Companion Report to accompany

Bedrock Geologic map of the Berlin 7.5' Quadrangle, New Hampshire

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BEDROCK GEOLOGIC HISTORY OF THE BERLIN, NH 7.5' QUADRANGLE

Introduction The bedrock geology of the Berlin, NH 7.5' quadrangle has been remapped at a publication scale of 1:24,000 during the field seasons of 2019, 2020, and 2021. The work was done in conjunction with Bates College Earth and Climate Sciences and the New Hampshire Geological Survey supported by the United States Geological Survey's StateMap Program. The quadrangle lies along the boundary between the Bronson Hill Belt and the Central Maine Belt. The geology consists of the Ordovician Oliverian Jefferson Batholith and Ammonoosuc Volcanics of the Bronson Hill Belt, the Silurian Rangeley, Perry Mountain, Smalls Falls Formations and Devonian Littleton Formation of the Central Maine Belt, and intrusions of Devonian-Carboniferous two mica granites. A bedrock geologic map and report that includes the quadrangle was made at 1:62,500 scale by Billings et al. (1979) and two 1:250,000 regional geo-tectonic compilations that also include the area were completed for the New Hampshire Bedrock geologic map (Lyons et al., 1997) and the Sherbrooke-Lewiston area (Moench et al.,1999). The mapping for this project was done by Prof. Dykstra Eusden of Bates College and assisted by Bates geology majors Elizabeth Folsom ('21), Peter Galloway ('21), Chris Sargent ('20), Forrest Hamilton ('20), Essie Martin ('21), and Peter Sheils ('21). GeoSeps Services and the Arizona Laserchron Center performed the crystallization and detrital zircon geochronology of samples in the study area reported in Table 1.

Rock Types The mapping has revealed the following units, from oldest to youngest, and organized by Bronson Hill and Central Maine Belt Units and Intrusive and Other units.
Bronson Hill Belt Units: 1) There are several belts of foliated Ordovician Ammonoosuc Volcanics (Oam), an amphibolite with rare zones of mylonite (Photos 1A, 1B, and 1C). 2) Other minor lithologies in the Ammonoosuc Volcanics include the Ordovician Ammonoosuc Volcanic Rusty Granofels (Oamr); the Ordovician Ammonoosuc Volcanic felsic meta-tuff and micaceous quartzite (Oamf); the Ordovician Ammonoosuc Volcanic conglomerate facies (Oamc), and the Ordovician Ammonoosuc Volcanic dark quartzite (Oamdq) (Photos 2, 13A, 13B, 14, and 15). 3) Several belts of Ordovician Oliverian biotite Granite (Oobg), a gray granitic gneiss with variable foliation are found and in places are dominated by xenoliths of Oam (Oobg_Oam). 4) Likely comagmatic with Oobg, and occurring in one large region, is the Ordovician Oliverian Biotite K-Feldspar Granite (Oobkg) (Photo 3). Oobkg is seen to be in intrusive contact with Oam (Photo 1), cross cutting the foliation and layering of the latter, and also displays sheared contacts with Oam suggested by the presence of mylonite.

Central Maine Belt Units: 5) The Silurian Rangeley Formation (Sr) is composed of slightly rusty red-brown weathering, well foliated, interbedded, dark gray schists and light gray quartzites with uncommon calc-silicate granofels pods (Photos 4 A and 4B). 6) The Silurian Perry Mountain Formation (Spm) sits stratigraphically above the Sr and is composed of light gray quartzites with interbedded but less abundant dark gray schists of variable thickness (Photos 5A and 5 B). 7) Overlying the Spm is the Silurian Smalls Falls Formation (Ssf), a well foliated, interbedded schist and less common quartzite that both weather to a deep rusty red-brown (Photo 6). 8) At the top of the Silurian section lies the Madrid Formation (Sm), a fine-grained granoblastic medium gray to purple, sometimes calc-silicate bearing granofels, with interlayered, darker, more bio-rich granofels (Photo 7). 9) The youngest metasedimentary unit is the Devonian Littleton Formation (Dl), composed of well-bedded and foliated dark gray schists and light gray quartzites of varying thicknesses (Photo 8).

Intrusive and Other Units: 10) The Carboniferous-Devonian Two Mica Granite (CDtmg) is a medium-grained, equigranular, whitish granite with distinct flecks of black biotite and clear muscovite and fairly common pegmatite associated with it (Photo 9). 11) The Permian-Carboniferous Pegmatite (PCpeg) represents mappable regions of pegmatite with no outcrops of tmg, and appears as a coarse-grained whitish pegmatite with crystals up to 10 cm in dimension. 12) Several regions of Triassic (?) silicified zones have been found, often with Pb-Zn-Ag mineralized zones and that host the historic Mascot and Shelburne lead mines (Cox, 1970) (Photos 10A and 10B). These zones as interconnected by LiDAR lineaments are interpreted to mark two significant NE striking late brittle normal (?) faults. 13) Rare Jurassic (?) basalt/diabase dikes occur sporadically in .5-3 m wide intrusions across the study area.

Geochronology Crystallization and detrital zircon U-Th-Pb ages were determined for seven samples from the study area and are listed in Table 1. These included crystallization ages from the Oliverian granite (Oobkg), the Two-Mica Granite (CDtmg), and the Ammonoosuc Volcanic felsic meta-tuff (Oamf), and detrital zircon ages from the Littleton (Dl), Perry Mountain (Spm), Rangeley (Sr) Formations, and the Ammonoosuc Volcanic micaceous quartzite (part of Oamf). For a complete description of the geochronlogy data the reader is referred to Eusden et al. (2021).

Crystallization ages: The Ammonoosuc Volcanic felsic meta-tuff yielded and age of 451 +/- 2 Ma confirming its crystallization age in the Ordovician. The Oliverian sample (Oobkg) yielded an age of 445 +/- 3 Ma. The age supports its designation as latest Ordovician and agrees well with similar crystallization ages from other Oliverian units in the adjacent Mt. Crescent quadrangle (Eusden et al., 2019). The Two Mica Granite sample (CDtmg) yielded an age of 347 +/- 3 Ma suggesting it is just younger than the Devonian-Carboniferous boundary. This age agrees well with those from similar two mica granites in the adjacent Mt. Washington East quadrangle (Eusden, 2010). No ages for the pegmatites were obtained but Bradley et al. (2016) suggest that pegmatites in this region range in age from the Carboniferous to the Permian.

Detrital zircon ages: The Ammonoosuc Volcanic micaceous quartzite (part of Oamf) yielded an Ordovician maximum depositional age of 460 +/- 3 Ma. The Rangeley Formation sample (Sr) shows an maximum depositional age 420 +/- 2 Ma supporting its age in the Silurian. This is younger than the circa 430-440 Ma age of the Rangeley Formation as reported by Bradley and O'Sullivan (2016) and is likely due to mixed metamorphic and igneous age populations, different sources, or diachronous ages within the formation. The Perry Mountain Formation sample (Spm) shows an maximum depositional age 424 +/- 5 Ma also supporting its age in the Silurian. The Littleton Formation sample (Dl) shows a maximum depositional age of 444 +/- 3 Ma that would place it in the Ordovician. This is not in agreement with the Devonian depositional age of circa 410 Ma as reported by Eusden et al. (1996) and Bradley and O'Sullivan (2016). However, there are some early Devonian zircons in this sample and the 444 age is within uncertainty of the Oliverian granite age suggesting that much of the source rock for the Littleton Formation sediment was the Oliverian granite or at least an Ordovician (Oliverian?) pluton nearby.

Deformation and Metamorphism The new mapping shows a complex sequence of deformation that overall supports a Devonian Acadian or Neoacadian timing of deformation with subsequent Alleghenian shearing, followed by later Permian or Triassic brittle faulting and jointing. All of the rocks have been complexly and repeatedly metamorphosed to the sillimanite zone or amphibolite facies except the Carboniferous-Devonian Two Mica Granite (CDtmg), Carboniferous-Permian Pegmatite (PCpeg), and the Jurassic (?) mafic and felsic dikes.

The sequence of deformation from oldest to youngest is as follows. 1) The Mahoosuc Fault represents D1, a period of pre-metamorphic faulting between the Bronson Hill and Central Maine Belts, and is likely a normal fault. This was previously recognized and named by Moench et al. (1999). The Mahoosuc Fault is isoclinally folded by D2 confirming its older age. 2) D2 folding is characterized by a isoclinal to open, nappe-stage folding observed well in two regions of the map, on the extreme east edge and where the Mahoosuc Fault is folded. In these places original bedding S0 is not parallel to S1 schistosity indicating the location of a regional F2 fold hinge (Photo 11) (see also Eusden et al., 1996). 3) D3 faulting, is defined by an inferred, folded thrust fault through the southeast portion of the quadrangle, here named the Steven Point Thrust, which cuts the D2 nappes, and is defined by the juxtaposition of the Rangeley and Perry Mountain Formations over the Littleton, Madrid and Smalls Falls Formations. This fault is approximately in the same position as the pre-metamorphic Plumbago Mountain Fault of Moench et al. (1999), which we have reinterpreted here as a compressional structure. 4) D4 is a period of doming in the Oliverian Jefferson Batholith as defined by schistosity in the Oliverian gneisses that dips southeast on the southeast flank of the dome (see also Eusden et al., 2019). 5) D5 folding is defined by abundant, late, minor, open folds (Photo 12) and many regional axial traces in the Central Maine Belt and to a lesser extent the Bronson Hill Belt. 6) D6 shearing is comprised of zones of mylonite (Photo 1B) in the Oliverian and Ammonoosuc units but that are scattered enough so as to make drawing a single shear zone impossible. 7) D7 faulting is characterized by silicified zones (Photo 10A), often with Pb-Zn-Ag mineralization (Photo 10B), two of which have been historically mined (Mascot and Shelburne mines, see Cox, 1970), and that form late brittle faults, the Lead Mines Fault and an unnamed fault, that strike northeast.

Metamorphic indicators of sillimanite zone or amphibolite facies and/or multiple metamorphisms include: 1) coarse muscovite replacing sillimanite which likely replaced andalusite in schists; 2) zoned garnets in Madrid Formation granofels; 3) diopside and grossular in calc-silicate pods of the Rangeley Formation; and 4) coarse hornblende often aligned or exhibiting garbenschiefer texture in the amphibolites of the Ammonoosuc Volcanics.

Sequence of geologic events The Bronson Hill Belt units of the Ammonoosuc Volcanics (Oam, Oamr, Oamc, and Oamf) and Oliverian Jefferson Batholith (Oobg, Oobg_Oam, and Oobkg) were erupted and intruded in the Ordovician, circa 440-460 Ma, in a volcanic arc setting during the Taconic and Salinic Orogenies. A period of Silurian and Devonian marine sedimentation in the Central Maine Belt followed in an active tectonic setting, probably a forearc basin. Deposition occurred over and along the southeast flank of the Oliverian granites, and is recorded by the Rangeley, Perry Mountain, Smalls Falls, Madrid, and Littleton Formations. All of the above rocks in both the Bronson Hill and Central Maine Belts were subsequently deformed and metamorphosed. D1 pre-metamorphic faulting along the Mahoosuc fault juxtaposed the Bronson Hill and Central Maine Belts. D2 nappe-stage folding was followed by D3 faulting along the Stevens Point Thrust in the early Devonian Acadian orogeny. D4 doming of the Oliverian Dome and D5 folding of the units likely occurred in the Late Acadian or Neoacadian Orogeny, sometime before the end of the Devonian period. Intrusion of the Carboniferous-Devonian two mica granites and associated pegmatites crystallized around 350 Ma and were likely derived from partial melts of thickened Appalachian crust. D6 shearing and mylonitization of the Bronson Hill units may have occurred in the Carboniferous to Permian Alleghenian orogeny. Episodes of pegmatite intrusion likely continued from the Carboniferous into the Permian, though radiometric ages are few. D7 late brittle normal faults, as marked by mineralized silicified zones, likely developed during the early stages of rifting of Pangea in the Triassic. Lastly, late mafic and felsic dikes probably developed under tensile stresses in the Jurassic as rifting continued.

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ROCK PHOTO GALLERY

numbers keyed to map

1A: Ordovician Ammonoosuc Volcanics (Oam) cut by the Oliverian Biotite K-Feldspar monzogranite (Oobkg). 1B: Mylonite in Oam showing reverse dip slip (thrust?) motion. 1C: Oam coarse-grained amphibolite with aligned amphiboles, occurs as a xenolith within the Oobkg.

2: Ammonoosuc Volcanics Rusty Granofels (Oamr) a rusty brown weathering , fine-grained, massive granofels and gneiss that has a weak foliation.

3: Oliverian Biotite K-Feldspar Monzogranite (Oobkg), medium to coarse-grained pink granite gneiss, commonly with a foliation.

4A: Rangeley Formation (Sr), a slightly rusty red-brown weathering interbedded dark gray schist and light gray quartzite. Graded bedding shows tops are inverted. 4B: Sr quartzite with an oval, calc-silicate granofels pod, the core of which contains coarse grossular and diopside.

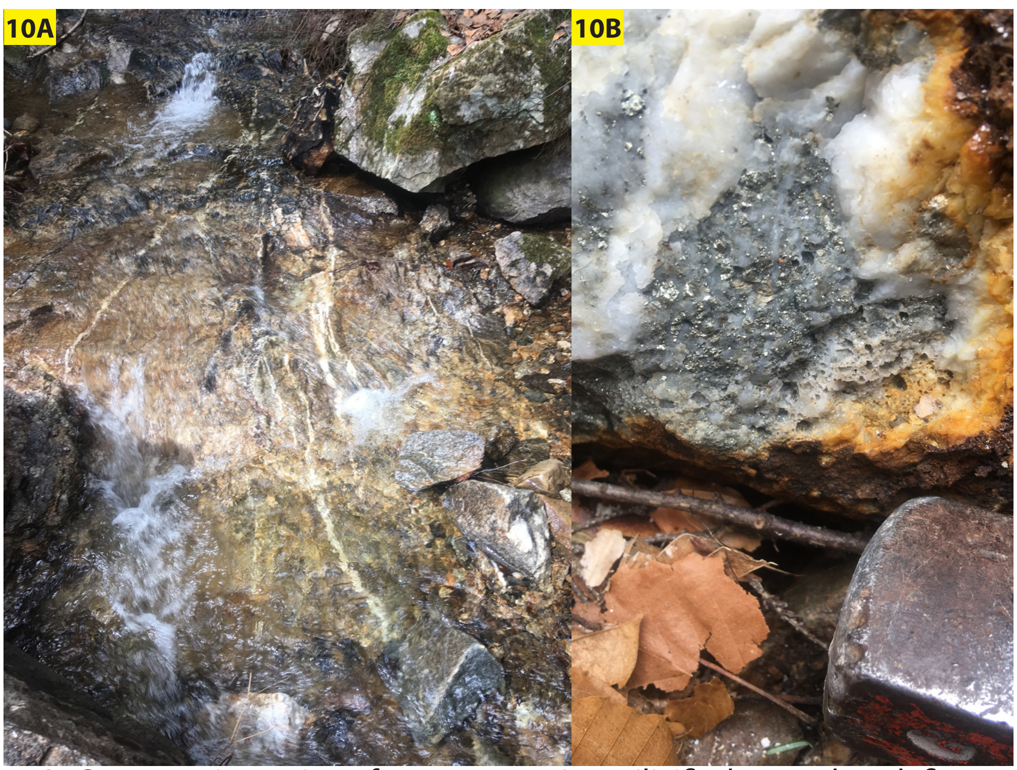
5A: Perry Mountain Formation (Spm), showing relatively thicker beds of light gray quartzites with thin interbedded, less abundant, dark gray schists. 5B: Spm showing thinner interbeds of quartzite and schist, some minor late D5 folding, and a late pegmatite intrusion parallel to layering.

6: Smalls Falls Formation (Ssf), well foliated, deep rusty red-brown weathering schists.

7: Madrid Formation (Sm), a fine-grained granoblastic medium gray to purplish, sometimes calc-silicate bearing granofels with interlayered darker, more bio-rich granofels.

8: Littleton Formation (Dl), a well bedded, but not graded, foliated dark gray coarse schists and light gray fine quartzites. The coarse muscovite in the schist is replacing sillimanite and earlier andalusite.

9A: Carboniferous-Permian Two Mica Granite (CDtmg), a medium-grained whitish granite with distinct flecks of black biotite and clear muscovite and fairly common pegmatite associated with it. 9B: Hand sample of CDtmg from same outcrop.



10A: Cross cutting veins of pure quartz in a silicified zone that defines a late normal brittle fault. 10B: Hand sample from a silicified zone showing chalcopyrite and galena mineralization in a quartz matrix.

11: Coarse schists and thinner quartzites of the Rangeley Formation (Sr) oriented vertically, cross cut by S1 schistosity striking parallel to notebook, and indicating this outcrops position in the hinge region of a regional nappe-scale F1 fold.

12: D5, open, late, fold in the Perry Mountain Formation (Spm). Yellow notebook is approximately parallel to the fold axial plane.

13A: Fine-grained felsic meta-tuff, with weak fabric (flow foliation?) of the Ammonoosuc Volcanics (Oamf) 13B: Rare, coarse-grained, well foliated, micaceous quartzite of the Ammonoosuc Volcanics, part of Oamf.

14: Ammonoosuc Volcanics conglomerate facies with amphibolite matrix and rounded clasts of predominantly felsic material (Oamc). Offset, cross cutting Oobkg intrusion in upper part of image.

15: Fine-grained, bedded, dark gray, granoblastic, magnetite and amphibole-rich quartzite and/or granofels of the Ammonoosuc Volcanics (Oamdq).