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B4: Bedrock Geology of Mt. Washington, Presidential Range, NH

J. Dykstra Eusden
Bates College, deusden@bates.edu

Brigit Anderson
Bates College

Carlos Castro
Bates College

Patrick Gardner
Bates College

Chris Guiterman
Bates College

See next page for additional authors

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Presenter Information

J. Dykstra Eusden, Brigit Anderson, Carlos Castro, Patrick Gardner, Chris Guiterman, Stephanie Higgins, Kelley Kugel, Adam Reid, Charles Rodda, and Caitlin Tamposi

BEDROCK GEOLOGY OF MT. WASHINGTON, PRESIDENTIAL RANGE, NH

By

J. Dykstra Eusden, Brigit Anderson, Carlos Castro, Patrick Gardner, Chris Guiterman,
Stephanie Higgins, Kelley Kugel, Adam Reid, Charles Rodda, and Caitlin Tamposi
All Department of Geology, Bates College, Lewiston, Maine 04240
Email: deusden@bates.edu

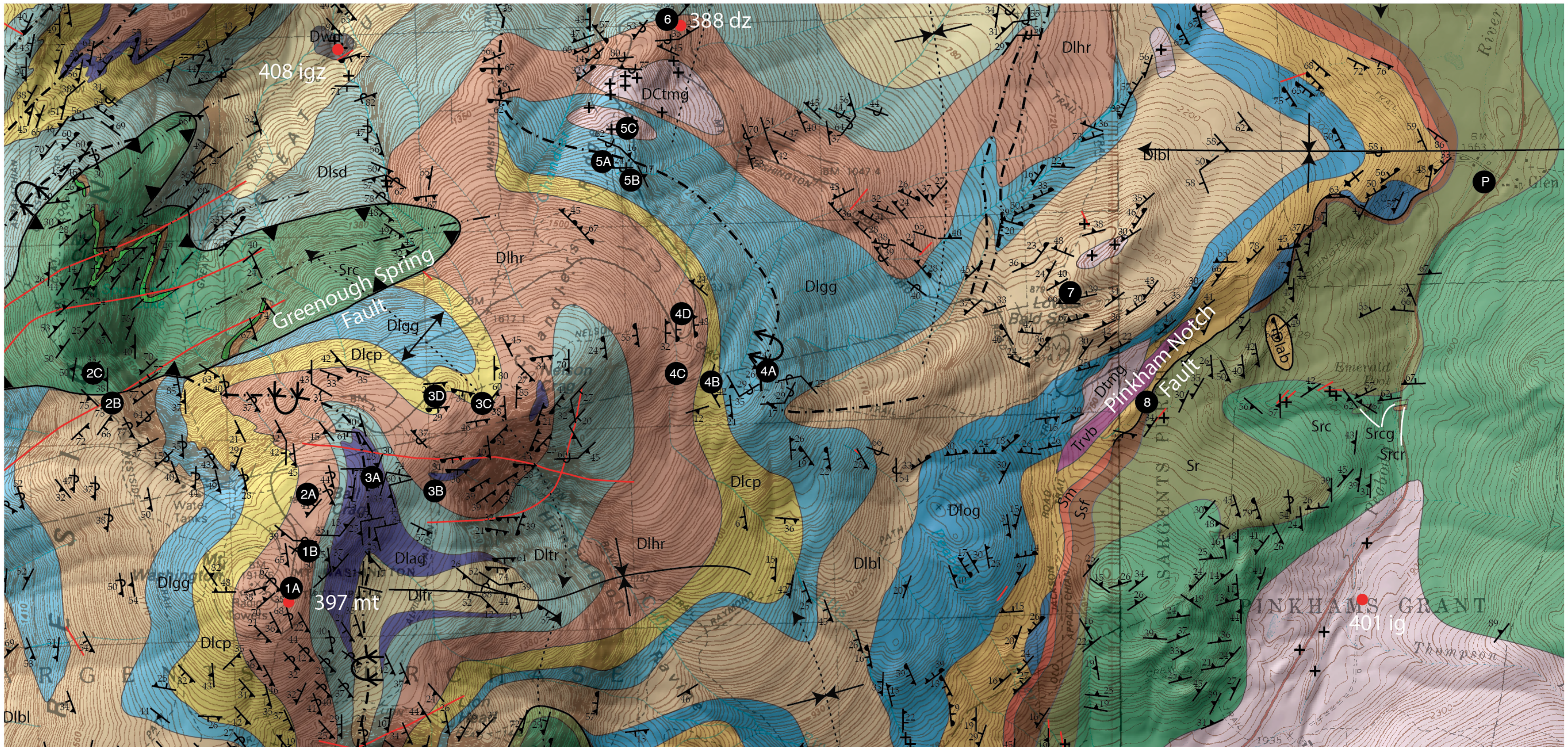
INTRODUCTION AND PREVIOUS WORK

This field guide outlines the bedrock geology of the Presidential Range, New Hampshire and describes some of the significant and readily accessible outcrops along the Auto Road of Mt. Washington. Nearly all aspects of the bedrock geology in the Presidential Range are explored. The Paleozoic stratigraphy, deformation, metamorphism, and plutonism is presented first, followed by the history of Mesozoic fractures and basalt dikes, and then finally the Cenozoic exhumation story as told by apatite fission track ages. During the fieldtrip we will see bits of all of these things at each stop. All of the Bates Geology students listed as co-authors for this field guide played an integral part in this work. Each did a full field season of fieldwork followed by a two-semester thesis project on some aspect of the bedrock history. Eusden is extremely grateful to all of them for their friendship and hard work.

The decades-long bedrock mapping campaign culminated in our finished bedrock geologic map (Figure 1) and report (Eusden, 2010). Other publications by our group include Eusden et al. (1996, 2000) and Roden-Tice et al. (2012). Eusden et al. (1996) has maps of several structural fabrics but the bedrock map does not include the lower wooded elevations. Roden-Tice et al. (2012) focuses on the apatite fission track exhumation history of the Presidential Range. In 2013 we published a layperson's book, "The Geology of New Hampshire's White Mountains", which covers many aspects of the geologic history in the Presidential Range (Eusden et al., 2013)

There has been excellent NEIGC fieldtrip representation for the Presidential Range over the past 21 years! An NEIGC field trip similar but not identical to this was first run by Eusden et al. (1996b). Eusden et al. (2006) led another NEIGC trip focusing on the geology from the Bronson Hill Anticlinorium east into the Central Maine Terrane south of U.S. Rte. 2 in Randolph, NH. The most recent NEIGC trip was led by Eusden et al. (2009) and covered aspects of the Ordovician to Carboniferous bedrock geology and apatite fission track cooling history of the West Branch of the Peabody River in Pinkham Notch and again the Randolph, NH valley. Added to this list are the four excellent NEIGC fieldtrips led by Tim Allen on the stratigraphy, structure, and migmatites of the Pinkham Notch and adjacent Carter-Moriah Range (Allen, 1996, 1996b, 2017 and 2017b (this volume)) and a pioneering trip led by Hatch and Wall (1986) who first proposed the Silurian age assignment for much of the geology and made the initial correlation to the Rangeley stratigraphy in Maine.

The Presidential Range bedrock geology was first mapped in any detail by the Billings in the late 1930's and early 1940's. 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). Tim Allen did his Ph.D. in Pinkham Notch and the difficult terrain of the Carter-Moriah region mapping the stratigraphy, structures, and migmatization (Allen 1996, 1996b, 2017, and 2017b; Allen et al., 2001). Wes Groome and his University of Maine at Orono colleagues 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). Gary Solar and students have also made meaningful contributions to our understanding of the migmatites, melts, diatexites, and deformation in the Pinkham Notch area (Fletch and Solar, 2014; Wisor and Solar, 2014).



IGNEOUS ROCKS

(red line)		Basalt dikes presumably Triassic or Jurassic in age. Normally 1-2 m in thickness and up to several hundred meters in length.
Trvb	TRIASSIC	Trvb - Triassic (?) vent breccia, predominately felsic in composition.
DCtmg	LATE DEVONIAN TO EARLY CARBONIFEROUS	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. Plus signs (+) are exposures of granite, pegmatite and/or aplite.
Dtmg	EARLY DEVONIAN	Dtmg - Two mica granite A medium- to coarse-grained, gray to rusty weathering two mica granite. Schlieren and xenoliths are common. In places a complete gradation with adjacent metasedimentary units is observed. Fine-grained aplite and pegmatite are common. Principally forms numerous small concordant plutons many of which are too small to map. Plus signs (+) are exposures of granite, pegmatite and/or aplite.
Dwd	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 Wamsutta Falls.

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
8 NEIGC STOP locality
397 mt U-Pb age in millions of years: mt = monazite metamorphic age; ig = monazite igneous age; igz - igneous zircon age; dz = detrital zircon age
24 Strike and dip of bedding. Tops unknown
24 Strike and dip of bedding. Tops upright

24 Strike and dip of bedding. Tops inverted
24 Strike and dip of foliation, S1.
Horizontal bedding and foliation. Tops unknown
60 45 Joined symbols indicating two, non-parallel fabrics Strike and dip of foliation and bedding
60 45 Strike and dip of foliation and upright bedding
60 45 Strike and dip of foliation and inverted bedding
24 Compound symbols indicating two parallel fabrics Strike and dip of foliation and bedding
24 Strike and dip of foliation and upright bedding
24 Strike and dip of foliation and inverted bedding

Figure 1. Bedrock geologic map of Mt. Washington modified from Eusden (2010). Field stops and parking area shown as black circles with white numbers. Explanation of metasedimentary rocks continues on the next page.

METASEDIMENTARY ROCKS

DEVONIAN

Dl - Littleton Formation - 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 1-3 cm in diameter, and elongate aggregates, from 1-15 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. All contacts between the members of the Littleton are gradational. Littleton Formation Members. Members in the Northern Presidentials are listed first followed by correlative members in the Southern Presidential Range

Dlsl / Dlfr

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 , 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 to well aligned pseudoandalusites, and up to approximately 10% quartzite that are 10 and 30 cm in thickness. In these places graded bedding is common.

Dlmm / Dlhr

Dlmm - Mt. Madison Member - Dlhr - Huntington Ravine Member
A rhythmically bedded schist and quartzite, each couplet 3 - 10 cm thick. Rare garnet coticules are found in the thinner bedded horizons. Aligned pseudoandalusites in the schist with poorly developed graded bedding. Minor occurrences of 1 to 1.5 m thick well bedded schist and quartzite and massive quartzites.

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 1 and 2 meters in thickness with 5 to 10 cm interbeds of schist.

Dlec / Dlbl

Dlec - Edmands 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 30 cm thick, 1.5 m long quartz pebble conglomerate lense was found in Oakes Gulf.

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 1 to 5 cm in thickness. Pseudoandalusites. are common 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 pseudoandalusites. 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 pseudoandalusites. 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 similar to Src below but without rusty weathering or calc-silicate pods.

Figure 1 continued

SILURIAN

Sm

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 is 10 - 50 meters.

Ssf

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 is 10 - 50 meters.

Spm

Spm - Perry Mountain Formation - Dark gray schist with interbedded light gray to white quartzites that are commonly 4 to 10 cm in thickness. Quartzites make up 30 to 40 % of the unit and can range up to 60 cm in thickness. The mineral assemblage includes quartz, plagioclase, biotite, muscovite, chlorite, sericite, and trace garnet, ilmenite, tourmaline, monazite, zircon, and sillimanite. The unit is discontinuous ranging between 0 and 75 m in thickness.

Sr - Rangeley Formation - A gray migmatitic orthogneiss with abundant calc-silicate lenses. Beds of schist and quartzite are sometimes preserved, having escaped migmatization, and in these 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.

Src

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.

Srcg

Srcg - Granofels
Within this member are sections of fine-grained, well layered granofels with alternating layers of dark gray biotite + plagioclase schistose granofels and gray to drab purple-green, garnet + actinolite + biotite calc-silicate granofels. Bedding is discontinuous with large blocks that range between approximately 50 and 700 m in length and 10 to 30 meters in width. Lithologically similar to Sreg and Sm.

Srcr

Srcr - Rusty Schist
A thin unit composed of platy schist with extreme red-brown rusty weathering. Minerals included are quartz, biotite, plagioclase, muscovite, chlorite, sericite, ilmenite, and trace amounts of monazite, zircon, graphite, and pyrrhotite. Bedding is indistinct due to the lack of quartzites. The unit is approximately 5 to 25 meters wide and has only been mapped in small belts, each approximately 500 m long. Lithologically similar to Ssf.

Sre

Sre - Eisenhower Member
A moderately red brown rusty weathering, medium- to coarse-grained, migmatitic gneiss with abundant calc-silicate lense. The distinguishing feature between the Crawford and Eisenhower Members is the prominent rusty weathering that the Eisenhower Member exhibits; otherwise these members are identical.

Sreg

Sreg - Granofels
Within the Eisenhower Member is a section of fine-grained, well layered granofels with alternating layers of dark gray biotite + plagioclase schistose granofels and gray to drab purple-green, garnet + actinolite + biotite calc-silicate granofels. The single section of this lithology mapped in the field area is approximately 800 m in long and 30 m wide. Lithologically similar to Srcg and Sm.

Srea

Srea - Amphibolites
This is an area within the Eisenhower Member migmatite where rare blocks of amphibolite are found. The blocks are dark brown to black in color, show indistinct layering and range in size from 1 to 20 m in length. Minerals include hornblende, quartz, plagioclase, biotite, magnetite, garnet, and trace amounts of monazite, and zircon.

Sr

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 thick 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 is not as defined as 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.

PALEOZOIC STRATIGRAPHY, DEFORMATION, METAMORPHISM AND INTRUSIONS

Overview

Here is a brief synopsis of the Paleozoic stratigraphy, deformation, metamorphism and geochronology in the Presidential Range. The stratigraphy (no fossils found yet!) is an on strike extension of the Rangeley, Maine sequence consisting of Silurian and Devonian turbidites and includes 7 members of the Early Silurian Rangeley Formation, the Middle to Late Silurian Perry Mtn., Smalls Falls, and Madrid Formations, and 11 members of the Early Devonian Littleton Formation.

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).

The igneous activity consists of the early, syn-kinematic 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).

The 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 the sillimanite zone (sill+bio+gar+/-staur+quartz+musc) and lastly retrograde metamorphism(s) occurred characterized by chlorite and coarse muscovite replacements. Monazite from Littleton and Rangeley formation schists and migmatites, and the syn-metamorphic Bigelow Lawn and Slide Peak Granite gives $^{207}Pb/^{206}U$ ages of circa 397–405 Ma, suggesting the peak of Acadian metamorphism and intrusion of early two-mica granites occurred then.

Stratigraphy

One of the hallmarks of the stratigraphy of the Presidential Range is the incredible control on topping given by graded bedding that has been reversed in grain size by metamorphism. A quick glance at the bedrock map (Eusden, 2010) shows hundreds of both upright and inverted graded bed strike and dip symbols across the Range (Figure 1). This afforded us excellent control on stratigraphic order and even more so on structural position of D_1 nappe folds (discussed below).

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.

Bradley and O'Sullivan (2016) recently published a detrital zircon age spectrum for a sample of Littleton Formation from a quartzite at the 4,000 ft. elevation level on the Auto Road. This was part of a regional detrital zircon age study of the Central Maine Belt in New Hampshire and Maine. The detrital zircon data show a Ganderian signature with peaks at 923, 576, 524 and 494, and 388 Ma, with a lesser peak at 1176 Ma (Bradley and O'Sullivan, 2016).

The Littleton Formation in the Great Gulf of the Presidential Range is cross cut by the 408.4 +/- 1.9 Ma Wamsutta diorite pluton (Eusden et al., 2000) part of the syn-tectonic Piscatquis Volcanic Arc (Bradley et al., 2000; Bradley and Tucker, 2002). Given this, the youngest detrital zircon age peak in the Littleton formation should be older than 408 Ma and that is why Bradley and O'Sullivan (2016) attributed the 388-Ma detrital zircon peak to a metamorphic over-print. However, given that peak's error of +/- 11 Ma and that we know from Bradley et al. (2000) and Bradley and Tucker (2002) that Littleton sedimentation was syn-collisional and syn-intrusion with the Piscataquis Volcanic arc, it is possible that deposition continued to as young as circa 400 Ma. and the detrital zircon data is representative of a maximum depositional age, not a metamorphic overprint. Regardless, a somewhat younger than accepted age of Middle to Early Devonian age for the Littleton Formation seems a reasonable conclusion given this new information.

It is interesting to note that three formations from the type Rangeley section in Maine sampled for detrital zircon analysis by Bradley and O'Sullivan (2016) gave maximum youngest age peaks much younger than the traditionally accepted stratigraphic ages. For example, Part A of the Rangeley Formation may be mid-Silurian rather than Early Silurian, the Perry Mountain Formation may be Early Devonian rather than mid-Silurian, and the Smalls Falls Formation may be Early Devonian rather than Late Silurian (Bradley and O'Sullivan, 2016). This trend toward younger than expected ages warrants a flurry of new mapping linked with detrital zircon geochronology.

D_1 Deformation

In terms of Paleozoic ductile structures, regional D_1 and D_4 folding and localized D_5 folding are highlighted on this trip. The D_1 folds are characterized by macroscopic east-facing nappes that are well characterized above treeline but less so in the wooded lower elevation regions. The topping direction of graded bedding has revealed a systematic geometry of broad upright limb regions, transitioning into narrow but mappable hinge zones, and in turn into broad inverted limb regions. This pattern coupled with the 1.5 kilometer of vertical relief and abundant rock exposure makes these early nappes some of the best-controlled fold structures in the Appalachians and as such potentially useful in reconstructing plate tectonic geometries. We interpret these east-facing folds to also have been east vergent as no evidence exists to suggest they have been backfolded. One of the problems this introduces is how east vergent early Acadian nappes fit neatly with the overall westward migrating Acadian orogenic front model of Bradley et al. (2000) and Bradley and Tucker (2002). Our favored tectonic model suggests that these D1 nappes verged east over a west, but shallow dipping Acadian subduction zone, probably on Ganderian continental crust in a retroarc setting. The east vergence can be explained as the west migrating orogenic front stalled upon contact with the Silurian "tectonic hinge" (Hatch and Moench, 1984) and Bronson Hill anticlinorium that likely acted as a buttress prohibiting any westward vergence of structures.

The pseudoandalusite porphyroblasts in the schists of the Presidential Range are very well developed and formed during syn-D_1 metamorphism. The andalusites are typically 1 to 2 cm in diameter and between 6 and 20 cm long. The andalusite was variably replaced by sillimanite during the peak of metamorphism, when conditions reached the upper sillimanite zone. Further pseudomorphing of this assemblage is characterized by coarse muscovite +/- staurolite during a retrograde event most likely caused by the intrusion of one or more late tectonic granitoids. Late stage chlorite alteration is also occasionally present. When replacement by muscovite is complete, it is common to see relict chiastolite crosses now completely composed of muscovite. Inclusion trails and microstructures have been obliterated by the retrograde metamorphism (Groome and Johnson, 2006), making the meso-scale of observation the best to use when quantifying strain patterns of this lineation fabric.

The porphyroblasts of the L_1 lineation lie mostly within the S_1 schistosity plane that in places exhibit reverse S_1 cleavage refraction with adjacent quartzites (Eusden et al. 1996, 1996b). Groome et al.'s (2006) study of the reverse refraction relationship showed that the stiffening effects of the andalusite porphyroblasts may have rendered the pelite more viscous than the adjacent psammites during foliation development**.** When aligned, porphyroblasts are also parallel to F_1 hinge lines. The hinge-parallel nature of the pseudoandalusite L_1 lineations has been extremely helpful in determining the geometries of F_1 nappe-scale folds. F_1 folds are non-cylindrical, as seen by fold geometries progressively changing across kilometer-scale hinge zone regions. F_1 folds with gently plunging hinge lines and moderately inclined axial surfaces change to folds with steeply plunging hinge lines and moderately inclined axial surfaces and finally to reclined folds. Overall, the F_1 geometries are probably best classified as sheath-like structures (Alsop & Carreras, 2007).

An interesting aspect of this lineation is its variable degree of alignment (Figure 2). Outcrops where the andalusites are not aligned are often within meters of those with a strongly developed L_1 lineation. In other places, the transition from non-aligned to aligned andalusite occurs gradually over hundreds of meters (Eusden et al., 1996). We assume that lineation's current orientation reflects strain conditions at the time of its development and alignment during D_1 - that is, we believe that the andalusite porphyroblasts were variably aligned during D1 deformation and that alignment has not been changed by D_4 or by any other subsequent phase of deformation. This is consistent with the general appearance of the schist-quartzite couplets that have well-preserved primary structures and no exposed mylonitic fabrics. Groome et al. (2006) also concluded that the porphyroblasts of the L_1 lineation had not been rotated after D_1.

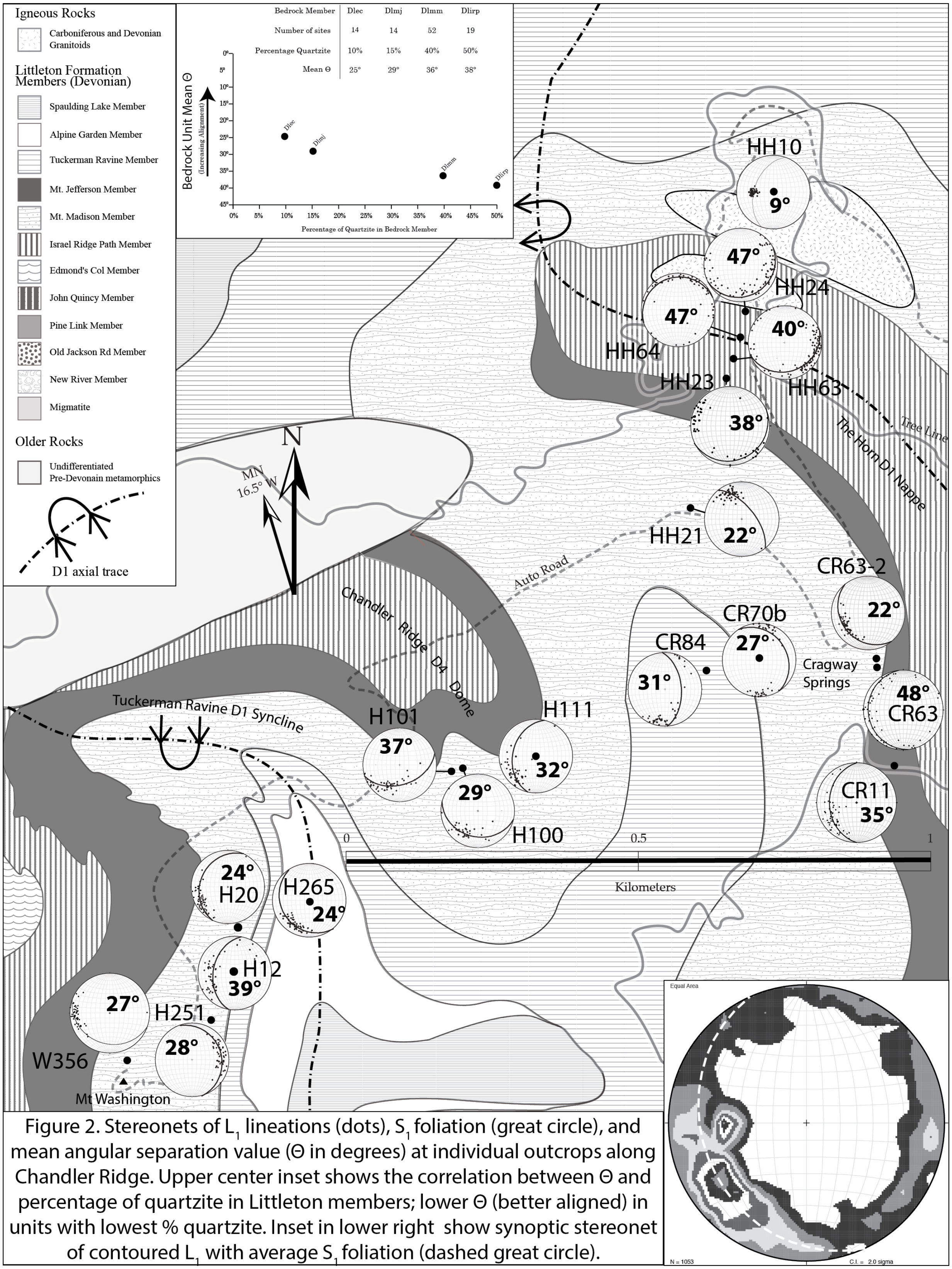


Figure 2. Stereonets of L_1 lineations (dots), S_1 foliation (great circle), and mean angular separation value (Θ in degrees) at individual outcrops along Chandler Ridge. Upper center inset shows the correlation between Θ and percentage of quartzite in Littleton members; lower Θ (better aligned) in units with lowest % quartzite. Inset in lower right show synoptic stereonet of contoured L_1 with average S_1 foliation (dashed great circle).

We've studied the variable development of the L_1 lineation throughout the Presidential Range (Guiterman and Eusden, 2004; Rodda and Eusden, 2005; Higgins and Eusden, 2008). In doing so we developed a quantitative metric (mean angular separation or "Θ" method) to measure the degree of lineation development. The mean angular separation method calculates the average acute angle between measured trends and plunges of a group of linear features and was developed by Bates senior thesis student Stephanie Higgins (2008). In this method, values of Θ lie between 0° at perfectly aligned sites, and <90° at randomly aligned sites. Values for mean angular separation ranged from a minimum of 9° near Mt. Washington, the most highly aligned site, to a maximum of 53° near Mt. Madison, the site with the lowest porphyroblast alignment. There was no statistical difference between andalusite lineation development or Θ on the upright limbs, inverted limbs, or the hinge zone regions of the D1 folds. There was a slight but not statistically significant increase in lineation development in the inverted limbs. This conforms to expectations, with slightly more alignment on inverted limbs that may have experienced greater shear strain. Regardless, structural position appears to not be the primary control on lineation development, or, if it was to a certain degree (e.g. on inverted limbs) that was greatly overprinted by another force.

There is a statistically significant correlation however between the proportion of quartzite at any outcrop and the degree of porphyroblast alignment at that site. In short, the more quartzite that surrounded a schist bed, the less aligned its porphyroblasts were. The data also show a clear connection between bed thickness and porphyroblast alignment: thicker beds yielded poorer alignment. We also examined the alignment variability on a larger scale than outcrop by studying the overall lineation development in these Littleton formation units: Edmond's Col Member (Dlec); Mt. Jefferson Member (Dlmj); Mt. Madison Member (Dlmm); and the Israel Ridge Path Member (Dlirp). There is a perfect positive correlation between percentage quartzite in the four bedrock members and porphyroblast non-alignment (high angles of Θ) in that member. Dlec (10% quartzite) shows the strongest alignment, with Dlirp (50% quartzite) showing the poorest alignment (Figure 2). Thus, the macroscale rheological variations of the different Littleton Formation stratigraphic members also reveal clear control of the lineation's development. The positive correlation between the development of this mineral lineation and the sedimentary features defined by the turbidite bedding in the Littleton Formation continues to argue for linking detailed mapping with any structural analysis.

D_4 Deformation

D_4 deformation is the most common and abundant phase of folding seen in the Presidential Range. F_4 folds are characterized as mesoscopic, moderately inclined to overturned, generally gently but often moderately plunging, asymmetric F_4 folds. The F_4 folds have no, or only a weakly developed, axial planar S_4 cleavage. F_4 folding is not uniformly distributed throughout the study area. All areas show some F_4 folding, but in places it is distinctly more pervasive than in others. Mesoscale folds have double amplitudes ranging from 10 cm up to several meters and wavelengths from 10 cm to 10 meters. Interim angles classify all mesoscale folds as open. Axial surfaces generally strike N and dip moderately to steeply W. Hinge lines trend N or S with shallow plunges. The typical shape of an F_4 fold consists of long, moderately dipping west limbs and short, steeply dipping east limbs. In some instances, the east limbs are overturned. This asymmetry gives a west over east sense of rotation, which we interpret to be related to east tectonic vergence of these folds. Pegmatite and aplite veins, dikes and sills seen throughout the alpine zone are folded by F_4. This deformation was syn-metamorphic but occurred after the peak of metamorphism in the region, likely around 380-365 Ma or in the late Acadian to Neoacadian timeframe.

Shortening calculations of well-exposed D_4 fold trains in the Presidential Range of New Hampshire were done at the mesoscale to quantify the strain and to evaluate the strain partitioning (Figure 3). Transects along Osgood Ridge on Mt. Madison, Chandler Ridge on Mt. Washington, and Caps Ridge on Mt. Jefferson, all containing well-exposed D_1 nappes refolded by D_4 fold trains were examined (Kugel and Eusden, 2004; Rodda and Eusden 2005; Reid and Eusden, 2005; Tamposi and Eusden, 2008). Shortening was calculated using the equation $e = (lf\text{-}lo/\ lo) * 100$, where lf = the hinge to hinge straight length of the fold train and lo = the length of the folded layer.

For Chandler Ridge, meso-scale fold train shortening varied systematically over a macro-scale D_4 Dome, ranging from 1.1% on the flank to 47.8% on the apex with a mean value of 14.2%. Osgood Ridge showed mesoscale shortening ranging from 5.9% and 32.3% on the limbs and crests respectively of macro-scale D_4 anticlinal synforms and synformal anticlines with a mean value of 16.4%. Caps Ridge mesoscale shortening ranged from 4% to 34% with a mean value of 12.4%. Collectively, these results suggest that mesoscale D_4 shortening is on average about 14% across the Presidential Range and this strain is preferentially partitioned on the crests and troughs of

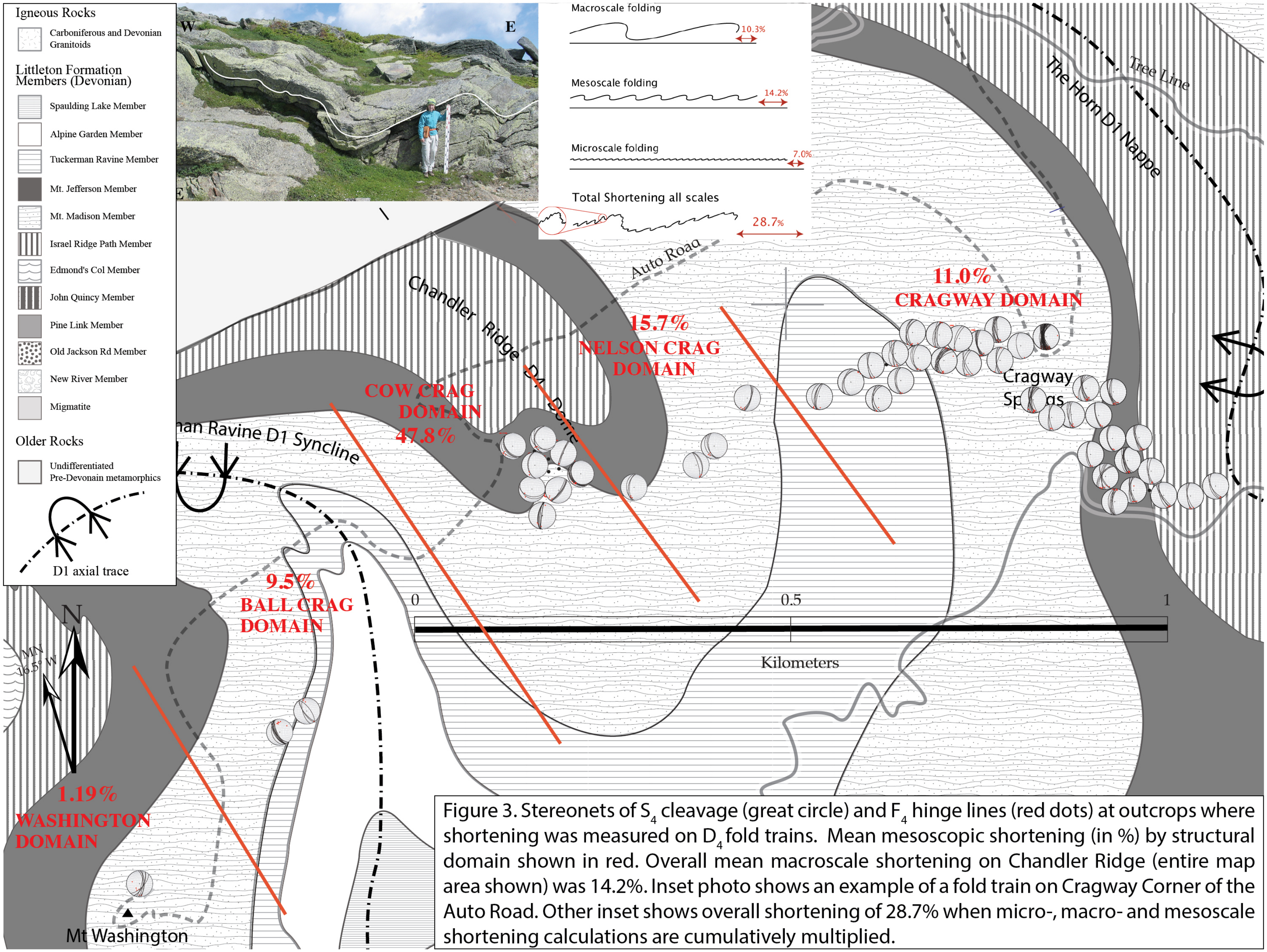


Figure 3. Stereonets of S_4 cleavage (great circle) and F_4 hinge lines (red dots) at outcrops where shortening was measured on D_4 fold trains. Mean mesoscopic shortening (in %) by structural domain shown in red. Overall mean macroscale shortening on Chandler Ridge (entire map area shown) was 14.2%. Inset photo shows an example of a fold train on Cragway Corner of the Auto Road. Other inset shows overall shortening of 28.7% when micro-, macro- and mesoscale shortening calculations are cumulatively multiplied.

macroscopic folds by parasitic mesoscale folding. The total D_4 shortening (micro+macro+meso) is approximately 30%. Depending on the duration of the D_4 event (10 my - 1 my), shortening or convergence rates would range from .1cm/yr to .01 cm/yr during the Late Acadian and Neoacadian orogenies.

D_5 Deformation and Doming

Uplift and doming of the Ordovician Oliverian Jefferson 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 (e.g. D_4 folding) but suspect that doming developed prior to the intrusion of the several Late Carboniferous plutons in the region. Regardless, it is likely Neoacadian and deforms all other fabrics in the rock except, of course, brittle structures created during Mesozoic rifting.

D_5 folding is a Neoacadian event, restricted to the Pinkham Notch area, and manifest as microscale crenulations and macroscopic folds that trend E-W and plunge quite shallow. D_5 is probably related to the Early Carboniferous intrusion of the 355 Ma. Peabody River Stock granite because D_5 folds are found in proximity to the contact and die out away from it.

MESOZOIC FRACTURES AND BASALTS

Mesozoic extensional structures were mapped in Great Gulf, Tuckerman Ravine, and Huntington Ravine in the Presidential Range, NH, to determine their relative ages, distribution, and paleostress fields (Castro and Eusden, 2010; Gardner and Eusden, 2010; Kindley and Eusden, 2011; Eusden et al., 2011). Over 3000 joints and 7 major dikes were measured within the folded Devonian Littleton Formation schist and quartzite and massive migmatites of the Silurian Rangeley Formation (Figure 4).

Two dikes were found in Tuckerman Ravine, three in Huntington Ravine (Pinnacle Gully, Diagonal Gully, and Escape Hatch dikes), and three in Great Gulf (Pipeline Gully, Airplane Gully, and Oblique Gully dikes). All dikes are 1-3 meters wide, extend for several 100's of meters, show composite dike textures, are often vesicular, are not significantly influenced by bedding plane anisotropies, and mostly classified as alkaline dolerites. The dikes all exhibit preferential erosion as compared to the schist country rock. As a result the dikes are found in the base of topographically prominent, narrow, steep walled gullies in the ravines.

Only common joints and few if any shear or conjugate joints were observed suggesting near surface conditions (<3 km?) under low lithostatic pressure. Four joint sets were identified and assigned relative ages based on field relations. From oldest to youngest the sets are: 1) NE striking vertical set; 2) E striking vertical set; 3) NNW striking vertical set; and 4) sub-horizontal to west dipping sheeted set. Key cross cutting relations were: 1) Pinnacle Gully where the Pinnacle NE striking dike is cut by the E-W joints; and 2) the south face of Mt Clay where the NNW joint set terminates in a "T" intersection against open E-W joints.

The oldest and most abundant joints have a NE strike and sub-vertical dip, are most abundant near and sub-parallel to the principal NE striking dikes in each ravine (the Tuckerman Ravine, Pinnacle, Pipeline, Airplane, and Oblique Gully dikes), and likely formed during regional NW-SE extension associated with the Late Triassic and Jurassic rifting of Pangea (Faure et al. 2006). The second oldest joint set has a E-W strike, is sub-parallel with the Diagonal Gully and Escape Hatch dikes in Huntington Ravine, and interpreted to be part of regional N-S extension associated with the Middle Cretaceous New England-Quebec province (McHone and Butler, 1984; Faure et al., 1996a and 1996b). The third youngest fracture set strikes NNW -SSE, has no correlative basalt dikes, and may correlate to the regional trend of the White Mountain Magma Series (McHone and Butler, 1984). The youngest joint set has shallow W-NW dipping sheeted joints thought to have formed from Quaternary glacial and Late Cretaceous tectonic unloading.

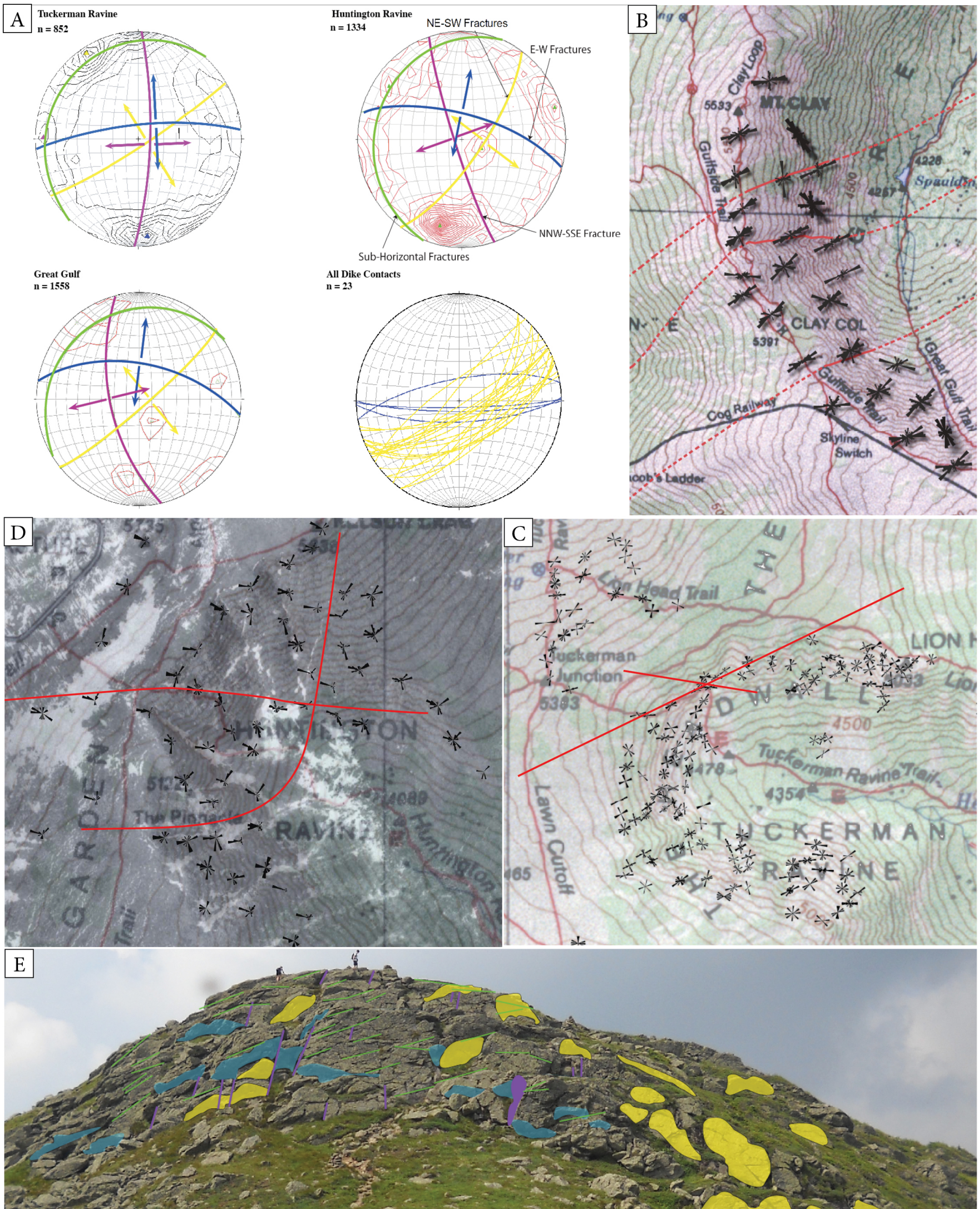


Figure 4. A. Stereonets of joints and dikes in the Presidential Range, arrows show extension direction; Rose plots of joints in Great Gulf (B), Tuckerman (C) and Huntington Ravine (D). E. Mt Clay joints color coded by set; steeply dipping sets from oldest to youngest: yellow NE, blue E, and purple N; and green sheeted set.

CRETACEOUS EXHUMATION

Apatite fission track (AFT) ages in samples collected along the 5000 foot relief (1500 m) exposed at Mt. Washington in the Presidential Range of New Hampshire have been used to constrain the Cretaceous cooling history of the area (Roden-Tice et al., 2011; Anderson et al., 2012). Nine AFT ages along the Mt Washington Auto Road and thirteen AFT ages along the Cog Railroad were collected for samples of the Littleton and Rangeley formations (Figure 5).

AFT ages range in from ~150 Ma at the highest elevations (~1900 m; ~6000 ft) to ~90 Ma at the base (~500 m; ~1,500 ft). These values yield an exhumation rate of 0.024 mm/yr between approximately 150 Ma and 80 Ma for both the Cog Railroad and Auto Road transects.

A 2D cross sectional view of the AFT age surfaces (surfaces at 140, 130, 120, 110, 100, and 90 Ma.) shows that the 140-120 Ma surfaces are tilted easterly between 3.2° and 10° with a mean of 6.8°. The 110-90 Ma surfaces are sub-horizontal with easterly dips between .5° and 2.9° with a mean of 1.8°. We suggest that the more tilted older surfaces were exhumed in a syntectonic setting and perhaps tilted by active faults in the area such as the local Ammonoosuc or Glen Ellis Faults, or perhaps even the distant Norumbega Fault. The sub-horizontal younger surfaces were exhumed during a period of post-tectonic erosion and were not deformed in any significant manner. One possibility is erosion due to incipient stream incision of the ancestral Androscoggin, Saco, and Connecticut River drainages. AFT track length modeling discussed below seems to support this hypothesis.

AFT track lengths along the two transects were nearly identical with longer tracks at the base of the mountain and shorter tracks at the summit. AFT track modeling suggests that there was rapid cooling (to produce the longer tracks) through the apatite partial annealing zone of 60° to 90°C at the base of the mountain during the time period from circa 125-60 Ma. This suggests that rapid exhumation occurred in the valleys of Pinkham and Crawford Notches during this time. Conversely the slower cooling through the apatite partial annealing zone (producing shorter tracks) at the summit suggests much slower exhumation for the same time period.

These heterogeneous trends in exhumation between the summit and the lower elevation notches may be due to late Cretaceous regional magmatic events associated with local asthenospheric upwelling (Matton and Jebrak, 2009) that reactivated zones of crustal weakness and possibly triggered the initiation of the ancestral drainage systems in the Presidential range. This would lead to rapid incision during the time period 125-60 Ma. in the notches while the summit eroded much more slowly.

From 60 Ma. to the present the AFT track modeling suggests a uniform exhumation rate across the topographic relief of the Presidential Range. We conclude that the most likely explanation for the common exhumation history across >1 km of relief is that the relief was established by the end of the Cretaceous and has persisted with steady-state topography through the Tertiary to the present (Roden-Tice et al., 2012).

The AFT results are consistent with an earlier relief method study employing $^{40}Ar/^{39}Ar$ muscovite cooling ages (Eusden and Lux, 1994). Geothermal gradients calculated from the results of both studies yield ~ 40 °C/km suggesting that this gradient persisted throughout Permian and Mesozoic times.

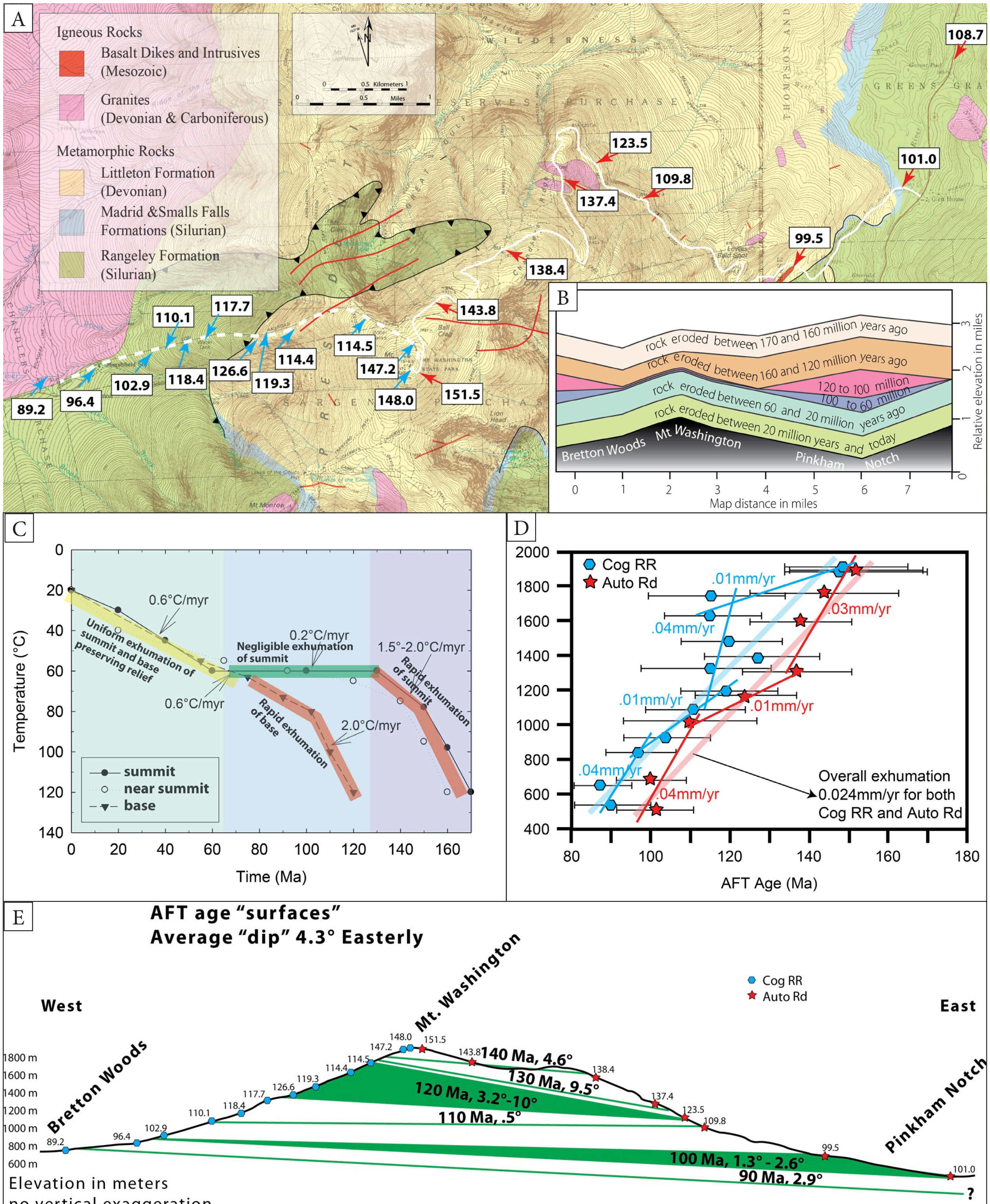


Figure 5. A. Apatite fission track ages (in Ma) on Mt. Washington. B. Proposed erosion and resulting topography over time. C. Track length modeling showing rapid exhumation in notches from 125-60 Ma. D. Exhumation rates calculated using relief method. E. Cross section of AFT surfaces through Mt. Washington. 140-120 surfaces are tilted by faulting and horizontal 110-90 surfaces are post-tectonic.

DRIVING AND WALKING LOG FOR STOPS

Time, Place, Logistics
Saturday September 30th, 7:30 AM in the gravel parking area on the west side of NH 16 to the immediate south of the Auto Road entrance (322363.00 m E, 4906302.00 m N). The base of the Auto Road is about 30 miles west of Bethel, ME and takes about 40 minutes to drive. From Bethel follow Rte. U.S. 2 west to Gorham, NH then take Rte. NH 16 south to the Auto Road entrance. Due to the fragile nature of the alpine ecosystem, please always walk on trails or rocks. *Warning:* Expect extremely cold and unpredictable weather. Be prepared with proper clothing and good hiking boots for very rocky, uneven terrain, winter–like conditions and extremely high winds. Bring your lunch and water as there will be absolutely no chance to pick up anything once the trip begins. There are no bathrooms facilities. Vehicles must be consolidated. The folks at the Mt. Washington Auto Road have kindly agreed to charge us only $29 per vehicle and waive the passenger fee. Half-ton vans are permitted up the road but with a maximum passenger and luggage weight of 900 lbs (that's approximately 6 people, including driver). If you are planning on driving your vehicle, please carefully check the vehicle restrictions on the Auto Road web site that can be found here.

Mileage
0.0 Base Station. Drive from the base of the Auto Road to the summit of Mt.Washington

8.0 Lower parking lot (elev. 6,200 ft.) of Mt Washington Summit. Park vehicles and walk to STOPS lA-B

STOP lA. In blasted outcrop along the NW side of the road just below parking lot, inverted graded bedding of Huntington Ravine member of Littleton Formation within inverted limb of the Mt. Washington Nappe, small sills of pegmatite as well. AFT ages in the summit region are between 147 and 151 Ma..

Walk down the road about .1 mile just below the parking lot with some oil tanks on the west side of the road at about elevation 6,100 ft..

STOP lB. On the east side of (downhill side) the road are blocks and outcrops of schists and thin quartzites of the Huntington Ravine member of the Littleton Formation with excellent L_l pseudoandalusite lineations. Where aligned, the L_1 orientation is parallel to the F_l fold axes throughout t he Presidential Range. Mean angular separation or "Θ" values for the andalusite lineation in this region are 15° to 25°, meaning strong alignment.

Return to vehicles and drive down the Auto Road.

8.6 Park vehicles in lot on west side of road which is just above the 6,000 ft elevation post. STOP 2 is a 2 mile walking loop to several outcrops.

STOP 2A. Walk .1mi. east and slightly uphill to Ball Crag (elev. 6,112 ft.) and examine inverted graded beds of the Huntington Ravine member of the Littleton Formation with well developed F_4 folds and poorly developed S_4 axial plane cleavage.

Walk back to the parking lot with the vehicles and walk .1mi west to the intersection of the Great Gulf and Gulfside Trails. Follow the Gulfside Trail WNW paralleling the Cog Railroad, passing the junction of the Westside Trail, to the Clay Col and junction of the Gulfside and Clay Loop trails, about .9 mi.

STOP 2B. In the Col the geology passes from schists of the Bigelow Lawn member of the Littleton Formation to the SE to gneisses and abundant pegmatites of the Mt. Clay member of the Rangeley Formation to the NW. The Madrid, Smalls Falls, and Perry Mountain Formations are cut out here. The contact between the Rangeley and Littleton is not exposed, but you can get within about 20 meters of it; look for the last outcrop of schist and the first outcrop of gneiss with calc-silicate lenses. This contact we have interpreted as the D_2 Greenough Spring Thrust Fault. The NE striking Airplane gully dike is exposed in the steep gully along the headwall of Great Gulf and blocks of basalt can be seen in the saddle.

Proceed N along and up the Clay Loop Trail for about .1 mi.

STOP 2C. In the trail and just to the W on the first pitch up from the Col, are outcrops of the Mt. Clay member of the Rangeley Formation gneisses with abundant quartz segregations (clasts?) and rare, oval, concentrically zoned, calc-silicate lenses (clasts?). Proceed up the first steep pitch on the Clay Loop Trail another .05 mi., which is halfway up the first or S summit of Clay. On the E side of the trail are exposed meter-long, bedded clasts of calc-silicate with bedding truncated by the gneissic matrix. We have interpreted this type of Rangeley to be a metamorphosed olistostromal mélange. This steep pitch also shows excellent fractures and all four joint sets (NE, E, N and sheeted) are well exposed. In a few places the N set exhibits "T" with the E and NE sets, demonstrating that the N joints are the youngest steeply dipping set.

Return to vehicles along Clay Loop and Gulfside Trails, about 1 mi., and drive down the Auto Road.

9.5 Park at the lot on t he NW side of the road at elevation 5,700 ft.; the relatively flat area of the so-called "Cow Pasture." STOP 3 is a 1 mile walking loop to several outcrops

Walk to the junction of the Nelson Crag and Huntington Ravine Trails and proceed up the Nelson Crag Trail about .1 mi to about elevation 5,800 ft.; this would be between the 14th and 15th cairns on the Nelson Crag Trail from the junction. Turn off the trail to the south, paralleling the slope and contours for about .1 mi to prominent outcrops marked by a small cairn.

STOP 3A. F_1 hinge zone exposures of the Tuckerman Ravine Syncline with thick bedded quartzites and thin schists of the Alpine Garden member of the Littleton Formation. S_0, bedding, and S_1, axial planar schistosity, are perpendicular here. Graded beds in the hinge zone suggest northeasterly facing directions for the F_1 folds.

"Rockwack" downhill, southeast, for about .2 mi to the headwall of Huntington Ravine and the junction of the Huntington Ravine and Alpine Garden Trails. Please only walk on rocks and keep off the vegetation!

STOP 3B. Pinnacle Gully and Diagonal dikes intruding upright schists and thick micaceous quartzites of the Huntington Ravine member of the Littleton Formation. The Pinnacle dike belongs to the NE striking earliest joint/dike set while the Diagonal dike is part of the E striking joint set. E joints cut the Pinnacle dike suggesting it is younger.

Follow the Alpine Garden trail .2 mi northeast to junction with the Nelson Crag Trail.

STOP 3C. Exposed is an outcrop of a F_4 warping fold about 15 meters southeast of the big cairn at the junction. This fold happens to be along the crest of the most significant macroscopic F_4 structure, the Chandler Ridge Dome. The F_4 folds exhibit maximum shortening of 47.8% on the crest of the Dome and D_4 folds are the most geometrically diverse in this region.

Follow the Nelson Crag trail about .1 mi. uphill to the unnamed crag at elevation 5,735'.

STOP 3D. On the north and northeast flanks of this crag are upright beds of the Cow Pasture member of the Littleton Formation. S_0 and S_1 are now parallel here as the F_1 hinge zone of the Tuckerman Ravine syncline is slightly above us.

Proceed .1 mi. to the junction with the Huntington Ravine Trail and then back to the parking lot with the vehicles. Drive down the Auto Road.

10.7 Park in the vicinity of Cragway Spring (elev. 4,800 ft.) in the small parking lots above and just at the hairpin turn. STOP 4 is a 1.5 mile walking loop to several locations.

Hike down the Nelson Crag Trail .6 km to treeline at approximately 4,300 ft. elev.

STOP 4 A. Outcrops of the Great Gulf member of the Littleton Formation. Exposed here are schists with 10 cm thick quartzite interbeds. Bedding, S_0, and schistosity, S_1, are not parallel indicating that we are in the F_1 hinge zone of the Horn Nappe. S_1 schistosity is refracted through the inverted bedding defined by the quartzites. Fresh, pink andalusite and andalusite rimmed by fibrolitic sillimanite is common. There is a nice float block with a complete F_1

fold exposed. There are good glacial striations on a quartz vein outcrop that also shows some unusual staurolite-bearing pegmatites.

Proceed back up the Nelson Crag Trail about .2 mi through the first patch of scrub spruce and into the next higher treeless area. Head off the trail to the south about .05 mi to the prominent outcrops.

STOP 4B. Exposed here are the predominately massive schists of the Cow Pasture member of the Littleton. L_1 lineations are folded by abundant F_4 folds with circa 11% macroscopic shortening which define the topography here. Bedding and S_l schistosity are again parallel as we are now above the Horn Nappe Fl hinge zone.

Proceed back up the Nelson Crag Trail about .1mi through another patch of scrub spruce and to the higher treeless area that includes the Auto Road at Cragway Spring. Head off the trail to the south about .05 mi.

STOP 4C. Exposed are schists and thin quartzites of the Huntington Ravine member. Well developed F_4 structures fold thin aplite sills here. These small granitic apophyses are the earliest phase of granitic intrusion and are pre-F_4 in age. Some of the larger granite plutons of this generation impart local staurolite grade metamorphism to the schists. Mean angular separation or "Θ" values for the andalusite lineation in this region are highly variable over short distances and range between 22° (well aligned) to 48° (poorly aligned)

Return to the vehicles examine the road cuts and outcrops on the "inside" of the hairpin turn.

STOP 4D. Exposed are schists and thin quartzites of the Huntington Ravine member. Upright graded beds are common. Pseudoandalusite is replaced by fibrolitic sillimanite in the core with coarse-grained muscovite and staurolite in the rim. A great place to see this texture is a 1m diameter lichen-free zone of bed rock marked by a small patch of concrete (4 cm diam) with a small metal pin (1 cm diam) embedded in it. F_4 folds are everywhere and as with all locations in STOP 4 are consistently oriented.

Return to vehicles and drive down the Auto Road.

11.7 Park in the lot at elevation 4,200 ft. just below the junction with the Winter Cutoff Road. STOP 5 is a short walking loop of about 1mile.

Walk back up the Auto Road to the Winter Cutoff road and proceed up that about .1 mi to elev. 4,400 ft.

STOP 5A. Outcrops of thick schists and 10-20 cm thick quartzites of the Great Gulf member of the Littleton. These outcrops show the exact hinge location for the Horn Nappe as bedding and schistosity are perpendicular. S_l is again refracted through the quartzites. Mean angular separation or "Θ" values for the andalusite lineation in this region are around 45° meaning poorly aligned. We think this is due to the thick quartzites of the Great Gulf member.

Walk about .2 mi up the ridge between the Winter Cutoff and Auto road to about elevation 4,450 and then bushwhack down to the Auto Road. Walk down the road about .1 mi.

STOP 5B. Nice exposure of a rare F_l mesoscopic fold hinge in the outcrops on the west side of the road. The fold exhibits reverse refraction where the steeper angle is in the schist, made more viscous by the growth of andalusite (Groom and Johnson, 2006; Groome et al., 2006). AFT ages range from 137 to 123 Ma in this vicinity.

STOP 5C. Garnet-bearing granite sill exposed in a road outcrop. We've tried to get zircon and monazite out of this for an age date but no luck. An age determination would nail down the timing of F_4 folding and associated contact metamorphism in the Range.

Return to vehicles and drive down the Auto Road.

11.9 Park in the lot on the east side of the road just above the 4,000 ft. elevation post.

Walk down the road about .2 mi. to just below the 4-mile post.

STOP 6. Examine the large outcrop of thick quartzites of the Oakes Gulf member of the Littleton. There is one enormous bed, 5 meters in thickness, which is wonderfully graded and inverted. Bedding and schistosity are not parallel, meaning we are still within an F_1 hinge zone. This outcrop was where Bradley and O'Sullivan reported a 388 Ma youngest zircon peak age, attributing that to a metamorphic age.

Return to vehicles and drive down the Auto Road

13.8 Park in the lot where the Madison Gulf Trail crosses the road.

Walk .5 miles up the trail to the junction with the Lowe's Bald Spot cutoff and hike up the trail to the top.

STOP 7. Lowe's Baldspot. Beginning from the trail junction and continuing to the top you will see the schists with thinly beds of quartzite or just massive schist outcrops of the Bigelow Lawn Member of the Littleton Formation. One of its characteristics is the presence of garnet +/- quartz coticule. Structurally there are two sets of crenulations one N-S trending and the other E-W trending. These are D_4 and D_5 folds respectively. D_5 spatially surrounds the Peabody River two mica granite intrusion which has been dated to be 355 Ma.

Return to vehicles and drive down the Auto Road .

14.3 Park in tight parking lot along the road.

Walk across the road to the south side and bushwhack .1 miles down a little drainage to outcrops of Silurian Smalls Falls Formation.

STOP 8. The Smalls Formation well bedded, rusty schists are exposed in the stream bed. Above this outcrop is found the Abandoned Bridge member of the Littleton Formation with no intervening Madrid Formation. We interpret this stratigraphic gap to have been caused by a pre-metamorphic fault and have named it the Pinkham Notch Fault. AFT ages range from 99 to 101 Ma in this vicinity. Proceed back to the road and examine the outcrops of Triassic (?) vent breccia. Besides the basalt dikes we saw earlier this is the only other mappable Mesozoic unit in the Presidential Range. A separate section of this unit can be seen at Crystal cascade on the Tuckerman Ravine trail.

Return to vehicles and proceed down the bottom of the Auto Road

16 Parking lot that we started from.

End of Trip

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