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The ordovician to carboniferous bedrock geology and cooling history of the Bronson Hill and Central Maine Belts, Presidential Range, New Hampshire

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THE ORDOVICIAN TO CARBONIFEROUS BEDROCK GEOLOGY AND COOLING HISTORY OF THE BRONSON HILL AND CENTRAL MAINE BELTS, PRESIDENTIAL RANGE, NEW HAMPSHIRE

by
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INTRODUCTION

This trip will examine the rocks of the Acadian Orogeny in the transition between the Silurian and Devonian turbidites of the Central Maine Belt and the Ordovician volcanics and dome rocks of the Bronson Hill Belt. The field trip will begin with a traverse down the West Branch of the Peabody River in Pinkham Notch where wonderful exposures of the Littleton, Madrid, Smalls Falls and Rangeley Formations are found. Aspects of the stratigraphy, structure and metamorphism will be presented. The trip will then cross over the Pinkham B Road (Dolly Copp Road) and, en route, stop at exposures of the Carboniferous two-mica Peabody River granite. Along the Route 2 valley in Randolph, NH, the trip will finish with a traverse across the Oliverian Jefferson Dome and Ammonoosuc Volcanics. Newly discovered mylonites, constrained by new microprobe monazite ages, will be shown and discussed. New apatite fission track cooling ages will be discussed at key outcrops on the entire trip. Expect about 5.5 miles of some rugged walking with stream traverses. Bring a huge lunch and water! Figure 1 shows the location of the stops on the topographic map of Washburn (1988).

Previous Work

The Presidential Range bedrock geology was first mapped in any detail by the Billings in the late 1930's and early 1940's. In keeping with good NEIGC historical tradition, we will pay a visit to the Dartmouth Outing Club's Billings Cabin where Marland and Katherine spent summers in Randolph while they mapped. Their efforts culminated in several papers and the 1979 Geology of the Mount Washington Quadrangle report published by the New Hampshire Department of Resources and Economic Development (Billings et al., 1979). Hatch and Moench (1984) made many important contributions to the region, most notably the extension and correlation of the Rangeley, Maine, stratigraphy across the border into New Hampshire, through the Presidential Range, and beyond to the south. The New Hampshire bedrock geologic map (Lyons et al., 1997) updated these previous efforts and more or less retained the contacts shown by the Billings' and the stratigraphic assignments of Hatch and Moench (1984).

Bedrock Mapping

The 18 year bedrock mapping campaign conducted by Eusden and Bates undergraduates has been completed and our new map has been in the hands of the New Hampshire State Geological Survey for a couple of years now. We hope the NHGS will eventually make the map available to the public! In the meantime, we are preparing a replacement to the Mount Washington Quadrangle report by the Billings and that is well underway. By mapping at a scale of approximately 1:3,000 we were able to distinguish the different lithologic members of the various formations exposed here. This in turn has enabled us to sort out the multiple phases of Acadian deformation and metamorphism. We have also used both thermal ionization mass spectrometry and electron microprobe analyses to obtain U-Pb radioactive age dates for many plutons and metamorphic events throughout the Presidential Range. We have published a couple of papers (Eusden et al. 1996 and 2000), three field guides (Eusden et al. 1996a, Allen et al.2001, and Eusden et al., 2006a), our new map (Eusden, 2006), and a multitude of GSA abstracts with the most germane to this trip being Anderson et al. (2001), Dupee et al. (2002), Eusden and Anderson, 2001, Larkin and Eusden (2004), Rodda and Eusden (2005) and Foley and Eusden (2009). Following in the footsteps of Charlie Guidotti's M.S. student Ellen Wall (Hatch and Wall, 1986), Orono Ph.D. Wes Groome has recently made many important contributions towards our understanding of the strain history during porphyroblast growth in the Littleton Formation as well as the development and strain patterns of the migmatites in the Rangeley Formation (Groome et al., 2006 and Groome and Johnson, 2006).

Figure 1. Location map showing stops and meeting point parking lot (P). Base map from Washburn (1988). Inset terrane map modified from Hibbard et al. (2007). Stops 1-3 and Stop 6 require hiking while the rest are roadcuts.

COOLING STUDIES

Roden-Tice and others have made several important contributions toward our understanding of the post orogenesis thermal evolution of the northern Appalachians using apatite fission-track (AFT) geochronology (Roden-Tice and Wintsch, 2002, West and Roden-Tice, 2003, Roden-Tice and Tice, 2005; West et al., 2008 and Roden-Tice et al., 2009). Mesozoic unroofing of the Acadian Orogen is complex and AFT ages reveal the following: 1) widespread Cretaceous cooling from 70 to 140 Ma; 2) normal sense reactivation of orogen parallel faults (e.g. Ammonoosuc Fault) at circa 80 Ma; and 3) the presence of a long-lived thermal anomaly in the Cretaceous (Great Meteor Hotspot) centered over central New Hampshire. The latter is defined by a northeast trending zone of young Late Cretaceous (70-118 Ma) AFT ages the result of regional extension and unroofing. Unroofing rates of 0.055 to 0.118 mm/yr suggest a period of renewed, rapid uplift in the Early to Late Cretaceous following the intrusion of the White Mountain Magma Series (Roden-Tice et al., 2009).

Aside from one AFT age of 85 Ma by Roden-Tice et al. (2009) from the Oliverian Jefferson Dome in Randolph, NH, the only other cooling study done in the Presidential Range was by Eusden and Lux (1994). Using the $^{40}Ar/^{39}Ar$ relief method, they report that muscovite ages increase systematically from the bottom to the top of the Presidential Range along the Auto Road, the oldest (Mount Washington summit, elevation 6288 ft) being 304 ± 3 Ma and the youngest (Route 16, elevation 1350 ft) 274 ± 3 Ma. The age and elevation data yield a very slow exhumation rate of 0.04 mm/yr in the Late Carboniferous to Early Permian (Eusden and Lux, 1994). With this in mind, last summer the authors resampled the same sites used in the Eusden and Lux (1994) study in an effort to constrain the lower temperature portion of the cooling history and calculate exhumation rates to compare to those determined by Roden-Tice et al. (2009).

The complete suite of samples has not yet been counted, however samples from the base and top of the Auto Road are reported here in this guidebook. Apatite fission-track ages of 152 Ma and 101 Ma have been determined for the summit area of Mount Washington and the base of the auto road (elevations of 6200 and 1674 ft., respectively). The AFT age of 101 Ma for the sample from the base of the auto road is within error of AFT ages from the surrounding White Mountain region which range from 85 to 99 Ma (Roden-Tice et al., 2009).

The difference in the AFT ages between the summit and base of Mount Washington is consistent with that given by Eusden and Lux (1994) for the same locations using $^{40}Ar/^{39}Ar$ muscovite ages and yields an unroofing rate of 0.027 mm./yr from the Late Jurassic to Early Cretaceous. This unroofing rate is comparable to that determined for High Peak summits and fault valleys (areas of maximum relief) in the Adirondack Mountains of northern New York (0.033 mm/yr) during the same time period using thermal history modeling of apatite fission-track length distributions (Roden-Tice and Tice, 2005).

BRONSON HILL ANTICLINORIUM

The unusual aspect of the Bronson Hill Anticlinorium in this part of the Appalachians is that the region between it and the Central Maine Belt lacks any of the mantling shelf facies such as the Silurian Clough and Fitch Formations. Instead, there is an abrupt boundary separating migmatized Rangeley Formation from the Ammonoosuc Volcanics and another separating Ammonoosuc Volcanics from the Oliverian Jefferson Dome. The abrupt boundaries show shear fabrics and provide much food for regional tectonic thought regarding a possible root zone for the embattled Piermont-Frontenac Parautochthon and the overall nature of the Ammonoosuc-Oliverian contact (intrusive, tectonic, both?). Lyons et al. (1997) report an age of circa 450 Ma. for the Jefferson Dome (the largest of the Oliverian domes) and several ages for the Ammonoosuc Volcanics ranging from 461-444 Ma.

The most significant result of our mapping has been to better define the contact between the Ammonoosuc and Oliverian Jefferson Dome. Over the years, the nature of the Ammonoosuc-Oliverian contact has been debated with some researchers supporting an intrusive contact (Billings et al., 1979; Moench and Aleinikoff, 2003) and others a fault contact (Hollocher, 1993; Kohn and Spear, 1999). In the Randolph valley, Billings et al. (1979) show the contact to be delineated by silicified pods that line up to form a late (presumably Mesozoic) brittle fault. Dupee et al. (2002) and Foley and Eusden (2009) were able to subdivide the Ammonoosuc Volcanics into a variety of different lithologic units including amphibolite, rusty gneiss and gray gneiss (Figure 2). They have not been able to easily correlate this new subdivision to the upper and lower Ammonoosuc designations on the state map (Lyons et

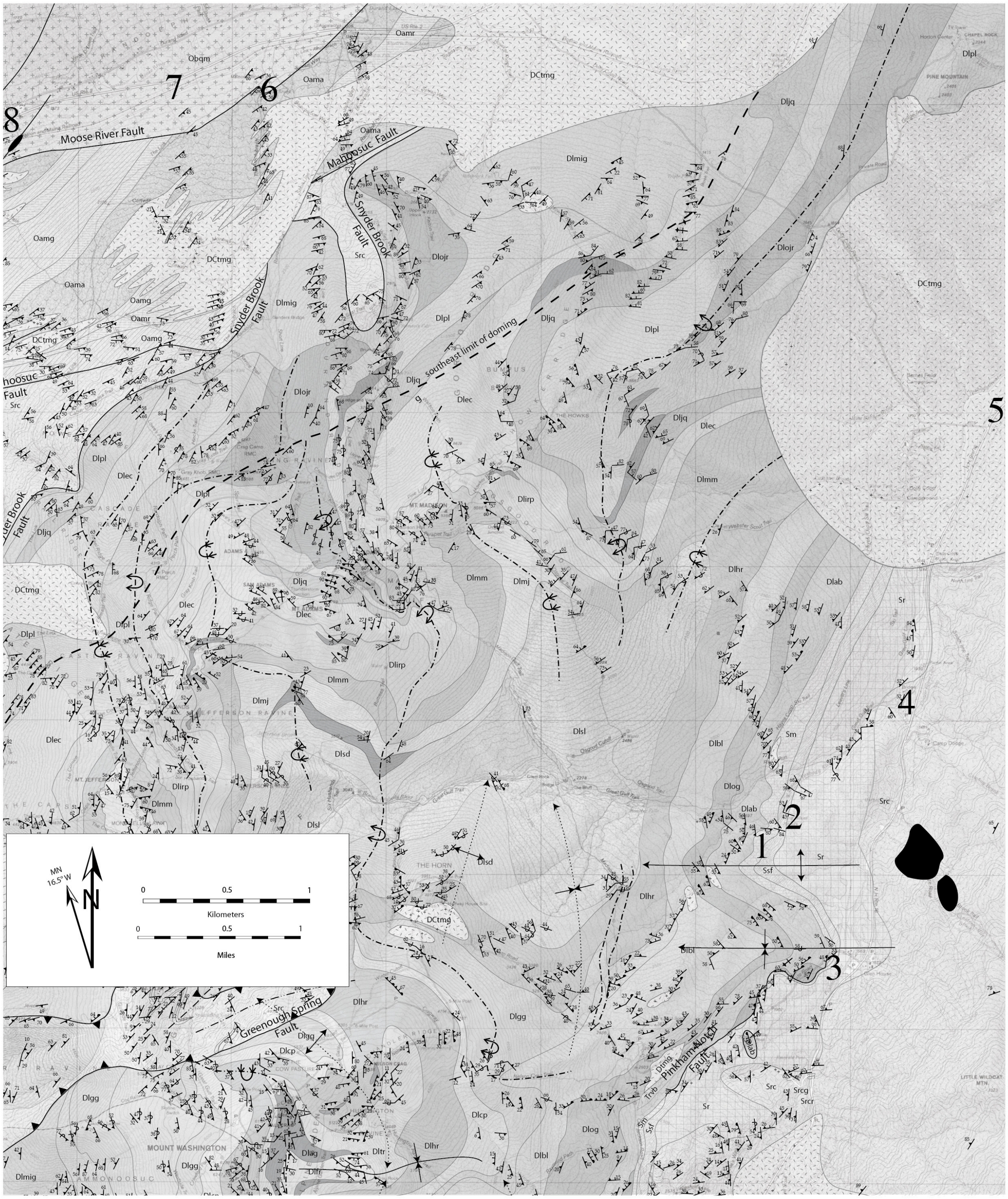

Figure 2. Bedrock geologic map of the Presidential Range after Eusden (2006).
Patterns and symbols are explained on Figure 3. Field trip stops shown with large black numbers.

IGNEOUS ROCKS

LATE DEVONIAN TO EARLY CARBONIFEROUS

DCtmg

DCtmg - Two mica granite
A medium- to coarse-grained, light gray to white, two mica granite. The granite is generally not foliated but in places zones of foliation exist. Zones of coarse-grained pegmatitic granite, pegmatite, and fine-grained aplite are also included in this lithology. Principally forms numerous small sills, dikes, veins, and random lenses, to small to map, intruding into gneissic metasedimentary rocks. Also occurs as scattered, small, sill-like, plutons up to 2 kilometers in length. Lenses of well-foliated schist and or gneiss are commonly found within these plutons.

EARLY DEVONIAN

Dwd - Wamsutta Diorite
A medium-grained, dark gray diorite. Zones of well foliated diorite are common. The one occurrence of this pluton is in the Great Gulf region at Wamsuttta Falls.

METASEDIMENTARY ROCKS

DEVONIAN

Dl - Littleton Formation - general description
The Littleton Formation consists of dark gray schists commonly with interbedded quartzite layers of varying thickness and abundance. The schists are composed of quartz, muscovite, biotite, plagioclase, chlorite, sericite, sillimanite, ilmenite, tourmaline, staurolite, garnet, and trace monazite, and zircon. Andalusite, generally completely pseudomorphed by muscovite, sillimanite, and sericite, is common in the schists forming lumps, approximately 1 to 3 cm in diameter, and elongate aggregates, from 1 to 15 cm in length, with rare relict cores of fresh pink andalusite and/or chiasolite crosses. Foliation in the schists is well developed and is usually parallel to bedding. In F1 fold hinges, bedding and foliation become oblique to each other. The quartzites are fine-grained, light gray, granoblastic and composed of quartz, plagioclase, muscovite, and biotite. Graded beds, reversed in grain size by high grade metamorphism, are common throughout the formation. The descriptions of the Littleton Formation members given below focuses on the variations in bedding style of the schists and quartzites and any other lithologic peculiarities. All contacts between the members of the Littleton are gradational.

Littleton Formation Members. Members in the Northern Presidentials listed first followed by correlative members found in the Southern Presidential Range

Dlsl

Dlsl - Spaulding Lake Member - Dlfr - Frog Rock Member
Massive schist with coarse, lumpy pseudoandalusites. Rare quartzite beds up to 10 cm thick, are occasionally found. Poorly bedded with very rare graded beds.

Dlag

Dlag - Alpine Garden Member - Massive quartzites commonly 1 to 4 meter in thickness with rare thin, 1 to 8 cm thick schist interbeds, often well graded. Most quartzites show a light rusty brown weathering near the base of the bed. Thickness, 0 to 175 m.

Dlsd Dltr

Dlsd - Sphinx Dome Member - Dltr - Tuckerman Ravine Member
Well bedded schist and quartzite, the couplet being approximately 10 - 50 cm in thickness and equally divided between the two lithologies. Well developed, aligned pseudoandalusites and graded beds.

Dlmj Dlcp

Dlmj - Mt. Jefferson Member - Dlcp - Cow Pasture Member
Massive schist with coarse, lumpy pseudoandalusites and up to approximately 10% quartzite. Where quartzites are found the beds range between .5 to 1 m in thickness with the quartzites between 10 and 30 cm in thickness. In these places graded bedding is common. Well developed aligned pseudoandalusites are found in the schist.

Dlmm Dlhr

Dlmm - Mt. Madison Member - Dlhr - Huntington Ravine Member
A rhythmically bedded schist and quartzite, each couplet remarkably uniform in thickness, approximately 3 - 10 cm. Rare garnet coticules are found in the thinner bedded horizons. Well developed aligned pseudoandalusites in the schist, poorly developed graded bedding. Minor occurrences of well bedded schist and quartzite, the couplet being approximately 1 to 1.5 m in thickness with about 33% quartzite. Exceptionally well graded. Minor occurrences of massive quartzites between 1 and 2 m in thickness with thin, 1 to 10 cm, interbeds of schist.

Dlirp Dlgg

Dlirp - Israel Ridge Path Member - Dlgg - Great Gulf Member
A well bedded quartzite and schist, the couplet being approximately 20 - 100 cm in thickness and equally divided between the two lithologies. Well developed, aligned pseudoandalusites and graded beds. Rare occurrences of massive quartzites between to 1 and 2 meters in thickness with thin, 5 to 10 cm, interbeds of schist.

Dlec Dlbl

Dlec - Edmonds Col Member - Dlbl - Bigelow Lawn Member
Massive schist with randomly spaced, thin quartzites approximately 1 to 5 cm in thickness. The quartzites make up approximately 5 to 10 % of the unit. Graded bedding is rare. Garnet coticules are occasionally found and pseudoandalusites are less coarse.

Dljq Dlog

Dljq - John Quincy Member - Dlog - Oakes Gulf Member
A well bedded quartzite and schist, the couplet being approximately 10 - 150 cm in thickness and equally divided between the two lithologies. Well developed, aligned pseudoandalusites and graded beds. One rare occurrence of a 30 cm thick, 1.5 m long quartz pebble conglomerate horizon was found.

Dlpl Dlab

Dlpl - Pine Link Member - Dlab -Abandoned Bridge Member
This member consists of massive, slightly rusty schist with thin beds of quartzite. The schist layers are commonly 1 to 1.5 m in thickness with rare occurrences of 2 m thick beds. The quartzite beds are commonly 1 to 5 cm in thickness. Pseudo-andalusites are very common in this member and both graded beds and garnet coticules are rare.

Dlojr

Dlojr - Old Jackson Road Member
This member consists of layers of quartzite alternating with thinner layers of schist. The quartzite layers are up to 1 m in thickness with rare beds up to 2 m. The schist layers are commonly 15 to 50 cm in thickness. Rare graded beds are found in this member and coticules and pseudo-andalusites are not observed.

Dlnr

Dlnr - New River Member
This member consists of mostly massive schist with thin quartzite beds. The quartzite beds are commonly 3 to 4 cm in thickness. Graded beds and pseudo-andalusites are not common but discontinuous 1 cm layers of garnet coticule are observed.

Dlmig

Dlmig - Migmatitic Littleton Formation
A light gray migmatitic gneiss with alternating layers of quartz + feldspar and biotite-rich schist. Layering is planar to swirly. Rare, oval 20 to 100 cm long granofels clasts(?) are found. Very simliar to Src below but without rusty weathering or calc-silicate pods.

SILURIAN

Sm - Madrid Formation -- The Madrid Formation is a fine-grained, thinly laminated, granofels with well-defined alternating layers of dark biotite-rich, schistose granofels and greenish-purple, calc-silicate-rich granofels. The individual layers of granofels are from 1 to 5 cm thick. No graded beds are found. The formation weathers to a dark greenish-gray and consists of actinolite, quartz, biotite, plagioclase, sphene, garnet, and trace amounts of chlorite, and epidote. Total thickness of the formation varies between 10 and 50 meters.

Ssf - Smalls Falls Formation - The Smalls Falls Formation is a well foliated schist with distinct red-brown rusty weathering. The formation has a dark gray to black fresh surface and is highly susceptible to weathering. The mineral assemblage includes muscovite, quartz, biotite, plagioclase, chlorite, sillimanite, graphite, pyrrhotite, and ilmenite. Quartzite makes up less than 5% of the unit, with layers up to 1 cm in thickness. No graded beds are found. Total thickness of the formation varies between 10 and 50 meters.

Sr - Rangeley Formation - general description
The Rangeley Formation is a gray migmatitic orthogneiss with abundant calc-silicate lenses. A few beds of schist and quartzite are sometimes preserved, having escaped migmatization, and in these rare locations, rare graded bedding is found. The mineralogy of the gneisses is composed of quartz, plagioclase feldspar, biotite, muscovite, chlorite, sericite, sillimanite, garnet, ilmenite, and trace monazite, zircon, and tourmaline. The calc-silicate lenses are most often aligned parallel to schistosity planes, but some are at slight angles or, in the extreme, perpendicular to schistosity. Minerals in these lenses include quartz, actinolite, plagioclase, diopside, biotite, clinozoisite, sphene, garnet, magnetite, and trace monazite, zircon, and ilmenite. Within the gneisses are mappable zones of rusty gneiss, rusty schist, calc-silicate granofels, and amphibolite. The descriptions of the Rangeley Formation members given below focuses on the lithologic variations in the gneiss and the mappable subordinate units mentioned above. Stratigraphic order is based on the uninterrupted juxtaposition of the younger Smalls Falls, Madrid, and Littleton Formations.

Rangeley Formation Members

Src - Crawford Member
A migmatitic gneiss with alternating layers of white quartz + feldspar and black biotite-rich schist. Layering is planar to swirly. Angular quartz and/or feldspar segregations (clasts?) between 2 and 8 cm in diameter are common. Elongate, rectangular lenses (clasts?), .5 to 2 meters in length, of well-bedded calc-silicate granofels and ellipsoidal lenses (clasts?), 10 to 50 cm long, of concentrically mineralogically zoned calc-silicate granofels without bedding are common throughout this unit. In places the gneiss is extensively injected by two mica pegmatites, aplites, and granites.

Sr - Rangeley Formation unmigmatized
The unmigmatized Rangeley weathers rusty gray to brown and is comprised of layers of dark schist and gray quartzite of variable thicknesses. The schist layers are generally well foliated and rusty and usually 30 cm to 1 m with rare layers of 1-5 cm. The quartzite layers range in thickness from 2 to 20 cm with rare beds of over 30 cm. The average ratio of schist to quartzite bedding thicknesses is 60:40. Graded beds are observed but are rare and grading was not as defined as in the Littleton schists and quartzites. Small lenses and larger layers of calc-silicates are observed up to 1.5 m in length. Injections of pegmatite are found throughout the entire unmigmatized Rangeley Formation and make up approximately 10% to 20% of the outcrops. Also present in this member is a massive quartz pebble conglomerate approximately 30 m in thickness containing 1-2 cm clasts of quartz in a well foliated muscovite/biotite/quartz matrix.

ORDOVICIAN

Oama - Ammonoosuc Volcanics - Amphibolite -
A predominantly dark-green actinolite biotite garnet amphibolite facies metavolcanic tuff. Amphibolite is interbedded with very thin (1-3 m) gray weathering, biotite, muscovite, garnet gneiss. Occasional sulfidic quartzite lenses also occur throughout the unit. The unit also contains zones of mylonite.

Oamg - Ammonoosuc Volcanics - Gneiss
This unit is a gray weathering, feldspathic, biotite, garnet gneiss. It is thickly to thinly interbedded (1-10 m intervals) with amphibolite and rusty gneiss and highly injected with two-mica pegmatite and granite sills.

Oamr - Ammonoosuc Volcanics - Rusty Gneiss
This unit is predominantly a regularly bedded rusty weathering, biotite, muscovite, garnet gneiss with a moderate foliation. Thin amphibolite layers ranging in thickness from .5 to 1 m are interbedded throughout.

Obqm - biotite quartz monzonite
The foliated biotite quartz monzonite is an intrusive gneiss of the Oliverian Plutonic Series. The unit mapped in this study area constitutes part of the Jefferson Gneiss Dome.

Explanation of symbols

- Geologic contact
- D0 normal fault.
- D1 fold axial trace
- D2 thrust fault. Teeth on upper plate
- D3 fold axial trace
- D4 fold axial trace
- D5 fold axial trace
- Southeast limit of Oliverian doming
- Mesozoic brittle fault with silicified zone (orange oval)
- Overturned syncline
- Overturned anticline
- Anticline
- Syncline
- Basalt dike
- Exposure of granite, pegmatite and/or aplite
- Strike and dip of bedding. Tops unknown
- Strike and dip of bedding. Tops upright
- Strike and dip of bedding. Tops inverted
- Strike and dip of foliation, S1.
- Horizontal bedding and foliation. Tops unknown
- Joined symbols indicating two, non-parallel fabrics Strike and dip of foliation and bedding
- Strike and dip of foliation and upright bedding
- Strike and dip of foliation and inverted bedding
- Compound symbols indicating two parallel fabrics Strike and dip of foliation and bedding
- Strike and dip of foliation and upright bedding
- Strike and dip of foliation and inverted bedding
- Photo locality. Number refers to photo on back of map

Figure 3. Explanation of rock units and symbols used on Figure 2. Modified from Eusden (2006).

al., 1997). The maps produced by Dupee et al. (2002) and Foley and Eusden (2009) show that the Ammonoosuc stratigraphy is cut off against the main contact with the Jefferson Oliverian Dome. Foley and Eusden (2009) have also mapped meter-scale intercalations of Ammonoosuc Volcanics and Jefferson Dome rocks. In addition, several new exposures of S-C mylonites that exhibit variable intensity have been mapped within the Ammonoosuc and Jefferson Dome rocks adjacent to the main contact (Dupee et al., 2002 and Foley and Eusden, 2009). Shear sense for the mylonites is complex with both normal and reverse motions found in the Ammonoosuc Volcanics and reverse motion only in the Jefferson Dome rocks. The foliations and lineations in the mylonites eventually die out away from the main Ammonoosuc-Jefferson Dome contact. It is tempting to interpret the normal motions as doming-related, having developed as simple shear dominated along the flanks of the rising dome. The main boundary between the Ammonoosuc and Jefferson Dome is probably a structure of this type and we have named it the Moose River fault, a late Acadian, normal sense, shear zone. The reverse motion indicators in the both the Ammonoosuc Volcanics and Jefferson Dome are not what one would expect during doming, and since doming is likely the last phase of Acadian deformation in the area, it is possible that the reverse motion indicators represent a pre-doming shear history. However, there are no age constraints on the different mylonites. As a final thought, if the overall doming deformation was characterized by pure shear, it would be possible to have both the reverse and normal shear sense indicators develop simultaneously.

Foley and Eusden (2009) performed monazite microprobe age determinations on two samples, one from a Jefferson Dome mylonitized sample in Cold Brook (sample MFC02, Stop 6a on this trip) and the other from an Ammonoosuc Volcanics mylonitized rusty gneiss (sample MFS01) in Snyder Brook, just above the main contact with the Jefferson Dome. The oldest monazite age population gives a late Silurian date of 415 +/- 7.2 Ma in MFS01 from the Ammonoosuc Volcanics. Both samples contain ages in the early to middle Devonian with MFC02 showing ages of 392 +/- 3 and 380 +/- 3 Ma and sample MFS01 giving an age of 382 +/- 4.4 Ma. The samples also show middle to late Devonian ages in the 370 Ma range with MFC02 yielding an age of 367 +/- 3.2 Ma and MFS01 an age of 370 +/- 6.2 Ma. Finally both samples show early Carboniferous ages with MFC02 yielding an age of 346 +/- 3.6 Ma and MFS01 an age of 357 +/- 6.4 Ma. The Silurian age is hard to interpret! Could this be an early, pre-Acadian, shearing event when the Ammonoosuc and Jefferson Dome initially came into contact with each other? The early Devonian ages are consistent with other ages we have determined for the peak of Acadian metamorphism in the Presidential Range (circa 400-380 Ma). The middle Devonian 370 ages may represent the age of doming. The Carboniferous ages are probably related to the intrusion of the local Bickford Granite.

CENTRAL MAINE BELT

Eusden et al. (1996, 2000, and 2006a NEIGC) provide a summary of the Central Maine stratigraphy, deformation, metamorphism and plutonism in the Presidential Range. But briefly, here is a synopsis: 1) the stratigraphy (no fossils found yet!) is an on strike extension of the Rangeley, Maine, sequence consisting of the Silurian and Devonian turbidites; 2) the deformation has seven phases with D_0 pre-metamorphic normal faults, D_1 east vergent, isoclinal nappes, D_2 thrust faulting, D_3-D_4-D_5 folding, and doming of the Oliverian (only D_1 and D_4 are seen nearly everywhere in the Presidentials) ; 3) the igneous activity consist of the early, 408 Ma, Wamsutta diorite suite, the intermediate, circa 390-400 Ma, Wildcat granite suite, and the youngest suite of Carboniferous (circa 360-350 Ma) two mica granites (e.g. Peabody River stock, Bretton Woods, and Bickford granites); 4) and finally, metamorphism started with the growth of large andalusite grains that define the L_1 lineation, sillimanite metamorphism (synchronous with the end of D_1) overprinted this and culminated in areas of stromatic migmatite almost exclusively restricted to the Rangeley Formation, the field gradient is in upper sillimanite zone (sill+bio+gar+quartz+musc), and lastly retrograde metamorphism(s) occurred characterized by chlorite and coarse muscovite replacements.

For NEIGC 2009, we will focus on the stratigraphic and structural aspects that we have not highlighted on previous fieldtrips. For the stratigraphers, one interesting aspect of the Central Maine Rangeley sequence exposed in the Presidential Range is the discontinuous nature of the Perry Mountain Formation due to non-deposition. In most sections, we see instead a stratigraphy, without breaks, from the Rangeley, Smalls Falls, and Madrid up to the Littleton Formations. Age constraints on the stratigraphy are all by correlation to distant fossiliferous sections. With this in mind, Dwight Bradley, USGS, has sampled quartzites from the Littleton and Rangeley Formations along the Auto Road as part of a regional detrital zircon age study of provenance in Silurian and Devonian sandstones from New Hampshire and Maine. Only one of the samples on the Auto Road has been studied so far, a sample of Littleton from elevation 4,000 feet. Zircon age populations are seen at 1485 Ma, 1164 Ma, 996 Ma, 900 Ma, 595 Ma, 496 Ma and 406 Ma. What this detrital zircon 'bar code" means as far as a Ganderian or Laurentian or Avalonian signature is unclear, but at least in these non-fossiliferous rocks we have some confirmation from the youngest detrital zircon ages that the Littleton Formation is truly early Devonian.

Structurally, regional D_1 folding, Oliverian doming, and localized D_5 folding are highlighted on this trip. The D_1 folds are characterized by macroscopic east verging nappes that are well characterized above treeline but less so in this wooded lower elevation region. We believe this east vergent deformation occurred as the Acadian orogenic front made contact with the Bronson Hill arc that likely acted as a buttress, prohibiting any westward vergence of structures. This deformation was syn-metamorphic but occurred prior to the peak of metamorphism in the region. Uplift and doming of the Jefferson Oliverian Dome was restricted to the Randolph valley region of the Presidential Range. A region of east-southeast dips occurs in a two mile wide zone immediately southeast of the contact between the dome and cover rocks. Beyond this zone the regional west dip prevails. We are unsure of the timing relationship between this doming and other late Acadian folding events but suspect that doming developed prior to the intrusion of Late Carboniferous plutons. Regardless, it is late Acadian and deforms all other fabrics in the rock except, of course, brittle structures created during Mesozoic rifting. D_5 folding is a late Acadian event restricted to the Pinkham Notch area. It is probably related to the Early Carboniferous intrusion of the Peabody River Stock granite because D_5 folds are found in proximity to the contact and die out away from it.

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Thanks to Great Glen Trails for allowing the fieldtrip participants use of their trails for access to the outcrops along the West Branch of the Peabody River. Thanks to the Randolph Mountain Club for letting us park at their Stearns Lodge. Thanks also to Dwight Bradley for providing the detrital zircon "bar code" of the Littleton Formation.

ROAD LOG

Assemble at 9:00 am by the base of the Mount Washington Auto Road at Great Glens. Park in the dirt lot on the west side of Rte. 16 just south of the entrance to the Auto Road.

Bring a lunch, warm clothes, boots and water. There will be no chance to pick up food along the trip. We do not recommend drinking out of the streams unless you treat or filter the water. There will be one long, circa 4.5 mile walk, and one short, about one mile walk. These will be through the woods on trails, off trail bush wacking, and will have many stream crossings where there is a very high probability that your feet will get wet! The best trail guide for the region is "Randolph Paths" (2005) by the Randolph Mountain Club.

Hiking mileage for Stops 1-3

0.0	Auto Road Parking Lot. Go north on the Great Glens trail system following the trail Great Grumpy Grade to the junction with Dugway Trace.
1.2	Junction of Great Grumpy Grade and Dugway Trace. Take a left (south) on Dugway Trace.
1.35	Sharp bend in the Dugway Trace trail where is turns from northwest to south. Bushwack downhill at a bearing of 0° (north) to the confluence of two unnamed tributaries of the West Branch of the Peabody River.
1.5	Confluence of the two unnamed tributaries, both flowing approximately east. Go upstream along the northern of the two tributaries.
1.53	Stream outcrop in a small gorge.

Stop 1a. **The basal Abandoned Bridge Member of the Littleton Formation (Dlab) and the first beds of the Madrid Formation** (Sm; described in Stop 1b)) are exposed at this stop. The Dlab member is primarily a massive schist with occasional thinly bedded schist and quartzites. Graded beds, predominately upright, within this member are rare, and discontinuous garnet coticules are common. An early cleavage (S_1) striking 140, 65 W is oblique to bedding that strikes N to NW and dips westerly. As you walk downstream, back toward the confluence, you should be able to convince yourself that the contact between the Littleton and Madrid is interbedded.

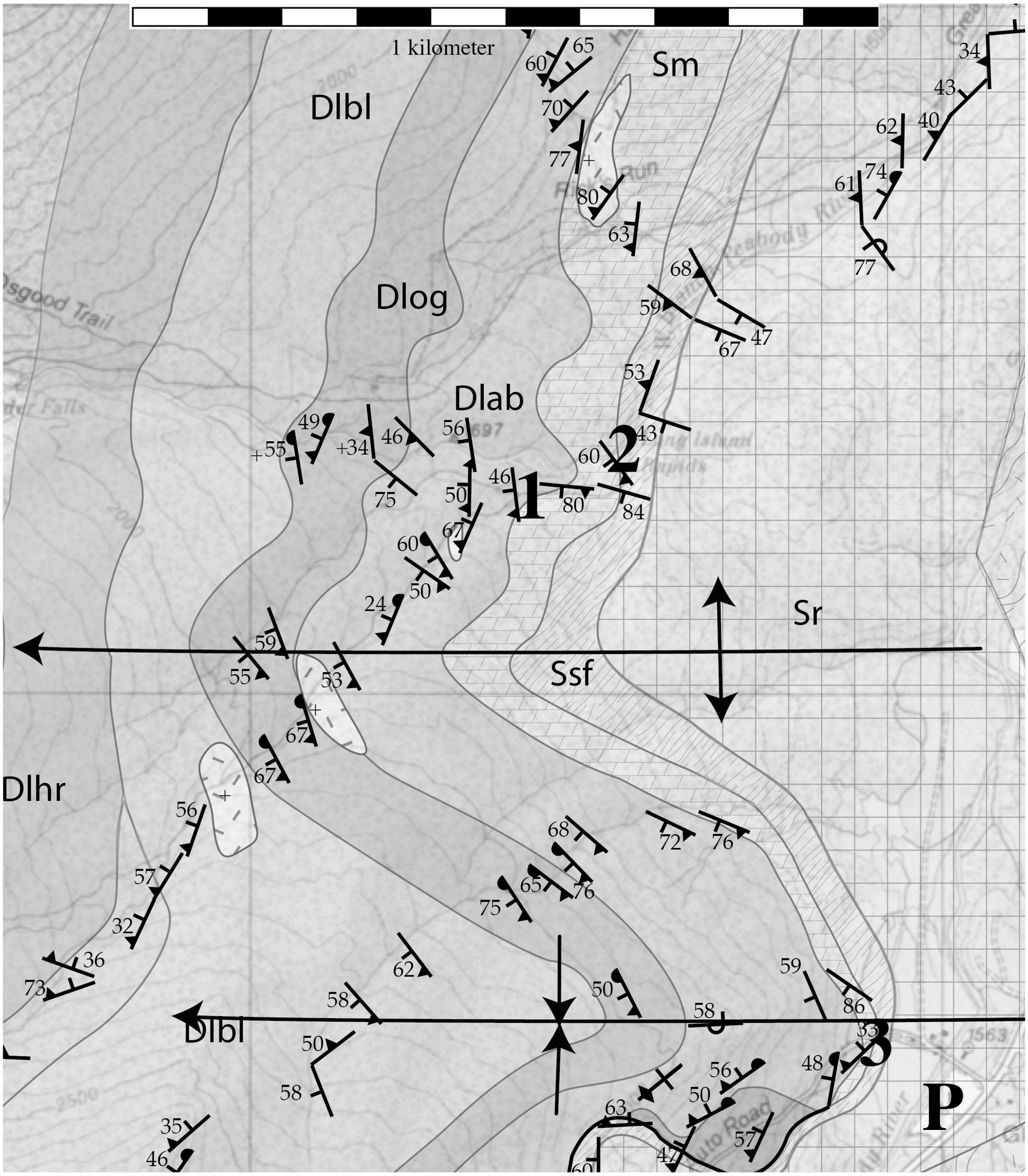

Figure 4. Geologic map in the vicinity of Stops 1-3. Map modified from Eusden (2006).
For explanation of symbols and patterns on map see Figure 3.

Proceed downstream, past some nice examples of boudined, then folded pegmatite sills, noting that the Madrid lithologies are becoming more prevalent and the Littleton is vanishing.

1.66 Large stream outcrop of Madrid Formation striking parallel to the stream flow direction.

Stop 1b. Fantastic exposure of Madrid Formation! The thin layers are generally between <1 cm to 10 cm in thickness and alternate between gray, biotite and plagioclase-rich granofels, to white, quartz and plagioclase-rich granofels, to greenish, actinolite-rich calc-silicate granofels. A few boudined and/or folded pegmatites are also present. Note that bedding now strikes east-west and dips steeply south. This change in bedding orientation reflects the strong macroscopic D_5 folds seen in this area of the Presidentials. This particular phase of folding is very localized, only found on the West Branch drainage and, coincidentally or not, near the Peabody River Stock granite, a two mica granite we will see later on in the trip. There are no discernible graded beds within this formation.

Continue downstream. Really slippery!

1.77 River changes direction and flows north.

Stop 1c. Exposed are the first beds of the Smalls Falls Formation interbedded with the last of the Madrid Formation. The Smalls Falls here is more granofelsic than lower down in the section where it is dominated by pelite, but the same characteristic deep rusty weathering is observed. This formation generally breaks into flaggy fragments and/or small "shards" from the typically angular weathering outcrops. The Smalls Falls Formation may exhibit a weak magnetic attraction and smell of sulfur due to the occurrence of pyrrhotite. A steep F_5 lineation (250, 55) is seen in some of the bedding planes.

Continue downstream until just before the confluence with the West Branch of the Peabody River.

1.83 Just upstream from the confluence.

Stop 1d. Coarse-grained pegmatite with xenoliths of rusty Smalls Falls. For some reason, the Smalls Falls Formation loves to be intruded by pegmatites and granites. Many years ago John Lyons pointed this out to Eusden while they were mapping in central New Hampshire. Lyons speculated that the rheology and/or bulk chemistry of the formation is such that magmas and associated fluids preferentially inject along it. The pegmatites are probably Devonian to Carboniferous in age and are composed of white to yellow to rusty weathering fine to coarse-grained two mica granites. The mineralogy of these granites is quartz, plagioclase, muscovite, tourmaline, +/- biotite, and +/- garnet. These granites come in various textures from coarse-grained pegmatites to fine-grained aplites. While some of the larger granite bodies can be shown on the map, most granites occur as dikes, veins, sills, and boudins too small to illustrate on the map. These granites may be part of the Peabody River Stock granite the main body of which is located approximately 3 miles northeast of here (Stop 5) or perhaps the older Wildcat granite suite located 3 miles southeast.

Walk to the confluence and proceed upstream on the West Branch of the Peabody River.

1.91 Large outcrop of Madrid Formation in the West Branch.

Stop 2a. The Madrid Formation is well exposed here. At the downstream end of the outcrop is a small, centimeter-scale, F_1 isoclinal fold. Just about the entire Madrid is exposed here a narrow section of approximately 50-100 meters.

Turn around and go back downstream past the confluence.

2.07 Outcrop of Smalls Falls on the east bank of the West Branch.

Stop 2b. The Smalls Falls Formation is nicely exposed in outcrops along the south bank of the river. Strikes are generally northerly but variable. In some stream washed sections you can see fresh surfaces of the formation illustrating that it is indeed a bedded turbidite with both schists and quartzites, not simply a massive rusty schist as most deeply weathered outcrops would suggest. Some of the schists have graphite in them and there are rare calc-silicate pods. There is a strong S_1 cleavage striking 160, 40 W, not parallel to the bedding, that is in turn crenulated by D_5 folding.

Continue downstream.

2.21 Large outcrop of pegmatite on the east side of the West Branch.

Stop 2c (optional). Exposed is a coarse-grained pegmatite with large muscovite and smaller biotite.

Continue downstream, go around the falls, stay to the east side of the river in the woods.

2.35 Bottom of falls on the east side of the river.

Stop 2d. The Rangeley Formation is exposed in the falls and consists of 10-50 cm thick bedded schists and quartzites that are slightly rusty weathering with rare granofels pods. Pseudoandalusites are seen as lumps and spots within the schists. The grading is 'fast' meaning it is hard to see smooth, continuous, graded beds. Bedding is parallel to S_1 schistosity and there are F_5 lineations and crenulations on some bedding surfaces. Really well developed mesoscopic F5 folds make up the main rock face of the falls.

Proceed back upstream along the West Branch to Stop 2c and at a small campsite.

2.5	Campsite on the east side of the river near Stop 2c. Take a bearing of 180° and bushwack to the roughly cut Great Glens trail called Drifter.
2.56	Follow the Drifter trail to its intersection with Dragon Corridor.
2.65	Junction of Dragon Corridor and Drifter trails. Take a left and head back toward the vehicles.
4.16	Make your way to the base of the Auto Road where it just begins to climb up out of the field and find the first set of road cuts on the north side of the Auto Road.

Stop 3. Well bedded Rangeley Formation with a few thick quartzites and thin garnet coticule pods and lenses. This is where we have sampled for both AFT and detrital zircon studies. The detrital zircon sample has not yet been processed but one from the Littleton Formation at elevation 4,000 feet has showing that the youngest grains are 406 Ma in keeping with the age of the Littleton Formation. The AFT age from this sample is 101 Ma, within error of AFT ages from the surrounding White Mountain region which range from 85 to 99 Ma (Roden-Tice et al., 2009). Using this age and the AFT age from the top of Mt Washington (152 Ma) we calculate a two point unroofing rate of 0.027 mm./yr from the Late Jurassic to Early Cretaceous. Much outcrop discussion will follow!

Return to the vehicles across the field.

4.42 Parking lot. End of hiking log. Maybe time for lunch?

Begin road log for fieldtrip

0.0	Great Glens parking lot. Get in the vehicles and drive north on Rte 16 to the Great Gulf Wilderness parking lot.
1.8	Great Gulf Wilderness parking lot. You can either chance it, and not get a temporary USFS parking permit, or pay for one ($3.00) and be safe!

Stop 4 (optional). Migmatites of the Rangeley Formation. (Stop 2D of Hatch and Wall, 1986). The description below is taken from Allen et al. (2001). "The migmatite leucosomes are usually elongate blebs or stringers, rather than continuous layers and the intensity of migmatization is highly variable. The age of this migmatization is circa 404 Ma. Calc-silicate pods and blocks with folded layering are abundant, and usually lie parallel to the migmatite layering, although sometimes they are at an angle to it. These rocks are obviously quite heterogeneous, but in bulk they are geochemically similar to the protolith schists (just downstream). This suggests that the migmatization of these rocks is the result of metamorphism in an iso-chemical or closed system. The migmatites have a lower oxygen isotope value than the schists and exhibit open-system isotopic behavior, which suggests infiltrating fluids may have been important in driving the migmatization process. Isotopic fractionation between the melanosome and leucosome components of the migmatites may be the result of partial melting. These migmatites have an identical metamorphic mineral assemblage to (the protoliths downstream) (sillimanite-muscovite), but garnet-biotite geothermometry indicates temperatures were higher. Two generations of pegmatite cut across the outcrop" Allen et al., 2001).

Proceed north on Rte 16.

3.9	Stay on Rte 16, going past the Pinkham B Road on your left.
4.2	Pull over by the low outcrops on the east side of the road. Watch traffic!

Stop 5. Peabody River Stock granite. Exposed is the main body of the Peabody River Stock granite. It is a fine- to medium-grained two mica granite that records the last pulse of the Acadian orogeny in this area. A few coarse pegmatites can also be observed. Eusden et al. (2000) have dated the Peabody Stock to be 355.4 +/- 1.6 Ma. giving the granite a Carboniferous age. This is one of three Carboniferous plutons in the Presidential Range, the others being the Breton Woods and Bickford granites. This pluton is spatially related to the region where D5 folding is seen. It is unlikely that this magma is related to the migmatization just observed in Stop 4. The cross cutting pegmatites at Stop 4 are probably part of the Peabody River Stock granite.

Turn around carefully and go south on Rte 16.

4.7	Take a right (west) on the Pinkham B Road.
5.0	Go past the entrance on your left to the Dolly Copp campground.
5.2	Bear left on the dirt Pinkham B Road. The Barnes Field access road is on your right.
6.6	Pass the entrance on your right to the Pine Mountain Road and Horton Center.
7.6	Cross the town line to enter Randolph, home to many geologists and ministers.
9.2	Junction with Rte 2, go left (west) towards Lancaster, NH
10.0	Pass the “Appalachia” trails parking lot on the left.
10.4	Take a right (north) on a dirt road marked by a street number sign (# 560)
10.5	Park near the Randolph Mountain Club workshop or Stearns Lodge.

Begin hiking mileage for stop 6

0.0	Go back up the dirt road toward Rte 2.
0.1	Pass by the Billings cabin where Marland Billings and Katherine Fowler Billings stayed while they mapped in the Presidentials in the ‘30’s and 40’s. Continue across Rte 2, crossing the old railroad bed, now a recreation path, to the power lines.
0.2	At power lines, bear right and follow trail into the woods in about 100 yards.
0.3	Woods road merges with Randolph Mountain Club Pine Link Trail.
0.35	Junction with the Beechwood Trail, bear right on the Pine Link Trail.
0.5	Memorial Bridge. This bridge was built in 1924 as a “Memorial to J.R. Edmands and E.B. Cook and those other pioneer pathmakers” in Randolph. The monument at the east end of the bridge is made of mylonitized Oama, the Ammonoosuc Volcanics Amphibolite member. This is a good rock in which to see the foliation and lineation so that you can determine the shear sense plane.

Stop 6a. Jefferson Dome. Just under and downstream of the bridge is an outcrop of Obqm, the foliated pinkish biotite quartz monzonite of the Oliverian Plutonic Series, part of the Jefferson Gneiss Dome of the Bronson Hill. The foliation formed during either the doming stage in the Late Acadian or during faulting along the Moose River Fault. The lineation is harder to see and trends moderately southeast. Also seen is a green, probably pre-Acadian, metamorphosed basalt dike and some pegmatite of the 363 Ma. Bickford granite. Maura Foley, Bates ’09, examined the shear sense in thin sections from this outcrop and found S-C fabrics with tops to the northwest (reverse slip). Shear sense for all of the mylonites in the Jefferson Dome rocks shows reverse motion. She also collected some monazite microprobe ages here with these age populations: early to middle Devonian ages of 392 +/- 3 and 380 +/- 3 Ma (peak Acadian metamorphism); middle to late Devonian ages of 367 +/- 3.2 Ma (doming?); and Carboniferous ages of 346 +/- 3.6 Ma (intrusion of local granites).

From the bridge continue up the west side of Cold Brook on the Sylvan Way trail to Cold Brook Falls.

.55	Cold Brook Fall (very slippery rocks here).

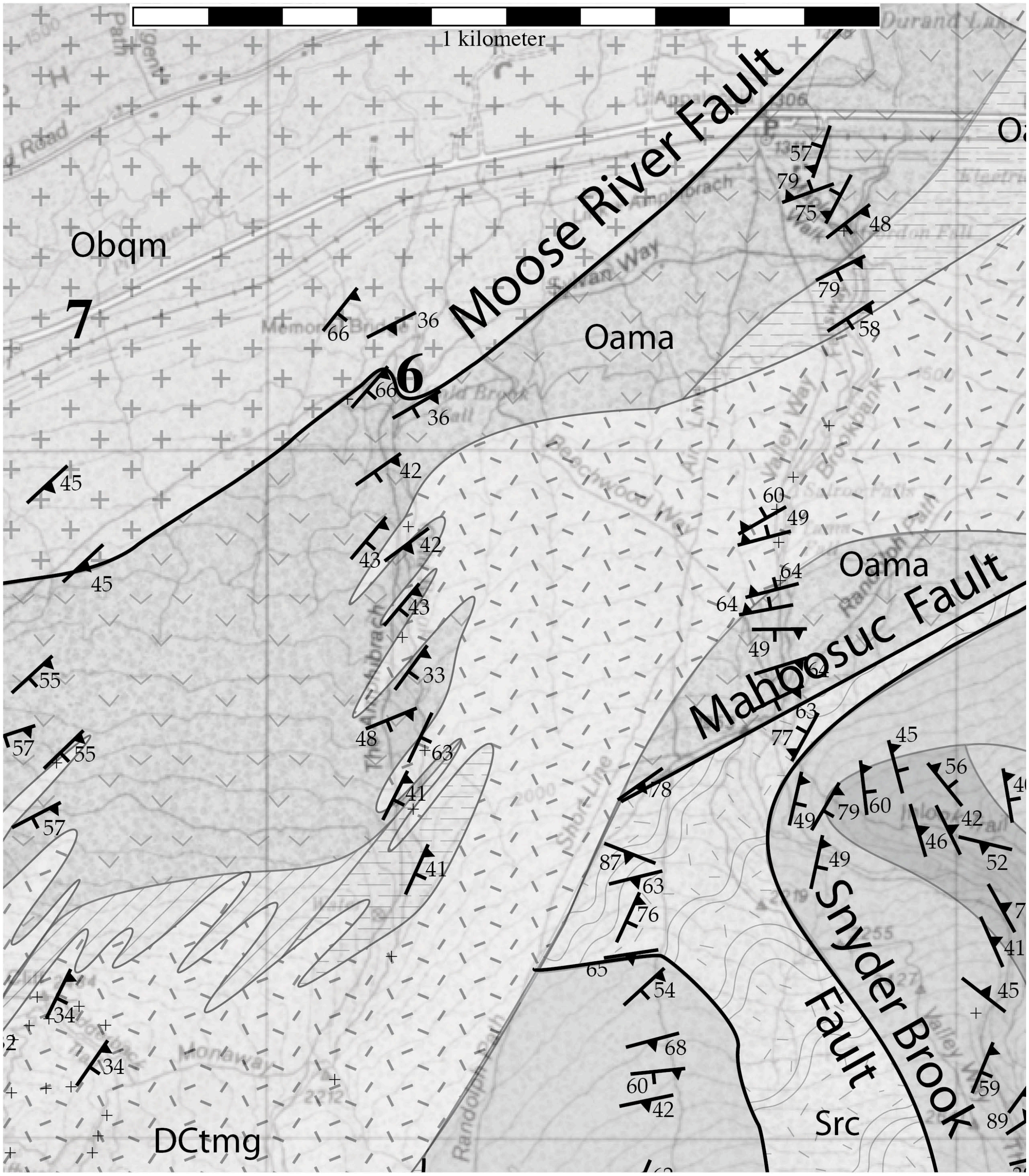

Figure 5. Geologic map in the vicinity of Stops 6-7. Map modified from Eusden (2006).
For explanation of symbols and patterns on map see Figure 3.

Stop 6b. **Moose River fault, Ammonoosuc volcanics, and mylonites.** At the falls are exposed Oama, the Ammonoosuc Volcanics Amphibolite member, and a few intercalated layers of Oamg and Obqm. The regional strike and dip (70°, 48 SE) is seen well in outcrop on both sides of the falls. The lineation (125°, 38°) is defined by fine-grained biotite and can be seen in good light. This dip is a result of doming by the Obqm when it diapirically rose up through the more dense cover rocks in the Late Acadian. Mylonitic fabrics are seen throughout the outcrops and particularly well in the amphibolite and gneiss horizons. Oriented thin sections from this locality show tops to the northwest sense (reverse slip) (Dupee et al., 2002). Based on the lineation orientation, there is some minor strike slip motion that is dextral, but the dominant motion appears to be dip slip. Collectively these mylonites make up the Moose River fault separating the Oliverian Jefferson Dome from the Ammonoosuc Volcanics. Farther upstream Foley has found normal shear sense indicators in mylonites. With both normal and reverse motions found in the Ammonoosuc Volcanics it is difficult to determine the overall motion of the Moose River fault. Are there two generations of faulting with early reverse followed by later normal motion? Is pure shear the mode of deformation here (unusual on the flank of a diapiric dome) resulting in both types of motion simultaneously? More work is needed! For good old NEIGC speculation and spirited outcrop conversation, we offer this hypothesis. The doming is clearly post-peak Acadian metamorphism as all migmatites are domed. If the mylonites formed during doming, the shear sense indicators would show normal motion in their present orientation given the likelihood of simple shear on the dome flanks. If so, the normal shear sense indicators would be younger and dome related. The reverse sense indicators often have porphyroclasts that appear to be pre-peak metamorphism due to the presence of composite tails that likely recrystallized during peak Acadian metamorphism. That would suggest the reverse motion indicators are older and pre-doming in age. If the effects of doming are removed, the layers would likely assume the regional west dip and as such the kinematic indicators would then become normal. Is it possible that the reverse sense indicators as seen currently in outcrop formed prior to the Acadian in this area, as normal faults, intercalating the Ammonoosuc and Jefferson Dome rocks?

Continue upstream on the east side of Cold Brook along an old abandoned trail.

.67 Outcrops above Cold Brook fall.

Stop 6c. Ammonoosuc Volcanics and sill of Bickford granite. Exposed in the river are a few more outcrops of mylonitized amphibolite and interbedded gneiss. One amphibolite horizon that has an abundance of sub-centimeter size plagioclase grains in a dark matrix suggests it was once a crystal lapilli mafic tuff. Above these rocks is a sill of medium to fine-grained, 363 Ma. Bickford Granite. Sills of medium to fine grained two mica and biotite granite and coarse pegmatite continue upstream for a couple of miles. The granite is not deformed by doming or shearing, and appears to mark the end of Acadian tectonism sometime at the end of the Devonian or the earliest Carboniferous. The age of the Bickford is coincident with the timing of the Neo Acadian to the south (Mass.) but here no deformation or extensive metamorphism of that age is seen here. There is also no evidence of any Alleghenian tectonism in this part of the Appalachians.

Proceed back to the vehicles and drive west on Rte 2.

1.1 Back at vehicles, end of hiking mileage for stop 6.

Continue road log

11.2 Large road cut of Oliverian Dome rock on south side of Rte 2.

Stop 7. The Ordovician biotite quartz monzonite (Obqm) of the Oliverian Jefferson Dome is well exposed in this long road cut exposes While there is a foliation and a lineation they are not as strong as the fabrics we just saw at Cold Brook and Stops 6a-c. One zone showing stronger foliation and lineation was sampled and yielded S-C fabrics showing reverse motion (Foley and Eusden, 2009). Roden-Tice et al. (2009) report an 85 Ma apatite fission track age from this outcrop. This age is part of a broad zone of young Late Cretaceous (70-118 Ma) AFT ages the result of regional extension and unroofing centered over central New Hampshire. This might be a good time to talk about the Great Meteor Hotspot!

Back in vehicles and continue west on Rte 2.

12.2 Go past Lowe's garage and store.

13.1 Take a left into the Bowman trails parking lot which is the trailhead for the Castle Ravine and Ridge Trails

Stop 8 (optional) Last stop showing the Oliverian Jefferson Dome and still even weaker fabrics as we get further init the main body of the dome. The shearing effects seen along the Ammonoosuc-Jefferson Dome contact have nearly completely died out.

End of trip. To get to the NEIGC welcoming party and registration, continue west on Rte 2 all the way to St Johnsbury, Vt (about 1 hour), picking up Interstate 91 and proceeding to Lyndon State (another 30 minutes). Safe travels, see you at the reception.

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