
INTERMEDIATE VOLCANICS IN A BIMODAL SETTING: SILURIAN ANDESITES OF THE FOX ISLANDS, ME

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INTRODUCTION

Within the Fox Islands in southern Penobscot Bay, the Early (?) Silurian Thorofare Andesite forms a ~750-meter-thick pile of gray to reddish-brown andesite to dacite lava flows and breccias, representing the only thick package of intermediate volcanic rocks in all of coastal Maine. To date, the most thorough and accurate description of the Thorofare Andesite appears in the explanation of Gates' (2001) map of the Fox Islands. In the final sentence of the map's explanation, however, Gates remarks that "the petrogenic and structural place of the Thorofare Andesite and its associated structural blocks in the coastal volcanic belt remains to be solved." Consequently, this study attempts to better characterize the field relations, petrography, and geochemistry of this unit and, to a lesser degree, the volcanic rocks of the Polly Cove Formation found stratigraphically just beneath the Thorofare unit.

Field studies and petrographic analysis of the flows and breccias of the Thorofare Andesite were undertaken to improve understanding of the eruptive style of these volcanics and to provide insight into their environment of deposition. A close examination of the breccias, in particular, coupled with geochemical data, provides opportunities for regional correlation. In addition, the geochemical data help to determine the tectonic setting and petrogenesis of this intermediate volcanic unit.

Field Investigations

Field work primarily in the northern part of Vinalhaven Island on Calderwood Point and stratigraphic studies from Birch Point to Zeke Point reveal that the Thorofare Andesite is a complex volcanic pile composed of massive to vesicular or amygdular andesite and a variety of fragmental rocks-- mostly laharic breccias, but also autobreccias, bedded tuff breccias, and rare airfall tuffs. Although the unit as a whole is continuous, individual lithologies are discontinuous, and tuffs and tuff breccias often occur as lenses where topographic lows once existed. In addition, a number of dikes and sills of various compositions intrude into the pile. Exotic blocks of the fossiliferous Early Silurian Ames Knob Formation occur throughout the unit, suggesting that the Thorofare Andesite initially erupted through this older formation (Gates, 2001).

In addition to the careful notes and photographs taken at all of the field sites, a total of 35 hand samples were collected on Calderwood Point and across the Thorofare Strait on the southern portion of North Haven Island. The 35 samples, chosen largely on the basis of lithology and relative freshness, include 19 massive andesites or fragments from andesite autobreccias, 8 dike rocks, 6 tuffs or tuff breccias, and a single sample each of a fossiliferous mudstone from an exotic block of the Ames Knob Formation and a silicified vitric tuff from the Polly Cove Formation.

Stratigraphic Relationships

The predominantly metasedimentary fossiliferous Ames Knob Formation and its stratigraphic and structural equivalent, the Polly Cove Formation (Gates, 2001), lie beneath the Thorofare Andesite (Fig. 1). The Polly Cove Formation is mainly composed of bedded argillites, but metavolcanics of the unit include feldspathic bedded tuffs, massive tuff breccias, and a newly interpreted highly silicified welded tuff. These rocks are significant because they represent an early episode of felsic volcanism prior to the deposition of the Thorofare Andesite. Immediately above the Thorofare Andesite lies a series of bedded tuffs and tuff breccias that compose the lower Seal Cove Formation (Szramek, this volume).



Fig. 1: Schematic stratigraphic column for North Haven and Vinalhaven, modified from Newton (1999).

The Thorofare Andesite and the underlying Polly Cove Formation occupy the lowest stratigraphic position in a thick package of mafic to felsic metavolcanic rocks and metasedimentary rocks that was intruded by the Vinalhaven Plutonic Complex. The granite of the Vinalhaven pluton has recently yielded a preliminary date of 420 \pm 1 Ma, or Late Silurian (Hawkins, pers. comm.). This new date, in conjunction with the Silurian

(Llandovery to Pridoli) ages of fossils in the Ames Knob Formation beneath the volcanic section, means that all of the volcanic and sedimentary units of this succession must have been deposited entirely within the Silurian Period, though all previous workers, including Gates (2001), had called them Siluro-Devonian and even Devonian. Possible future dating of the vitric tuff in the Polly Cove Formation may help to constrain more precisely the age of the volcanic pile.

Petrography

In general, the massive andesite flow rocks of the Thorofare Andesite are homogenous, porphyritic, and weakly metamorphosed to lower greenschist facies. In some of the lithologies phenocrysts are large enough to be seen in hand specimen, while in others the texture becomes apparent only in thin section. Set in a dense, fine-grained, pilotaxitic groundmass, the phenocrysts are predominantly euhedral oligoclase-labradorite plagioclase crystals (Gates, 2001), some of which show oscillatory zoning, and clinopyroxene. Widespread chloritization of ferromagnesian minerals, saussuritization of plagioclase crystals, and occasional infilling of vesicles with chlorite or calcite indicate that all of the samples have been altered to some degree. A number of samples show evidence of a flow fabric or even rare flow banding, and some samples, particularly near the base of the unit, are characterized by irregular amygdules of quartz, chlorite, calcite, or some combination thereof.

The majority of the Thorofare breccias are matrix-supported, and the commonly silicified matrix varies in composition from mudstone (laharic breccias) to andesite (autobreccias) to felsic ash (tuffs and tuff breccias). The clasts in the laharic breccias and the tuff breccias represent a wide range of lithologies including andesite, quartz, mudstone, and felsic volcanic fragments such as tuff, pumice fragments, and spherulitic rhyolite. The highly silicified welded tuff of the underlying Polly Cove Formation contains relict, devitrified glass shards and pumice fragments and pieces of flow-banded rhyolite; it could represent a local source for some of the breccia fragments.

Geochemical analyses

Of the 35 samples collected, only 15 were chosen for geochemical analysis on the basis of lithology and relative freshness (a significant limiting factor for these rocks). The selected samples, which included massive andesites, dike rocks, and the Polly Cove tuff, were analyzed by X-ray fluorescence (XRF) at Franklin and Marshall College, PA, for major and minor elements and selected trace elements. All of the samples were then sent to XRAL laboratories in Ontario for Instrumental Neutron Activation Analysis (INAA) to obtain the remainder of the desired trace element data.

In the massive andesite samples, SiO_2 content ranges from 51.4% to 65.7% and total alkalis range from 3.1% - 8.0%. Because of the age of these rocks, their low-grade metamorphism, and their degree of alteration, immobile trace elements were used whenever possible for the characterization and comparison of samples. All of the non-dike Thorofare Andesite rocks plot as andesite or dacite on a Zr/TiO_2 vs. Nb/Y classification scheme (Winchester and Floyd, 1977, Fig. 2).

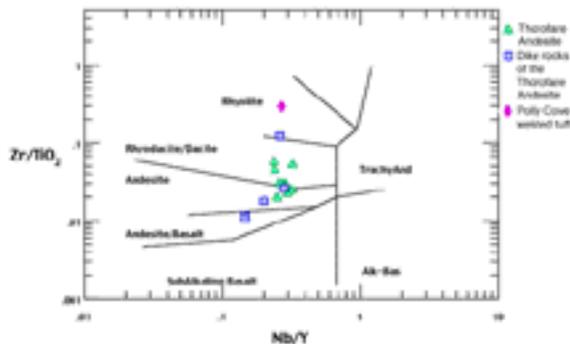


Fig. 2: Winchester and Floyd (1977) classification diagram of the Thorofare Andesite and Polly Cove welded tuff.

A Pearce-type spider diagram (Fig. 4) shows that these rocks are enriched in large-ion lithophile elements relative to MORB values. The slight spread of the data in both of these diagrams likely reflects a combination of original compositional differences within the Thorofare volcanic pile and subsequent alteration and metamorphism. On the Winchester and Floyd diagram, dike rocks that cut the Thorofare layered units plot over a wide range of compositions from basaltic andesite to andesite to rhyolite, and the Polly Cove welded tuff plots in the rhyolite field.

Tectonic setting

A tectonic discriminant diagram after Mullen (1983) (Fig. 3) shows that all but one sample of the massive Thorofare Andesite plot within the Island Arc Tholeiite (IAT) field. The trace element diagram after Pearce (1983) (Fig. 4) indicates relative enrichments in large-ion lithophile elements (LILEs) and relative depletions in some of the Ti-group elements, a pattern consistent with an island arc setting. The diagram does not show a significant tantalum depletion, but values for this element may be artificially high because a number of the samples contained Ta in concentrations which were below the detection limit (1 ppm) of the analytical method.

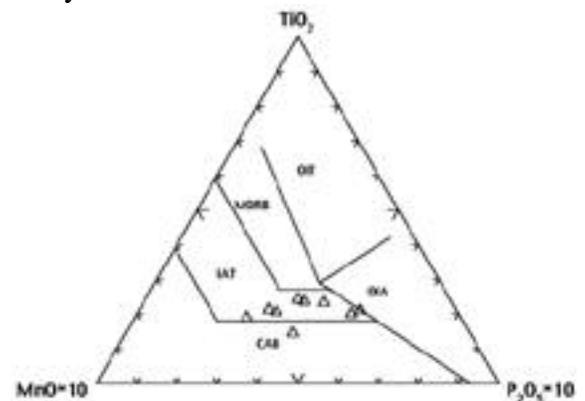


Fig. 3: Mullen (1983) tectonic discriminant diagram of the massive flow rocks of the Thorofare Andesite.

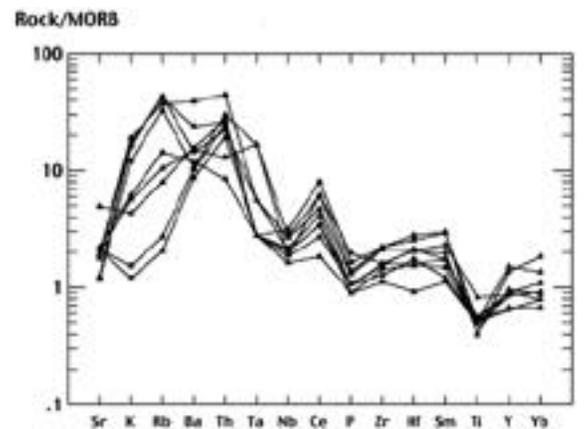


Fig. 4: Pearce (1983) spider diagram for the Thorofare Andesite using trace elements.

In an AFM diagram (not shown), data points straddle the tholeiite/calc-alkaline boundary, suggesting that the arc was moderately evolved. This is corroborated by the fairly pronounced negative europium anomaly in the Nakamura (1974) spider diagram of rare earth elements (Fig. 5), suggesting a degree of plagioclase

fractionation prior to crystallization of the Thorofare flows.

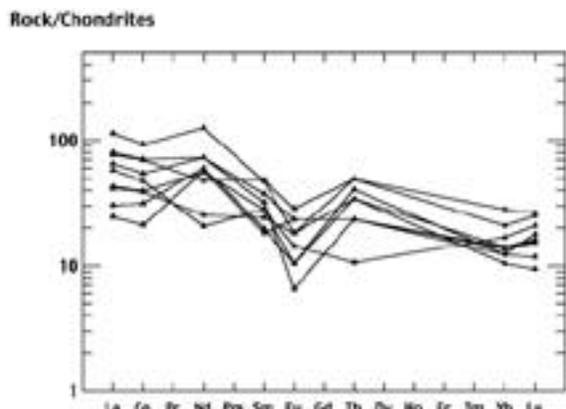


Fig. 5: Nakamura (1974) spider diagram for the Thorofare Andesite using REEs.

DISCUSSION/CONCLUSIONS

Field and petrographic study of the Thorofare Andesite support Gates' (2001) conclusion that the unit built a partly subaerial, partly marine volcanic pile in the Ames Knob-Polly Cove shallow sea. As discussed by Gates (2001), evidence for the eruption of the intermediate lavas into water includes the extensive brecciation due to rapid chilling seen particularly in the autobreccias, the widespread hydrothermal alteration and oxidation of the unit produced by the circulation of heated seawater, and the presence of exotic blocks of the Ames Knob Formation in the Thorofare Andesite.

The welded tuff of the Polly Cove Formation indicates that a period of explosive felsic volcanism occurred prior to the deposition of the Thorofare Andesite, and the tuffs of the lower Seal Cove Formation show that felsic volcanism continued after Thorofare time. These three units thus represent a significant period of volcanic activity that occurred before the onset of bimodal volcanism and plutonism represented by the Vinalhaven Diabase, the Perry Creek Formation, the Vinalhaven Rhyolite, and the Vinalhaven Plutonic Complex.

Geochemical tectonic discriminant diagrams and the recently determined date for the Vinalhaven Pluton suggest that the andesite to dacite lava flows and breccias of the Thorofare Andesite were deposited in the Early (?) Silurian Period in an island arc setting. Later

Silurian (ca. 420 Ma) bimodal plutonic and volcanic units indicate a change from an arc to a back-arc environment during the evolution of Vinalhaven. This interpretation supports Stewart et al's (1995) model of arc terrane amalgamation offboard of ancestral North America prior to the accretion of this composite landmass during the closing of the Iapetus Ocean to form coastal Maine.

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