal) than Stop 1 even though Stop 3 appears now to be slightly further east of the axis of the Bronson Hill anticlinorium than Stop 1? Or do the differences in present thickness simply reflect differential tectonic thinning? Of interest also is the observation that although both the Littleton rocks and the Rangeley rocks at this locality have been thoroughly converted to gneiss, the Smalls Falls sulfidic quartzites and the Madrid calc-granulites which must have gone through the same metamorphic conditions have resisted the "gneissification" process. Other examples of this same phenomenon were observed throughout a large area of central eastern New Hampshire and adjacent westernmost Maine.

Climb back up to the cars and cross over Route 16 to the cut on the east side of the highway for

Stop 3B. Projection of the exposure of Smalls Falls and Madrid at Emerald Pool says that this road cut of gneiss is north of them and thus that the cut is in upper Madrid or Littleton. Although some local rusting is visible in the cut, it is not as rusty weathering as most exposures of Rangeley gneiss. Furthermore, the fresh rock is gray, not brown or gray-brown, and calc-silicate "footballs", if present, are extremely rare in the cut. The gneissic banding is highly contorted and swirled, and the gneiss is laced with tourmaline-rich pegmatite and two-mica granite. No trace of original bedding can be detected. Clots of muscovite 1-5 cm across are believed to be pseudomorphous after andalusite. The high percentage of muscovite suggests that the protolith of the gneiss was aluminous schist, and thus we interpret this gneiss to be Littleton Formation rather than upper Madrid.

Return to cars and continue south on Route 16.

5.8 Pull into paved parking area on the right (west) side of highway and walk down onto the outcrops in the river from the north end of the parking area.

Stop 4. Rangeley Formation (?) gneiss. Rock here is moderately rusty-weathering gneissic granite or granitic gneiss with abundant "footballs", some as much as a meter across, that are compositionally layered suggesting original bedding. The "footballs" and their internal layering are oriented in all directions, and some contain folds in their layering. Regional stratigraphic and structural relations say that this rock should be Rangeley Formation, and both the presence of rusting and the calc-silicate "footballs" support this conclusion. The degree of gneissification here is extreme, however, and locally the rock looks like a slightly foliated granite. Does this rock represent introduced granitic melt, with inclusions of Rangeley calc-silicate "footballs", which was subsequently somewhat deformed to produce the foliation, or does it represent intensely metamorphosed and migmatized Rangeley Formation?

Return to the cars and continue south on Route 16.

6.6 Wildcat Mountain Ski area on left.

6.7 Outcrop on right of moderately rusty-weathering two-mica granite and pegmatite.

7.5 Turn right at sign "Pinkham Notch Camp, Appalachian Mountain Club" into parking area and park. From steps up from parking area walk about 1600 feet (500 meters) up the Tuckerman Ravine Trail to wooden bridge over the Cutler River. [300 feet further up trail is outlook for Crystal Cascade--a very pretty waterfall in the Cutler River.] From the wooden bridge go up the river over ledges of two-mica granite and pegmatite and gray post-metamorphic dike rock presumably of the White Mountain Plutonic-Volcanic Suite.

Stop 5A. Smalls Falls and Madrid Formations. 30-45 meters above the wooden bridge on both sides of the river are outcrops of rusty-weathering, flaggy, sulfidic schist and quartzite bounded on the west (upstream) by nonrusty-weathering green calc-silicate granulite. We map these rocks as the top of the Smalls Falls and the basal beds of the Madrid Formation. Beds and parallel schistosity here strike about north-south and dip about 40° west.

Return to the bridge and walk down the river across outcrops of two-mica granite and pegmatite for about 250 feet to

Stop 5B. Smalls Falls and Rangeley Formations. At this point cross contact from two-mica granite into deeply rusty, thinly bedded (1-3 cm), dark-gray, graphitic schist and quartzite containing much pyrrhotite in the fresh rock. We map this rock as Smalls Falls. Stream flows roughly parallel to beds and schistosity in this rock for about 30 meters, then swings southeast across bedding, exposing the contact between the rusty sulfidic Smalls Falls to the west and only slightly rusty well-bedded schist and granulite to the east. This latter rock contains lenticular "footballs" of calc-silicate granulite, and we map it as Rangeley Formation. The contact is exposed and can be pinpointed to an interval of a few inches. About 10 meters of well-bedded Rangeley schist and granulite are exposed before the outcrop runs out downstream. Note that in contrast to the gneiss seen at Stops 2D and 4, the Rangeley rock exposed here retains good bedding. Grading is questionable, but a few beds in both the Rangeley and the Smalls Falls may indicate tops to the west. Across the valley to the east, all of the rocks are intensely gneissic.

Walk about 10 meters north from the river to the Tuckerman Ravine Trail and walk back down the trail to the cars.
This is the end of the field trip.

For the shortest route back to Lewiston, turn left (north) from the Pinkham Notch Camp parking lot onto Route 16 and follow Route 16 north to Gorham, N. H. In Gorham turn east onto Route 2 to Bethel, Maine, and take Route 26 southeast through Norway. At Welchville turn left onto Route 121, which joins Route 202 in Auburn. Cross the Androscoggin into Lewiston and Bates College.