Orientation, Spatial Distribution, and Chemical Composition of Paleozoic Diabase Dikes on Swans Island and Neighboring Islands, Penobscot Bay, Maine

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Introduction

The central Maine coast is underlain by the accreted Avalon terrane which is composed of over 100 granitic and gabbroic plutons that range in age from Silurian to Carboniferous; this region is commonly referred to as the Coastal Maine Magmatic Province (CMMP) (Hogan and Sinha, 1989). Early tectonic models explained the magmatism in the CMMP as being a result of subduction during the accretion of Avalonia to North America during the Acadian Orogeny (Dewey & Kidd, 1974).

In the vicinity of Swans Island in central Penobscot Bay (Fig 1.), late Silurian magmatism was bimodal, with excellent field evidence for the commingling and limited mixing of gabbroic and granitic magmas (Fig. 3b). Melone et al. (2016) determined that the Swans Island complex is composed of two distinct plutons, one Silurian and one Devonian. Diabase dikes have only been observed cutting the Silurian pluton (Fig. 2).

This study is the first to systematically examine the orientations and chemical compositions of the diabase dikes intruding the Avalon Terrane of the central Maine coast in order to better understand the stress regime that existed, and the compositions of mafic magmas that were generated, during this episode of bimodal magmatism.

Geologic Map of Coastal Maine

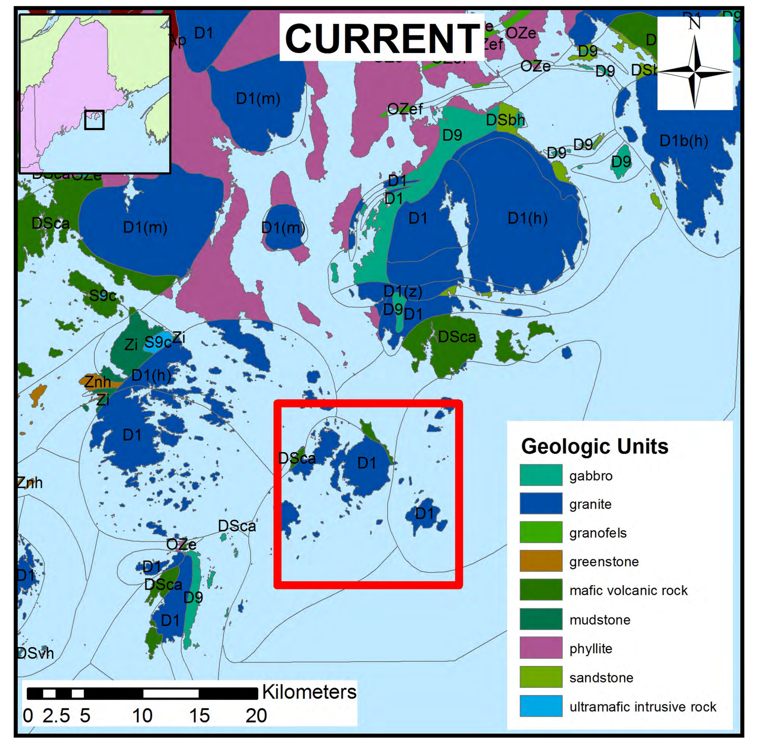

Figure 1: Geologic map of coastal Maine as mapped by the Maine Office of GIS and the USGS.

Updated Geologic Map of Swans Island

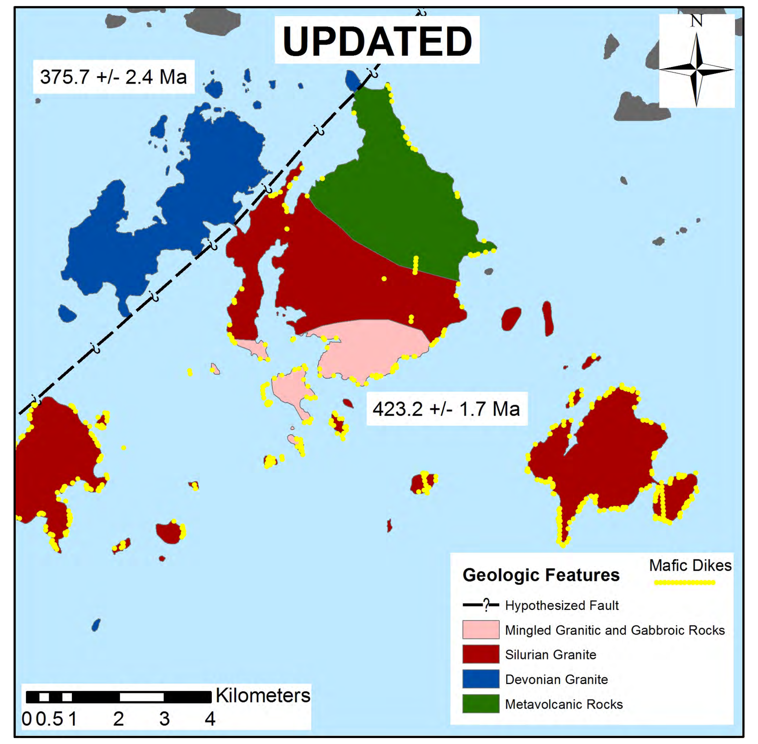

Figure 2: Updated geologic map of Swans Island and surrounding islands as prepared by Melone et al. (2016). Diabase dikes are only present in the Silurian Pluton.

Methods

This study compiles and analyzes dike and fracture orientation data, and whole-rock XRF chemical data, obtained from previous student research projects at Hamilton College. Because the chemical data were collected over a period of more than 20 years, and from different labs, a subset of 33 samples are currently being re-analyzed on a state-of-the-art Thermo X-ray Fluorescence system to evaluate the accuracy and overall quality of the compiled data set.

To supplement the existing XRF data, we examined thin sections of the diabase dikes in order to look for patterns and correlations between dike chemistry and petrography.

We then looked for patterns in the spatial distribution of each compositional group in order to better understand the sequence of magmatic events in the Coastal Maine Magmatic Province.

Figure 3a: Mafic Dikes in the Silurian Pluton. Most are 1-2 m in width.

Figure 3b: Magma mingling and limited mixing on the southeastern portion of Swans Island. This is evidence of contemporaneous formation and interaction of mafic and silicic magmas during the Silurian.

Previous Studies

Early studies suggested that the dikes were oriented parallel to the dominant joints in the host granites (Bursaw, 1989).

Millar (2008) made strike and dip measurements on ~150 dikes in the field, and Gregory (2014) determined the trend of over 500 dikes using satellite and aerial imagery. These data sets revealed that the dikes are strongly preferentially oriented, with strikes essentially due north-south, and with near vertical dips (Fig 4).

Gregory (2014) also measured the orientations of fractures in both the Silurian and Devonian plutons. From these measurements, there appear to be two major sub-vertical, nearly orthogonal, joint sets in both of the plutons (one at ~N25E and the other ~N75W) (Fig 5).

Because both plutons exhibit the same orientations of fractures, Gregory (2014) concluded that these fractures developed post-Devonian, most likely during Mesozoic uplift and unroofing. And because these fracture orientations do not align with the dike orientations, we conclude that they are not associated with the intrusion of the dikes. The fractures are younger and indicate a different regional stress regime than the one that prevailed during intrusion of the diabase dikes.

Dike Orientations

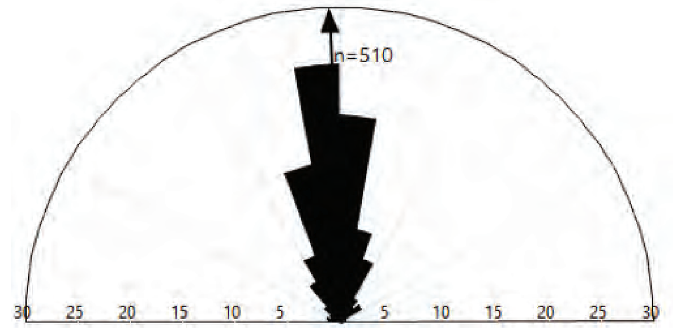

Figure 4. Orientation of diabase dikes in the Silurian pluton.

Granite Fracture Orientations

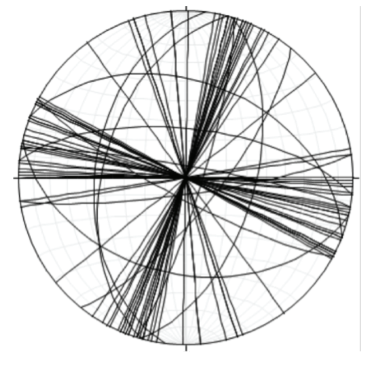

Figure 5a. Field data of fracture orientations in the Devonian Pluton (n=69).

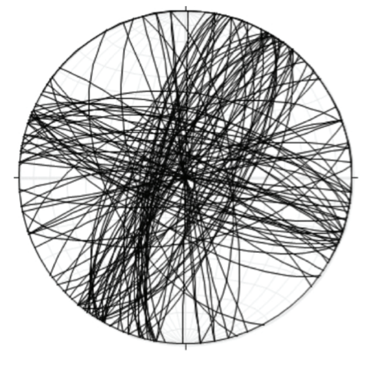

Figure 5b. Field data of fracture orientations in the Silurian Pluton (n=126).

Petrography

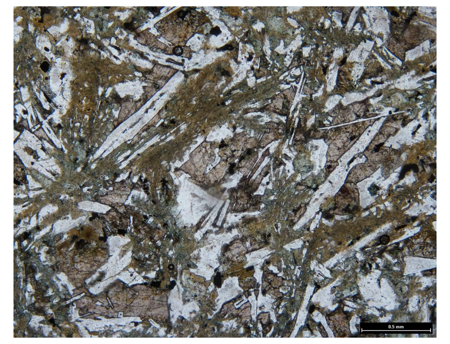

Figure 6. Aphyric fine-grained diabase with a plagioclase, clinopyroxene, hornblende and Ti-Mt groundmass (SI-KK-2).

Thin section analysis reveals that the majority of the dikes are aphyric, with a plagioclase, hornblende, clinopyroxene, and Fe-Ti oxide-rich groundmass (Fig. 6). Phenocrysts of plagioclase and olivine are present in some samples, although all olivine has been altered (Fig. 7,9). Virtually all of the dikes exhibit the effects of alteration / metamorphism; most of the feldspar is sericitized, and most groundmass clinopyroxene has been overgrown and/or replaced by brown-green to blue-green amphibole.

This alteration must be considered when analyzing the whole-rock chemical data, as the initial rock compositions were very likely modified.

Several dikes also show clear evidence of contamination in the form of rounded and embayed quartz (and less commonly K-Feldspar) xenocrysts that were picked up from intrusion into the granite pluton (Fig. 8,9).

Figure 7. Medium-grained diabase dike composed predominantly of plagioclase and green-brown hornblende. Minor clinopyroxene is present (LI-MM-34).

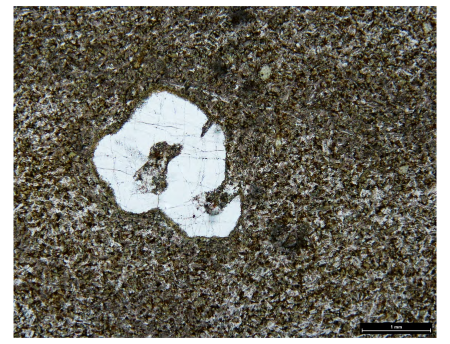

Figure 8. An rounded and embayed quartz xenocryst showing contamination of the diabase with granitic material (MM07-22).

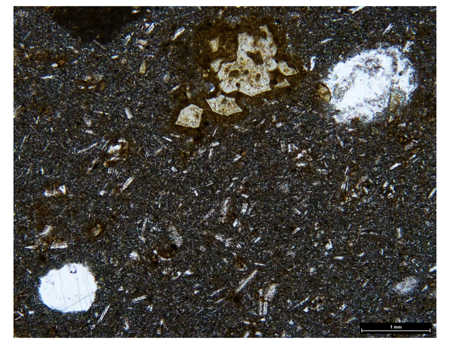

Figure 9. Plagioclase and olivine (altered) phenocrysts in a fine-grained diabase with quartz xenocrysts (MM07-32).

Discussion

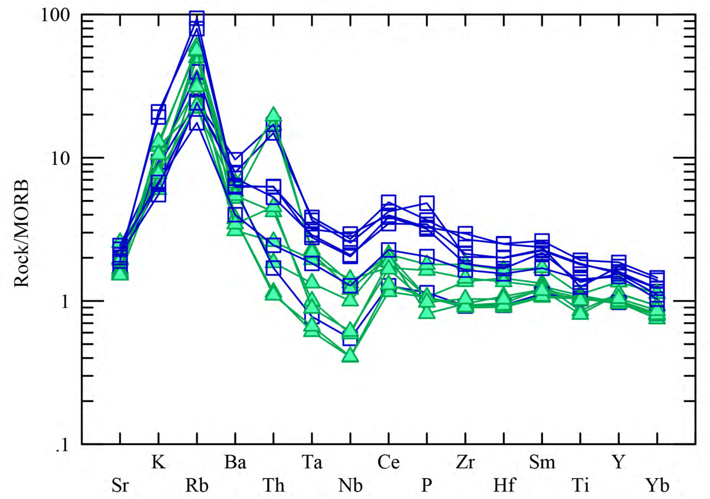

Figure 15. MORB-normalized trace element abundances of the two major groups of diabase dikes. Normalized factors from Pearce (1983).

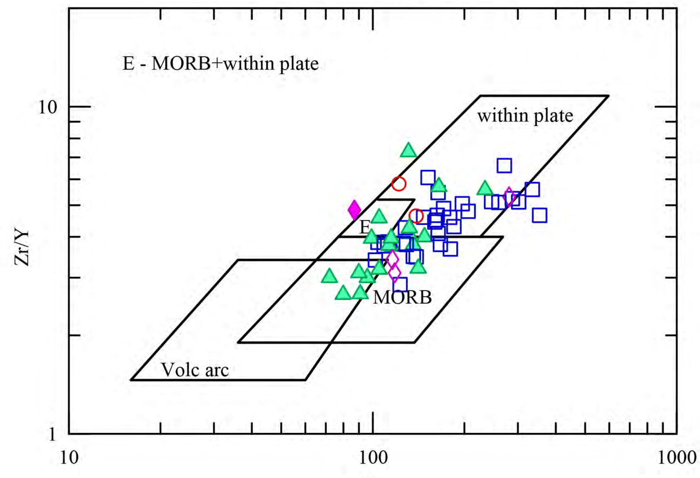

Figure 16. Zr/Y versus Zr diagram shows that the diabase dikes on Swans Island do not resemble those of a typical volcanic arc. Diagram of Pearce and Norry (1979).

The majority of the Paleozoic diabase dikes on Swans Island have tholeiitic compositions that can be found in a wide range of tectonic environments. Their MORB-normalized trace element profiles (Fig. 15) at first glance look a bit like the patterns observed in subduction related tholeiites: they are relatively enriched in the large ion lithophile (LIL) elements, and exhibit a slight Ta-Nb trough. The apparent enrichment in the LIL elements is, however, most likely the result of both contamination by the granitic pluton during emplacement, and by post-crystallization metamorphism / metasomatism. The REE and high field strength (HFS) trace elements, on the other hand, seem to preserve the signature of the original magma, with relatively flat profiles. Plots of HFS element ratios (e.g. Zr/Y vs. Zr; Fig. 16) suggest that the dike magmas more closely resemble those typically associated with mid-ocean ridges or within-plate volcanic activity rather than a subduction zone.

The two major sub-groups of dikes have very similar trace element patterns (Fig. 12), and appear to be genetically related, with the high Fe-Ti dikes being derived by fractional crystallization from the low Fe-Ti magma, coupled with minor to moderate degrees of assimilation /contamination by the associated Silurian granite.

Before any detailed petrogenetic models can be constructed, or any firm conclusions as to the tectonic setting of the Avalon terrane during the Silurian can be made, additional data are required. The geochemical data presented here were collected over the course of more than 20 years, using different analytical methods in different labs; as a result, there is considerable uncertainty as to the overall quality of the compiled data. In the coming weeks we hope to rerun most of these samples using Hamilton College's new state-of-the-art XRF instrument. This will decrease uncertainty in this data set and allow us to more accurately determine the nature and origin of these diabase dikes. In addition, whole-rock isotope ratios on the least altered samples will be performed to provide additional insight into the magma source(s) for these dikes.

Whole-Rock Geochemistry

TiO_2 vs FeO*

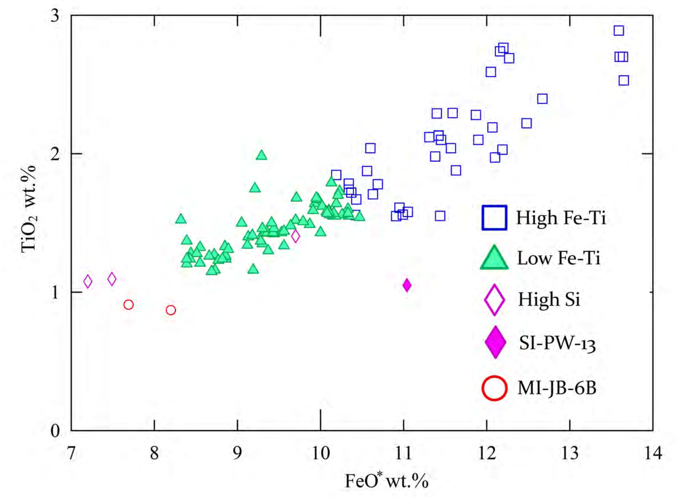

Figure 10. Groupings of dikes as defined by abundance of TiO_2 and FeO* (by weight%).

Petrographic analysis revealed that all of the dikes experienced low-grade metamorphism and are now composed almost entirely of amphibole, plagioclase feldspar, and Fe-Ti oxides; fresh groundmass clinopyroxene is uncommon. Whole-rock geochemical data indicate that, despite the metamorphism, two major varieties of mafic magma were generated during this magmatic event: a high Fe-Ti and low Fe-Ti tholeiite (Fig 10).

Not surprisingly, the majority of the diabase dikes are basaltic in composition (Fig. 11). Those with higher silica contents have more andesitic compositions, and many of the high Fe and Ti dikes also have fairly high alkali contents and plot in the trachybasalt and trachyandesite fields (Fig. 11). The majority of dikes have tholeiitic compositions, while a few are more alkaline (Fig. 14).

While for the most part the dikes exhibit similar compositions, there appears to be two major groups of dikes. The dominant group is a low Fe and Ti tholeiite that has overall very low concentrations of the incompatible elements and very flat REE profiles (Fig. 12, 13). The second group contains higher concentrations of Fe and Ti and is relatively enriched in incompatible trace elements, likely due in large part to fractional crystallization. A third, smaller group of dikes is characterized by unusually high concentrations of silica (~53 wt.%)(Fig 11). In thin section, these dikes all contain quartz xenocrysts that are likely a result of contamination from intrusion into the surrounding granite (Fig. 8,9). In addition, there are two anomalous dikes that are placed into their own compositional groups. One dike has unusually low concentrations of Fe and Ti and has an unusually steep rare earth profile (Fig. 13). This dike is located on the eastern coast of Marshall Island and has a north-south orientation. The other dike has a very low Al content, has the highest abundances of the REE and all incompatible elements, and shows a distinct europium anomaly (Fig. 13).

TAS Classification

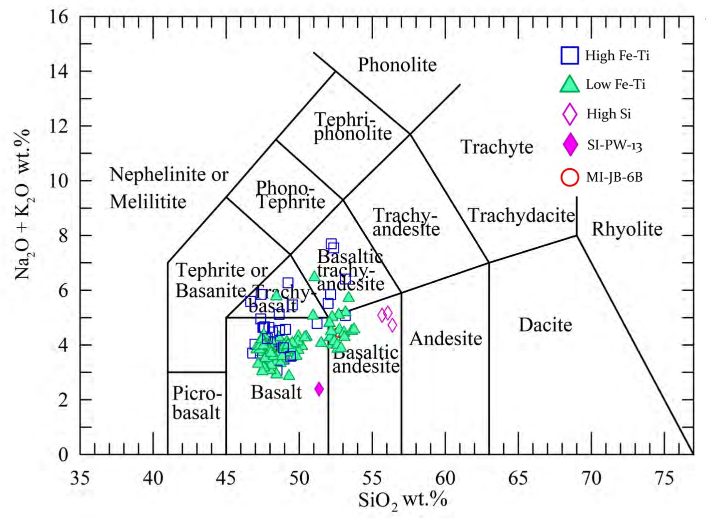

Figure 11. TAS classification showing name of each rock sample. Most dikes are basaltic in composition.

Rare Earth Elements

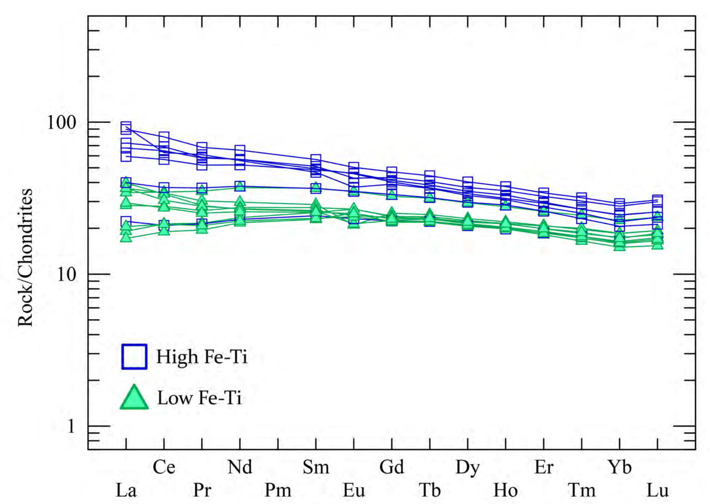

Figure 12. REE profiles of the two major groups of dikes.

Rare Earth Elements

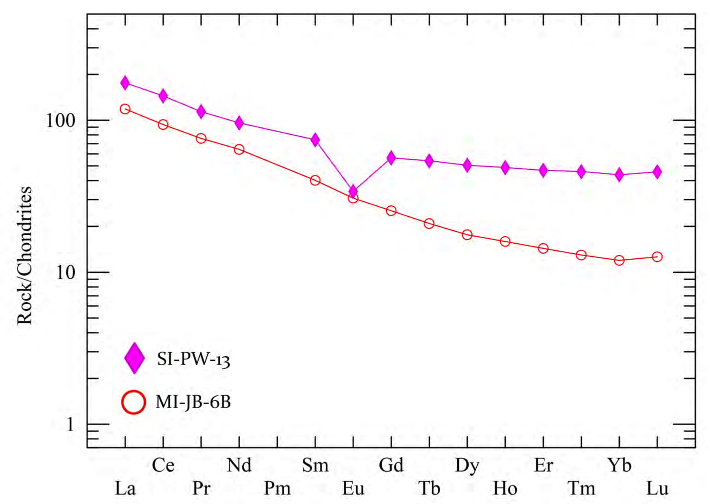

Figure 13. REE profiles of the two anomalous dikes.

Alkali and Tholeiite Basalts

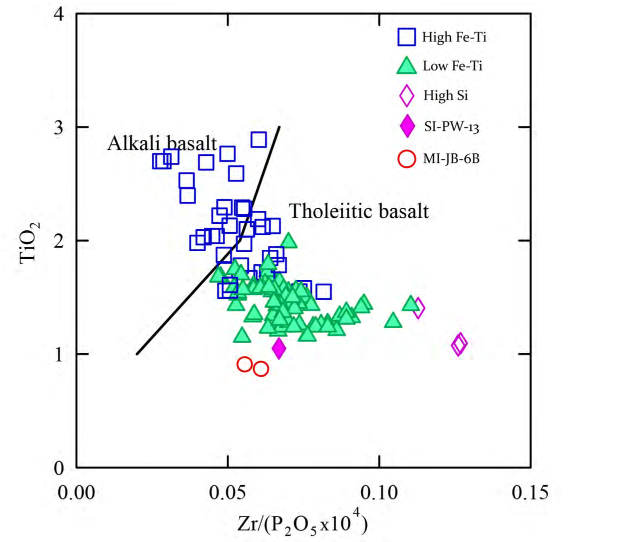

Figure 14. Classification of diabase dikes based on Ti vs Zr/P diagram of Pearce and Winchester (1976).

Summary

- The diabase dikes are only found in the Silurian pluton and are, therefore, pre-Devonian in age. In addition, the fact that diabase magma is seen mingling and mixing with the Silurian granite indicates that most of the dikes intruded contemporaneously with the emplacement of the granitic pluton (~424 Ma).
- The dikes have a strong north-south preferred orientation, indicating a strong regional stress field at the time of intrusion.
- Two major sets of fractures with similar orientations are seen in both plutons; neither set is oriented north-south. The fractures must be post-Devonian and developed in a weaker, and shifting regional stress regime.
- The majority of the diabase dikes are aphyric, fine-grained tholeiites.
- The rare earth element concentrations in most of the diabase dikes are uniform and relatively flat, with moderate enrichment seem in the high Fe-Ti tholeiites, likely due to fractional crystallization.
- The diabase dikes have the chemical signature of extension related tholeiites. This feature, along with the bimodal nature of magmatism in the CMMP, strongly favors formation of the Avalon terrane in an extensional tectonic environment, and not in a classic subduction zone environment as originally thought.

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Acknowledgements

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