Supra-subduction magmatism in the Moretown Terrane, a fragment of Gondwana in the western Appalachians

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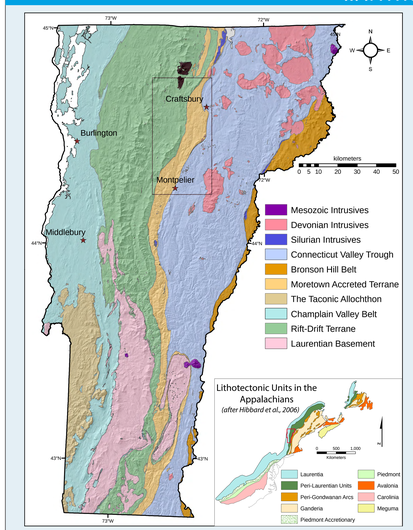
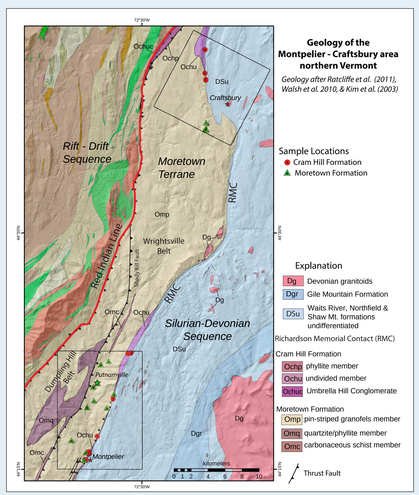
I. ABSTRACT

Meta-sandstones of the Moretown terrane in western New England contain detrital zircons that reveal an affinity with the Gondwanan (eastern) rather than the Laurentian (western) side of the Cambrian-Ordovician Iapetus Ocean. In the Vermont Appalachians, metamorphosed mafic rocks, in the form of dikes and sills, cut this Moretown terrane. The meta-mafic rocks have geochemical characteristics similar to modern-day supra-subduction volcanics. Geochemistry suggests that the meta-mafic rocks geochemically were formed as mostly basalts or basaltic andesites. They have moderate TiO_2 contents (1- 2.5 wt %), are slightly enriched in the light-rare earth elements relative to the heavy rare earths, and have negative Nb-Ta anomalies in MORB-normalized extended rare earth element diagrams. ε_{Nd} values for two samples are +3 and +5. The chemistry, taken together, suggests protoliths of the meta-mafic rocks may have formed in an extensional marginal basin(s), perhaps near a volcanic arc(s). The meta-mafic rocks of this study are similar in chemistry to the pre-Silurian Mount Norris Intrusive Suite (MNIS) of north-central Vermont, and also to the Silurian-aged Comerford Intrusive Suite (CIS) of northeastern Vermont. If the meta-mafic rocks of the Moretown are correlated with the MNIS, then the supra-subduction extensional environment could have formed in response to lithospheric delamination, following collision of the Gondwanan Moretown terrane with either a Laurentian microcontinent or Laurentia itself in the Ordovician. If , on the other hand, they are correlated with the CIS, then the extensional environment may have formed by lithospheric delamination following collision of a Ganderia fragment with Laurentia in the Silurian. In either case, it is likely that the magmatism occurred after the peri-Gondwanan Moretown terrane became part of the Laurentian plate.

II. INTRODUCTION



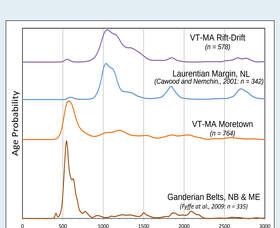
Generalized geologic map of Vermont (adapted from Ratcliffe et al., 2011). The Moretown Terrane includes the Moretown and Cram Hill Formations, which are the focus of this poster.



Detailed map of the study area, showing sample locations of mafic rocks collected from the Montpelier Quadrangle and Craftsbury Township. Thick red line represents the postulated Red Indian Line in Vermont, as suggested by Ryan-Davis et al. (2013) and Macdonald et al., (2014).

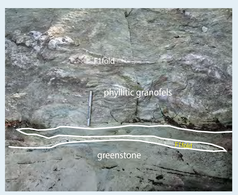
The western Vermont Appalachians expose rocks of the Proterozoic Laurentian basement, a Neoproterozoic rift and drift sequence, and Early Paleozoic passive margin sediments in the Champlain Valley and Taconic sequences. In central and eastern Vermont, terranes accreted to the Laurentian margin are exposed. The Moretown Terrane comprises the Moretown and Cram Hill formations. The Moretown Formation comprises mostly schist, granofels (quartzite), and greenstone (Walsh et al., 2010). The Cram HIll Formation consists mostly of phyllite and greenstone. Detrital zircons extracted from quartz-rich units of the Moretown by Ryan-Davis (2012) yielded age distributions that indicate their provenance is peri-Gondwanan (Ganderian) rather than Laurentian, as had previously been assumed. Furthermore, the maximum age, based on the youngest zircons, is 514 Ma (Macdonald et al., 2014). The Shelburne Falls arc was established on this peri-Gondwanan Moretown Terrane perhaps as early as 500 Ma but with a locus of magmatic activity at ~475 Ma (Macdonald et al., 2014). By 460 - 470 Ma, the Shelburne Falls arc had collided with Laurentian and basins associated with it may have been receiving detritus from Laurentia as well as peri-Gondwanan terranes.

Mafic rocks (greenstones) of uncertain age occur in both the Moretown and Cram Hill formations as dikes and possibly sills or flows. Here, we use geochemistry to show that the mafic rocks formed in supra-subduction regions, perhaps in response to two lithospheric delamination events in the tectonic history of the Vermont Appalachians.



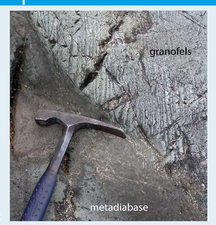
Detrital zircon data for the Moretown Formation metasedimentary rocks (Ryan-Davis, 2012; Ryan-Davis et al., 2012; Coish et al., 2013; Macdonald et al., 2014). Peaks at 600 - 800 Ma clearly indicate provenance of the Moretown is Gondwanan rather than Laurentian.

III. Field Relationships

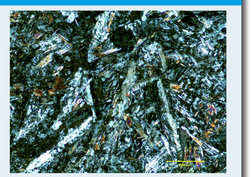


Folded greenstone near Craftsbury, Vermont

Concordant contact of greenstone with phyllite in Hubbard Park, Montpelier



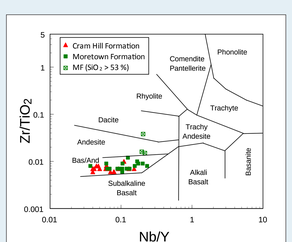
Mafic dike cutting the dominant foliation (S_2) at Putnamville, Vermont



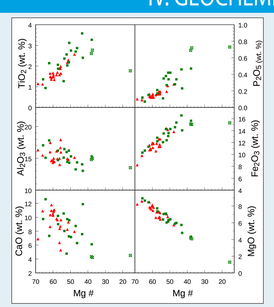
Thin section illustrating rarely preserved igneous texture in greenschist mineralogy: albite, chlorite, epidote, actinolite and titanite.

A few metamafic rocks are clearly folded by F_1 generation folds; others cut across S_2 foliations and exhibit chilled margins; many contacts simply parallel foliations without showing diagnostic relationships. So in the absence of radiometric age dates, we conclude that there are at least two generations of mafic rocks. Some are clearly dikes whereas others could have been sills, flows or dikes. All samples are metamorphosed to greenschist facies. Igneous texture is preserved in a few samples only.

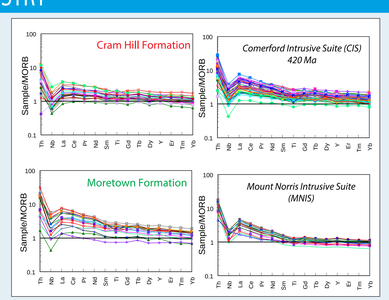
IV. GEOCHEMISTRY



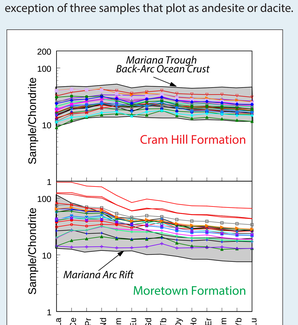
Classification of mafic rocks as mostly basalts with the exception of three samples that plot as andesite or dacite.



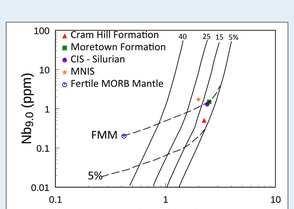
Oxide variations with Mg number are consistent with fractionation of olivine, pyroxene & plagioclase.



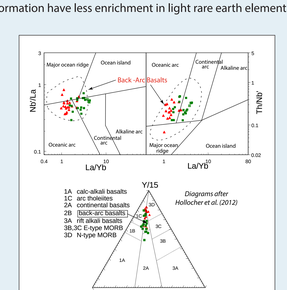
Extended element plots. All suites show negative Nb anomalies, characterisitc of subduction-influenced mantle. Mafic rocks of Moretown are similar to the Ordovician MNIS and Silurian CIS mafic rocks. Mafic rocks from the Cram Hill Formation have less enrichment in light rare earth elements.



Rare earth element patterns are similar to those from basalts formed during arc and back-arc rifting in the western Pacific.



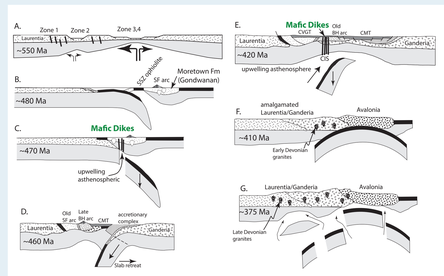
Calculated Nb and Yb values for primitive magmas (at 9% MgO) show that the Moretown mafic rocks formed by ~10% partial melting of fertile MORB mantle (Pearce & Parkinson, 1993) whereas Cram Hill magmas may have formed from a slightly more depleted MORB mantle. Initial ε_{Nd} values of +3 to +5 are consistent with this interpretation.



Trace element contents in mafic rocks from Moretown and Cram Hill formations are consistent with formation in extensional environments near subduction zones.

The geochemistry of mafic rocks from the Moretown and Cram Hill formations indicates their origin from depleted mantle in a supra-subduction zone environment. Chemical differences between the two formations may be explained by derivation from slightly different mantle sources. The chemistry of the mafic rocks from the Moretown especially is similar to mafic rocks from the Ordovician Mount Norris Intrusive Suite and the Silurian Comerford Intrusive Suite.

V. TECTONIC IMPLICATIONS



A sequence of sketches showing the tectonic evolution of the New England Appalachians from Coish (2010), modified after van Staal et al. (2007), Karabinos et al. (1998), and Moench and Aleinikoff (2002).

Mafic rocks of this study may have formed at two different times: 1) during the mid-Ordovician as a result of lithospheric delamination following collision of the Shelburne Falls arc with Laurentia, and 2) during the Silurian following collision of greater Ganderia with amalgamated Laurentia.

VI. CONCLUSIONS

1. Metamorphosed mafic rocks in the Cram Hill and Moretown formations of north-central Vermont formed as dikes (and probably lava flows) in Early Ordovician to Silurian times.
2. Their geochemistry suggests they were mostly tholeiitic basalt or basaltic-andesite.
3. Rare earth element patterns and negative Nb anomalies (relative to Th and La) are consistent with derivation of primitive magmas in suprasubduction zone extensional environments.
4. The suites may have been derived by ~10 to 15% partial melting of fertile MORB mantle that had been variably enriched in selected elements mobilized from a subducting plate. The mantle source for the Cram Hill suite was less enriched than the source for the Moretown suite.
5. The magmas of the Cram Hill and some of the Moretown meta-mafic rocks may have formed after collision of the Shelburne Falls arc with Laurentia in the Middle Ordovician, perhaps as melts associated with slab break-off of an easterly-directed subducting plate, as postulated for the Mount Norris Intrusive Suite (Kim and others, 2003). Other meta-mafic rocks from the Moretown may have formed from delamination in the Late Silurian, by analogy with the Comerford Intrusive Complex (Rankin and others, 2007). Unfortunately, the chemistry of the mafic rocks cannot be used to distinguish different magmatic ages.

VII. REFERENCES

Cawood, P. A., and Nemchin, A. A., 2001, Paleogeographic development of the east Laurentian margin: Constraints from U-Pb dating of detrital zircons in the Newfoundland Appalachians: Geological Society of America Bulletin, v. 113, p. 1234-1246.

Coish, R., Ryan-Davis, J., Amidon, W., Kim, J., and Dietsch, C., 2013, Origin of an Early Paleozoic arc-related sedimentary basin in the northern Vermont Appalachians: a detrital zircon study, AGU Fall Meeting Abstracts, p. 2404.

Coish, R. A., 2010, Magmatism in the Vermont Appalachians, in Tollo, R., Bartholomew, M. J., Hibbard, J. P., and Karabinos, P., editors, From Rodinia to Pangea: The Lithotectonic Record of the Appalachian Region, Geological Society of America Memoir 206, p. 91-110.

Fyffe, L. R., Barr, S. M., Johnson, S. C., McLeod, M. J., McNicoll, V. J., Valverde-Vaquero, P., van Staal, C. R., and White, C. E., 2009, Detrital zircon ages from Neoproterozoic and Early Paleozoic conglomerate and sandstone units of New Brunswick and coastal Maine: implications for the tectonic evolution of Ganderia: Atlantic Geology, v. 45, p. Pages 110-144.

Hibbard, J. P., van Staal, C. R., Rankin, D. W., and Williams, H., 2006, Lithotectonic map of the Appalachian Orogen: Geological Survey of Canada Map 2096A, scale 1:1,500,000.

Hollocher, K., Robinson, P., Walsh, E., and Roberts, D., 2012, Geochemistry of amphibolite-facies volcanics and gabbros of the Støren Nappe in extensions west and southwest of Trondheim, western gneiss region, Norway: A key to correlations and paleotectonic settings: American Journal of Science, v. 312, p. 357-416.

Karabinos, P., Samson, S. D., Hepburn, J. C., and Stoll, H. M., 1998, Taconian orogeny in the New England Appalachians: Collision between Laurentia and the Shelburne Falls arc: Geology, v. 26, p. 215-218.

Kim, J., Coish, R., Evans, M., and Dick, G., 2003, Supra-subduction zone extensional magmatism in Vermont and adjacent Quebec; implications for early Paleozoic Appalachian tectonics: Geological Society of America Bulletin, v. 115, p. 1552-1569.

Kim, J., Gale, M., King, S. M., Orsi, C. M., and Pascale, L., 2003, Bedrock Geology of the Montpelier Quadrangle: Vermont Geological Survey Open File Map VG03-1, scale 1:24,000.

Macdonald, F. A., Ryan-Davis, J., Coish, R. A., Crowley, J. L., and Karabinos, P., 2014, A newly identified Gondwanan terrane in the northern Appalachian Mountains: Implications for the Taconic orogeny and closure of the Iapetus Ocean: Geology, v. 42, p. 539-542.

Moench, R. H., and Aleinikoff, J. N., 2002, Stratigraphy, geochronology, and accretionary terrane settings of two Bronson Hill arc sequences, northern New England: Physics and Chemistry of the Earth, v. 27, p. 47-95.

Rankin, D. W., Coish, R. A., Tucker, R. D., Peng, Z. X., Wilson, S. A., and Rouff, A. A., 2007, Silurian extension in the upper Connecticut Valley, United States and the origin of middle Paleozoic basins in the Quebec Embayment: American Journal of Science, v. 307, p. 216-264.

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

Ryan-Davis, J., 2013, Origins of the Moretown Formation, northern Vermont: A detrital zircon study: B.A. thesis, Middlebury College, 74 p.

Ryan-Davis, J., Coish, R., and Amidon, W. H., 2013, Origins of the Moretown Formation, Vermont: a detrital zircon study: Geological Society of America Abstracts with Programs, v. 45, no. 1, p. 95.

Twelker, E., 2004, Geochemistry and field relations of greenstones in the Moretown and Cram Hill Formations, Montpelier Quadrangle, Vermont: B.A., Middlebury College, 66 p.

van Staal, C. R., Whalen, J. B., McNicoll, V. J., Pehrsson, S., Lissenberg, C. J., Zagorevski, A., van Breemen, O., and Jenner, G. A., 2007, The Notre Dame arc and the Taconic orogeny in Newfoundland, in Hatcher Jr., R. D., Carlson, M. P., McBride, J. H., and Martínez Catalán, J. R., editors, 4-D Framework of Continental Crust, Geological Society of America Memoir 200, p. 511-552.

Walsh, G. J., Kim, J., Gale, M. H., and King, S. M., 2010, Bedrock geologic map of the Montpelier and Barre West quadrangles, Washington and Orange Counties, Vermont: U.S. Geological Survey Scientific Investigations Map 3111, scale 1:24,000.

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