Bedrock Geology of the North Grantham, NH, 7.5′ Quadrangle
by
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Introduction

The shapes of the mountains and valleys in the North Grantham Quadrangle are controlled by the geometry of the underlying bedrock. More resistant rock layers, such as biotite gneiss (Bethlehem Gneiss, Db2b), staurolite schist (eastern part of Littleton Formation, Dl) and quartzite and sillimanite schist (Clough Quartzite, Sc) tend to form ridges and hills. The highest land in the quadrangle, Croydon Mountain, is underlain by an especially thick layer of Clough. Millions of years of erosion have removed thousands of feet of material since the rocks were first formed (see cross sections). More recent erosion by glaciers and streams in the last several thousand years has further molded the landscape. Although outcrops are abundant in the quadrangle, thick glacial till obscures the bedrock on many slopes and alluvium covers valley bottoms. Some of the brooks that drain larger watersheds have cut deeply enough into the till to expose bedrock, but many of the smaller streams are disappointingly bouldery.

The surficial materials are not represented on this map, which shows the bedrock as it might appear if the overburden were not there. Calcium-rich soils that would support "Rich Northern Hardwood Forest" communities (E.H. Thompson and Sorenson, 2000) have developed on the Ammonoosuc Volcanics (Oa) and the Fitch Formation (Sf). Species which thrive in limey soils such as hepatica, green spleenwort and blue cohosh are especially abundant on areas underlain by Fitch, such as north and south from Chase Pond. The area around Smith Pond is interesting in terms of human history: the Shakers dug a series of canals in the glacial till to guide water from Smith Pond to their mills in Shaker Village.

Regional Geology

The North Grantham Quadrangle is situated west of two Ordovician Oliverian domes, the Mascoma Dome and the Croydon Dome. These domes are composed of meta-igneous rocks that are foliated to various degrees. The Paleozoic metamorphic rocks in the rest of the quadrangle belong to the classic package of rock units known as the Bronson Hill sequence (Billings, 1937), consisting of Ordovician metavolcanic units and their Silurian and Devonian cover. A Mesozoic fault, the Grantham fault, trends parallel to the east margin of the quadrangle.

The Ordovician part of the Bronson Hill sequence was originally deposited about 450 million years ago as volcanic flows and ash falls (Oa and Opf), interlayered with marine black shales (metamorphosed to schist) of the Partridge Formation (Op), which extend the length of New Hampshire and represent the remains of an ancient volcanic island arc. These rocks were intruded by quartz diorite, granodiorite and granite, which were later foliated to become the gneiss of the domes (Oliverian rocks, Oo). The volcanics and intrusive rocks together form the core of the so-called Bronson Hill anticlinorium (Billings, 1955; Lyons et al., 1997). As oceanic crust between Laurentia and the arc moved eastward it was subducted, or drawn under, the volcanic arc, eventually closing the basin. The volcanic arc collided with the Laurentian continental margin farther west during the Taconian Orogeny, a mountain-building episode that produced the Green Mountains. The Ordovician rocks in New Hampshire do not seem to have been deformed during the Taconian.

Erosion eventually leveled the volcanic arc to the point where a beach sand (Clough Quartzite, Sc), carbonate-rich materials (Fitch Formation, Sf) and mud and sand deposits (Littleton Formation, Dl) were unconformably deposited on the remnants of the arc about 400 million years ago. Then the whole package was deformed and metamorphosed during a second mountain-building episode, the Acadian Orogeny, as another land mass (the Gander terrane) became accreted to the continental margin from the east. A strong foliation developed (S_1 on the map), especially in the schists, perpendicular to the maximum stress direction. Giant overturned F_1 folds developed as material moved toward the west.

Geologically soon after the Acadian Orogeny, the Oliverian gneiss domes, mantled by the previously folded rocks, were pushed up from below along the length of the Bronson Hill anticlinorium, possibly as a result of jostling due to arrival of a land mass called Avalon far to the east. During this doming episode, upright F_2 folds were superposed on the older structures.

During the Mesozoic era, as the modern-day Atlantic Ocean opened (about 200 million years ago), the Grantham normal fault developed as a branch from the Ammonoosuc fault, which is more or less parallel to the Connecticut River. Basalt and diabase dikes (KJd), which formed from magma rising along extensional cracks in the crust, also date from this era.

Details of Bedrock Geology

The youngest feature on the map is the Mesozoic Grantham fault. It is marked by a series of northeast-trending silicified zones (sz), some of which form prominent quartz ridges across the topography. The east side of the fault moved relatively down, bringing the Bethlehem Gneiss down to the level of the present erosion surface. On the up-thrown west side, only a small area of Bethlehem remains, all the rest having been removed by erosion to reveal the rocks under it. The fault takes a dog-leg turn in North Grantham, and leaves the quadrangle NE of Butternut Pond. A portion of the Enfield Center quadrangle is included on the map to show how the Grantham fault curves from NE to NW, where it continues along Mascoma Lake into the Enfield quadrangle.

The Devonian Littleton Formation, in the middle of the map, is the youngest of the Bronson Hill sequence, named after the area around Littleton, NH, and first described by Billings (1937). A thick blanket of mud and sand was laid down in an ocean basin, spreading from the east onto the older rocks. All the rocks in the quadrangle, with the exception of the Mesozoic dikes, were metamorphosed under tremendous pressure and heat during the Acadian Orogeny. The grade of metamorphism increases from west to east, from biotite in the North Hartland quadrangle (Walsh, 2016) to garnet (gt) and staurolite (st). The staurolite crystals have been replaced by quartz and muscovite in a band about 250 meters wide along the western edge of the staurolite zone (st pseudo). Schists in the Clough contain sillimanite, perhaps due to a more aluminous chemical composition rather than to increased metamorphic conditions. Even at this high grade, fossils can occasionally be found near the Clough/Fitch contact (Boucot and J.B. Thompson, 1963). Numerous metamorphosed basalt dikes are found cross-cutting the Ordovician and Silurian rocks, probably related to a period of extension in the Silurian, before the Littleton was deposited.

Older units in the Bronson Hill sequence are exposed on either side of the Littleton. To the west, there is a thin layer of white quartzite, which is continuous with the so-called Hardy Hill Quartzite in the Enfield quadrangle, now correlated with Silurian Clough Quartzite (Lyons et al., 1997; P.J. Thompson, 2014). It is well exposed on Methodist Hill. West of the quartzite, the Ammonoosuc Volcanics and Partridge Formation are exposed in the Cornish nappe, a huge Acadian F_1 fold that brought the rocks westward about 20 kilometers from where they were originally deposited. Bedding and foliation dip northwest toward the south end of the Lebanon dome, where it is overturned toward the south (as portrayed in cross-sections for the Hanover quadrangle, P.J. Thompson, 2015). Prior to the dome-stage overturning, the sequence had been inverted, with the older Ammonoosuc above Partridge. Open F_2 folds plunge NE, with a sinistral sense related either to the dome-stage Meriden antiform or the Northey Hill shear zone, or both (P.J. Thompson, 2016).

A nappe-stage F_1 isoclinal fold in the Littleton metavolcanic member (Dlv) is also sinistral, but it plunges south. This layer is well exposed at the Montcalm Golf course and at Whaleback ski area. In cross-section view this fold can be seen to lie on the west limb of a major F_1 syncline within the Littleton. This is the Garnet Hill syncline, which lies between the Cornish nappe and the domes.

The map pattern east of the Garnet Hill syncline is rather complicated. The Ammonoosuc Volcanics are exposed here as well, overlying the Oliverian gneiss domes. The dome rocks originally intruded the volcanics, but during the Acadian Orogeny, they rose as dome-shaped bodies, along with the overlying younger rocks. The Mascoma and Croydon domes plunge toward each other, overlain by intensely folded Ammonoosuc, Clough and Fitch. Above these folded rocks, in the hills between Smith Pond and Miller Pond, the Bethlehem Gneiss is exposed, which had intruded along an east-dipping thrust fault during the Acadian Orogeny before the domes rose. The Bethlehem continues north along the east side of the Mascoma dome, and far to the south it runs into the Brennan Hill thrust fault NE of Keene.

Map-scale F_1 folds in the Clough Quartzite above the domes have a dextral rotation sense and lie on what was originally the upright limb of the Garnet Hill syncline, which opened westward. To visualize this in the cross-sections, one must mentally undo the large F_2 dome-stage fold cored by Oliverian Gneiss. All the rocks from here west to Great Brook, in fact, were overturned during the dome stage of deformation.

Main contributions of the present mapping

The intensely folded rocks south of Mascoma Lake have puzzled geologists for years. The Bronson Hill sequence overlies Oliverian Gneiss in the two domes. The map pattern is the result of several interfering sets of folds: F_1 isoclines between the domes and the overlying Bethlehem Gneiss, a large overturned F_2 fold trending NE, and open upright cross folds that plunge toward the gneiss. A weaker set of approximately E-W cross folds can be seen in some outcrops, and locally kink folds with gently dipping axial planes also deform older fabrics. The kink folds are likely associated with the Grantham normal fault.

Between the two domes, bedding and nappe-stage S_1 foliation dip towards the overlying Bethlehem Gneiss. Chapman (1939) mapped the interlayered quartzites, conglomerates and schists between the Ammonoosuc and the Bethlehem all as Clough Quartzite. J.B. Thompson (1988) reinterpreted the major schist layers as three F_1 infolds: Littleton in a syncline and two anticlines of Partridge, separated by attenuated Clough Quartzite layers. Thompson thought of these folds as the root zone for another large nappe, the Skitchewaug nappe. The present mapping does not support this reinterpretation. Fitch and Clough are continuous all along the west side, precluding a connection between the main area of Littleton and the lowermost Scs. Numerous outcrops of schist and granofels occupy the center of the F_2 anticline along I-89 south of Smith Pond, shown by Thompson (1988) as Partridge Formation. Although somewhat rusty, the rocks do not resemble Partridge, even at sillimanite grade. Analysis of zircons from a sample of the granofels yielded a maximum age of about 417 Ma (Strauss, 2019, unpublished data), which is too young to be Partridge. We interpret these rocks as part of the Fitch.

The major F_1 Garnet Hill syncline continues to the north as far as Lisbon (Billings, 1937). In Lyme the syncline is intruded by Bethlehem Gneiss as the Indian Pond pluton (P.J. Thompson, 2008). The overturned limb of this syncline reappears to the west, where Ordovician rocks lie above the Clough in the Cornish nappe. The Littleton apparently continues west underneath the Cornish nappe to connect with similar Devonian rocks units in Vermont. If this interpretation is correct, it implies some important conclusions: (1) The Garnet Hill syncline opens downwards, not upwards like the usual syncline, because it is an F_1 fold that was deformed by a younger F_2 anticline. (2) The Bethlehem Gneiss cuts downward across the Skitchewaug nappe from its usual tectonic position above the Skitchewaug (i.e. Fall Mountain nappe/Brennan Hill thrust) into the underlying syncline. (2) The Skitchewaug and Cornish nappes are one and the same. See Robinson et al. (1993) and J.B. Thompson et al. (1968) for details of the nappe theory in New Hampshire.

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