lCompanion Report to accompany

Bedrock Geologic Map of the Cowen Hill 7.5' Quadrangle, New Hampshire

David R. Converse, Wallace A. Bothner, Christian E. Jahrling, II, and Philip S. Koch[1]

This geologic map was funded in part by the USGS National Cooperative Geologic Mapping Program under StateMap award number
G21AC10863

Shane Csiki, New Hampshire State Geologist
New Hampshire Geological Survey, 29 Hazen Drive, P.O. Box 95, Concord, NH 03302

December 2022

[1] David R. Converse (drconverse7@gmail.com), 2119 McGraw Ranch Road, Estes Park, CO 80517; Wallace A. Bothner (Wally.Bothner@unh.edu), Professor Emeritus, Earth Sciences, University of New Hampshire, James Hall Rm 334, Durham, NH 03824; Christian E. Jahrling, II (cjahrling@outlook.com), 4240 NW 107th Avenue, Apartment 4401, Doral, FL 33178, Philip S. Koch (pskoch@mines.edu), Geology and Geological Engineering Department, Colorado School of Mines, 1516 Illinois Street Golden, CO 80401.

Abstract

Cowen Hill is the third of three 7.5' quadrangles in northernmost NH that were recently mapped at a scale of 1:24,000 as part of the NHGS-USGS StateMap project – 2 more maps are in progress. The field area includes the eastern edge of the Connecticut Valley Synclinorium and the westernmost edge of the Bronson Hill Anticlinorium. Previous NH bedrock maps (1970s-1990s) were at a scale of 1:250,000 (except locally). The adjacent Quebec geology was mapped in detail recently (Perrot, 2019).

New analytical data acquired during this project, Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) zircon crystallization (7 CZ) and detrital zircon (12 DZ) ages as well as 19 whole-rock geochemical analyses, aided in mapping the Cowen Hill area. Most metasediments and metaigneous rocks have maximum depositional ages (MDAs) or CZ ages in the Early Devonian. Laurentian ages are preserved in metaigneous rocks across the larger area.

West of the Monroe Fault, the Cowen Hill bedrock consists of N-NE-trending metasedimentary rocks (graywackes, black shales, variably calcareous siltstones, debrites, volcaniclastics) of the Ironbound Mountain (IBM) and Gile Mt. (GM) formations. The early Devonian GM age is based on dating of a pillow metabasalt and of plant fossil fragments (Hueber et al. 1990) - both from the Pittsburg Quad to the southwest. The middle Devonian age of the IBM Halls Stream "Grits" member is based on a maximum depositional age (MDA) from tuffaceous sediments. Both Devonian ages appear to be close to or depositional ages. The stratigraphy correlates well across the international border. The major structure is the NE-trending Beaver Brook Anticlinorium, which plunges shallowly to the north, but locally "porpoises". The rocks exhibit multiple foliations and folding events. The Monroe Thrust Fault separates GM and IBM from the Siluro-Devonian Frontenac Formation (FF) to the east. The MDAs are similar in all formations, although the older DZ populations differ indicating different sediment sources over time. The structural features and orientations are very similar throughout the three mapped quadrangles, as well as in neighboring Quebec (Perrot, 2019).

East of the Monroe Fault, the Cowen Hill bedrock consists of N-NE-trending Frontenac metaigneous (mafic volcanics and diabase intrusives), and metasedimentary rocks (volcaniclastics, siltstones, shales). The FF MDA ages in the area are: 434 ± 4 Ma (Cowen Hill), 408 ± 6 Ma and 415 ± 5 Ma (Lake Francis). Additional thrust faults are present farther east as well as a normal fault that separates FF from possible GM.

Introduction

This area is sparsely populated by year-round residents, but with many part-time residents and visitors. It is a favorite location for recreation – both winter and summer/fall activities. Forestry has been a major industry in the region for many years.

The first mention of its geology is found in Charles Hitchcock's 1877 Geology of New Hampshire and his map folios. Subsequent mapping was performed nearby by Billings (1956), his students (Hatch, 1963; Green, 1964, 1968; Myers, 1964), and later in the quadrangle by Converse (1977), Jahrling (1983) and Bothner, Jahrling and Moench (unpublished mapping 1980 – 1990). The USGS published a regional map (2° sheet) in 1995 (Moench et al., 1995 and references therein) and a modified version of that regional map was included in the Geologic Map of New Hampshire (Lyons et al., 1997). The bedrock geology of northeastern Vermont was compiled by Ratcliffe et al. (2011). Geophysical maps are available in Bothner et al. (1997).

The bedrock geology of southern Quebec that is adjacent to the New Hampshire border was mapped in the last decade by Tremblay et al. (2015) and Perrot (2019).

The aim of this project is to provide modern bedrock geological maps of northernmost New Hampshire, which can be used for both practical and scientific applications. The Cowen Hill Geologic Map is the third of 5 geologic maps that will cover the 1926 Indian Stream 15' quadrangle. The Geologic Map of the Pittsburg 7.5' Quadrangle (Bothner et al., 2020) and the Geologic Map of the Lake Francis 7.5' Quadrangle (Converse et al., 2021) were completed in September 2020 and September 2021, respectively. Mapping in the remaining Metallak Mountain and Greeley Brook 7.5' quadrangles is already underway. Further refinement of this map is anticipated as the remaining maps in Northern New Hampshire are completed.

Regional Bedrock Geologic Setting

Northernmost New Hampshire is underlain largely by low grade metamorphic Silurian and Devonian rocks of the Connecticut Valley - Gaspé Trough (CVGT) as shown in Figure 1. The CVGT is fault-bounded on the west by Ordovician and older rocks of Taconic and Grenville orogenic belts and on the east by the Bronson Hill – Boundary Mountain belt (BHA). The CVGT recorded initial extensional tectonics as well as contractional tectonics as island arcs and microcontinents collided with North America during the Siluro-Devonian Salinic Orogeny and the Late Devonian Acadian Orogeny.

The late Paleozoic Alleghenian orogenic and Mesozoic Atlantic rifting events are poorly represented at this latitude except for plutons and dikes of White Mountain affinity.

Geology of the Cowen Hill Quadrangle

Surficial Geology

This mapping effort did not focus on the surficial geology of the Cowen Hill Quadrangle. The surficial geology consists of Quaternary sediments of fluvial and glacial origin. Glacio-fluvial

gravel accumulations are found along streams in the area as well as on elevated terraces above current waterways' beds and are frequently mined for road materials. Glacial striations throughout the quadrangle record a consistent transport direction of ~ 140° (S40°E). Large erratics are commonly found throughout the quadrangle.

Bedrock Geologic Summary

The bedrock geology as exposed consists of dominantly of deformed and metamorphosed Silurian and Devonian bedrock with very minor Mesozoic felsic intrusive rocks. The Silurian and Devonian bedrock consists of low-grade metamorphic slates, siltstones, sandstones and volcaniclastic sediments as well as metamorphosed intrusive and extrusive rocks. Extrusive rocks include meta-basalts, which were extruded as lava flows (including pillow lavas), and lapilli tuffs. The intrusive rocks consist of metadiabase dikes and sills.

Structurally, at least two major deformational episodes are recognized: 1) the upper Silurian-Lower-Devonian Salinic Orogeny (with both extensional and contractional events) and 2) the Late Devonian Acadian Orogeny contractional event. These deformations folded the older bedrock in tight to isoclinal folding (depending on the competency of the rock units) and then refolded the bedrock into generally open folds (e.g. Perrot, 2019; Perrot et al., 2018).

This map includes field data collected from 1976 through 2022. Field data include structural, mineralogical, lithological data, geochemical and U-Pb age determinations from zircons. Data from surface exposures constrain Cross-section A – A', which shows the interpreted distribution of rock units in the subsurface. Key photos are also included to provide examples of different rock types, geometries, and textures.

Stratigraphy

We recognized three formations in the quadrangle – the Ironbound Mountain, the Gile Mountain, and the Frontenac Formations – for details on their lithology and ages, see the unit descriptions on the map. The Ironbound Mountain consists of a main unit (Di) composed of black meta-phyllites, dark fine-grained metasiltstones and metasandstones (locally). There are three members, with presumed youngest to oldest being: 1) Dibp – Black Phyllite member, 2) Dih, Dihm – the Halls Stream Grits, and 3) Digg, Diggc – graded graywacke member. The Frontenac is separated into three members (2 meta-igneous units and 1 metasedimentary). A correlation chart showing the overall age constraints is shown in Figure 2A. Age dates from the Pittsburg, Lake Francis and Cowen Hill Quadrangles indicate that the Frontenac Formation is approximately co-eval with the Gile Mountain Formation. However, the sedimentary source terranes appear to be different for the Frontenac and the Gile Mountain Formations (Figure 2B).

Many intrusive bodies (primarily metadiabase dikes or sills) are mapped largely within the Frontenac and are described in detail in the Summary of Map Units on the map itself. Figure 3 shows examples of pillowed meta-basalts, metadiabase Intrusives and meta-lapilli tuffs.

Figure 4 shows characteristic metasediments for the Ironbound Mountain, Gile Mountain and Frontenac Formations respectively.

Geochronology

No fossils were noted in the Cowen Hill Quadrangle. An Emsian(?) fossil plant locality (Hueber et al., 1990) was discovered to the southwest in the Pittsburg Quadrangle; the age is consistent with the zircon age date in the nearby Gile Mt pillow basalt (Table 1B). In southern Quebec, Emsian (Eifelian?) plant fossils are reported from the Lac Drolet member of the Compton Formation at La Patrie and Ste. Cecile (Hueber et al., 1990).

Crystallization and detrital zircon U-Pb age assignments were determined for meta-igneous and meta-sedimentary rocks in the area using Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) analytical results from GeoSep Services and the University of Arizona Laserchron Center, the IsoPlotR software program, and analytical methods described by Vermeesch 2018, 2021a, 2021b, Coutts et al., 2019, Gehrels et al., 2008, Horstwood et al., 2016, Herriott et al., 2019. Ten new analyses were made in the Cowen Hill, Lake Francis, Magalloway and Second Connecticut Lake Quadrangles for this work. Additional ages were available from the Pittsburg Quadrangle (Bothner et al., 2020), Lake Francis Quadrangle (Converse et al., 2021), the southern Quebec (Perrot, 2019, Perrot et al., 2017, 2018, 2020)) and the Second Lake Quadrangle (Dorais et al., 2017). Zircon age determinations are summarized in Table 1.

Earlier whole rock U-Pb age determinations in the region were reported by Lyons et al. (1986) and Moench et al. (1995).

Crystallization ages: Table 1A

Three new analyses were made: 1) IS2020-151RV[2] (biotite meta-granite sill – Lake Francis Quadrangle), 2) IS2021-258 (East Inlet Pluton – Second Connecticut Lake Quadrangle) and 3) IS2022-4 (felsic metavolcanic rock – Magalloway Mountain Quadrangle) were analyzed for purposes of establishing regional context. The three age determinations were: 424 ± 4, 416 ± 4 (inherited age: 1046 ± 13) and 416 ± 4 Ma respectively.

These new age determinations are younger than the crystallization ages of zircons from felsic metaigneous rocks on the southern shore of Second Lake (432 ± 8 Ma – Dorais et al., 2017), and younger than whole rock age dates from the East Inlet Pluton (430 ± 4 Ma – Lyons et al., 1986), and the biotite granite at Round Mt in the Lake Francis Quadrangle (432 ± 10 Ma Moench et al., 1995).

The older ages from the whole rock age dates are not surprising as the meta-igneous samples from the area can contain significant zircon populations with older inherited ages (e.g., East Inlet Pluton), which likely would skew a whole-rock age determination.

Detrital Zircon ages: Table 1B, Figure 2A & B

[2] samples collected in 2018 – 2022 were labeled with the prefix IS and year (e.g., IS2021).

Age determinations from detrital zircons are typically used for two purposes:

- To establish the maximum depositional age of the sample. The actual age of the sample can be considerably younger, especially if the sediment source area doesn't include young rocks. Determining maximum depositional ages can be challenging due to small numbers of age determinations and intermixed age populations with similar statistical characteristics (e.g., Vermeesch, 2021a; Coutts et al., 2019, Gehrels et al., 2020).
- To establish sedimentary provenances and stratigraphic correlations by comparison of the detrital zircon age distributions indicating variable contributions from different sedimentary sources. The reliability of comparisons depends on the numbers of age determinations, age populations and distributions (Gehrels et al., 2020).

In this study, seven metasediment samples (6 in Cowen Hill and 1 in Lake Francis) Quadrangle were analyzed for detrital zircon ages.

- Halls Stream Grits (Dih)
  - **IS2021-240** (West of Beaver Brook Anticline): Subangular quartz and plagioclase grains averaging ~0.5 – 0.8 mm in a siltstone matrix with fragments of fine-grained quartzite. Minor mica, chlorite, pyrite and iron oxide. No igneous rock fragments noted, but widespread twinned plagioclase and a few likely potassium feldspars.
    - Splits of this sample were sent to two labs to assess the relative analytical and sample uncertainty.
      - The ages from one lab did not yield a well-defined (MWSD=2.7) young cluster with a mean age of 413 ± 6 (2σ) Ma.
      - The ages from the other lab did yield a well-defined (MSWD=0.79) young cluster with a mean age of 425 ± 7 (2σ) Ma.
      - Ages from both labs overlap within the 2σ uncertainty.
  - **IS2021-241** (East of Beaver Brook Anticline): well foliated, moderate shear fabric, defined by fine-grained white mica and chlorite wraps around 0.1 – 0 .5 mm augen of quartz and lesser plagioclase. No obvious rock fragments, possible detrital garnet(?). Well-developed cluster of younger ages yielding a mean of 413 ± 6 (2σ) Ma.
  - All three maximum depositional ages are quite significantly older than the 391 ± 4 (2σ) Ma from the massive sub member of the Halls Stream Grits (IS2019-172). In all three samples, the percentage of feldspar laths (serving as proxy for a local igneous component) is much less than in the IS2019-172 sample and the samples are more similar to the siltstones and sandstones that compose much of the Ironbound Mountain and Gile Mountain Formations.

- Graded Graywacke (Diggc)
  - **IS2021-477**: Interpreted as possible stacked channels. Somewhat gritty, poorly foliated altered pyrite-bearing metasandstones, with 0.2+/- (trace 0.4) mm

quartz and twinned plagioclase in fine-grained matrix. Weakly defined young age cluster – best approximation is 417 ± 4 (2σ) Ma (MWSD = 2.1)

- Gile Mountain Formation (Dgm)
  - **IS2021-436**: Similar to composition of IS2021-477, but shows strong shear fabric and grain shape modification. Many small augen: 0.1 – 0.2 mm in length; white mica and chlorite define close spaced < 0.1 mm foliae. Identified 3 young age clusters: 1) 388 ± 7 (2σ), 2) 411 ± 6 (2σ) and 3) 426 ± 7 (2σ) Ma. Having a population that is less than 400 Ma was somewhat surprising, but it meets the filter criteria and is similar to the age noted in the Halls Stream Grits (Dihm) sample (IS2019-172) of 391 ± 4 (2σ) Ma and the 403 ± 6 (2σ) Ma age of the Gile Mt basaltic andesite (IS2019-184) as well as the Emsian(?) fossil plant. Note that the youngest population is also similar to the youngest IS20-18 sample population.

- Frontenac Formation (Dfrs)
  - **IS2021-96D**: A lapilli meta-tuff unit that contains lapilli (typically < 3 cm). The maximum depositional age was determined to be 415 ± 5 (2σ) Ma. (Lake Francis Quadrangle)
  - **IS2021- 419:** a metasiltstone with probable volcaniclastic input (mm size lapilli) – the maximum depositional age is 434 ± 4 (2σ) Ma.
  - The younger age may reflect a greater contribution of younger zircons from locally derived larger lapilli.

A summary plot of the maximum depositional ages is shown in Figure 2A.

Unfiltered detrital zircon profiles (unfiltered) are shown in Figure 2B, which allows a comparison of the contributions of sediment of different ages.

Structure

Broadly speaking, the northeast plunging, asymmetric (and "porpoising") Beaver Brook Anticline and the Monroe Fault define the major structures in the Cowen Hill Quadrangle. The eastern flank of the Beaver Brook Anticline is truncated by the westward verging, steeply east-dipping Monroe Fault, that thrust the Frontenac Formation over the Gile Mountain Formation. The overall northward plunge causes the younger Ironbound Mountain to dominate the surface bedrock geology in the northern two-thirds of the quadrangle as the Gile Mountain Formation dips below the surface elevation.

There are many scales of smaller folds that subparallel the Beaver Brook Anticline and exhibit both northward and southward plunges ("porpoising"). One "porpoising" asymmetric anticlinal fold brought thick bedded, highly folded Gile Mountain metasediments back up to the surface adjacent to the Monroe Fault.

At least two major deformational events are recorded by the D1 and D2 folds which involve bedding (S0), foliation (S1), and cleavages (S2 and S3 (minor)) – Figure 5.

Three deformation events, D1, D2, and D3 are recorded by folding and consequent generation of foliation/cleavage involving S0, S1, S2, and S3(minor). Isoclinal to tight to open F1 folds, often with well-preserved graded beds (are refolded about asymmetric generally westerly inclined, shallow northeasterly and southwesterly plunging mesoscopic F2 folds (see stereonets in Figure 6). Abundant F1 and F2 folds outcrop in the Gile Mountain near the Monroe Fault and the Ironbound Mountain Formation along the western boundary (Figure 7) at both large and small scales with low plunges (ca. 10°). Late S3 cleavage in more pelitic layers sparingly represents D3.

The Monroe Fault is the only fault recognized in the map area. Faults are very rarely exposed in outcrops in northern New Hampshire – the Cowen Hill Quadrangle is no exception. The Monroe Fault is mapped at the contact of the Frontenac metavolcanic and metasedimentary units with the Gile Mountain and Ironbound Mountain metasediments. Although ages of the three formations are quite similar based on zircon age dating, the lithologies are distinct both in terms of volcaniclastic input, metaigneous units and different sourcing based on zircon age distributions (Figure 2B). The Monroe Fault is consistent with geophysical modeling (gravity and magnetic) of the subsurface geometry (Jahrling, 1983).

The structural attitudes of the deformation events (Figure 6 A, B, C) both on a quadrangle scale and in contrasting the area east and west of the Monroe Fault are similar (although the structural measurements east of the Monroe Fault in the Cowen Hill Quadrangle are relatively sparse). In addition, the apparent large-scale folding of the Frontenac Formation (meta-basalt and meta-sediments in the northeast corner of the quadrangle and in the adjacent Second Connecticut Lake and Greeley Brook Quadrangles) also suggests that the Monroe Fault was folded during the Acadian Orogeny. Note in Figure 6C, the similarity with the structural data from nearby Quebec (Perrot, 2019 – La Patrie transect).

Frontenac and Gile Mountain Igneous Geochemistry

In collaboration with Professor M.J. Dorais (BYU), we are investigating the whole rock geochemistry of the Frontenac metaigneous rocks to understand better the origin, tectonic setting, and possibly to develop a geochemically-based igneous stratigraphy. No additional results were acquired this year – the geochemical data closest to the Cowen Hill meta-basalts in the northeastern corner are in the adjacent NW corner of the Second Connecticut Lake Quadrangle. Figure 7 shows all data (separated into groups assigned by rock type and location) on two standard geochemical plots as well as an inset map showing the Second Connecticut Lake samples. Note that these two samples highlighted with the red circles, are from the meta-basalts shown on the extended cross-section A – A'.

Economic Geology

Possible thin exhalative beds were observed associated with Frontenac meta-pillow basalts in the northeast corner of the Cowen Hill Quadrangle. Other than small pyrite cubes and quartz veins, no mineralization was noted with a hand lens.

Possible Health Issue

Much of the Pittsburg township is underlain by Gile Mt and Ironbound Mt black phyllites with significant amounts of pyrite – both oxidized and unoxidized. In some areas of Vermont, groundwater extracted from black phyllites with abundant pyrite, have elevated arsenic levels (Ryan et al., 2013). It would seem prudent to test water wells (if any) that produce from either fractured Gile Mt or Ironbound Mt formations for arsenic. The authors are unaware of any well water analyses from the Pittsburg Township that include arsenic.

Acknowledgements
We thank Joshua Keeley of NHGS for his help with base map generation (Lidar and topographic), map layout and all things ARC-related and Shane Csiki, New Hampshire State Geologist, for continuing support of this STATEMAP project. We benefited greatly from a southern Quebec – New Hampshire geologic field trip with Professor Alain Tremblay, Dr. Morgann Perrot, Dr. Lori Summa, Dr. David Awwiller and Joshua Keeley as well as subsequent informative conversations. LA-ICP-MS work to determine zircon U-Pb age dates from metasedimentary and metaigneous rocks was conducted with Paul O'Sullivan, GeoSep Services, Moscow, ID and Dr. Mark Pecha and Daniel Alberts, University of Arizona LaserChron. to analyze additional detrital and igneous zircons for age dates. Professor Michael Dorais (BYU) arranged for the geochemical analysis of the metaigneous rocks and provided helpful commentary. Chris and David Craigue kindly arranged lodging in Pittsburg, NH.

References Cited

Allmendinger, R.W., 2022, https://www.rickallmendinger.net/stereonet

Billings, M.P. 1956, Geology of New Hampshire, Part II: Bedrock Geology, New Hampshire Planning and Development Commission. Concord, New Hampshire (and geologic map, 1955, scale 1:250,000).

Bothner, W.A, Kucks, R.P., Jahrling, C.E.,II, Carnese, M.J., and Moench, R.H.,1997, Complete Bouguer gravity and aeromagnetic maps of the Lewiston and Sherbrooke 1° x 2° quadrangles, Maine, New Hampshire, and Vermont: U.S.Geological Survey Miscellaneous Field Studies Map I-1898-F, scale 1:250,000.

Bothner, W.A., Converse, D.R., Jahling, C.E., II, and Koch, P.S., 2020, Bedrock Geologic Map of the Pittsburg 7.5' Quadrangle, New Hampshire. Bedrock Geologic Map Open-File Series GEO-008-024000-SMOF

Converse, D.R., 1977, Reconnaissance Geology of the Indian Stream Area Northern New Hampshire: BSE thesis, Princeton University, 127 p.

Converse, D.R., Bothner, W.A., Jahrling, C.E, II, and Koch, P.S., 2021, Bedrock Geologic Map of the Lake Francis 7.5' Quadrangle, New Hampshire. Bedrock Geologic Map Open-File Series GEO-009-024000-BMOF

Coutts, D.S., Matthews, W.A. and Hubbard, S.M. (2019) 'Assessment of widely used methods to derive depositional ages from detrital zircon populations', Geoscience Frontiers, 10(4), pp. 1421–1435. Available at: https://doi.org/10.1016/j.gsf.2018.11.002.

Dorais, M.J., Marvinney, R.G., Markert, K., 2017. The age, petrogeneis and tectonic significance of the Frontenac Formation basalts, northern New Hampshire and western Maine. Am. J. Sci. 317 (9), 990–1018.

Gehrels, G., Giesler, D., Olsen, P., Kent, D., Marsh, A., Parker, W., Rasmussen, C., Mundil, R., Irmis, R., Geissman, J., 2020. LA-ICPMS U–Pb geochronology of detrital zircon grains from the Coconino, Moenkopi, and Chinle formations in the Petrified Forest National Park (Arizona). Geochronology 2, 257–282.

Green, J.C., 1964, Stratigraphy and Structure of the Boundary Mountain Anticlinorium in the Errol Quadrangle, New Hampshire: Geological Society of America Special Paper 77, 78 p.

Green, J.C., 1968, Geology of the Connecticut Lakes Parmachenee area, New Hampshire and Maine: Geological Society of America Bulletin, v. 79, p. 1601–1638

Hatch, N.L., 1963, Geology of the Dixville quadrangle, NH: NH Department of Resources and Economic Development, Bulletin 1, Concord, NH, 81 p, map scale 1:62,500.

Herriott, T.M., Crowley, J.L., Schmitz, M.D., Wartes, M.A., Gillis, R.J., 2019. Exploring the law of detrital zircon: LA-ICP-MS and CA-TIMS geochronology of Jurassic forearc strata, Cook Inlet, Alaska, USA. Geology 47, 1044–1048.

Hitchcock, C.H, 1874. 1877, 1878, Geology of New Hampshire, Concord, NH. 3 volumes.

Horstwood, M.S., Košler, J., Gehrels, G., Jackson, S.E., McLean, N.M., Paton, C., Pearson, N.J., Sircombe, K., Sylvester, P., Vermeesch, P., 2016. Community-derived standards for LA-ICP-MS U-(Th-) Pb geochronology–Uncertainty propagation, age interpretation and data reporting. Geostandards and Geoanalytical Research 40, 311–332.

Hueber, F.M, Bothner, W.A., N. L. Hatch Jr, S.C. Finney, and J. N. Aleinikoff, 1990, Devonian Plants from Southern Quebec and Northern New Hampshire and the Age of the Connecticut Valley Trough, The American Journal of Science 290, no. 1–6 p. 360–95.

Jahrling, C.E., II, 1983, Geophysical, structural, and stratigraphic relations across the Monroe line and related contacts in the Indian Stream area, northern New Hampshire: Durham, NH, University of New Hampshire M.S. thesis, 106p.

Lyons, John B., John N. Aleinikoff, and Robert E. Zartman, 1986, Uranium-Thorium-Lead Ages of the Highlandcroft Plutonic Suite, Northern New England American Journal of Science 286, no. 6, p. 489–509.

Lyons, J.B., Bothner, W.A., Moench, R.H., and Thompson, J.B., Jr., 1997, Bedrock Geologic Map of New Hampshire: U.S. Geological Survey Map, scale 1:250,000, 2 sheets.

McWilliams, C.K., Walsh, G.J., Wintsch, R.P., 2010. Silurian-Devonian age and tectonic setting of the Connecticut Valley-Gaspe trough in Vermont based on U-Pb SHRIMP analyses of detrital zircons. American Journal of Science 310, p. 325–363.

Marvinney, R.G. (1994) Sedimentological Aspects Of The Frontenac, Ironbound Mountain, And Northeast Carry Formations Near Seboomook Lake, Maine, New England Intercollegiate Geological Conference, 86th, Millinocket, ME, 1994, Guidebook [p. 67-89], p. 24.

Marvinney, R.G. et al. (2001) Resolved Silurian-Devonian stratigraphic correlation across the Québec-Maine-New Hampshire borders and its bearing on Silurian extension, Atlantic Geology, 37(1).

Meyers, P.B, Jr.,1964, Geology of the Vermont portion of the Averill Quadrangle, Vermont: Vermont Development Department, Bulletin 27, 69p. scale 1:62,500.

Moench, RH, et al., 1995, Geology of the Lewiston-Sherbrook Area, Maine, New Hampshire, Vermont, United States, and Quebec, Canada: US Geological Survey Map I-1898D, scale 1:250,000 and pamphlet.

Perrot, M., 2019. Évolution tectonique des bassins sédimentaires tardi-à post-taconiens des Appalaches du sud du Québec et du nord du Vermont (PhD Thesis). Université du Québec à Montréal.

Perrot, M., Tremblay, A., David, J., 2017. Detrital zircon U-Pb geochronology of the Magog Group, southern Quebec–stratigraphic and tectonic implications for the Quebec Appalachians. American Journal of Science 317, 1049–1094.

Perrot, Morgann, Tremblay, A., Ruffet, G., and David, J., 2018, Detrital U-Pb and 40Ar/39Ar geochronology of the Connecticut Valley – Gaspé trough, southern Quebec and northern Vermont – Transitional tectonism from Salinic to Acadian orogenic cycles: Tectonophysics, v.745, p. 430-452.

Perrot, M., Tremblay, A., Ruffet, G., Labrousse, L., Gervais, F., and Caroir, F., 2020, Diachronic Metamorphic and Structural Evolution of the Connecticut Valley–Gaspé Trough, Northern Appalachians." Journal of Metamorphic Geology 38, no. 1 p 3–27

Ratcliffe, N.M., Stanley, R.S., Gale, M.H., Thompson, P.J., and Walsh, G.F., 2011, Bedrock Geologic Map of Vermont: U.S. Geological Survey Scientific Investigation Map 3184, scale 1:100,000

Ryan, P.C. et al. (2013) Arsenic in a fractured slate aquifer system, New England, USA: influence of bedrock geochemistry, groundwater flow paths, redox and ion exchange, Applied Geochemistry, 39, pp. 181–192.

Tremblay, A., De Souza, S., Perrot, M., Theriault, R., 2015. Géologie des Appalaches du Québec, Feuillet Sud-Ouest, regions de Montérégie, Cantons de l'Est, Centre-du Québec et Chaudière-Appalaches. Ministère des Ressources Naturelles du Québec, MB 2015-2011, 1:300,000.

Vermeesch, P., 2018. IsoplotR: A free and open toolbox for geochronology. Geoscience Frontiers 9, 1479–1493.

Vermeesch, P., 2021a, Maximum Depositional Age Estimation Revisited, Geoscience Frontiers 12, p. 843–50.

Vermeesch, P., 2021b, On the Treatment of Discordant Detrital Zircon U–Pb Data." Geochronology 3, no. 1 p. 247–57.

Walker, J.D., Geissman, J.W., Bowring, S.A., Babcock, compilers, 2018. Geologic Time Scale v. 5.0, Geological Society of America. https://doi.org/10.1130/2018.CTS005R3C

Figures & Tables

Figure 1A: Regional Map
Figure 1B: Northern NH map
Figure 2: A. Stratigraphic age constraints
B. Summary of detrital zircon age profiles (unfiltered)
Figure 3: Meta-igneous units
A. Meta-basalts / contorted meta-volcaniclastic Sediments
B. Metadiabase dikes/sills
C. Lapilli Tuffs
Figure 4: Meta-sedimentary units.
A. Halls Stream Grits photographs 22-163
B. Graded Graywacke (Indian Stream Canyon)
C. Graded Graywacke possible stacked channels
D. Gile Mt
E. Frontenac metasediments
Figure 5: Large Structures
A. Ironbound Mt
B. Gile Mountain
C. Frontenac
Figure 6: Steronet Analysis
A. Cowen Hill structural attitudes
B. Comparison of Structures east and west of the Monroe Fault
C. Comparison of Cowen Hill and La Patrie Transect (Perrot, 2019, p.134)
Figure 7: Geochemistry
A. Major Element
B. Trace Element
Table 1A: Maximum Depositional Ages
Table 1B: Zircon Crystallization Ages

Figure 1 – Regional geology

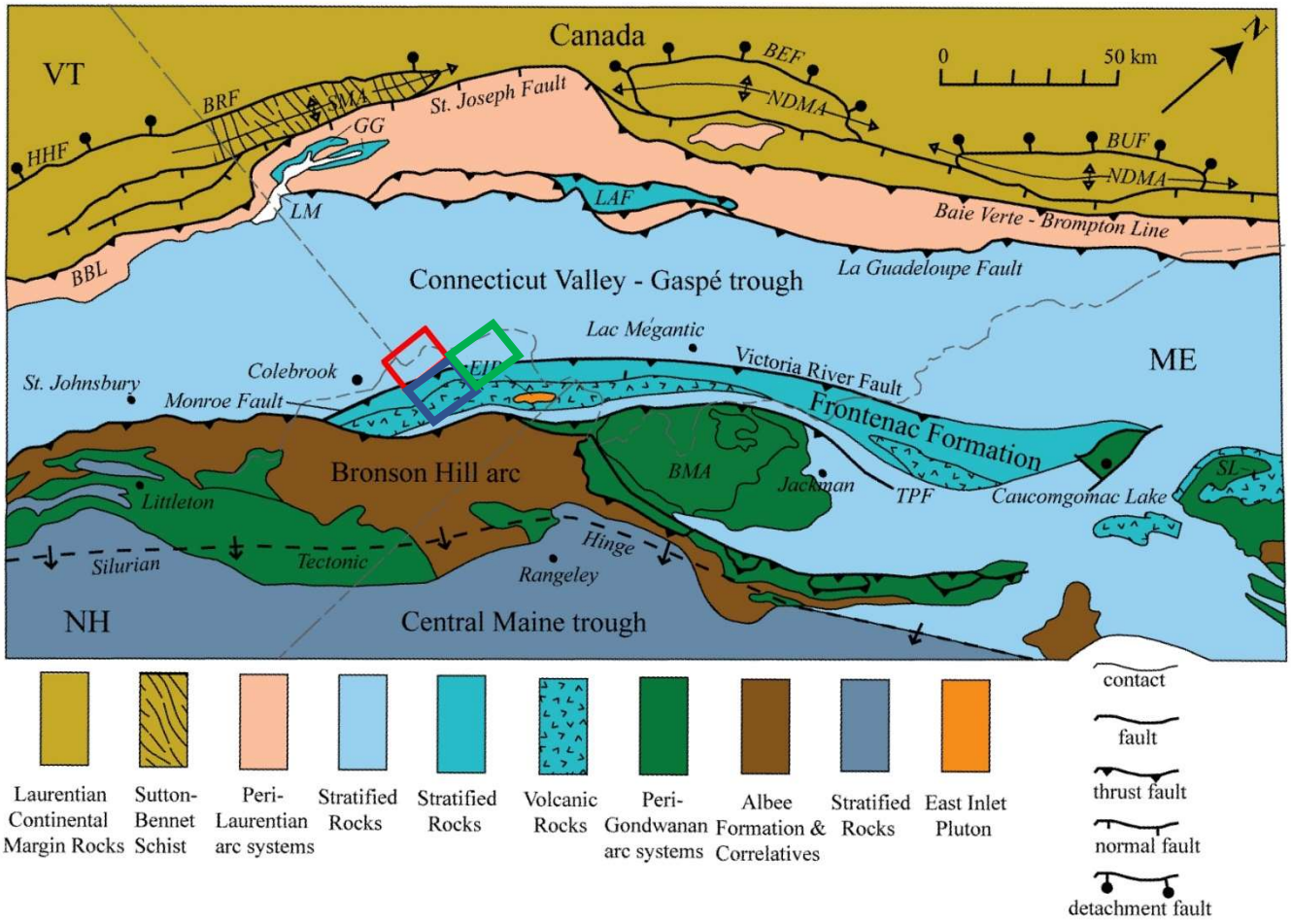


Figure 1A. Simplified geologic map (modified after Dorais and others, 2017) showing the location of the Cowen Hill Quadrangle (green), Lake Francis Quadrangle (blue), and Pittsburg Quadrangle (red) at the southeastern border of the Connecticut Valley – Gaspé Trough. The Bronson Hill arch separates the CVGT from the Central Maine Trough. The Monroe fault is extended northerly to join the Victoria River (Belle) fault in Quebec and separates the Frontenac Formation from rocks of the CVGT in northern NH. EIP, East Inlet pluton; BMA, Boundary Mountains arch, BRF, Brome fault; BUF, Buckland fault; GG, Glenbrooke Group; HHF, Honey Hollow fault; LAF, Lac Aylmer Formation; LM, Lake Memphremagog; NDMA, Note Dame Mountains anticlinorium; SMA, Sutton Mountains anticlinorium; SL, Spider Lake; TPF, Thrasher Peaks fault

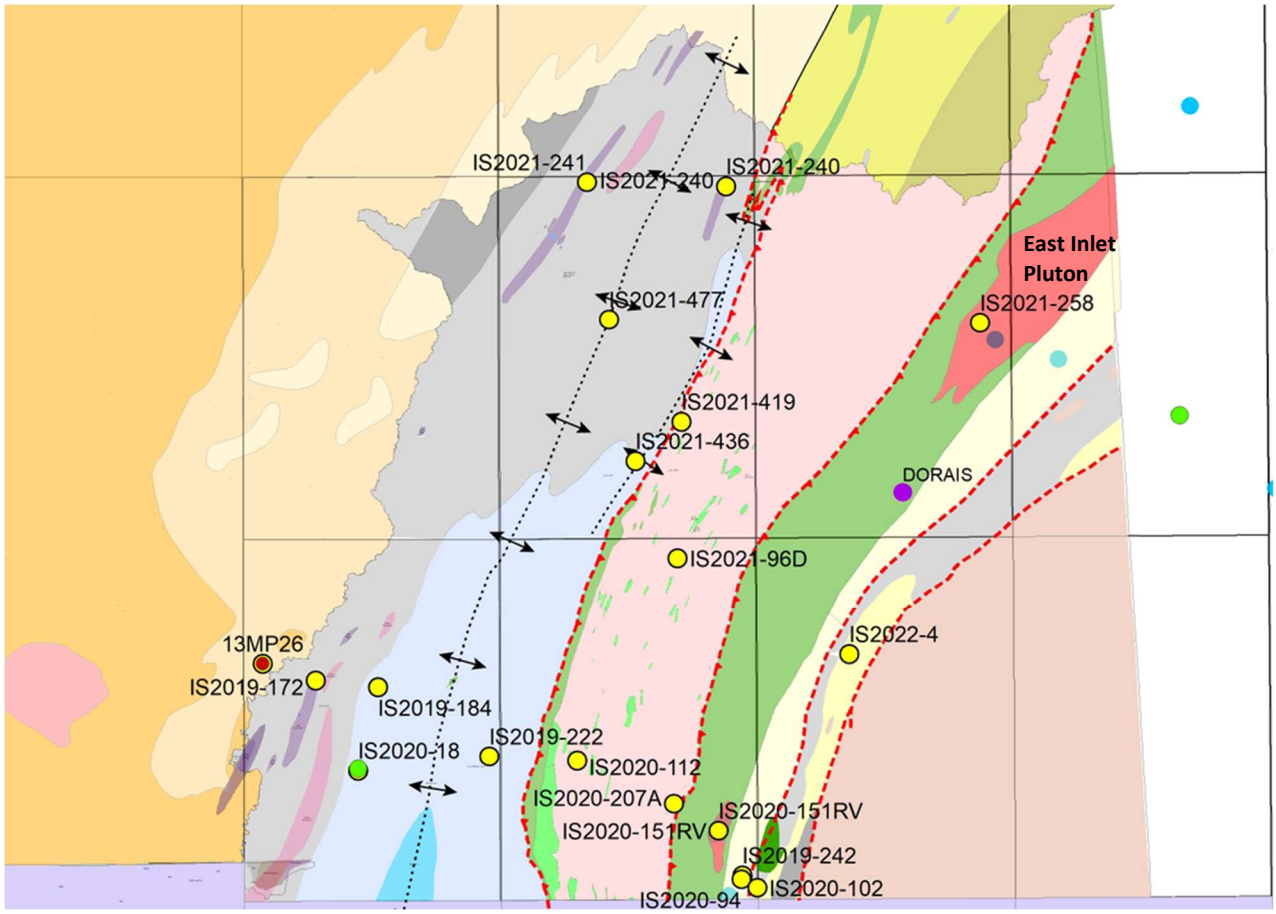


Figure 1B: Northern New Hampshire Geology: Geology of the area east of Cowen Hill and Lake Francis Quadrangles is adapted from the NH State Geological Map (Lyons et al., 1997). Geologic units have the same colors as our recent Pittsburg, Lake Francis and Cowen Hill maps. Faults were not extended to the northeast. Samples studied for Zircon age dates are: Yellow dots: our studies (2019 – 2022). Red dot: Perrot (2019) Purple dot: Dorais et al., 2017; Light blue dots: Whole rock studies: Lyons et al., 1987; Moench et al., 1995; Green dots: Plant Fossils (Hueber et al., 1990). Geologic map of southern Quebec from Perrot, 2019.

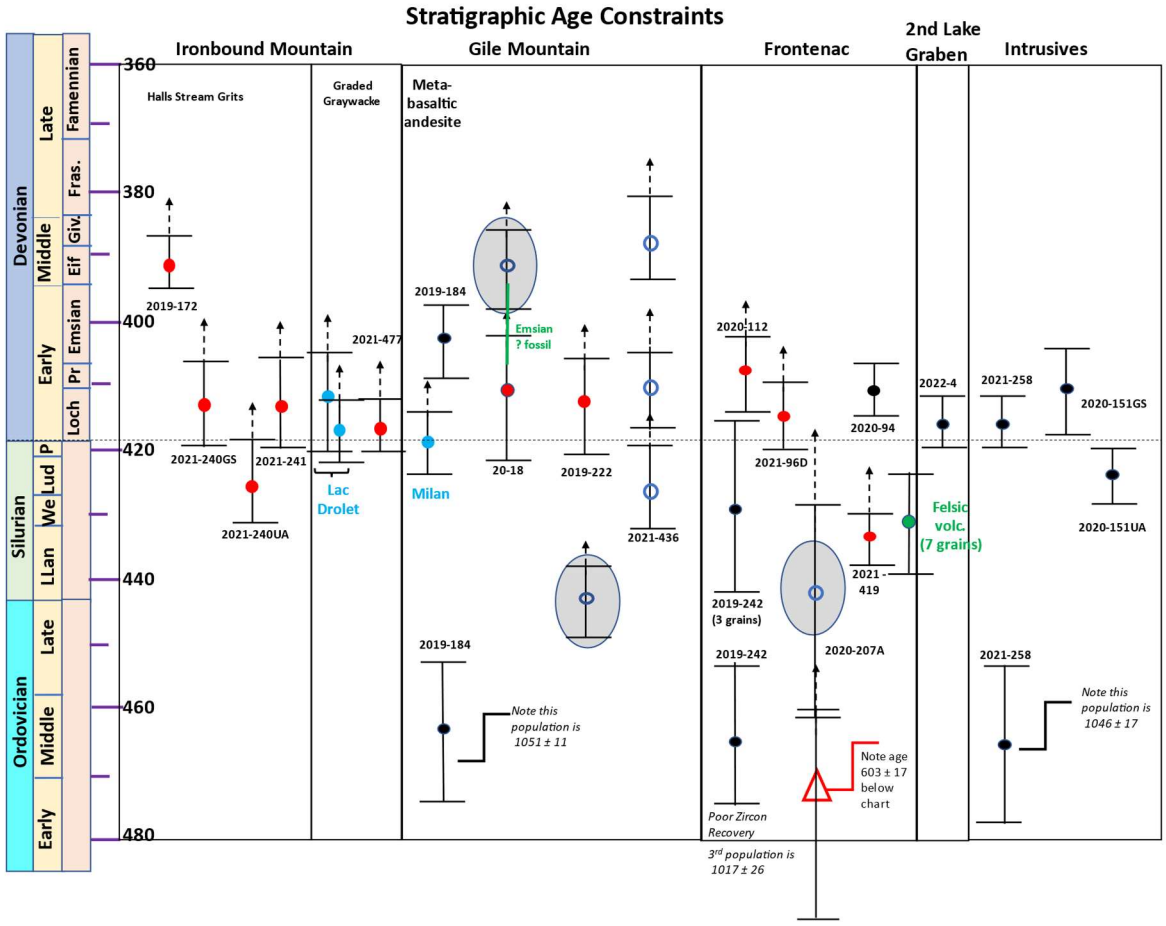


Figure 2: A) Zircon age determinations. Quebec dates (cyan dots) are from M. Perrot (2018) and green dot is from Dorais et al., (2017), the remainder are analyses of U-Pb from LA-ICPMS analysis conducted by GeoSep Services and University of Arizona LaserChron Center. Two types of age determinations are shown – 1) crystallization ages (black dots) and 2) maximum depositional ages (MDAs – red dots, alt MDAs – blue circle). It is important to understand that MDAs only provide an upper bound but not a lower bound for the depositional age – for one sample, the MDA is much older than the sediment age from other constraints, due to low zircon recovery). The age results are shown with 2σ uncertainty. In some cases, the data can support alternative interpretations for the MDAs – either due to limited number of zircons or issues with data quality. Note that a gray circle is added to indicate if an alternative interpretation is considered unlikely or of poor quality. Red triangle indicates that the MDA is significantly older than the likely depositional age.

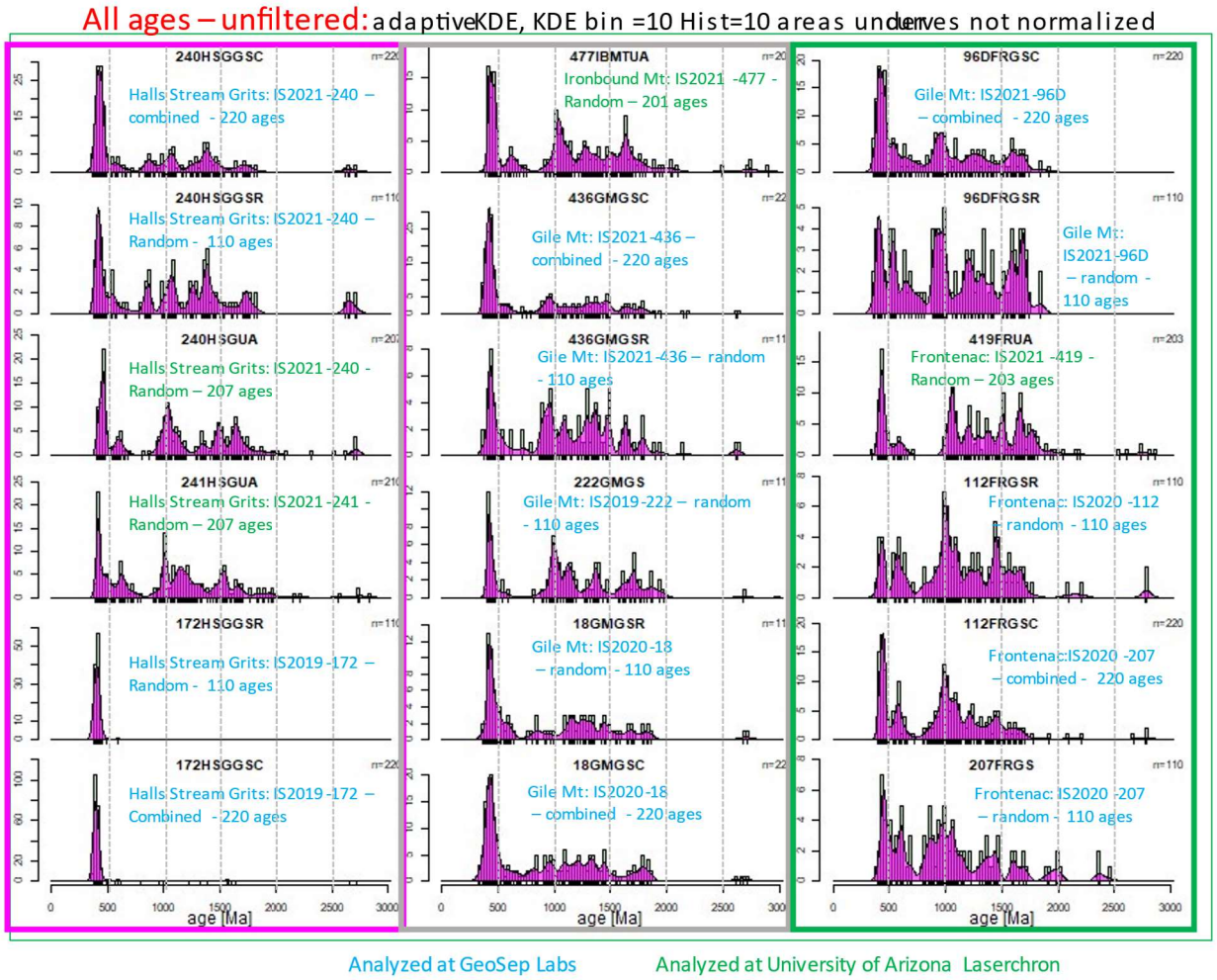


Figure 2: B) Detrital zircon age distribution (unfiltered) for all samples. For some samples run at GeoSep, the first run was done with zircon grains selected at random and the second run was generally done were targeted for younger grains (more euhedral) with the exception of IS2019-172 (Halls Stream Grits) in which older (more rounded grains) were sought. The combination of runs 1 and 2 are listed as combined.

B

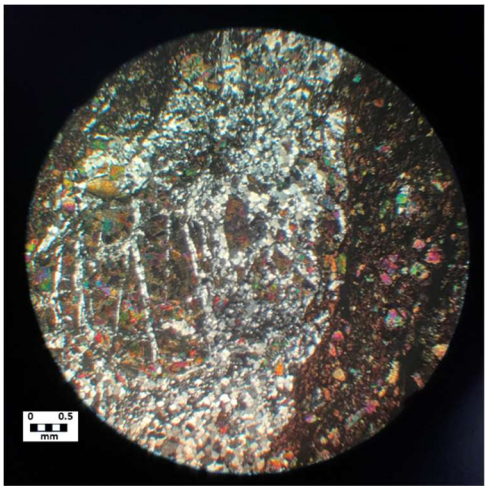


Figure 3 A: Frontenac Meta-pillow basalts (IS2021-154) B. Cross-nichols photomicrograph, and C. Contorted metasediments (IS2021-151).

Figure 3B: IS2022-257: 10-15 m Frontenac metadiabase wall x 30-40 m long; medium-grained at base, very coarse-grained at top. Truly massive wall. Some fine-grained near eastern edge (right side).

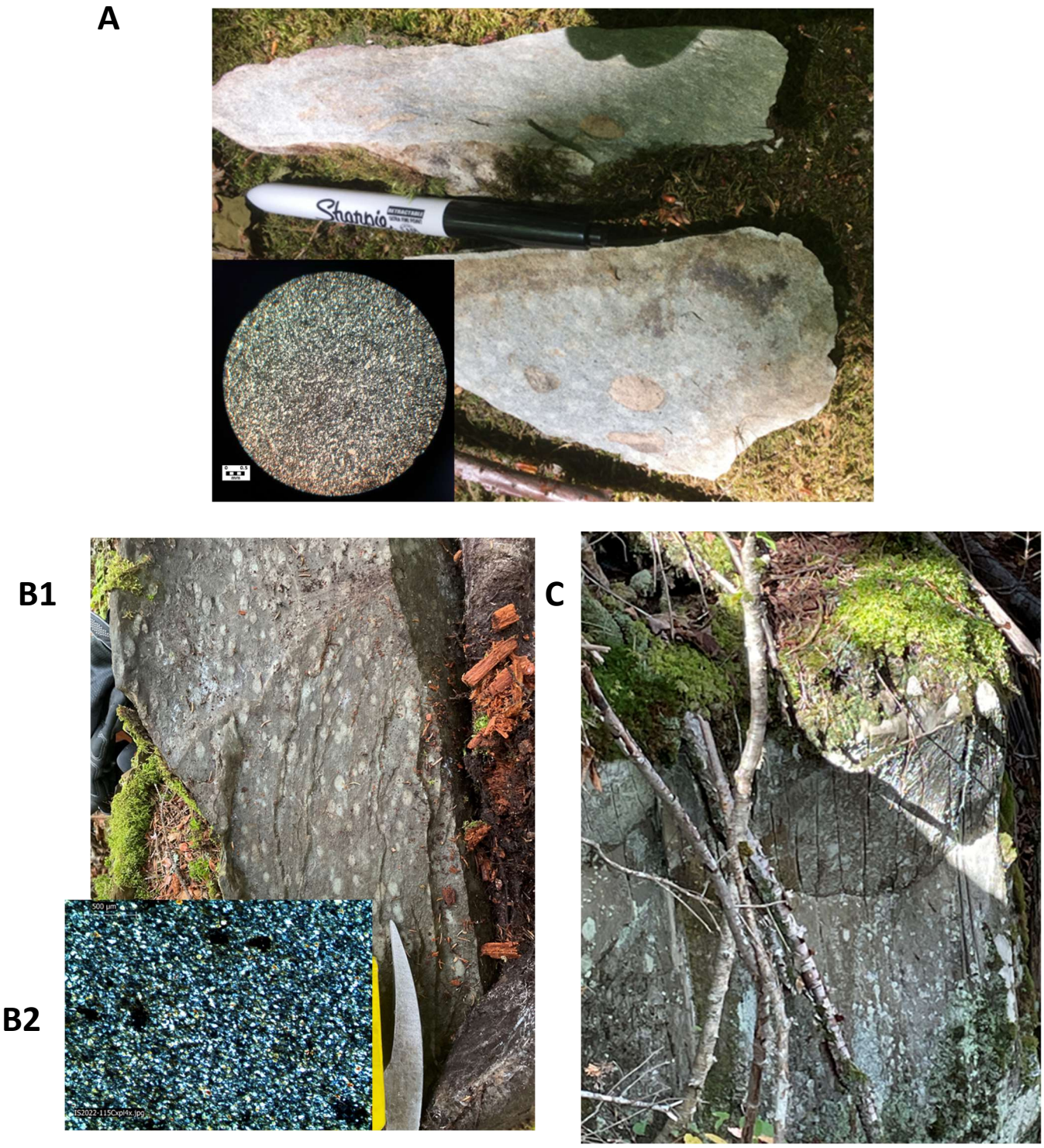


Figure 3C: Frontenac Lapilli Tuff and meta-volcaniclastic rocks: A) Meta-Lapilli tuff /tuffaceous sediment with rounded rock fragments (IS2021-96D) – northeastern corner of Lake Francis Quadrangle and photomicrograph (XN). **B1**) Meta-Lapilli Tuff (IS2022-115C) from western bank of Perry Stream adjacent to a metadiabase body and B2) cross-nichols photomicrograph. **C)** Probable meta-tuff (IS2021-419) and meta-volcaniclastic sediments.

Figure 4A Ironbound Mt Halls Stream Grits Massive sub member:A,B) IS2022-167 (above Terrell Pond): massive cliff with bedding dipping at low angles on the eastern side of the outcrop (shown above) with near vertical dips at the western end of the cliffs. Tighter folds in the more phyllitic rich zones as shown to the right. C) IS2022-112 (above Ad Chase Road, Pittsburg) – massive (no obvious bedding) cliff and D) close-up: hand sample and photomicrograph from C.

.

Figure 4B: Ironbound Mt Graded Graywackes in the middle of Indian Stream Canyon. Note that bedding dip varies from near vertical at the north end of the canyon to moderate dips in the middle (as shown here) to very low angle dips in the southern end of the canyon. Note the well-developed S2 cleavage.

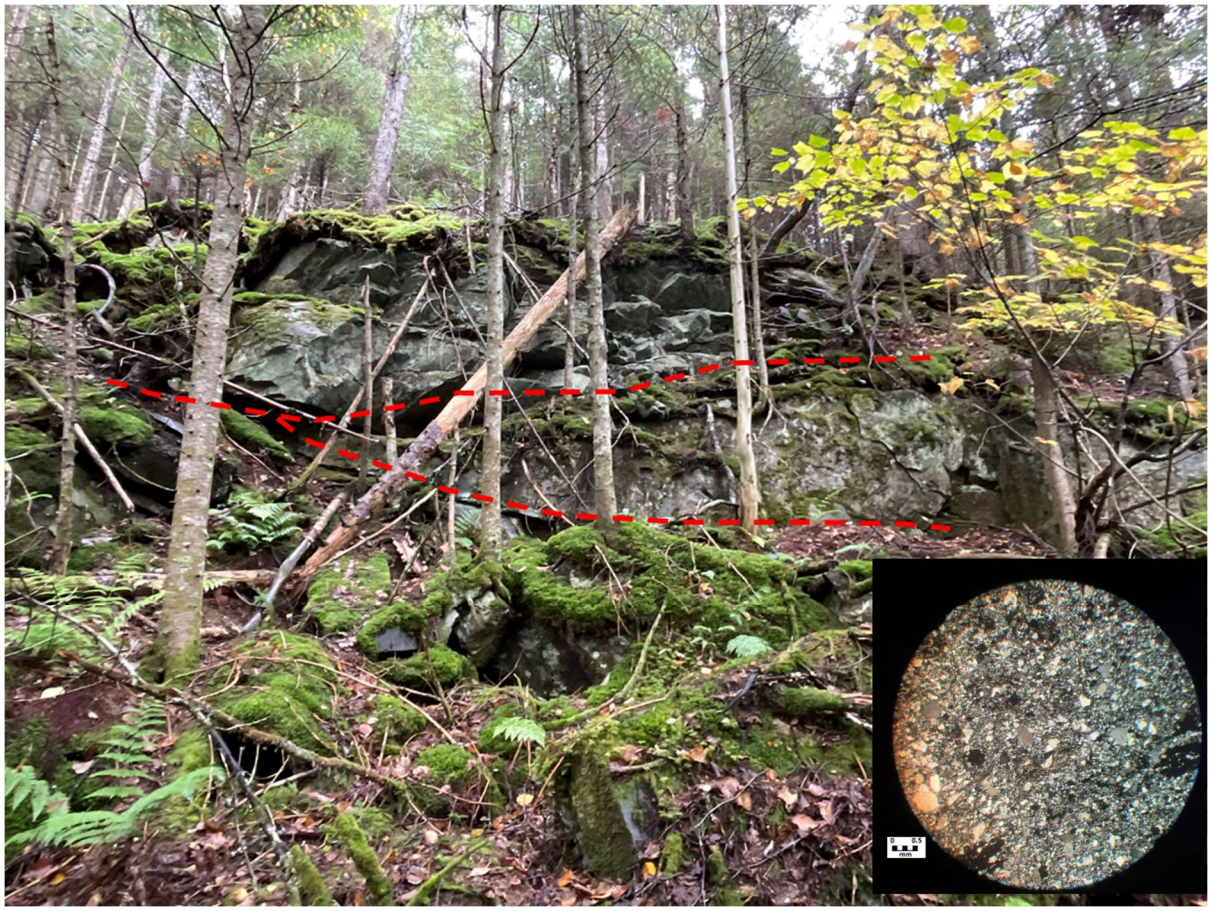


Figure 4C: Ironbound Mountain possible graded graywacke channel: IS2021-473 (also IS2021- 477). Appears to be a set of stacked channels that are each 2 -3 m thick. Thin-section description: Somewhat gritty, poorly foliated altered pyrite-bearing metasandstones? With 0.2+/- (tr 0.4) mm quartz and twinned plagioclase in similar fine-grained matrix (see inset photomicrograph)

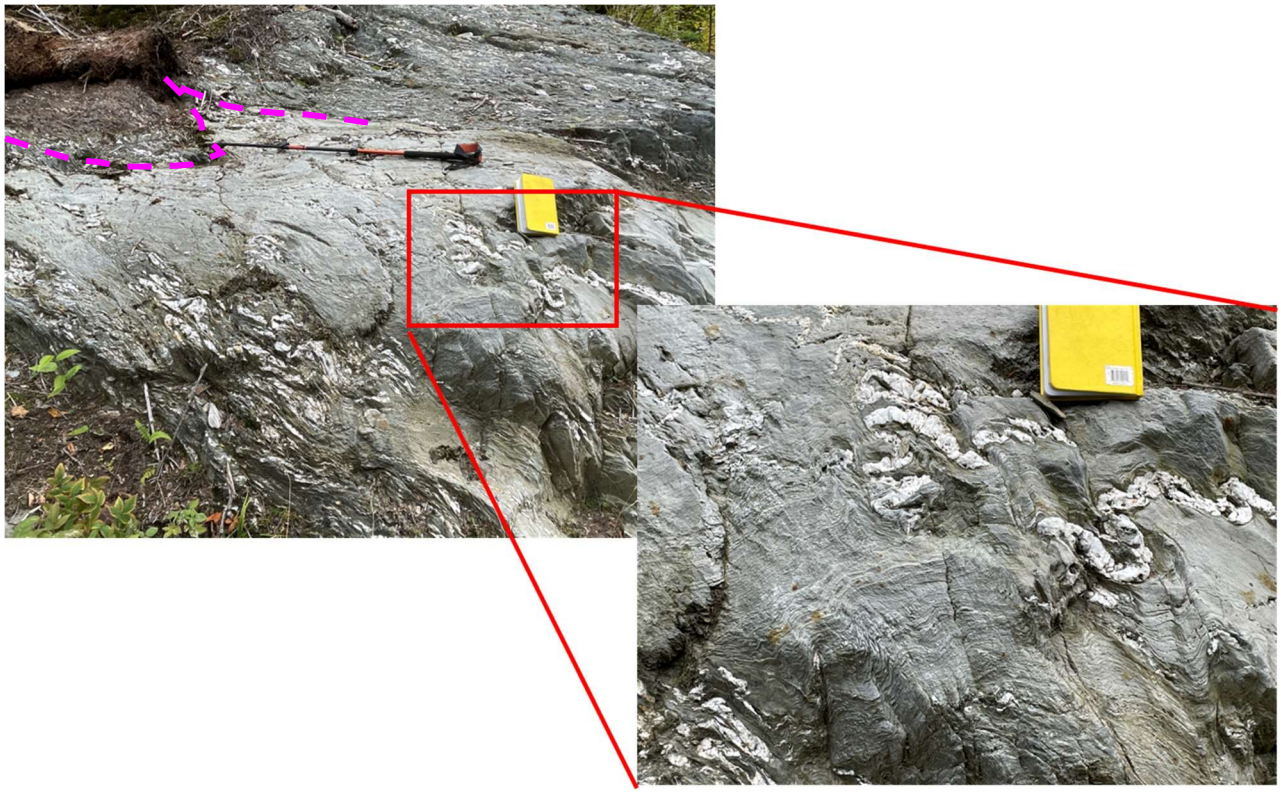


Figure 4D: Gile Mountain: IS2021-429 Highly deformed outcrop of gray meta-siltstones and black phyllites. In the upper photo, the trekking pole points to a tight black phyllite filled synform (magenta dashed line) photos taken looking 062°). The photo and the closer-up inset show multiple generations of foliations and folding as well as ptygmatic quartz folds. Outcrop ca. 30m long x 15 m wide x 5 m high.

Figure 4E: Frontenac meta-siltstone: 1) IS2022-254. No obvious bedding but clear S1 foliation. 2) Very fine-grained “clean” meta-siltstone as seen just below the meta-diabase outcrop. Possible contact metamorphism? 3) IS2022-262 – large outcrop broken into large blocks.

Figure 5A: Ironbound Mountain: IS2022-287. Amazing cliff (ca. 30-50 m tall) metasiltstone-sandstone outcrops that cover almost the entire north side of creek; Outcrop is divided into several ridges trending ~ perpendicular to the creek which are made up of highly broken-up large folds. Photo 1 looking 054° of westernmost outcrop with easily discerned anticline with a wavelength of ca. 15 m. Estimated fold axis A2 is 54 10 with minor fold vergence being west over east on the west flank and east over west on the east flank. Inset is of a hand sample and crossed-nichols photomicrograph.

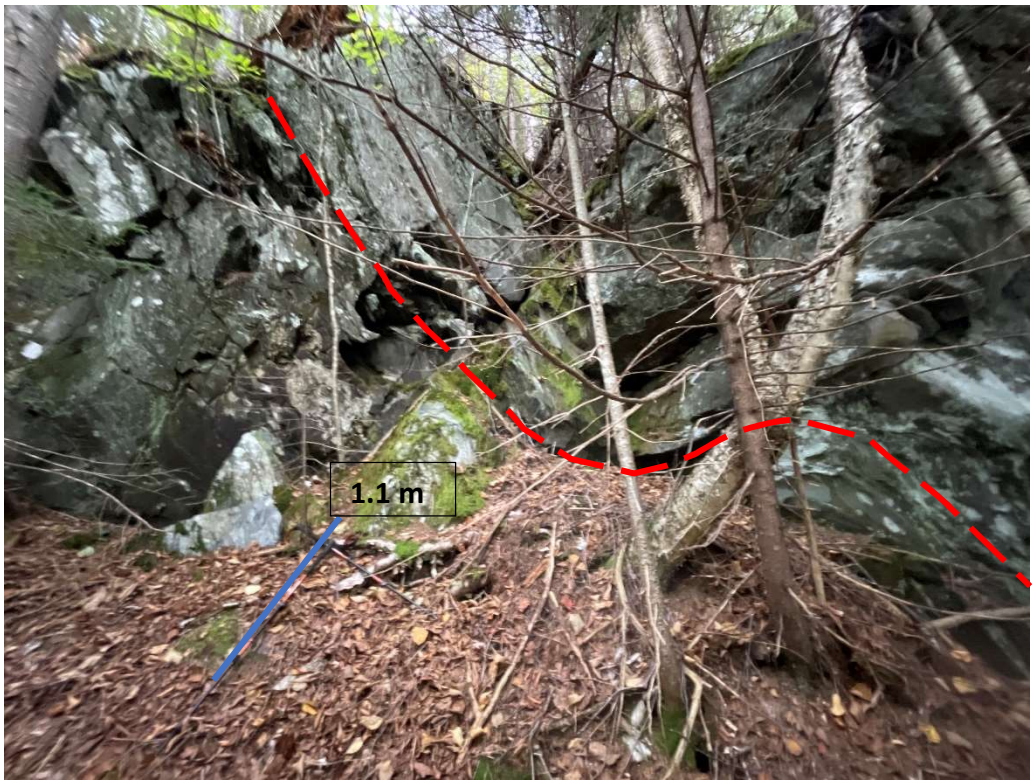


Figure 5B: Gile Mt: IS2021-438: looking N54E at thick-bedded (~ 2.5 m) siltstone/sandstone folded cliff. Large open fold 63.3 30.9 with bedding on the eastern flank striking 36° and dipping 57°. Amplitude of major fold is ~ 10 m; Also has minor folds with 15-25 cm wavelengths. Rock feels very gritty - almost friable.

Figure 5C: Frontenac IS2022-264 Looking almost due north at the eastern half of a large fold in the metasediments. The very steep foliated (S1) metasiltstone / sandstone layers on the lefthand side (west) of the photo represent axial foliation in the core of the anticline. On the right side (east) of the photo are massive meta-siltstone and meta-sandstone beds that have low angle dips and define the eastern limb of the anticline.

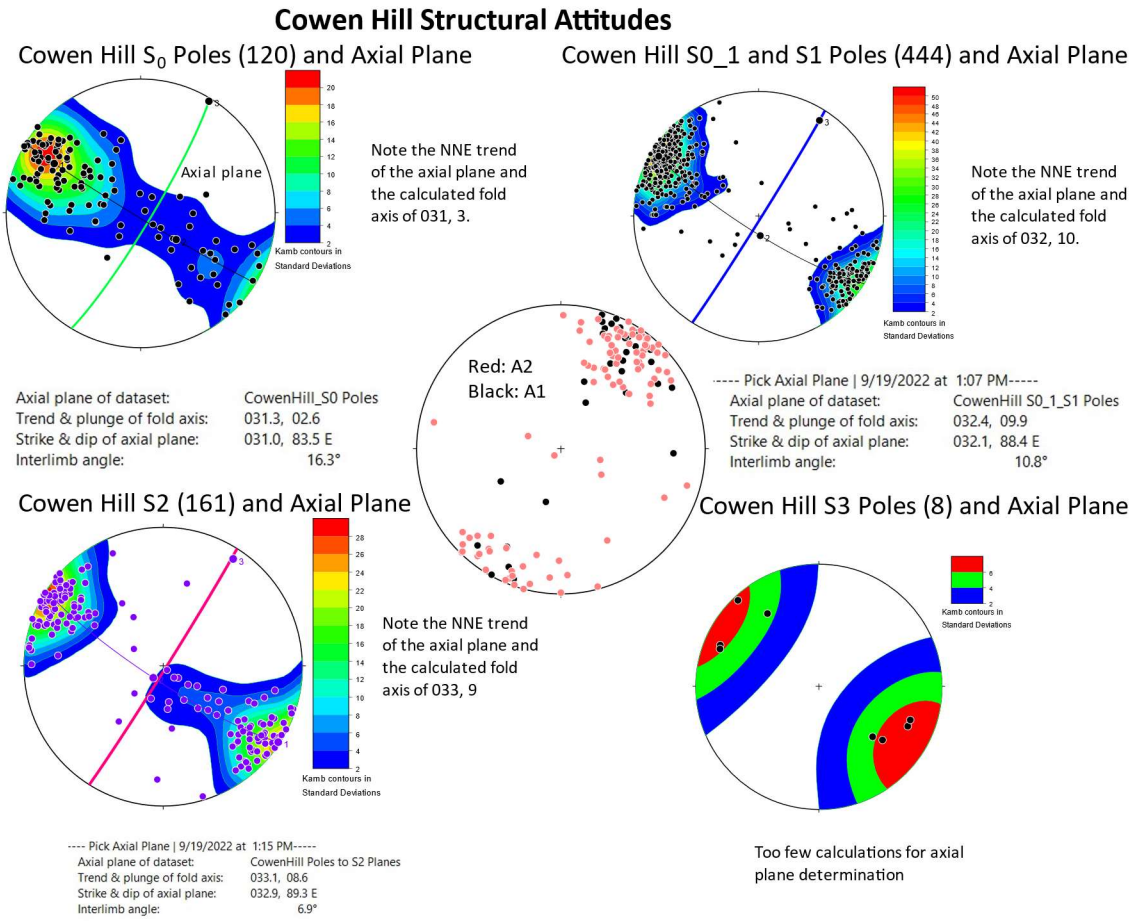
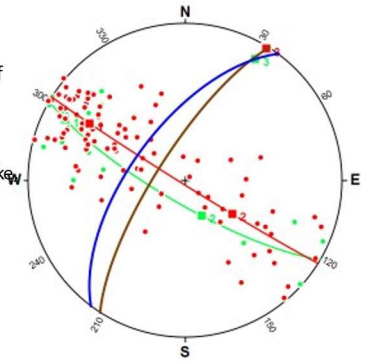


Figure 6 A: Structural Attitudes in the Cowen Hill Quadrangle

Cowen Hill: Comparison of structure east and west of the Monroe Fault

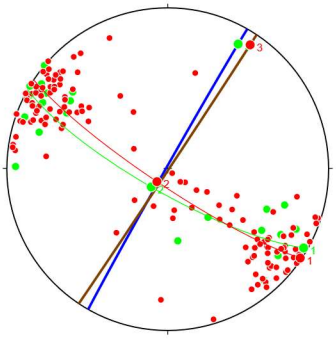
Cowen Hill So poles

- 121 observations
- Green points from east of Monroe Fault (19)
- Red points from west of Monroe Fault (102)
- Best-fit great circles (strike dip RHR)
  - Green =120.3 78.1
  - Red = 122.08 87.9
  - Axial Planes
  - CHWest = 213, 76 Brown
  - CHEast= 217, 63 Blue



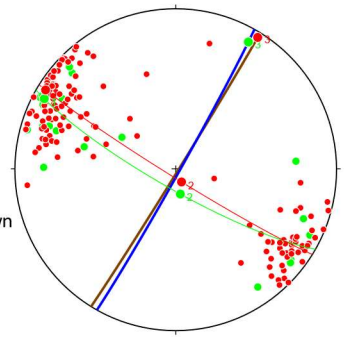
Cowen Hill S2 poles

- 161 observations
- Green points from east of Monroe Fault (21)
- Red points from west of Monroe Fault (140)
  - Axial Planes
  - CHWest = 34 90Brown
  - CHEast= 210 88 Blue
  - Fold Axes
  - CHWest: 034 8
  - CHEastL029 12



Cowen Hill S1 poles

- 172 observations
- Green points from east of Monroe Fault (23)
- Red points from west of Monroe Fault (149)
  - Axial Planes
  - CHWest = 32 88 Brown
  - CHEast= 29 88 Blue
  - Fold Axes
  - CHWest: 032 4
  - CHEastL030 10



Cowen Hill A1 and A2 poles

- A1: Triangles: Green – east of Monroe Fault, Red – west.
- A2: Dots: Green – east of Monroe Fault, Red – west.
- Fisher mean vectors
- A1 east 1 obs, 049 40
- A1 west 7 obs, 047 64
- A2 east 32 obs, 035 29
- A2 west 89 obs, 047 41

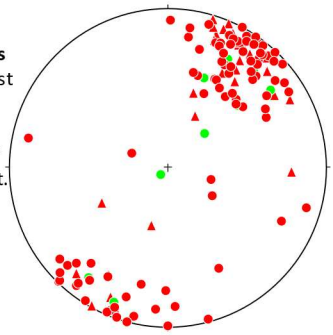


Figure 6B: Structural Analysis comparing the areas of Cowen Hill east and west of the Monroe Fault.

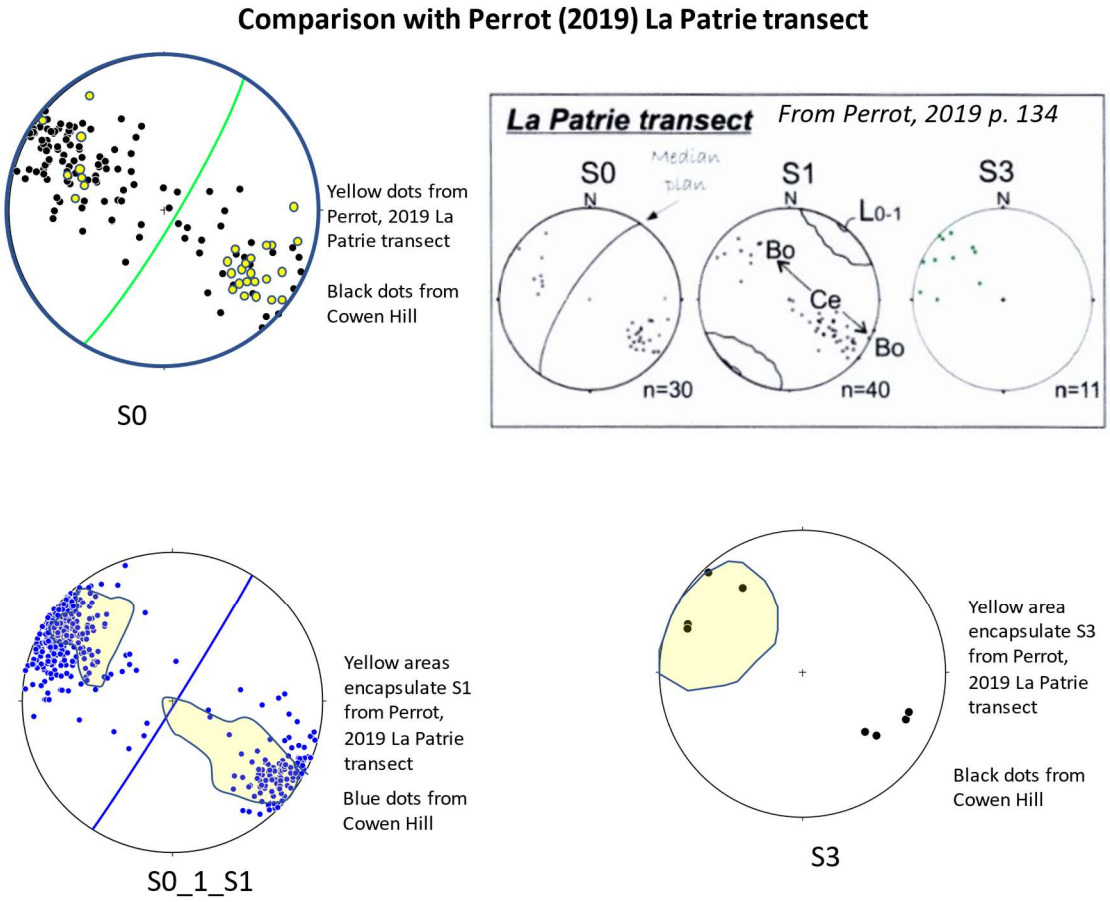


Figure 6C: Comparison with the structural attitudes in the La Patrie Transect (Perrot, 2019, p.134)

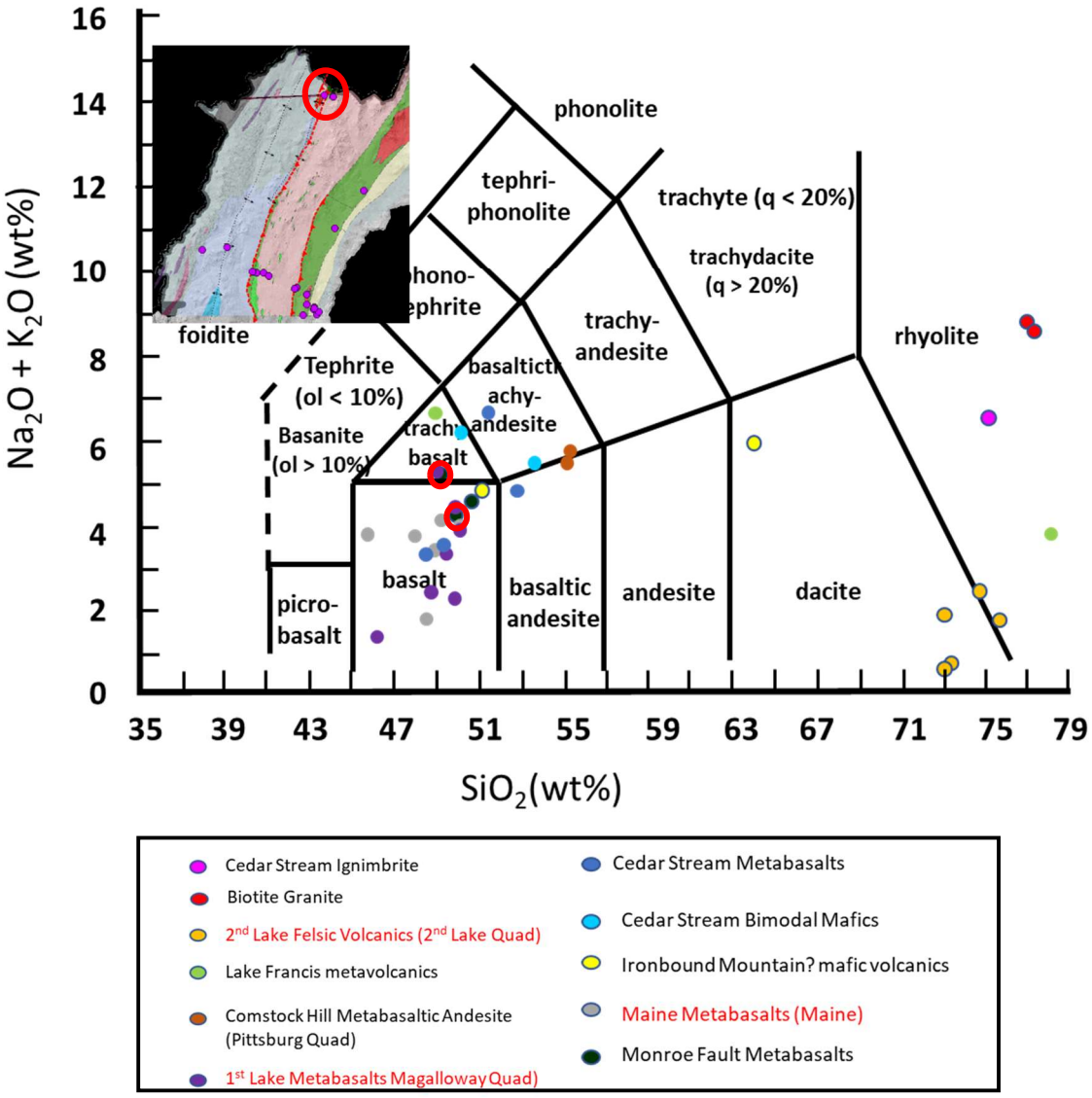


Figure 7A: Frontenac Meta-Igneous Rocks and Gile Mt metabasaltic andesite Major Element Chemistry – range of meta-basalts, meta-basaltic andesites, dacites, rhyolites/granites. The two black dots circled in red are contiguous meta-basalts in the northwestern corner of Second Connecticut Lake Quadrangle (IS2020-26 and 39).

All red legend entries indicate data from Dorais et al., 2017; remaining data generated during collaboration with Professor M.J. Dorais (BYU),

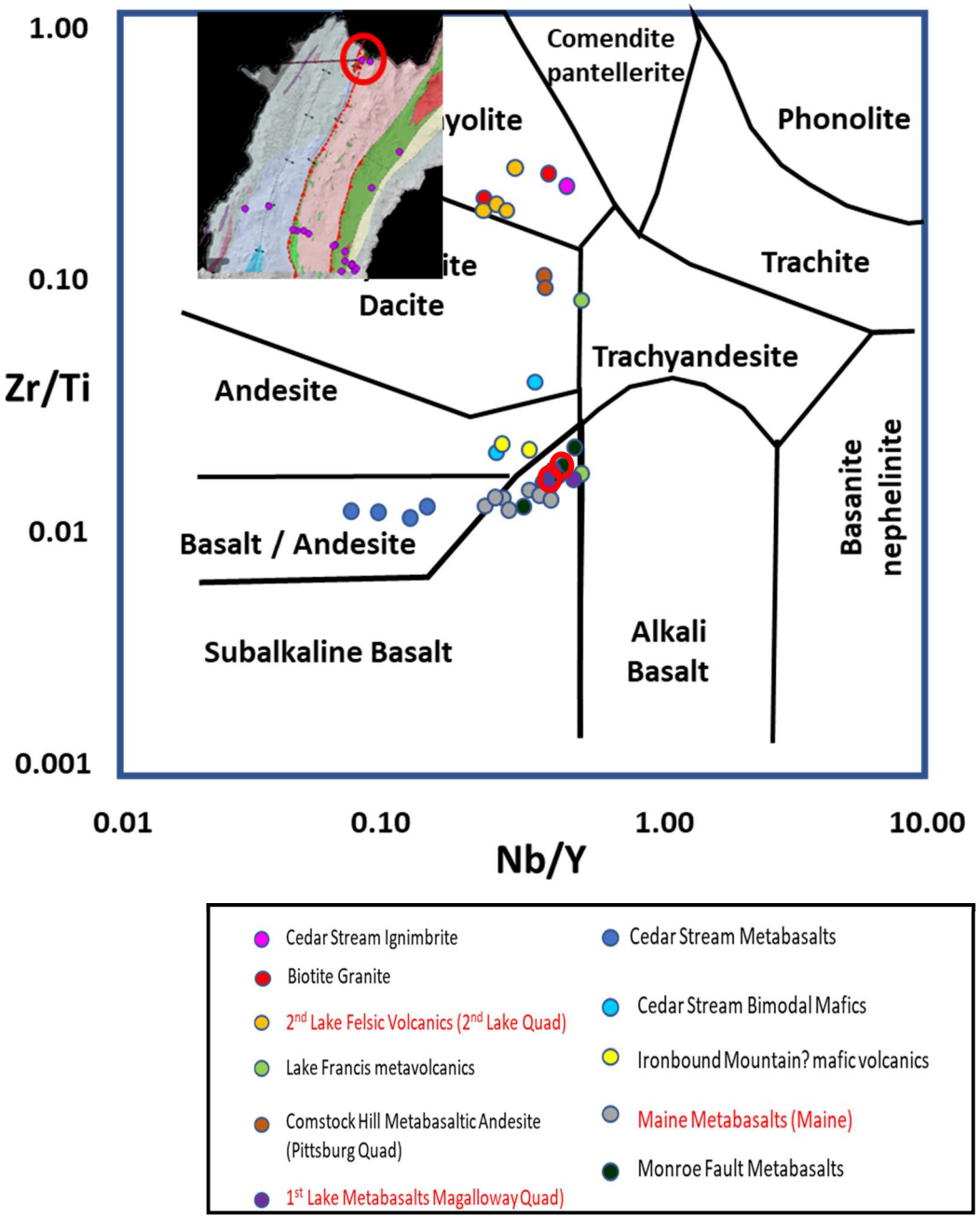


Figure 7B: Frontenac Meta-Igneous Rocks and Gile Mt metabasaltic andesite
Trace element chemistry – see separation of meta-basalts from Monroe Fault, similarity of biotite granite and metaignimbrite, unusual meta-basaltic andesite from Gile Mt. (PIttsburg). The two black dots circled in red are from contiguous meta-basalts in the northwestern corner of Second Connecticut Lake Quadrangle (IS2020-26 and 39).

Table 1A Detrital Zircon Maximum Depositional Ages

Detrital Zircon Maximum Depositional Ages

Sample	Location	Formation	Max. Depositiona; Age (Ma)	Comments
IS2019-172 Geosep	Ridge W of Indian Stream	Halls Stream Grits –high feldspar content	391 ± 4 (2σ) or 2 peaks381 - 386 Ma and 397-406	Possible multiple ash fall events; Only zircon age population.
IS2021-240 GeoSep	Northern Cowen Hill boundary	Halls Stream Grits	413 ± 6 (2σ)	Not a well-defined cluster – MWSD = 2.7
IS2021-240 Univ. Arizona	Northern Cowen Hill boundary	Halls Stream Grits	425 ± 7 (2σ)	Good cluster MWSD= 0.79 with 17 ages
IS2021-241 Univ. Arizona	Northern Eastern Cowen Hill Quad	Halls Stream Grits	413 ± 7 (2σ)	18 ages well clustered
IS2021-477 Univ. Arizona	Near center Cowen Hill Quad	Ironbound Mt - metasandstone	417 ± 4 (2σ)	Difficult to pin down a tight age
IS2021-436 GeoSep	Just north of Cowen Hill	Gile Mt Graded Beds Channel (Diggc) – meta sandstone/siltstone	1) 388 ± 7 (2σ) 2) 411 ± 6 (2σ) 3) 426 ± 7 (2σ)	Youngest age is consistent with Emsian (?) fossil, IS2019-172, and 184 ages and alt. interpretation of IS20-18.
IS20-18 GeoSep	Tabor Notch Rd & US 3	Gile Mt - – meta sandstone/siltstone	411–414 ± 8-10 (2σ) Alt: 391 ± 6 (2σ)	Difficult- youngest ages have high discordance
IS2019-222 GeoSep	Lake Francis Spillway	Gile Mt – meta sandstone/siltstone	413 ± 8 (2σ) or 443 ± 5 (2σ)	Few young ages with discordance < 15%
IS2020 – 112 GeoSep	N Shore Lake Francis	Frontenac meta-tuff	408 ± 6 (2σ)	Seems reasonable
IS2020-207A GeoSep	NE Corner Lake Francis	Frontenac Volcaniclastics	603 ± 17 (2σ) Alt. 443 ± 16 (2σ)	Very few "young" ages and high discordance.
IS2021-96D	NE Corner Lake Francis Quad	Frontenac Meta-tuff	415 ± 5 (2σ)	Reasonable cluster with concordia distance filter
IS2021-419 Univ. Arizona	East of Monroe Fault, SE Cowen	Frontenac Volcaniclastics	434 ± 4 (2σ)	Well-defined minimum age

Table 1B Zircon Crystallization Ages

Sample	Location	Formation	Crystallization Age (Ma	Comments
IS2019-184 Geosep	Indian Stream - Comstock Hill	Gile Mt: Metabasaltic Andesite	1) 403 ± 6 (2σ) 2) 1051 ± 11 (2σ) 3) 1288 ± 18 (2σ)	Good result
IS2020-151RV GeoSep	Cedar Stream	Biotite Granite	411 ± 7 (2σ)	Tight age distribution.
IS2020-151RV Univ. Arizona	Cedar Stream	Biotite Granite	424 ± 4 (2σ)	Very good fit – 49 ages; 1 age determination > 1500 ma but with high discordance (53%) and high ^{204}Pb content
IS2020-94 GeoSep	Cedar Stream	Meta-Ignimbrite	411 ± 3 (2σ)	Tight age distribution
IS2019-242 GeoSep	Cedar Stream – very near IS2020-94	Mafic metavolcanic	1) 419 ± 18 (2σ) 2) 464 ± 11 (2σ) 3) 1017 ± 26 (2σ)	Recovered 13 zircons, Either 2 or 3 age populations
IS2021-258 Univ. Arizona	East Inlet Pluton	Biotite Granite	1) 416 ± 4 (2σ) 2) 1046 ± 13 (2σ)	2 age populations
IS2022-4 Univ. Arizona	A short distance east of 1st Connecticut Lake	Felsic Metavolcanics	416 ± 4 (2σ)	Tight cluster MSWD= 1.2
DoraisAge (Dorais et al., 2017)	On southern shore of Second Connecticut Lake	Felsic metavolcanics	432 ± 8 (2σ)	Based on 7 out of 84 zircon ages (83 ages < 500 Ma)
IS2020-102 GeoSep	SE corner Lake Francis Quad	Metabasalt	No ages determined	Did not recover any zircons
IS2020-56 GeoSep	Lang Hill, Dixville Quad	Calcium-rich Metadiorite	No ages determined	Only recovered 7 zircon grains