

## NAPPES, GNEISS DOMES AND PLUTONIC SHEETS OF WEST-CENTRAL NEW HAMPSHIRE

by

Tim Allen, Geology Dept., MS 2001, Keene State College, Keene, NH 03435-2001,  
tallen@keene.edu

### Introduction

The area between Keene and Hanover in west-central New Hampshire (NH; Figure 1) is home to some “classic” geology of the Acadian Appalachians. This geology includes (1) fold nappes which transported highly metamorphosed deep-basin sediments over less-metamorphosed shelf sediments, (2) gneiss domes which subsequently deformed (and metamorphosed) these nappes, and (3) large anatectic plutonic sheets, whose emplacement may have been intimately involved with the formation of the nappes. These rocks are encompassed within the Central Maine Terrane (CMT; Eusden & Lyons, 1993), and astride the Bronson Hill Anticlinorium (BHA; Billings, 1956). On this trip, we are primarily interested in the relationships between and among rocks on the BHA and those further east in central NH. The relationship of these rocks (NH sequence) with those to the west (Vermont sequence) is the subject of other trips at this conference (A6, Armstrong *et al.*, 1997.; and C1, Thompson *et al.*, 1997).

### Metasedimentary and Metavolcanic Stratigraphy

An important part of understanding the geology in any region is the ability to recognize the relative sequence in which the rock units were deposited or intruded, from principles of super-position and cross-cutting relationships, but also from fossil assemblages and radiometric dates. On the basis of fossils discovered in the Littleton area, Billings and others (1934, 1935, 1937) were able to define a stratigraphic sequence for the metavolcanic and metasedimentary rocks of the BHA (Figure 2). Once a sequence is established, mapping in adjacent areas can commence by making correlations back to the known rocks. Billings, his students and others proceeded to map much of the rest of NH, with reference to the Littleton section, leading to the publication of a NH state geologic map in 1956. Most of the rocks throughout NH (with a few notable exceptions) are, however, devoid of the fossils needed to corroborate one’s position in the stratigraphic sequence, thus correlations must be made primarily on the basis of lithologic characteristics. Given a high degree of structural complexity, a wide range of metamorphic changes and degrees of weathering, large expanses of intervening plutonic rocks, and significant original sedimentological variations, such correlations (upon which structural and tectonic interpretations hinge) are often problematic.

As the state map was being compiled, Thompson (1954, 1956) discovered structural complications on the BHA, arising from the recognition of distinct stratigraphic units (based on fossil occurrences) in rocks that had previously been mapped as belonging to one formation. This led to a second round of mapping in the region, still referencing the Littleton section, that culminated in the oft-cited 1968 paper by Thompson and others, establishing the current paradigm outlined above.

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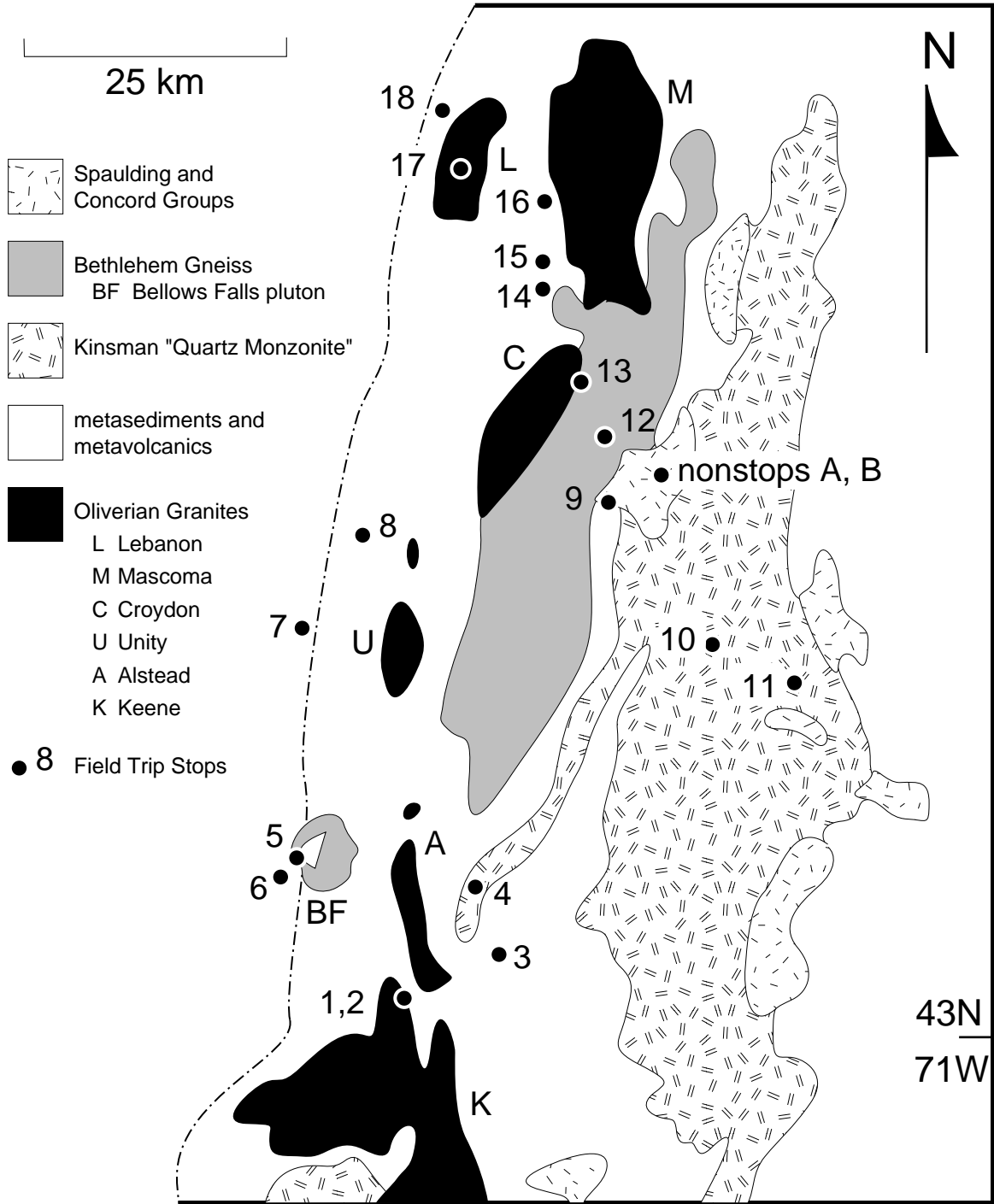
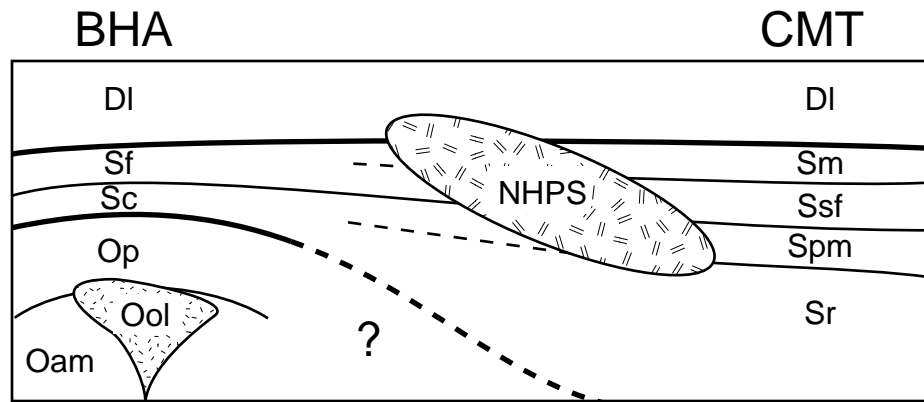


Figure 1: Schematic geologic map of west-central New Hampshire, showing approximate locations of field trip stops



### Bronson Hill Anticlinorium

DI: Devonian Littleton formation, an aluminous marine turbidite (good graded bedding) with quartzites and minor volcanics. This rock is regarded as a flysch deposit preceding the Acadian orogeny, and was derived from a source terrane to the east.

Sf: Silurian Fitch formation, a shelf-type dirty limestone or limey mudstone

Sc: Silurian Clough formation, a clean quartzite and quartz pebble conglomerate, with minor amounts of dirty limestone and greywacke or aluminous shales; locally bearing fossils (Boucot and Thompson, 1958, 1963). The Silurian rocks unconformably overlie the Ordovician rocks, including the Oliverian Granites.

Ool: Oliverian Gneiss, foliated calc-alkaline granites, tonalites and trondjhemites with ages of approximately 442-456 Ma (Naylor, 1969; Zartman & Leo, 1985; Aleinikoff c.f. Lyons et al., 1996).

Op: Ordovician Partridge formation, a carbonaceous and sulfidic black shale, with significant volcanogenic material (abundant coticles). The upper volcanics are probably coeval with the Oliverian granites.

Oam: Ordovician Ammonoosuc Volcanics, bimodal volcanics including basalt and rhyolite flows, tuffs, and pyroclastics. At ~468 Ma old (Aleinikoff c.f. Moench et al., 1995) they have been intruded by the Oliverian granites.

### New Hampshire Plutonic Series

Dcg: Concord Granite, a two-mica granite: 354±5 Ma (Harrison et al., 1987)

Dsg: Spaulding Group, diorite to granite in composition: 392 Ma (Lyons & Livingston, 1977)

Dbg: Bethlehem Gneiss, foliated granite to tonalite, 407±5 to 410±5 Ma (Moench et al., 1995)

Dkqm: Kinsman Quartz Monzonite, tonalite to granite, 413±5 Ma (Barriero & Aleinikoff, 1985)

### CMT metasediments

DI: Devonian Littleton formation, as described at left

Sm: Silurian Madrid formation, a dirty “ribbon” limestone, with occasional black shales, sulfide rich zones, and arenaceous (sandy) rocks containing calcareous concretions.

Ssf: Silurian Smalls Falls formation, includes quartzites, argillites (shales), and limestones, generally black in color, with abundant pyrrhotite and pyrite.

Spm: Silurian Perry Mountain formation, typically impure but well bedded sandstones, sometimes with thinly interbedded (cyclic) shales (rarely showing graded beds). Non-calcareous and usually non-sulfidic.

Sr: Silurian Rangeley formation, includes all kinds of rocks including graphitic and sulfidic black shales, polymict conglomerates (matrix dominant), and arenaceous lenses with calcareous concretions. The Rangeley has been described as an olistostrome (Eusden et al., 1996a, b; Allen, 1996a), and was deposited in a rapidly subsiding basin from a source terrane to the northwest (Moench, 1979).

Figure 2: stratigraphy and rock descriptions for the field trip area

Meanwhile, Lyons, his students, and others working in central NH found that the BHA stratigraphy didn't fit very well with rocks exposed there, and developed a new informal lithostratigraphy for their work (*c.f.* Duke *et al.*, 1988). Billings and others (1941, 1946, 1975) had earlier wrestled with this problem in the Mount Washington-Gorham area further north, and in revisiting this area Hatch and others (1983; Duke *et al.*, 1988) extended to central NH a stratigraphic sequence established in the Rangeley area of Maine (Figure 2; Boone *et al.*, 1970). A key component of this interpretation is the recognition of a change in depositional environments, from a shelf-type on the BHA to a deep closed basin in the CMT. A third generation of mapping was undertaken in western NH to determine the relationship between the stratigraphy of rocks on the BHA and that to the east in central NH (Chamberlain *et al.*, 1988). While the rocks themselves have remained essentially unchanged for several hundred million years, their exposures (too often too few and far between) and our interpretations of them seem to change continuously. The release of a new NH state geologic map is imminent (Lyons *et al.*, 1997), but many interesting problems persist.

### **Intrusive Igneous Rocks**

Billings' state map (1956) also showed several suites of intrusive igneous rocks in this region (Figure 1), including the Oliverian magma series and the New Hampshire Plutonic Series (NHPS), including the so-called Kinsman Quartz Monzonite (KQM), Bethlehem Gneiss, Spaulding Group and Concord Group. At that time, the details of age relationships, the sources of these magmas, and their modes of emplacement were uncertain. Since then, the application of radiometric dating techniques, petrologic and isotopic studies, geophysical and structural investigations, and thermal modelling have vastly improved our understanding of the Oliverian and NHPS rocks.

The Oliverian suite is comprised of granites, tonalites and trondjhemites ranging in age from 442–456 Ma (Naylor, 1969; Zartman & Leo, 1985; Aleinikoff *c.f.* Lyons *et al.*, 1996) which form the core rocks of the *en echelon* mantled gneiss domes making up the BHA, as well as a few discordant intrusions just off the axis of the BHA to the west. These rocks have an internal gneissic foliation paralleling their contacts with wall rocks, giving rise to their (sometimes asymmetric) domal structures. Structures within the mantling strata, including Silurian and Devonian rocks substantially younger than the core gneisses, also exhibit this doming. In addition, metamorphic isograds in these strata commonly wrap around the domes, with the grade of metamorphism increases toward the center of the dome. It is thought that the domes might have been created by diapiric rise (Thompson *et al.*, 1968), resulting from a density inversion between the core materials and the mantling strata (Fletcher, 1972), during the early Devonian Acadian orogeny. Such a model has been demonstrated by scaled gravity tectonic experiments (Ramberg, 1973). Lyons and others (1996) used gravity measurements to confirm the geometry of these domes, and their mushroom-shaped models support reactivated diapiric rise of the core rocks. The metamorphic patterns might be the result of focussed heat flow due to contrasts in thermal conductivity (Allen & Chamberlain, 1989). The cores of the domes may also represent relict volcanic islands of an oceanic island arc (Hitchcock, 1883, 1890 *c.f.* Thompson *et al.*, 1968)—an interpretation which is not incompatible with diapiric rise. One school of thought suggests that

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the docking of the Bronson Hill island arc with the Laurentian continent was responsible for the Taconic orogeny.

The NHPS were emplaced during and after the early Devonian Acadian orogeny. Of these, the Mount Clough pluton and the Cardigan pluton are the most voluminous. Both of these plutons are heterogeneous granitoids, ranging from granite (*sensu stricto*) to quartz diorite but being predominately granodiorite. Although compositionally very similar (Billings & Wilson, 1964), the rocks of these plutons do differ in texture and mineralogy and have been identified as separate units, the Mount Clough pluton being comprised of Bethlehem Gneiss, and the Cardigan pluton of KQM (although no longer considered a quartz monzonite).

Characteristic of the KQM are abundant potassium feldspar megacrysts in a coarse groundmass of quartz, plagioclase, biotite, muscovite and garnet. In some places, garnet becomes the dominant mineral suggesting zones of restite entrained within the magma. The Bethlehem Gneiss is a more homogeneous micaceous granodiorite distinguished from the KQM by a prominent gneissic foliation and the lack of potassium feldspar megacrysts and restites.

Lathrop and others (1994, 1996) made detailed Sr, Nd and O isotopic studies of the Mount Clough and Cardigan plutons to address questions about the nature of origin and source for these rocks. Their results show that, while isotopically heterogeneous and complex, the Bethlehem Gneiss and KQM magmas formed from anatectic melting of the adjacent metasedimentary rocks found in the BHA and the CMT, with very little if any contribution from the mantle. The original sedimentary material in the CMT was enriched in heat producing elements, which when the crust was thickened during the Acadian orogeny, would have provided a sufficient heat source for melting *in situ* (Chamberlain & Sonder, 1990). However, the rocks of the BHA are not so enriched, and so would have required an external heat source or deeper burial for melting.

In addition to the Mount Clough and the Cardigan plutons, several smaller satellite plutons of Bethlehem Gneiss (or KQM) have also been mapped, for example the Bellows Falls pluton. Geophysical investigations, combined with geologic structural constraints, indicate that these plutons are floored by metasedimentary rocks and were probably emplaced as large sill-like bodies, not much thicker than about 2000 meters (Nielson *et al.*, 1976; Kruger & Linehan, 1941). It is thought that several of these plutons may have at one time been connected, covering the entire area; the Bellows Falls Pluton perhaps being an outlier of the Mount Clough Pluton, for example.

It should further be noted that the Bethlehem Gneiss and the KQM cannot be distinguished from one another on the basis of Nd, Sr, or O isotope compositions (Lathrop *et al.*, 1996), nor their major element compositions (Billings & Wilson, 1964). Thus it has been suggested that these two magmas were originated from the same parent material, with their mineralogical differences the result of different metamorphic conditions during their crystallization, or perhaps post-crystallization metamorphism (Chamberlain & Lyons, 1983). Differences in texture could be related to the degree to which the plutons were involved in nappe-stage deformation, the Mount Clough pluton of Bethlehem Gneiss being the further west on the eastern flanks of the BHA, while the Cardigan pluton is within the CMT. Allen proposed (1984, 1985) that the upper-most Fall Mountain nappe may have been aided in its transport to the west by the intrusion of Bethlehem

Gneiss as a sheet along its sole, such that the Fall Mountain outlier and the Bellows Falls pluton are a package. To the east, the Huntley Mountain Spur of the Cardigan pluton is mapped along the sole of the Fall Mountain nappe (Chamberlain *et al.*, 1988).

The Spaulding Group rocks, also syn-orogenic, and the post-orogenic Concord Group, may be associated with migmatite zones (Allen & Chamberlain, 1992; Allen, 1994, 1996a, b) found extensively along the axis of the Central NH Anticlinorium (Eusden *et al.*, 1987; Eusden & Lyons, 1993). Thermal relaxation following the crustal thickening of the Acadian orogeny could have lead to melting of CMT rocks to produce the post-orogenic Concord Group plutons (Chamberlain & England, 1985).

### Structure and Metamorphism

Thompson and others (1968) mapped a series of several west-vergent isoclinal fold nappes lying on and lapping over the BHA. These were recognized on the basis of repeats and inversions of the stratigraphy as well as structural features. The nappes were then deformed and backfolded by the subsequent diapiric-rise of the Oliverian domes (Robinson & Hall, 1979), greatly complicating the structure of the region. Further to the south, thrust faulting was recognized as an intermediate stage between emplacement of the fold nappes and subsequent doming (Thompson *et al.*, 1987). Clearly, not all of the nappes are strictly fold nappes, the upper-most Fall Mountain nappe probably being more of a thrust structure (Allen, 1984, 1985, Chamberlain *et al.*, 1988), with intimate involvement of rocks from the NHPS, as discussed above. On the eastern flanks of the CMT, to the east of the Central NH Anticlinorium, a somewhat similar set of early nappes are recognized, there being east-vergent (Eusden *et al.*, 1987). The Central NH Anticlinorium is interpreted as a “dorsal zone” or “pop-up” structure forming the core of the Acadian orogeny (Eusden *et al.*, 1987; Eusden & Lyons, 1993).

The succession of nappes emplaced over the BHA explained the inversion of metamorphic isograds observed in the region (Chapman, 1953). Each nappe, rooted to the east of the BHA in the CMT, brought deeper, hotter rocks westward with it, over colder previous nappes and autochthonous rocks. Thus rocks of high metamorphic grade were correlated to high tectonic level, in this case later nappes (Thompson *et al.*, 1968). Spear and others (1990, 1992; Kohn *et al.*, 1992) have correlated this scenario with pressure-temperature-time (P-T-t) histories of metamorphism found in rocks from the various nappes, wherein the nappe or thrust emplacement of hot rocks drives metamorphism of underlying colder rocks as the nappe cools. Indeed, they have gone on to postulate the existence of additional nappes (or thrust sheets), that are not exposed anywhere, on the basis of P-T-t histories. Certainly, within the CMT east of the BHA, the metamorphic pattern shows localized regions of high- or low-grade metamorphism (Chamberlain & Lyons, 1983). Chamberlain (1986) has explained these as the result of metamorphism enhanced by sequential episodes of intersecting folds.

### Conclusion

The geology seen here in west-central NH appears to be characteristic of many orogenic belts. Thompson and others (1968) drew analogies between their interpretation of nappes and gneiss domes with similar structures observed in the western Alps, as further developed by Thompson

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and others (1990, 1993). Mantled gneiss domes are present in many deeply eroded mountain belts, including the Alps, Caledonides, Canadian Cordillera and the Appalachians (Eskola, 1949; Allen & Chamberlain, 1989), as well as the Himalaya and Karakorum (Allen & Chamberlain, 1991; Searle *et al.*, 1989; Kundig, 1989). Perhaps their previous experience in west-central NH influenced their thinking, but Allen & Chamberlain (1991) recognized in the Karakorum of Pakistan a very similar scenario to that outlined here: fold-and-thrust nappes inverting the crust and thus metamorphic isograds, with subsequent deformation by gneiss domes of re-mobilized earlier granitic intrusives (Allen, Smith, Zeitler & Chamberlain, unpublished data).

### Acknowledgements

I would like to express my sincere appreciation to C. Page Chamberlain, James B. Thompson, Jr., and John B. Lyons for first showing me these outcrops, and introducing me to and involving me in the study of the geology of my home stomping grounds. Any errors or omissions are mine alone. I'm sure that I have overlooked some important references, and haven't adequately represented all of those cited.

### Road Log

We will depart at 8:00 AM from the intersection of Routes 12 and 12A (Maple Avenue) in northwest Keene, NH. Please carpool, bring a lunch, and have a full tank of gas—enough for at least 150 miles of driving. The best reference map I can suggest would be a NH state highway map—we're going to cover a lot of ground!

### Mileage

- 0.0 Set trip meter to zero at the Rt. 12 overpass over Rt. 12A.
- 0.7 Stoplight, continue on Rt. 12A towards Surry.
- 4.6 roadside outcrops of Oliverian granite in the Keene Dome, view of Surry Mountain (see stops 1 & 2 below) to the east.
- 7.0 Park on the right side, as far over as possible. Leave hazard indicators flashing.

**STOP 1: Border Gneiss of the Keene Dome** (10 minutes) The Oliverian rocks of the Keene Dome are non-peraluminous granodiorite to quartz monzonite, here strongly laminated in the border region of the dome, adjacent to Surry Mountain—a septum of metasediments between the Keene and Alstead domes, in a vertical syncline that folds the axial plane of the nappes. Within the border gneiss, one finds thin mafic layers and quartz “eyes.” Return to the vehicles and continue north on 12A.

- 7.2 Turn right onto River or Gilsum road
- 7.4 Park on the right side, as far over as possible. Leave hazard indicators flashing.

**STOP 2: Surry Mountain Septum** (10 minutes) Exposed here are some of the metavolcanic and metasedimentary rocks of the Surry Mountain septum (see stop 1 above). We may find gedrite-cordierite assemblages in a “garbenschiefer” texture (better exposed up on Surry Mountain); the rock is also reported to contain Na-micas with talc intergrowths (J. B. Thompson, Jr., pers. comm., 1992). Return to the vehicles and continue east.

- 11.4 Stop sign across stone arch bridge, turn left onto Rt. 10 north through Gilsum  
 15.0 Park on the right side, as far over as possible. Leave hazard indicators flashing. Take care in crossing the highway.

**STOP 3: High-Grade Rangeley Formation** (15 minutes) This is Stop 9 of Chamberlain and others (1988) and Stop 10 of Spear (1992). The metamorphic mineral assemblage is garnet + cordierite + biotite + K-feldspar + sillimanite + plagioclase, and represents a localized metamorphic “hot spot.” Chamberlain and others (1988) mapped these rocks as part of the root zone for the Fall Mountain nappe, and Chamberlain (1986) interpreted the high grade of metamorphism to be the result of metamorphism enhanced by sequential episodes of intersecting folds (e.g. syncline + syncline). Spear (1992) mapped these rocks as the upper plate of the Chesham Pond nappe, and interprets the P-T-t path as cooling following thrust emplacement and backsliding. Return to the vehicles and continue north on 10.

- 18.6 Turn left onto Rt. 123 west at Marlow  
 19.9 Park on the right side, as far over as possible. Leave hazard indicators flashing.

**STOP 4: Huntley Mountain Spur** (10 minutes) This is a spur of KQM extending southwest from the Cardigan pluton, mapped as representing the sole of the Fall Mountain nappe (Chamberlain *et al.*, 1988). The rocks are highly foliated. Continue west on 123.

- 23.1 Flashing yellow light, East Alstead. Continue straight through on 123 west  
 24.3 Mill Hollow. Continue through on 123 west  
 27.2 Rt. 12A comes in from the left, continue on 123 west  
 28.0 Rt. 123A comes in from the right, continue on 123 & 12A through Alstead village  
 28.6 Rts. 12A and 123 diverge, turn left staying on 123 west  
 30.6 Stop sign, Rt. 123 turns left, continue straight across onto Cold River Road  
 31.2 (optional stop) outcrops in the river are of a window to the floor of the Bellows Falls pluton  
 31.9 outcrop on far bank of the river are of the Bellows Falls pluton  
 32.5 another river outcrop of the floor under the Bellows Falls pluton, Fall Mountain looms to the right.  
 33.3 Stop sign, intersection with Rt. 123, bear right on 123 west  
 33.5 Stop sign, intersection with Rt. 12, turn right onto 12 north  
 34.5 Stop lights, continue through to just past the railroad yard  
 34.6 Park on the right side, as far over as possible. Leave hazard indicators flashing. Take care in crossing the highway and scrambling down to the outcrops in the river.

**STOP 5: Fall Mountain Nappe and Bellows Falls Pluton** (20 minutes) This is Stop 1 of Chamberlain and others (1988) and Stop 5 of Spear (1992). Gray schists of the Rangeley Formation from the CMT, containing characteristic calc-silicate and amphibolite “pods,” is here in contact with the Bethlehem Gneiss of the Bellows Falls pluton. Note the sillimanite pseudomorphs after andalusite (“turkey tracks”) in the schist, and garnets in the Bethlehem Gneiss associated with assimilated blocks of schist. The CMT rocks on Fall Mountain were clearly of higher metamorphic grade than the BHA rocks surrounding and underneath the Bellows Falls pluton, which implies significant horizontal transport from the root zone in Marlow. Much of this transport and shortening may have been taken up within the Bellows Falls pluton (Allen, 1984, 1985; Spear, 1992). The metamorphic evolution of Fall Mountain shows cooling following emplacement of hot rocks over cold (Allen, 1984); Spear (1992) develops a more complex scenario. The hike up Fall Mountain (Mount Kilburn) via the tower access road is interesting (Stop 2 of Chamberlain *et al.*, 1988). Return to the vehicles and continue north on Rt. 12.



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- 35.1 Stop light, turn left and cross the bridge to Vermont
- 35.3 Stop sign at end of bridge, turn left onto Rt. 5 south
- 35.6 Downtown Bellows Falls, continue south on 5
- 35.9 Stoplight, bear right uphill on Rt. 121 west
- 36.9 Turn left around monument onto Gage St.
- 37.1 Continue straight ahead onto dirt road
- 37.3 Park on the right or left sides, as far over as possible.

**STOP 6: Littleton Formation in the Saxton's River** (20 minutes) This is Stop IV-2 of Zen (1989) and Stop 3 of Spear (1992). *No hammering, please.* The rocks here are a staurolite schist and quartzite showing spectacular graded bedding (grade reversed due to metamorphism) characteristic of a turbidite deposit. The rocks are isoclinally folded and otherwise deformed, with inverted topping directions and several hinges apparent. Much of the deformation may well have occurred during deposition, when these rocks were still soft sediment. These rocks are part of the Skitchewaug nappe, structurally below the Bellows Falls pluton and the Fall Mountain nappe. P-T paths from other outcrops in this section show heating with loading (Spear, 1992), consistent with the emplacement of the hot Fall Mountain rocks over these colder rocks. After getting your photographs, return to the vehicles and continue along the dirt road.

- 37.9 Rejoin Rt. 121 headed back into town
- 38.4 Stoplight at bottom of hill, turn 90° to the left onto Rt. 5 North (to I-91)—*not* back through downtown
- 39.2 Stop sign, continue north on 5
- 42.0 Rt. 5 turns off to the right, Rt. 103 ahead to the left—go straight up the on-ramp to I-91 north
- 46.2 first view of Mount Ascutney, a remnant volcano associated with the White Mountain Magma Series, straight ahead For more information, see Schneiderman (1988).
- 48.6 Exit at Springfield
- 48.9 Stop sign at end of ramp, turn left to go north on Rt. 5 & east on Rt. 11
- 49.3 Turn left onto Rt. 5 north, just before the toll bridge
- 50.6 Park in the fork on the right.

**STOP 7: Fossiliferous Clough Quartzite of the Skitchewaug Nappe** (10 minutes) This is Stop IV-1 of Zen (1989). *No hammering, please.* These rocks have been highly deformed, and metamorphosed to the staurolite zone, and yet calcareous bands within the quartzite contain recognizable fossils and fossil fragments, including crinoid stems, corals, and brachiopods (Thompson, 1954; Boucot & Thompson, 1963). Similar fossils have been found in several other locations within the Clough Quartzite throughout the region, such that it is a good Silurian marker and very useful in deciphering the stratigraphy and structure of the BHA. Continue north on 5.

- 54.7 Rt. 143 comes in from the left, continue north on 5
- 60.3 Yield sign, turn right towards Claremont
- 61.2 Stoplight at intersection with Rt. 12A, continue straight towards Claremont
- 63.6 Turn left, following sign for Newport and Sunapee (*not* downtown)
- 64.2 Stoplight, continue straight through
- 64.6 Park in turnout to the right, just before the stoplight at intersection with Rt. 120. This may well be our Lunch Stop. Take care in crossing the highway to roadcuts at the intersection.

**STOP 8: Blue quartz eyes in pyroclastic volcanics** (15 minutes) The blue quartz eyes, from the exsolution of very fine rutile crystals within the quartz, are indicative of very high temperatures, but these rocks have only been metamorphosed to biotite zone (low grade). This

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rock represents a high-temperature volcanic ignimbrite, with lenticles of pumice, lapilli, etc...; probably equivalent to the Post Pond Volcanics in Vermont. The coarse pyroclastic sequence is best visible on a water polished surface (cross back to the riverside park). A slaty cleavage has been superposed, creating a lineation in the rock. Look down-dip to see these features. (J. B. Thompson, Jr., pers.comm., 1992) Return to vehicles and continue towards Washington Street.

- 64.8 Stoplight, turn left onto Rts. 11 & 103 east (Washington Street, Claremont). Continue through all the stoplights along this strip.
- 71.7 outcrops of Bethlehem Gneiss
- 73.7 Stoplight, go straight
- 74.1 Stoplight at intersection with Rt. 10 (Main Street, Newport), turn left to follow Rts. 11 & 103 east
- 74.2 Turn right following sign for Rts. 11 & 103 east
- 74.4 Yield sign, continue onto Rts. 11 & 103 east
- 77.3 Rts. 11 & 103 diverge (Guild), bear right to stay on Rt. 11 east toward Sunapee
- 79.7 Rt. 103B on the right, continue straight
- 79.8 Flashing yellow for Sunapee Harbor, continue straight
- 80.0 Turn left onto Sargent Road, park on dirt track by Sunapee Fire Station. Take care in crossing the highway.

**STOP 9: Spaulding Quartz Diorite and pegmatite autoliths** (15 minutes): The Spaulding, dated at 392 million years, somewhat foliated, cross-cuts the KQM and the Bethlehem Gneiss, thus a late tectonic intrusive. Here it is cut by pink pegmatites (with perthitic feldspar). The pegmatite and the Spaulding are magmatically related, and here you can see “autoliths” of the pegmatite within the Spaulding and vice-versa. At the north end of the outcrop are true xenoliths (as opposed to autoliths) of the country rock, including the KQM. In some places the KQM has become disaggregated, with incorporation of feldspar xenocrysts into the Spaulding. This represents an igneous breccia, with flow foliation, resulting from explosion venting of fluidized magma. (J. B. Lyons, pers. comm., 1988). Return to the vehicles and enter Rt. 11 heading west from the fire station.

- 80.3 Flashing yellow for Sunapee Harbor, continue straight
- 80.4 Turn left onto Rt. 103B south
- 81.0 small quarry operation, with antique steam tractor on left
- 82.8 View of Mount Sunapee Ski Area ahead through trees.

The ridge extending south-southwest from Mount Sunapee to Lempster Mountain, and north from Sunapee to Mount Cardigan, represents a septum of metasediments (interdigitated with the Huntley Mountain Spur) caught between the Cardigan pluton to the east and the Mount Clough pluton to the west. Mapped by Dean (1976) based on the BHA stratigraphy, a new look at these rocks with insights from the CMT and other areas, may help tie together the stratigraphy and structure of southwestern NH with that to the north and west, as well as furthering our understanding of the relationships between the Cardigan and Mount Clough plutons.

- 83.8 Stop sign, proceed across and around the Mount Sunapee Traffic Circle, leaving on Rt. 103 east.
- 84.7 outcrops of KQM injected with multiple dikes of aplite
- 85.1 outcrops of KQM with rafts of metasediment
- 86.2 Newbury Harbor
- 86.3 Intersection with Rt. 103A

***Alternate Route (shortcut):***

- 86.3 Turn left onto Rt. 103A north

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- 88.7 Pull off on the *LEFT* side of the road to park just before Ramblewood Circle. Leave hazard indicators flashing, and take care in crossing the highway. Across the road is an interesting outcrop of the KQM.
- 89.2 Rt. 103A bears to the left, continue following it to the north.
- 91.3 Turn right onto King Hill Road, towards I-89 southbound
- 92.3 Bog Road takes off the left, continue on King Hill Road
- 92.5 The author's childhood home is on the left
- 93.0 View of Mount Kearsarge ahead (see comments at mile 99.0).
- 93.7 Under the highway, turn left on to entrance ramp for I-89 northbound. Pick up the road log at mile 109.7, and subtract about 16 miles from subsequent mileage readings.

**Original Route (the long way):**

- 86.3 Rt. 103A goes off to the left, continue east on Rt. 103
- 86.8 more outcrops of KQM
- 87.1 Mountain Road on the right, continue on 103 east. K-Ar dating of kaolinite gouge from the Newbury Fault zone exposed here yielded an age of 160 Ma (J. B. Lyons, pers. comm., 1988)
- 89.1 Flashing yellow, South Newbury
- 91.4 Park on right side of road, as far over as possible. Leave hazard indicators flashing. Take care in crossing the highway.

**STOP 10: Restites in the Kinsman Quartz Monzonite** (15 minutes) This is Stop 10 of Lyons (1988) and Stop IV-5 of Zen (1989) Garnetite (garnet-cordierite-biotite-plagioclase-quartz) pods and layers within the KQM represent restites of xenoliths of Littleton schist undergoing anatexis, anatectic melting of CMT and BHA metasediments being the source of the magma making up the pluton (Lathrop *et al.*, 1994, 1996). The KQM is here a granodiorite with the characteristic K-feldspar megacrysts and a mineral assemblage including sillimanite (fibrolite) as well as garnet and cordierite. The Cardigan pluton is at its maximum preserved thickness of 2.5 km here, based on gravity studies (Nielson *et al.*, 1976; Lyons, 1988). The Cardigan pluton to the south of here was briefly considered as a potential host for the disposal of high-level radioactive wastes (Department of Energy, 1986, p. 3-435). Return to the vehicles and continue east on 103.

- 91.7 Stoplight at intersection with Main Street, Bradford. Continue straight on Rt. 103 east
- 92.4 Stoplight at intersection with Rt. 114, continue straight on Rt. 103 east to Warner
- 98.7 Park on right just before onramp to I-89 south, as far over as possible. Leave hazard indicators flashing. Take care in crossing the highway.

**STOP 11: Kinsman Quartz Monzonite with garnets** (15 minutes) This is Stop IV-6 of Zen (1989). Here we are near the eastern edge of the Cardigan pluton, in a garnetiferous phase of KQM, with garnet rimmed or replaced by biotite, and K-feldspar megacrysts partly sericitized and mantled by myrmekite. The Cardigan pluton does not appear to have been initially homogeneous melt (Clark & Lyons, 1986; Lathrop *et al.*, 1994, 1996). The occurrence of garnet within the pluton has been interpreted as both metamorphic (Chamberlain & Lyons, 1983) and igneous (Clark & Lyons, 1986), with evidence now favoring igneous garnet (Lyons, 1988). Return to vehicles and continue east on 103 under the interstate.

- 99.0 Turn left on to ramp for I-89 north, and take in the view of Mount Kearsarge

Mount Kearsarge (Lyons, 1988), Mount Monadnock to the south (P. J. Thompson, 1988) and Mount Washington to the north (Eusden *et al.*, 1996a, b), are all composed of highly erosion-resistant members of the Littleton formation, noted on each summit for the occurrence of "turkey

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track” sillimanite pseudomorphs after andalusite and dramatic cyclic graded bedding of quartzites and schists. These peaks essentially mark the trace of the Kearsarge-Central Maine synclinorium.

- 105.9 View of Mount Kearsarge over right shoulder (exit 10, continue N on I-89)
- 109.7 outcrop of abundant pegmatite (exit 11, continue N on I-89)
- 111.0 Slow down and look out the vehicle to the left.

**NONSTOP A: “Mount Radon,” New London** Over the years since the interstate was built, weathering had destabilized the high roadcuts ahead, at NONSTOP B. Several years ago, the NH Department of Transportation undertook a blasting program to re-stabilize this roadcut. It was discovered after the roadcut was first opened that the rock was highly radioactive, as the joint surfaces were covered with ore-grade Uranium deposits. Most of this “ore” had been used as fill for the roadbed. During the re-stabilization effort, great care was taken to keep the dust down and the material removed from the cut was landfilled here in the median strip. This location was chosen in part because it was hoped that any Uranium leached from the rock would be trapped in the highly-reducing environment of the organic sediments of the Messer Pond - Clark Pond bog system down gradient (off to the right; we pass over “Bog Road” ahead). However, much of the Uranium had already been leached from these rocks due to the lowering of the water table resulting from the initial road cut (Dick Lane & Gene Boudette, oral comm., 1995). The author’s childhood home is about 3/4 of a mile through the woods to the left!

- 111.3 overpass over Bog Road
- 113.0 Slow down and look out the vehicle to the right.

**NONSTOP B: Sunapee pluton, New London** Note that when the roadcuts were re-stabilized several years ago, the entire height of the cut was blasted in a single lift, for which special permission was needed from the Federal Highway Administration (Dick Lane & Gene Boudette, oral comm., 1995). The rocks are two-mica granite of the Concord Group. This outcrop is famous for the heavy coating of joint faces with Uranium phosphate minerals. This mineralization is presumably represents late hydro-thermal mobilization, and is focussed on fractured zones—it has now largely been weathered away. Zircons from this rock show little evidence of inheritance, but Uranium loss, with an age of crystallization of  $354 \pm 5$  Ma (Harrison *et al.*, 1987), about the right timing to be the result of anatectic melting following thermal relaxation after tectonic loading (Chamberlain & England, 1985). The pluton intrudes both the Mount Clough pluton and the Cardigan pluton, cutting off the Sunapee Septum of metasediments. As a young boy, the author used to accompany his father who would practice rock-climbing on these roadcuts before the Interstate was officially opened.

- 114.3 outcrop of Bethlehem Gneiss
- 115.6 Take Exit 12A for Georges Mills
- 115.8 Stop sign at end of ramp, turn left under highway
- 116.0 Turn right onto Stoney Brook Road
- 116.5 Park on left, just under the highway.

**STOP 12: Bethlehem Gneiss of the Mount Clough pluton** (10 minutes): A syn-kinematic intrusion inside the Skitchewaig Nappe, and/or below the Fall Mountain Nappe. Granite to tonalite in composition, although highly variable. The rock has a foliation that may be due to flow, and may also be related to its interactions with the nappes. Continue northwest on Stoney Brook Road.

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118.3 View ahead of the white ledges over Grantham

These ledges, well-viewed from the interstate, are outcrops of the Clough Quartzite in the mantle of the Croydon dome. Samples from these outcrops contain well preserved brachiopod and other fossils (J.B. Thompson, Jr., pers. comm., 1984). Contained within the boundaries of the private Blue Mountain hunting reserve, they are now essentially inaccessible.

- 120.9 Stop sign, bear to the left on the Grantham–Springfield Road
- 122.0 Stop sign, turn right onto Rt. 10 north
- 122.6 Pass under I-89, continue straight ahead on Old Route Ten
- 122.9 View to the left of the gray ledges, opposite the entrance to the Eastman development
- 125.1 Turn left onto Miller Pond Road, under the highway
- 125.2 Park just past the underpass in class VI road.

**STOP 13: Mantle of the Croydon Dome** (10 minutes) The rocks here are Ammonoosuc Volcanics exposed at the north end of the Croydon dome, rich in sulfur (pyrrhotite, sphalerite has been found within the Blue Mountain preserve). The core rocks of the Croydon dome, exposed in interstate road cuts a few hundred feet to the south are a true trondhjemite—a high-sodium granitoid, completely lacking in K-feldspar—whatever K there is is tied up in biotite and/or hornblende (J.B. Lyons, pers. comm., 1988). Backtrack to Old Route Ten.

- 125.3 Turn left to continue north on Old Route Ten
- 127.7 Turn right and pass under highway
- 127.9 Turn left up on ramp to I-89 north
- 128.1 outcrops on the right of Bethlehem Gneiss
- 128.4 outcrops on the right of Bethlehem Gneiss
- 128.7 outcrop on the right of the core of the Skitchewaung Nappe
- 130.0 Exit off I-89 at Montcalm
- 130.2 Stop sign at end of ramp, turn left under highway
- 130.3 T-intersection, turn left (now heading south)
- 131.4 Park in turnaround at dead end by the Humane Society

**STOP 14: Skitchewaung Nappe** (30 minutes). This is Stop 1 of J.B. Thompson, Jr. (1988), and you are referred to that source for detailed information about these rocks. We'll make a traverse along the bike path, looking at outcrops of the BHA stratigraphic sequence (Figure 3). The outcrops of Bethlehem Gneiss where we got onto I-89 at Exit 14 are an outlier of the Mount Clough pluton, separated by the Grantham Fault. It appears to be folded into the core of the Skitchewaung Nappe. With a sharp eye, fossils can be observed in the glacially polished surface at the top of northernmost outcrop of the Clough (Stop 14-A in Figure 3). *No hammering please!* Return to the vehicles and head back the way we came.

- 132.6 Turn right to pass under the highway
- 132.7 Turn left on to the ramp to I-89 north, park on right side (as far over as possible) before merging with highway. Leave hazard indicators flashing.

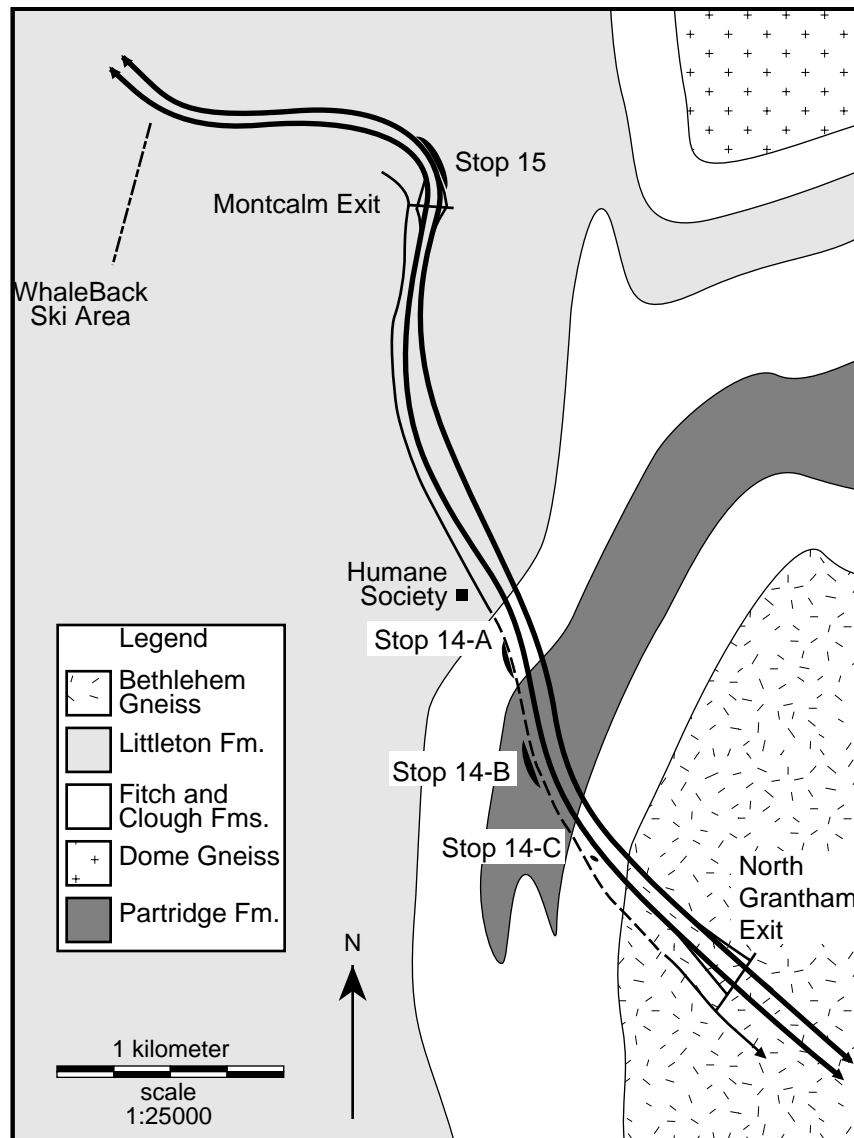


Figure 3: Geology of the Skitchewaugh Nappe between North Grantham and Montcalm, after J. B. Thompson, Jr. (1988), showing the locations of Stops 14 and 15 of this field trip.

**STOP 15: Littleton Formation** (10 minutes) This is Stop 2 of J. B. Thompson, Jr. (1988). A thick section of Littleton schist (Figure 3), rich with staurolite crystals—some with cruciform twins—giving the rock a lumpy appearance. Few of the crystals are very fresh, most showing incipient alteration. Bedding is obscure, although the rock has good foliation and a dome-stage mineral lineation. Continue onto I-89 northbound.

136.0 If planning to visit optional stop 16, exit off I-89 at Rt. 4 east for Enfield, otherwise continue on I-89 northbound.

**STOP 16: (optional) Mantling Strata of the Mascoma Dome on Moose Mountain**

136.3 Yield sign at end of ramp, bear right onto Rt. 4 east

137.9 Intersection with Rt. 4A, continue straight ahead on 4 east across the Mascoma River

138.9 Turn left onto Rudsboro Road

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139.8 Turn around and park in turnout on left

*This is Stop 6 of J. B. Thompson, Jr. (1988). We will hike uphill through the woods to fields, across the fields, through a sugarbush and more woods to open ledges along the ridge top. Along the way, we will cross over gray schists of the basal Littleton and calc-silicates of the Fitch. Fossils have been found here in the Clough. The ledges are pink quartzite, and from them we can look out to the east over a steep drop down to the Oliverian granite of the Mascoma dome. Return back down to the vehicles, and return down Rudsboro Road towards Mascoma Lake.*

140.7 Stop Sign, turn right onto Rt. 4 west

141.8 Rt. 4A again, continue of Rt. 4 west

143.2 Bear right on to ramp to I-89 northbound; rejoin field trip route and add about 7 miles to subsequent mileage readings.

**Original Route:**

138.2 Exit off I-89 for Lebanon & Hanover

138.5 Yield sign at end of ramp, bear right onto Rt. 120 north

138.7 Stoplight, continue straight on 120 north

139.1 Stoplight, continue straight on 120 north

140.0 Park on right side of road, as far off as possible, or just ahead at the tire dealer. If on Rt. 120, leave hazard indicators flashing and beware of traffic.

**STOP 17: Oliverian Granite of the Lebanon Pluton** (10 minutes) The Lebanon pluton is a discordant pluton of Oliverian granite in the core with an envelope of granodiorite to tonalite. It is found west off the main axis of the BHA, intruded into Partridge Volcanics. Structural and gravity studies show that it is an inverted cone shape plunging to the north-northwest, deforming the Cornish nappe (Lyons *et al.*, 1996). Gravity anomalies suggest that the pluton must be underlain by a sizable body of subjacent metagabbro—represented by three small bodies of metagabbro which outcrop along the western margin of the pluton. Metamorphism in the adjacent Partridge Formation has been attributed to contact metamorphism associated with original magma intrusion (Spear *et al.*, 1984); focussed heat flow due to contrasting thermal conductivities (Allen & Chamberlain, 1989); and upward domal transport of deeper, hotter rocks (Lyons *et al.*, 1996; Allen & Chamberlain, 1989). Here, the Lebanon granite includes mafic enclaves and pyrite. Once quarried for building stones, the pyrite lead to rust stains on the resulting blocks, and quarrying was abandoned. Return to the vehicles and continue north on 120.

140.5 Stoplight at top of hill (entrance to DHMC), continue straight on 120 north

141.4 Stoplight (entrance to DHMC and Jesse's), continue straight on 120 north

141.8 Stoplight, bear to the left staying on 120 into Hanover

142.6 Stoplight at the Hanover Food Coop, bear to the right staying on 120 north

143.1 Stoplight, turn left onto Rt. 10 south (East Wheelock St)

143.2 Turn right up Dartmouth driveway

143.4 Dartmouth Observatory

143.5 Park wherever there is a spot. Climb down to outcrops alongside building housing Dartmouth College's Department of Earth Sciences and the Kresge Physical Science Library.

**STOP 18: Metavolcanics in mantle of Lebanon Dome**— a green chlorite-amphibolite, with well-developed foliation, apparently meta-basalt.

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## End of Trip

To get to Pico from here, go down and around the Dartmouth Green to the head of Main Street. Turn right onto West Wheelock Street and follow this across the Ledyard Bridge to Norwich. Take I-91 south to I-89 north to Route 4 west. It is approximately 45 miles.

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