Bedrock Geology of the Mount Moosilauke, NH, 7 ½′ Quadrangle
by
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Introduction

The shapes of the mountains and valleys in the Mount Moosilauke quadrangle are controlled by the geometry of the underlying bedrock. Biotite gneiss (Bethlehem Gneiss, Db2b), sillimanite schist (Littleton Formation, Dl) and porphyritic granodiorite (Kinsman Granodiorite, Dk2x) are all resistant rocks that tend to form ridges and hills. Millions of years of erosion have removed thousands of feet of material since the rocks were first formed. The deep valleys drained by Tunnel Brook and Little Tunnel Brook may be in part controlled by steep faults and associated less resistant rocks (Fig.1).

More recent erosion by glaciers and streams in the last several thousand years has further molded the landscape. Jobildunc Ravine is a classic bowl-shaped glacial cirque, and three of the other brook headwaters may also have been gouged by mountain glaciers (Haselton, 1975; Davis, 1999). Thick glacial till obscures the bedrock on many slopes and alluvium covers valley bottoms. Surficial materials are not represented on this map, which shows the bedrock as it might appear if the overburden were not there. Some of the brooks have cut deeply enough into the till to expose bedrock, but surprisingly, the bed of Baker River reveals zero outcrop in the quadrangle.

Details of Bedrock Geology

Stratigraphy

The Mount Moosilauke quadrangle contains the eastern margin of the Moody Ledge dome, one of many Oliverian Gneiss domes that extend along the length of the Bronson Hill anticlinorium (Lyons et al., 1997). Zircons sampled from the granitic gneiss (Oo) that cores the dome, from just west of the quadrangle, yielded a late Ordovician U/Pb age of 450 +/-2 Ma (Moench and Aleinikoff, 2002). The granite intrudes the Ammonoosuc Volcanics (Oa), which are the oldest rocks in the area, and which consist of mafic, metabasaltic gneiss (amphibolite) interlayered with lesser amounts of felsic gneiss (Fig.2). Calc-silicate granofels and amphibolite (Oac) that crop out just above and below where Tunnel Stream Road crosses Tunnel Brook are interpreted as part of the Ammonoosuc, apparently lying in a sliver between two faults (Fig. 16B). Discontinuous, thin Silurian units, the Clough Quartzite (Sc) and Fitch Formation (Sf) are found here and there east of the Ammonoosuc, between it and the overlying Early Devonian Littleton Formation (Dl).

The commanding bulk of Moosilauke and its ancillary spurs occupy much of the southern half of the quadrangle. The mountain is held up by a very resistant and unusually thick section of sillimanite schist and granofels, about 4900 meters thick, which belong to the Littleton Formation. To the north the Littleton narrows to 1600 meters (Billings, 1935), where it is intruded by Bethlehem Gneiss. In the Mount Kineo quadrangle to the south, it becomes only about 600 meters thick (Page, 1940). The sediments that became the Littleton Formation were deposited by turbidity currents that swept fine sand and mud into a marine basin between the remnants of a volcanic arc (Ammonoosuc Volcanics) to the west and tall mountains on the leading edge of a continental fragment called Avalonia to the east. Lower Devonian or Silurian brachiopod fossils were found by Billings

(1937) on an avalanche scar on the east slope of Mt. Clough. Boucot and Rumble (1978) described several species of brachiopods and a gastropod from bedrock in Beaver Brook. They concluded that the rocks are likely Oriskany in age (Lower Devonian, 407 to 413 Ma).

Konrad (1989) mapped out eight informal members within the Littleton, under the direction of John Lyons at Dartmouth College. My mapping presents a simpler subdivision, but her overall conclusion of a homoclinal sequence topping to the east has been confirmed, thanks to numerous graded beds (Fig.3). Nickelsen (1980) also reported graded beds that top east. I concluded that the lower part of Konrad's Benton member and her four youngest members are so similar to one another that they do not warrant separate designations. Thus the dominant facies of the Littleton Formation consists of turbiditic sillimanite schist with 1 to 3 cm, paler gray quartzose laminations (Fig.4).

The Summit member (Dls), by contrast, is a rusty-weathering, well bedded granofels, which corresponds to the upper part of Konrad's Benton member (Fig.5A and 5B). The lower part of the Benton member is similar to the typical Littleton at the top of the section, so it is shown here as undifferentiated Littleton. The Summit member forms the ridgeline of Moosilauke from South Peak across the main summit to the high ridge north of Mt. Blue. It may have been deposited as greywacke sandstone. One amphibolite layer is exposed along the Carriage Road south of the summit, and rare amphibolite clasts occur in the granofels (Fig.6). North of the Wild Ammonoosuc River, rusty granofels is associated with more extensive metavolcanics (Dlv): fine- to coarse-grained amphibolite, salt-and-pepper metadacite and white metarhyolite (Fig.7). Metavolcanics also occur along the eastern contact of Littleton with Kinsman, where they have been sampled for U/Pb zircon analysis (Fig.8).

Konrad's Stark Falls member (Dlsf) lies east of the Summit member and consists of monotonous gray schist without quartzose laminae. I have also retained her Beaver Brook member (Dlbb) as a lens of calc-silicate-bearing rocks (Fig.9) 200 m west of the Kinsman Granodiorite, where Boucot and Rumble (1978) collected their fossils.

Intrusive Rocks

To the west of Moosilauke, the Mt. Clough pluton of Bethlehem Gneiss (Db2b) is in apparent intrusive contact with the Littleton and a discontinuous layer of Fitch Formation. It consists of well foliated biotite granodiorite gneiss, locally with biotite-rich schist xenoliths. The spacing of foliation varies from about 5cm to less than 1cm (Fig.10). The Bethlehem seems to have intruded between Fitch and the older Clough Quartzite, which is exposed along its western contact in the East Haverhill quadrangle on the west slope of Mt. Clough. (Note that this is not the Clough type locality, which lies about 25 km to the north in the Clough Hill district of Lyman. See Rankin and Rankin, 2014). A fault, the Mud Pond fault, offsets the eastern Bethlehem/Fitch/Littleton contact.

The Lincoln pluton of Kinsman Granodiorite (Dk2x) intrudes the Littleton east of Moosilauke, where the contact is confused by numerous pegmatite and aplite sills and dikes. Bethlehem Gneiss is generally more strongly foliated than the Kinsman and lacks the distinctive 4-8cm long K-feldspar phenocrysts that are the hallmark of the Kinsman (Fig.11). The reader is referred to a thorough comparison of the Bethlehem and Kinsman by Dorais (2012). Both the Bethlehem and Kinsman crystallized in the Lower Devonian and are compositionally identical (Dorais, 2003). Lyons et al. (1997) cited an age of 410 +/- 5 Ma for the Bethlehem. The age of the Kinsman has been estimated as 413 +/- 5 Ma (Barreiro and Aleinikoff, 1985). Zircons from samples collected during this project will be analyzed to provide more precise ages for the plutons. The plutons have been interpreted as sheet-like bodies that intruded along thrust faults within the metasedimentary packages during the first stage (D_1) of Acadian deformation (Thompson et al., 1968; Allen, 1997).

Planar, granitic pegmatite dikes and sills are common in some areas. In Tunnel Brook valley, where quartz veins and pegmatites trend roughly north-south, they are likely related to the Mud Pond fault. Other, older pegmatites and quartz veins are deformed by D_1 and D_3 folds (Fig.12A). Pegmatite is responsible for some dramatic waterfalls in the quad, for example: cutting Kinsman Granodiorite in Lost River Gorge (Fig.12B), and cutting mafic metavolcanics in Black Brook. In Lost River, the coarser crystals apparently make the pegmatite more resistant, whereas in Black Brook the pegmatite is more resistant mostly due to its more felsic composition. Unmetamorphosed, presumably Mesozoic, dikes (KJd) intrude the older rocks of the quadrangle along two dominant directions: NE and E-W (Fig.13). They range in composition from basalt and diabase to camptonite and bostonite. The map includes a prominent NE-trending diabase dike along an unnamed brook south of Wildwood, an E-W pyroxene-bearing lamprophyre east of Rt.116 and several of the dikes studied by Billings (1937) that were not revisited in this study.

Structure

Although all the rocks in the quadrangle lie east of the Bronson Hill anticlinorial axis, the bedding, foliation and intrusive contacts, rather than dipping east as they do on the east flank of Owls Head dome just to the west, have been rotated such that they are nearly vertical in the western part of the map and dip steeply to moderately west across Mt. Moosilauke (see cross section). The cause of the tilting is uncertain. It may be related to the Mud Pond fault system (see below), along which dominant foliation in the Bethlehem Gneiss and Littleton go through the vertical.

Bedding (S_o) and the dominant foliation (S_1) were presumably deformed by the rise of the domes to the west, but no folds or foliation were recognized related to this D2 event. S_1 foliation in the schists, which is defined by biotite and muscovite, is subparallel to bedding in nearly all outcrops. It lies at high angles to bedding only in the vicinity of rare D_1 nappe-stage isoclinal folds. Two well exposed isoclines can be seen along the Beaver Brook Trail, about 5m apart and with opposite vergence (Fig.14). The fold axes plunge moderately west. Outcrop-scale, open D_3 folds, which deform bedding, foliation, and early quartz veins and pegmatites, are common in many outcrops throughout the quadrangle. These folds generally plunge westerly and lack any obvious axial plane cleavage. The open folds are related to a very broad warping of S_1 foliation across Moosilauke, well documented by Konrad (1989). Her analysis of the large anticline between the South Peak and Mt. Blue yielded a fold axis plunging 59º NW and an axial plane oriented WNW. In several places, a second strong foliation (S_4) developed along shear zones up to 20cm wide, which are younger than both S_1 and the open D_3 folds.

A prominent valley extends from Mud Pond at the south end of Tunnel Brook NNE, continuing parallel to Rt.116 to the northern edge of the quadrangle. Billings (1935) had mapped a small body of sheared Moody Ledge Granite where this lineament crosses the Wild Ammonoosuc River, and he mapped the adjacent volcanics as part of the Littleton (Dlv). Hatch and Moench (1984) mapped the same rocks as Oliverian (Oo) and Ammonoosuc Volcanics (Oa). Moench and Aleinikoff (2002) dated the granite as 435 +/- 3 Ma, somewhat younger than the main body of Moody Ledge Granite. They suggested that the younger age may represent a time of intense shearing rather than original crystallization. Hatch and Moench (1984) proposed that a fault follows Tunnel Brook and then wraps east around the area underlain by the Ordovician rocks.

I propose in this report that the Mud Pond fault stays west of the Ordovician rocks, and continues NNE to the northern edge of the quadrangle. The fault is exposed in Slide Brook at about 2150' elevation, where it strikes N20E and dips 72º in a zone rich in quartz veins and sheared rock (Fig.15). It is probably partly responsible for the deep ravine between Mt. Clough and Mt. Moosilauke, which was later carved into a U-shaped valley by glacial action. The east side moved up, bringing a portion of the south-plunging Moody Ledge dome toward the surface.

I have also found Oliverian rocks in the bed of Little Tunnel Brook (Fig.16A), which I interpret as lying east of a splay from the main fault. Displacement on the splay decreases toward the south, and a shear zone was found at 2340' elevation where Littleton is on both sides as the brook's gradient abruptly steepens. Calc-silicates (Oac) in Tunnel Brook itself occupy a narrow slice between the two faults. Bedding within this slice dips at uncharacteristically low angles (Fig.16B).

A minor right-lateral fault is tentatively proposed to explain offset of some contacts across the Wild Ammonoosuc River valley. Metavolcanic rocks in the Littleton are exposed in the river bed itself, but not on the slopes to the south. The fairly abrupt end of the mass of Bethlehem Gneiss north of the river is also poorly understood. As mapped, it appears to represent the original intrusive relationship with the surrounding country rocks, but another fault parallel to the Mud Pond fault cannot be ruled out.

Metamorphism

All rocks in the quadrangle have been deformed and metamorphosed, except for the Mesozoic dikes. In addition to quartz and muscovite, biotite, garnet, sillimanite +/- staurolite are commonly present in the schists. Fine-grained sillimanite is nearly ubiquitous. Local coarser sillimanite appears to be pseudomorphic after andalusite (Fig.17A and B). Konrad (1989) noted relict andalusite in thin section, and retrograde chlorite associated with biotite. She found that staurolite is not present SE of the Moosilauke summit, which she attributed to the prograde reaction in which staurolite plus muscovite were replaced by sillimanite, biotite, garnet and water as temperature increased. In the next quadrangle west, for example at Black Mountain, kyanite is the stable aluminosilicate mineral instead of andalusite (Rumble, 1993). Thus, the rocks at Black Mountain experienced lower T but higher P than those at Moosilauke. Sillimanite is present in both areas, implying that the P-T "triple point" where all three aluminosilicates are stable would lie somewhere between the two mountains.

Rumble (1993) estimated metamorphic conditions of 600º C and pressure of 3.5 Kb from the mineral assemblages present at Beaver Brook. The calc-silicate granofels matrix for the fossils contains quartz, diopside, grossular garnet, titanite +/- zoisite, a metamorphic assemblage that is compatible with that in the nearby schists. The actual fossil shells were partly silicified early in their metamorphic history, and at higher grade some of the calcite and quartz reacted to yield wollastonite and water (Boucot and Rumble, 1978). They estimated metamorphic conditions of about 600º C and 3.5 Kb, consistent with amphibolite facies in the mafic metavolcanics. Konrad (1989) documented the high-grade mineral idocrase in thin sections from the Ammonoosuc calc-silicates along Tunnel Brook.

Regional Context

In the Monadnock 15' quadrangle, Thompson (1985) mapped an Acadian fault, the Brennan Hill thrust fault, between the classic Bronson Hill stratigraphic sequence (Oliverian-Ammonoosuc-Clough-Fitch-Littleton; Billings, 1935) east of the Keene dome and the overlying Monadnock sequence (Rangeley-Francestown-Warner-Littleton; Moench and Boudette, 1970). Allen (1997) presented a tectonic model whereby the Bethlehem Gneiss intruded along the Brennan Hill thrust (equivalent to the Fall Mountain thrust-nappe) during the Acadian Orogeny. Thus the Bronson Hill stratigraphy should lie west of and below the Bethlehem Gneiss in the original stacking order of nappes and thrusts. If this interpretation holds true in the Mount Moosilauke quadrangle, then the rocks east of the Bethlehem Gneiss should belong to the Monadnock sequence. If not, then the Bethlehem has intruded across the nappe-stage stack of folded and faulted rock units such that Bronson Hill sequence rocks lie on both sides. Or perhaps an equivalent to the Brennan Hill thrust lies within the thick section of Littleton on Moosilauke.

During initial mapping for this project, the present author wondered if the Summit member might be Rangeley Formation, in which case its western contact would correspond to the Brennan Hill thrust fault.

Although like the Rangeley Formation, the Summit member is massive and rusty, it lacks the Rangeley's characteristic calc-silicate pods, and no rocks equivalent to Francestown or Warner were found along its eastern contact with the Stark Falls member. So we must conclude that the entire section at Moosilauke is part of the Bronson Hill sequence. Within 15 kilometers north of the quadrangle, the Bethlehem and Kinsman are in contact (Lyons et al., 1997). The position of the Brennan Hill thrust, then, remains uncertain in northern New Hampshire. To the south the story is more consistent with that of southern New Hampshire. In Wentworth, at a similar distance south from Moosilauke, the Bronson Hill sequence is exposed around a small Oliverian dome, surrounded by the overlying sheet of Bethlehem Gneiss in the Mt. Clough pluton, which is succeeded to the east by the Rangeley sequence (Malinconico et al., 2012).

Economic Resources

Many amateur prospectors pan for placer gold in Tunnel Brook and the Wild Ammonoosuc River. A free permit for panning or other mineral collecting is required from the White Mountains National Forest (WMNF) headquarters in Campton. The Mud Pond fault zone may well be a local source of the gold, although some probably was brought in by glaciers and deposited in the till, from which streams have eroded small particles of gold. Hurricane Irene in 2011 and a big storm in 2017 resulted in major erosion, especially in the Tunnel Brook watershed, which exposed previously buried alluvial material and flushed new sediment downstream. Tiny euhedral garnets that weather out of the Kinsman Granodiorite and Littleton Formation are also common in stream sediments, but they are mostly too small for use as gemstones.

Although Bethlehem Gneiss and Kinsman Granodiorite have been used as dimension stone, rip-rap and crushed stone, the quadrangle has no rock quarries. In the early 1800's, magnetite-rich amphibolite was excavated from a small iron prospect pit in the town of Easton, northeast of the Rt.112/Rt.116N intersection on WMNF land Fig.18). The site is referred to as "the ore lot" in town records (Kris Pastoriza, Easton Conservation Commission, pers. comm., 2022). Ms. Pastoriza also alerted us to the borehole data available at NH DOT from the defeated Northern Pass project. An interesting historical note is that until the mid-19th century, an important trade route followed the Tunnel Ravine – Ham Brook corridor. Jack Noon's (2019) historical novel relates how iron goods were transported by horse-drawn pungs south through the valley from the blast furnace at Franconia. His book also explains the ironworks process at Franconia in excellent detail.

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Fig. 1 View southwest toward Mt. Moosilauke. The U-shaped valley of Tunnel Brook Notch is on the right. Little Tunnel Brook is the middle, curved valley on the slope of Moosilauke.

Fig. 2. Ammonoosuc Volcanics exposed in the Wild Ammonoosuc River near the mouth of Bowen Brook. Dark green amphibolite with sheared pods and stringers of epidote. View toward the south.

Fig. 3. Graded beds in Littleton Formation topping E (towards bottom of photo) north of Route 112.

Fig. 4. Laminated schist and quartz-rich granofels typical of the Littleton Formation exposed in Forest Service Road 171 north of Mt. Moosilauke. The granofels layers are about 1 to 2cm thick. Topping direction in this exposure is equivocal, but elsewhere several E-topping graded beds can be observed. The 6-cm thick pegmatite vein strikes due N (upper left). Exposures of this quality are rare on heavily vegetated Mt. Moosilauke.

Fig. 5A. Slabby-weathering, somewhat rusty-weathering granofels, Summit member of the Littleton Formation along the Appalachian Trail as it approaches the summit from the north.

Fig. 5B. Summit member of the Littleton Formation. Gray granofels along abandoned Gorge Brook Slide Trail at elevation 3800'. Bedding dips 64 degrees NW. In the massive schist of the Stark Falls member directly below this ledge, foliation has a similar strike but dips more gently at 58 degrees NW.

Fig. 6. Amphibolite clasts in the Summit member, Littleton Formation, on the ridge north of Mt. Blue.

Fig. 7. Intermediate and felsic metavolcanics in the Littleton Formation. Dime for scale

Fig. 8. Pillow-like structures in mafic metavolcanics of the Littleton, just west of the Kinsman Granodiorite, at the top of a tall Rt. 112 road cut North of Beaver Pond. Author to the left with Rebecca Cain of the NHGS and Greg Walsh of the USGS.

Fig. 9. Calc-silicate granofels in Beaver Brook, near where fossils were recovered by Boucot and Rumble (1978).

Fig. 10. Strongly foliated Bethlehem Gneiss in the Wild Ammonoosuc River, near the contact with Ammonoosuc Volcanics. North is toward the right. Sigmoid-shaped feldspars suggest left-lateral shear.

Fig. 11. Kinsman Granodiorite

Fig. 12A. Littleton Formation and early pegmatite sills deformed by F_1 folds in Beaver Brook.

Fig. 12B. An east-west pegmatite sill forms the lip of Paradise Falls at Lost River Gorge.

Fig. 13. Mesozoic aphyric basalt dike dipping moderately south in a Rt. 112 cut in Kinsman Granodiorite just north of Kinsman Notch. The dike is about two meters thick. Note columnar jointing near upper contact.

Fig. 14. Isoclinal F_1 fold exposed in laminated Littleton schist on the Beaver Brook Trail, a very steep section of the Appalachian Trail west of Kinsman Notch. S_1 is poorly developed parallel to the axial plane. Vertical scratches are from hiking poles.

Fig. 15A. View north in bed of Slide Brook of strongly sheared gneiss and quartz veins.
Fig. 15B. Some shear surfaces display steeply plunging slickenlines.

Fig. 16A. Steeply dipping sheared granitic gneiss in Little Tunnel Brook, elev. 1880’.
Fig. 16B. Gently dipping calc-silicate granofels in Tunnel Brook, elev. 1370’.

Fig. 17A. Cobble of coarse sillimanite schist.

Fig. 17B. Sillimanite after andalusite.

Fig. 18. Early 19th century iron mine NE of Rt.112-116 intersection.