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Geochemical Aspects of Volcanic Rocks on Islands in East Penobscot Bay, Maine

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ABSTRACT

The volcanic rocks on the Great Spruce Head-Eagle group of islands in East Penobscot Bay, Maine, belong to two different suites. The two suites are differentiated in field mapping on the basis of differences in structural style and metamorphic character and these differences are also brought out by their chemistry. These differences suggest that the two suites are unrelated to each other, have different ages, and have different tectonic affinities.

Rocks of the older suite belong to the North Haven Formation that has an ill-defined age of Ordovician or older. They are dominated by basalts and basaltic andesites with only minor amounts of felsic volcaniclastic rocks and epiclastic sedimentary rocks. Most of their major and trace element data do not distinguish unequivocally among the possible tectono-magmatic settings. The TiO_2 contents of the basalts are in the range for typical ocean-floor basalts. Negative Ta-Nb anomaly in the basalts suggests that they may be part of an immature oceanic arc.

Rocks of the younger suite belong to the Silurian-Lower Devonian Castine Formation. Most of these rocks are flows and tephra of rhyolite and dacite with subordinate pillowed basalt and basaltic andesites. The TiO_2 concentrations of the basalts are intermediate between those of typical ocean floor basalts and basalts from continental rifts. Trace element diagrams that most successfully classify the tectonic setting of the basalts suggest a within-plate origin. The large volume of felsic rocks present and the inferred continental basement for the region are compatible with an ensialic rift setting. However, the large volume of agglomerate in the Castine Formation and the existence of andesites in outlying areas may suggest that at least some of these volcanic rocks could have been formed in an Andean-type plate margin.

INTRODUCTION

The area of this study is situated in the coastal volcanic belt that extends from Massachusetts northeastward into Maine and New Brunswick (Fig. 1). A suite of Silurian and Lower Devonian volcanic and associated sedimentary rocks have spectacular development within this belt (Brookins et al., 1973; Gates, 1975; Brookins, 1976; Shride, 1976; Gates and Moench, 1981; Hon and Thirlwall, 1985). In East Penobscot Bay, Maine (Fig. 2), the Silurian-Lower Devonian volcanic rocks include the Castine Formation, the Thorofare andesite, and the Vinalhaven rhyolite (Smith et al., 1907). These formations lie above the less extensive North Haven Formation (Smith et al., 1907), which also has a volcanic character. Within the area of study, the Castine Formation contains abundant agglomerates, tuffs, rhyolite and dacite, and less abundant basalts, and the North Haven Formation contains abundant basalts and minor dacite, rhyolite, and tephra. This paper focuses on the geologic and

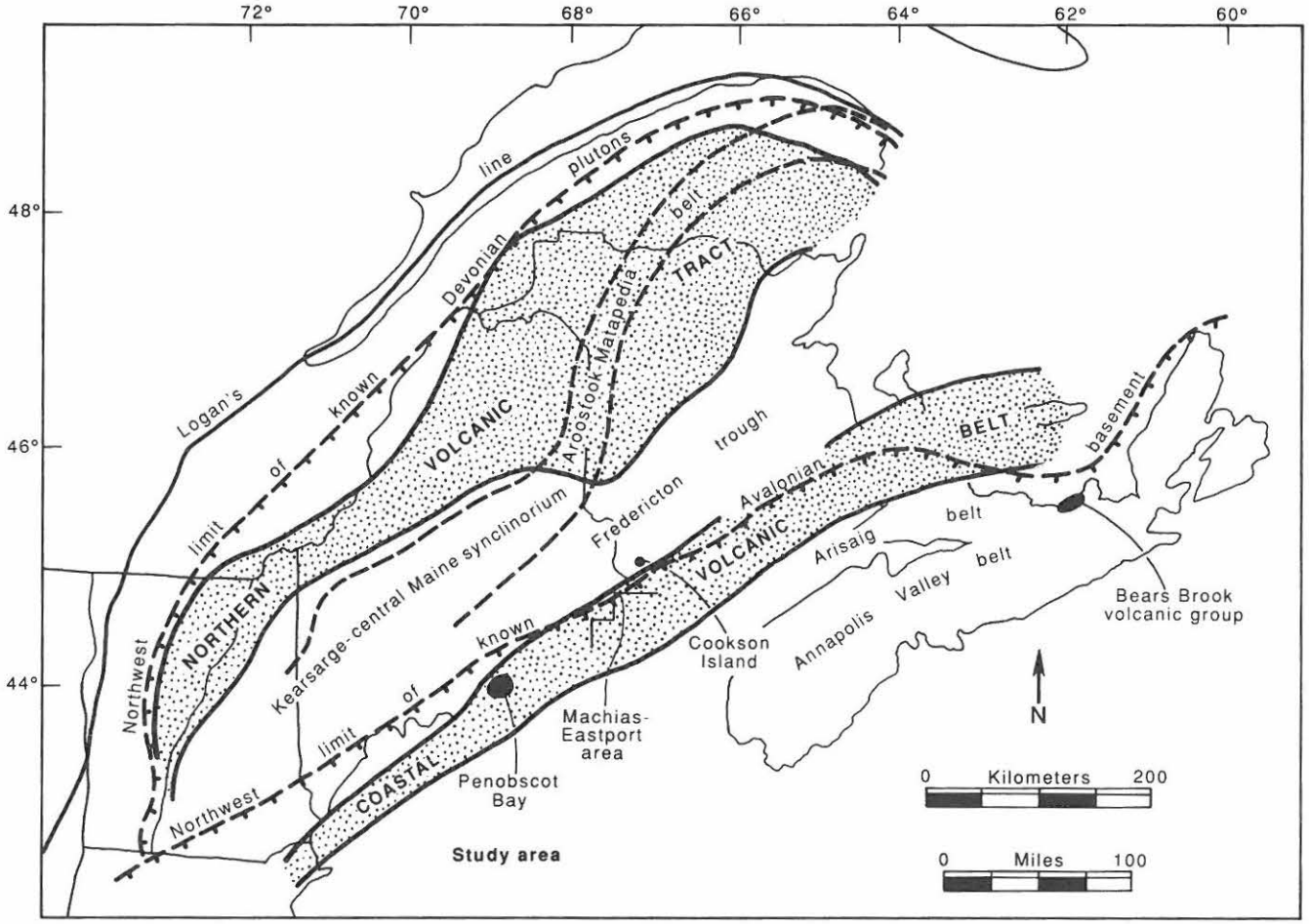


Figure 1. Map of northern New England and Maritime Provinces showing Silurian and Lower Ordovician volcanic tracts and principal paleotectonic features. Adapted from Gates and Moench (1981).

chemical nature of the Castine Formation and the underlying North Haven Formation.

Rocks of both the Castine Formation and the North Haven Formation are metamorphosed to regional and low greenschist facies, but higher grades of thermal metamorphism occur locally around the granitic plutons. Outside of contact aureoles, the Castine Formation exhibits only a single metamorphic event, whereas the North Haven Formation may be polymetamorphic. Volcanic rocks of the Castine Formation carry a metamorphic fabric which is barely perceptible to imperceptible, and they are deformed by a single, prominent fold set. In contradistinction, the volcanic rocks of the North Haven Formation display a well developed foliation and exhibit several sets of minor folds. Both volcanic suites are cut by numerous high-angle faults, and local zones of high strain develop along some of these.

The North Haven Formation is here interpreted to unconformably underlie the Castine Formation. This conclusion is predicated on: (1) the existence of an unconformity at Ames Knob on the island of North Haven, where the Thorofare andesite (equal to Castine Formation) overlies the fossiliferous Ames Knob Formation (Smith et al., 1907), and where a basal conglomerate in the Ames Knob Formation contains clasts of the underlying North Haven Formation; and, (2) on observations that the North Haven Formation is polydeformed and possibly polymetamorphic when compared to the Silurian-Lower Devonian section. The North Haven Formation has no firm age, but permissible ages range from Precambrian to Ordovician. Because of the above relationships, we believe that the North Haven Formation is an earlier volcanic suite, possibly unrelated to the Castine Formation. However, it must be noted that Bouley et al. (1981) interpreted the unconformity at Ames Knob as a local feature, and they included the rocks of both formations in the same magmatic suite.

Basement to these volcanic suites is not exposed in the area of study. Although the North Haven Formation could be a fragment of oceanic basalt, regional considerations suggest that basement with continental affinities underlies both the North Haven Formation and the Castine Formation. In southern New Brunswick, McCutcheon and Ruitenberg (1987) interpret the Silurian section, which includes volcanic rocks similar to the Castine Formation, to rest unconformably on Precambrian granite. In East Penobscot Bay, Maine, the volcanic rocks of the

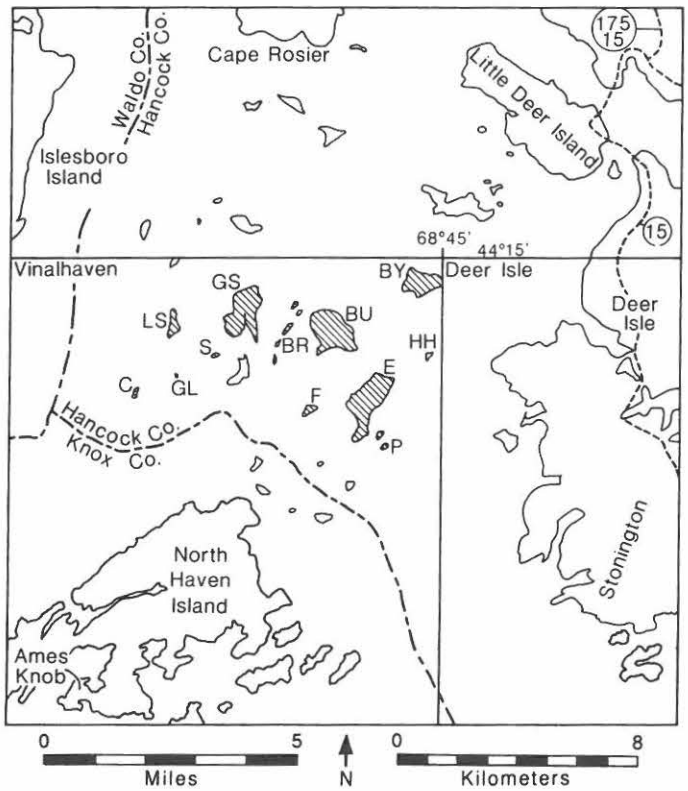


Figure 2. Location map of East Penobscot Bay, Maine. The islands included in this study are diagonally ruled and labelled as follows: Barred Islands (BR), Bradbury (BY), Butter (BU), Compass (C), Eagle (E), Fling (F), Grass Ledge (GL), Great Spruce Head (GS), Hard Head (HH), Little Spruce Head (LS), Porcupines (P), Scragg (S).

Castine and North Haven Formations contact the Islesboro sequence along steeply dipping faults (Stewart, 1974). David B. Stewart (pers. commun., 1985) has reported dikes cutting the Islesboro sequence that he believes contain rocks related to the Castine Formation. These relationships suggest that the rocks of the Castine Formation had stratigraphically overlain the Islesboro sequence before their erosion, and further suggest that the Islesboro sequence underlies the current outcrop of the Castine Formation. The Islesboro sequence contains metamorphosed volcanic rocks, schist, and marble that are cut by pegmatitic dikes dated at 600±15 Ma (Brookins, 1982). Younger sequences contain quartzite, quartzose phyllite, marble, and conglomerate. These are undated, but may have ages ranging from Late Precambrian into the Cambrian. These rocks represent a cover sequence that almost certainly has continental affinities.

The rocks of the coastal volcanic belt are thought to represent the western margin of the Avalon plate prior to the closing of an ocean basin (Osberg, 1974; see also Berry and Osberg, in press). Pridolian through Gedinnian fossils having Rhenish-Bohemian-Baltic provinciality (Johnson, 1979; Berdan, 1983) support this idea. However, there is little consensus amongst researchers regarding the nature of the suture separating Avalonia from North America.

The origin of the Silurian-Devonian volcanic rocks in the coastal belt must be considered to be equivocal, perhaps because of an insufficient data base or the presence of more than a single suite of volcanic rocks. McKerrow and Ziegler (1971), Osberg (1978), and Bradley (1983) interpreted the Silurian-Lower Devonian volcanic rocks as having been generated near a subduction plate margin. On the other hand, Ruitenberg and Ludman (1978) and Gates and Moench (1981) noted that the volcanic rocks located in the vicinity of Eastport and adjacent New Brunswick had a persistent and strongly bimodal character. On this basis, Gates and Moench (1981) suggest that these rocks are more characteristic of continental-rift volcanic rocks than they are of subduction-generated volcanic rocks. At the southern end of the coastal volcanic belt, Shride (1976) described a section that contains abundant andesite. Hon and Thirlwall (1985), on the basis of the chemistry of those rocks, interpreted them as having island-arc affinities.

This paper incorporates geological observations and data, laboratory analyses, and interpretations presented in Pinette (1983). The area of study includes the following islands located in East Penobscot Bay: Barred Islands, Bradbury, Butter, Compass, Eagle, Fling, Grass Ledge, Great Spruce Head, Hard Head, Porcupine Islands, Little Spruce Head, and Scragg (Fig. 2).

STRATIGRAPHY AND LITHIC DESCRIPTIONS FOR THE EAST PENOBSCOT BAY AREA

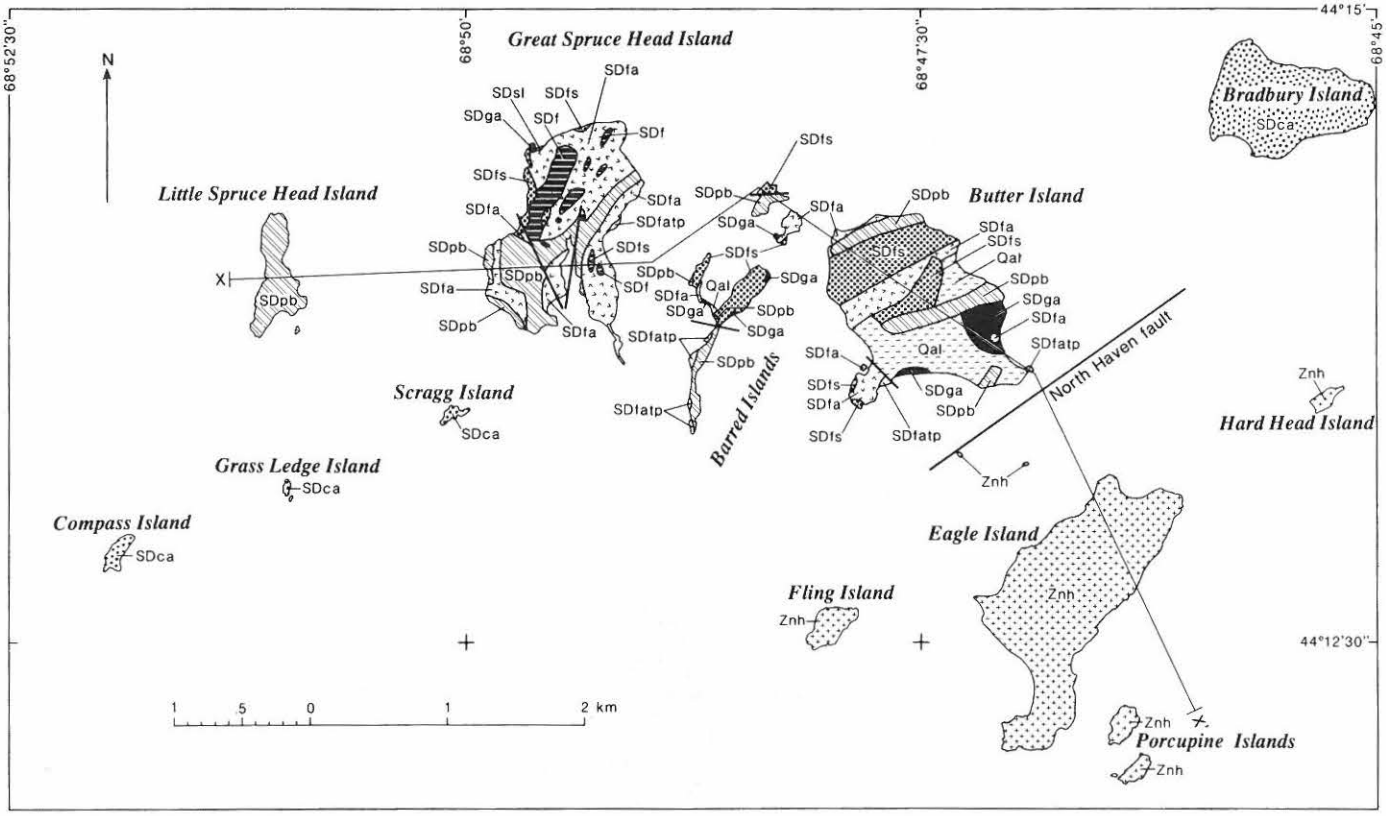
General Statement

Figure 3a shows the general geological features of this part of Penobscot Bay. The volcanic rocks exposed in this area belong to two suites: an older suite correlated with the North Haven Formation (Smith et al., 1907), and a younger suite included in the Castine Formation (Smith et al., 1907) as redefined by Stewart (1956) and Wingard (1961). Figure 4 presents a structural section for the rocks described in this report. A stratigraphic column for the study area is presented in Figure 5.

Displacements along high-angle faults disrupt the local stratigraphy, and in this region a major high-angle fault, the North Haven fault, is thought to separate the Castine and North Haven Formations. Upright folds on some of the outlying islands indicate that the Castine Formation has been deformed by large-scale folds. Observations of minor folds and schistosity suggest that the North Haven Formation is polydeformed.

North Haven Formation

Rocks belonging to the North Haven Formation crop out on Eagle, Fling, the Porcupines, and Hard Head Islands. These rocks are predominantly mafic (>90%), principally basalts and basaltic andesites. Relict pillows and mafic agglomerate are locally preserved, but much of the rock has been recrystallized



LITHOLOGIC SYMBOLS

Quaternary

- Qal — Undifferentiated alluvium and glacial deposits

High-angle fault

• E33 — Outcrop sampled for chemical analyses

CASTINE FORMATION

Silurian - Devonian

Eruptive Rocks

- SDca — Undifferentiated Castine formation lithology; reconnaissance mapping only
- SDpb — Dominantly pillowed basalts and basaltic andesites
- SDfatp — Felsic lapilli tuff-agglomerate with tuffaceous to phyllitic matrix, may be in part spherulitic
- SDfa — Felsic agglomerate with vague clasts
- SDfs — Felsic unit with abundant spherulites
- SDf — Felsic unit weathering white and lacking any field-evident distinguishing textural features

Intrusive Rocks

- SDga — Fine- to coarse-grained mafic (gabbroic ?) intrusion

Sedimentary Rocks

- SDsl — Laminated siltstone unit occurring with limestone unit

NORTH HAVEN FORMATION

Late Precambrian to Ordovician

- Znh — Undifferentiated sequence of metabasalts interbedded with relatively minor felsic volcaniclastics and very minor sedimentary rocks

Figure 3a. Generalized geologic map of study area.

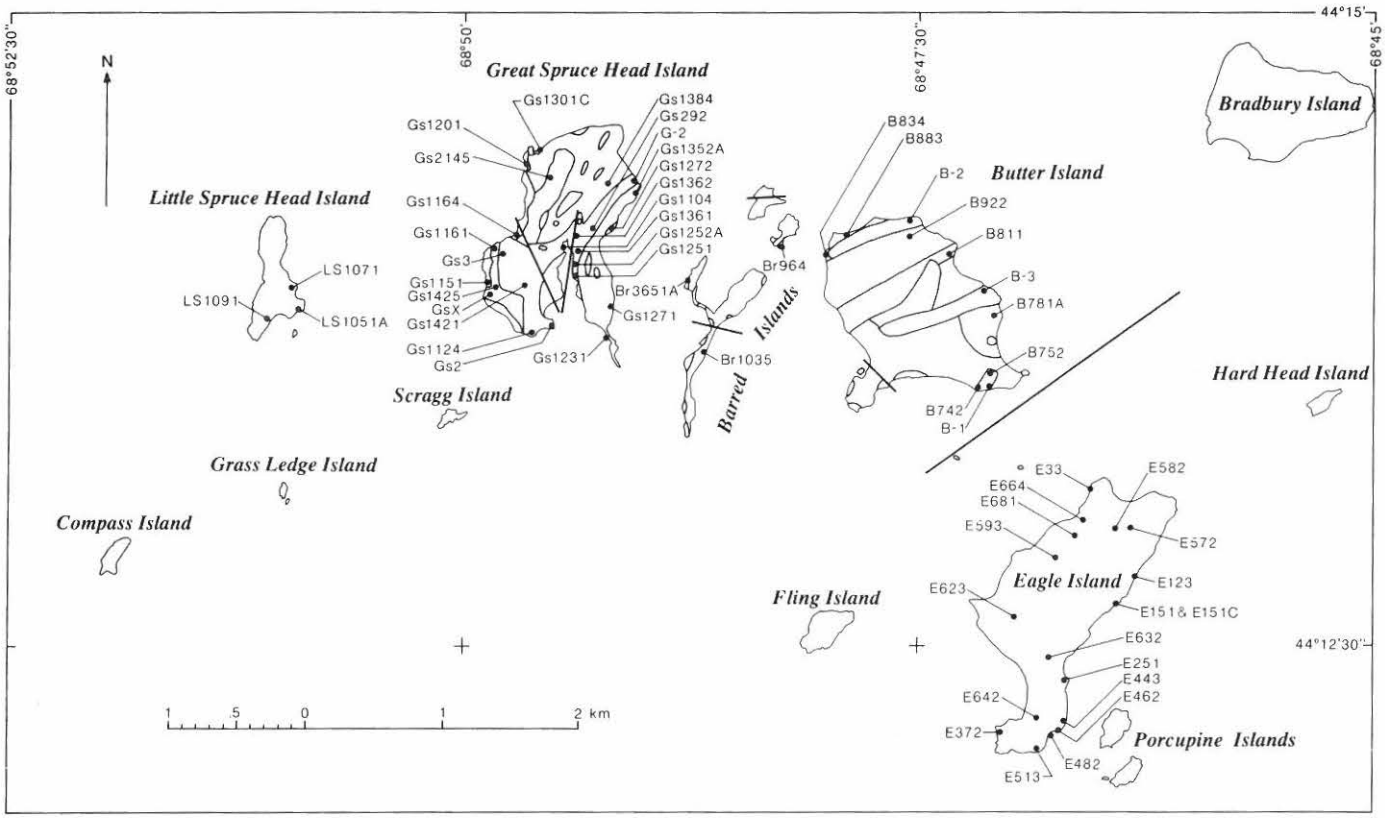


Figure 3b. Locations of chemically analyzed rock samples (see Table 1).

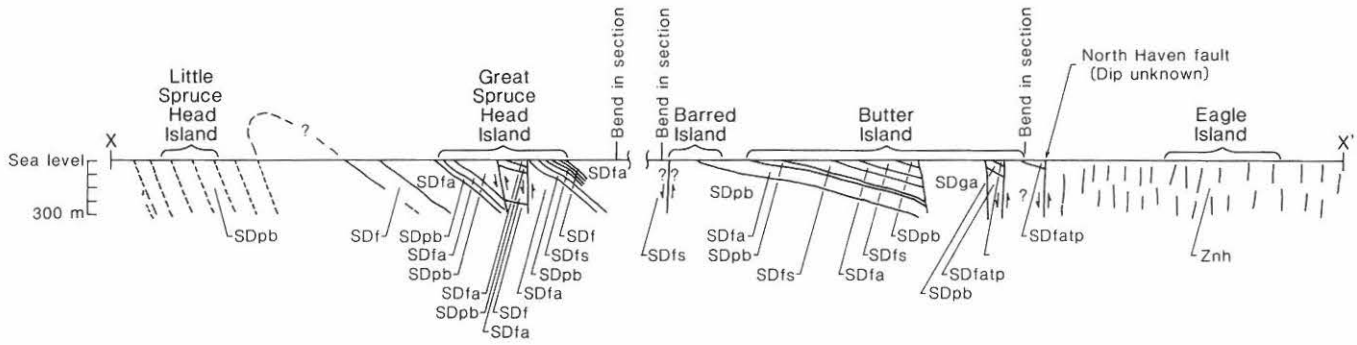


Figure 4. Stratigraphic cross-section of the study area. Symbols and scale are same as in Figure 3a.

to mafic phyllites. Felsic tuffs, felsic lapilli tuffs, and felsic lapilli tuff-agglomerates form layers one to tens of meters thick that are interbedded with the mafic volcanic rocks. These rocks, classified chemically as dacites and alkali rhyolites, make up a small volume of the formation (<10%). Minor amounts of slightly metamorphosed mudstone, graywacke, and quartzofeldspathic wacke are also present. Bedding in these rocks, where identified, is steeply dipping.

The rocks are thoroughly recrystallized and contain chlorite with two different compositions, possibly signifying polymetamorphism. In addition, they contain a pervasive foliation which, in outcrops displaying both bedding and foliation, is essentially parallel to bedding. Isoclinal upright folds with two different orientations deform both bedding and foliation. Small asymmetrical kink folds postdate the other structural features. The features taken together suggest a complicated deformational history for rocks of the North Haven Formation.

Castine Formation

The Castine Formation is exposed on Bradbury, Butter, Compass, Grass Ledge, Great Spruce Head, and Scragg Islands,

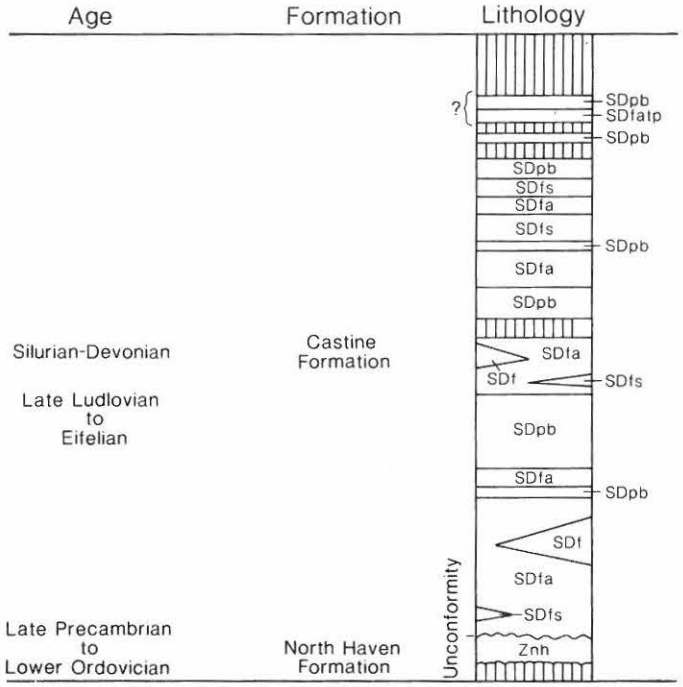


Figure 5. Stratigraphic column of the study area. Symbols same as in Figures 3a and 3b.

and on the Barred Islands. Unlike the North Haven Formation, the Castine Formation is dominated by felsic lavas and volcaniclastic rocks (~70%); mafic lavas are subordinate (~30%). Chemically, the felsic rocks are dacites and alkali rhyolites. These rocks vary spatially in their textural characteristics. Locally they are massive and featureless; at other locations they are flow-banded, spherulitic, or agglomeratic. Felsic tephra deposits include ash tuffs, lapilli tuffs, and lapilli tuff-agglomerates. Most felsic units, except for the fine tephra, occur as distinctive 1-3 meter thick beds. The mafic rocks are basalts and basaltic andesites. Mafic flows commonly are pillowed, although locally mafic pillow agglomerates and lapilli tuff-agglomerates are associated with them. Mafic units are from 2-4 meters thick. Minor amounts of siltstone and limestone are intercalated with the volcanic rocks. Rapid lateral and vertical lithofacies changes and great variability in the volcanic assemblage suggest several nearby sources and some topographic influence on the distribution of these rocks (Stewart and Wones, 1974). In general, the rocks of the Castine Formation are slightly recrystallized, but they do not carry a pervasive foliation.

Rocks of the Castine Formation as exposed on Great Spruce Head, Butter, and the Barred Islands have uniformly gentle dips toward the east. Observation of facing directions, such as pillow tops, lapilli tuff tops, and brecciated tops of flows, without exception indicate that this section is right-way up and essentially homoclinal. The local stratigraphic section shown in Figure 4 incorporates these observations.

Although the Castine and North Haven Formations are juxtaposed across the North Haven fault in the area of this study, regionally the Late Silurian-Early Devonian section, including the Castine Formation, is interpreted to lie unconformably on the North Haven Formation. The stratigraphic relationship at Ames Knob on the island of North Haven, where the Silurian-Early Devonian section rests unconformably on the North Haven Formation, supports this interpretation. Randomly oriented, foliated clasts of the underlying North Haven Formation have been incorporated into the basal conglomerate of the Early Silurian Ames Knob Formation. The randomly oriented, foliated clasts and the absence of a penetrative foliation in the matrix of this conglomerate indicate that the foliation developed in the North Haven Formation before erosion and burial of the Early Silurian rocks.

Fossil evidence found on nearby islands outside of and on Compass Island within the study area indicates that the Castine Formation spans at least Late Silurian through Early Devonian time. Fossil fauna in the Ames Knob Formation on the island of North Haven range from Late Llandoverian to Pridolian in age (Smith et al., 1907; Gates, 1969; Berdan, 1971; Brookins et al., 1973). Therefore, the maximum age for the overlying Thorofare andesite and the equivalent Castine Formation must be Pridolian. Brookins et al. (1973) found ostracodes in a limestone interbedded with pillowed andesite on the southwestern corner of Compass Island which they interpreted to range in age from Early Devonian to Eifelian. Thus, the age of the Castine Formation can be bracketed between Late Silurian (Late Ludlovian or Pridolian) and Eifelian.

Intrusive Rocks

Small bodies of gabbro intrude both formations, and two types of mafic dikes and sills are present in the study area. Gabbros, having idiomorphic texture, are massive and unfoliated. One type of mafic dike/sill intrudes only the Castine Formation. It has aphanitic to fine porphyritic texture with feldspar laths up to 1 mm long. Some of these dikes are multiple, and their spatial relations to pillow basalts in the Castine Formation suggest the possibility that they are feeder dikes for the basalts. The second type of mafic dike is similar to the first, but fresher. It also has an aphanitic texture, but in addition it possesses well developed columnar joints. D. B. Stewart (pers. commun., 1982) reports that one of these dikes located on Great Spruce Head Island contains analcime, and he believes it to be Mesozoic.

PETROGRAPHIC DESCRIPTION

General Statement

Petrographic descriptions of rocks in the North Haven and Castine Formations and in several cross-cutting bodies of gabbro

are given below. Compositions of feldspar are mainly determined by extinction angles.

North Haven Formation

Microscopically, the mafic phyllites and pillow basalts, locally amygdaloidal, contain phenocrysts of plagioclase with pilotaxitic texture and augite. These are set in a matrix which originally must have been finely crystalline or glassy. The plagioclase consists of albite microlites and laths as long as 3 millimeters. These crystals must have been completely recrystallized from more calcic feldspar. In thoroughly schistose rocks, albite has a resorbed outline and shows little evidence of twinning. In many rocks inclusions of calcite, epidote, and sericite in plagioclase occur as alteration products of the original feldspar. Locally, acicular mineral aggregates tentatively identified as pumpellyite also occur within the albite. In this regard, D. B. Stewart (pers. commun., 1982) has microprobe data to confirm the presence of pumpellyite in similar rocks just to the north of the study area. Augite crystals ($Z\wedge C = 43^{o}$, and 2V (+) = ~50°) with ophitic to subophitic and intergranular textures range to 3 mm in prismatic section. It may occur as relatively unaltered grains, or as barely perceptible cores which are largely replaced by actinolite, chlorite, and opaque pseudomorphs. Accessory minerals in the mafic volcanic rocks include opaques and sphene, commonly altered to leucoxene. Much of the groundmass consists of fine-grained albite, chlorite, and actinolite. Parallelism of chlorite and actinolite defines a pronounced bedding plane metamorphic foliation. Chlorites with two different compositions are present in some rocks, possibly indicative of polymetamorphism. In these rocks, chlorite with a berlin-blue interference color (Fe-rich; Albee, 1962) overprints chlorite with an anomalous brown interference color (Mg-rich; Albee, 1962).

The felsic tephra of the North Haven Formation consists of alkali feldspar fragments, commonly exhibiting trachytic alignment, set in a groundmass of microscopic to submicroscopic, interlocking, anhedral feldspar and quartz. Sericite is locally an alteration product of the larger feldspar crystals, and it also occurs along with sparse actinolite, chlorite, and opaques in the matrix. Both Fe-rich and Mg-rich chlorite may be present. Parallelism of sericite and actinolite defines a metamorphic foliation in these rocks.

Castine Formation

Pillow basalts, which locally carry amygdules, and basalts contain small phenocrysts and a fine-grained to submicroscopic groundmass. Laths of plagioclase, up to 2 millimeters long, have trachytic development. Plagioclase compositions vary between albite and andesine. Minor saussuritization of the plagioclase is evident from the presence of fine-grained inclusions of epidote, calcite, sericite, and possibly pumpellyite in plagioclase. Calcic augite (B. A. Bouley and R. L. Barnett, unpub. microprobe data), occurring in grains measuring as much as 2.5 mm in prismatic section, has ophitic to subophitic and intergranular texture. The augite is relatively unaltered, but locally grains are rimmed with thin alteration coronas of chlorite and actinolite. The groundmass consists of microscopic to submicroscopic grains of plagioclase and lesser amounts of actinolite and chlorite. Sphene and opaques are distributed throughout the groundmass. All of the chlorite in these mafic rocks is Fe-rich in contradistinction to those in the North Haven Formation. Most of the basalts do not possess a penetrative mineral foliation; an exception being the basalts exposed on Little Spruce Head Island (Fig. 2), where a well developed foliation along with rotated crystals of pyrite suggests that these structures formed in a localized zone of high strain.

The rhyolites and dacites consist of microporphyritic, partially resorbed albite crystals having a trachytic development and set in a fine-grained to submicroscopic felsitic matrix. The matrix consists of varying amounts of fine-grained felty albite with intergranular, microscopic to submicroscopic, interlocking, anhedral quartz and feldspar. Minor amounts of opaques, probably magnetite, are disseminated throughout the rock. Minor sericite is the only obvious alteration product. Felsic ash tuffs and lapilli tuffs have similar mineralogy to the rhyolites and dacites. The main difference is the presence of fragmental feldspars scattered throughout the rock. The alignment of sericite flakes produces a subtle foliation in all of the felsic rocks.

Intrusive Gabbroic Rocks

The gabbros have a fine- to medium-grained idiomorphic texture. Phenocrystic plagioclase and augite are set in a dense groundmass of fine-grained anhedral to subhedral plagioclase and pyroxene. Albite occurs as euhedral laths measuring up to 5 mm long. Sericite ranges from minor to important as an alteration product within the plagioclase. Augite ($Z\wedge C = 43^{o}$ and 2V (+) = 50°) occurs as salmon-colored euhedra measuring as much as 3 mm in prismatic section. Minor actinolite and Fe-rich chlorite are alteration products of the augite. Magnetite and apatite are ubiquitous accessory minerals. At one locality on Eagle Island (Fig. 2) basaltic hornblende appears as an additional phase.

ANALYTICAL TECHNIQUES

Sample preparation for the determination of seven major element oxides excluding silica was done by HF-aqua regia-boric acid aluminosilicate digestion modified from Buckley and Cranston (1971). Sample preparation for the determination of silica used a technique modified after Shapiro (1967). Major element oxide analyses for 57 rock samples were performed by one of the authors (S.R.P.) on a Perkin-Elmer 703 Atomic Absorption Spectrophotometer according to the techniques outlined in Perkin-Elmer (1976). Precision and accuracy determinations for the major element oxide concentrations in these samples were

performed by replicate analyses of rock standards GSP-1, AGV-1, and BCR-1 (Flanagan, 1967). Major element oxide and trace element analyses for 6 of these samples were done by the U.S. Geological Survey, and for these the major element oxides were determined according to the procedure described in Shapiro (1975). Four samples analyzed by the U.S. Geological Survey are duplicates of samples analyzed by Pinette, and they were used to compare the accuracy of the two major element oxide analytical techniques. Trace elements for the 6 basalt samples analyzed by the U.S. Geological Survey were done by either X-ray spectroscopy or instrumental neutron activation techniques. The rare-earth element concentrations in these samples were determined by instrumental neutron activation analysis.

CHEMICAL ALTERATION

Rocks of the North Haven and Castine Formations have been variably metamorphosed, developing new mineral assemblages from the original assemblages. Thin section study indicates that the mafic rocks are more susceptible to this recrystallization than are the felsic rocks. The compositional and textural characteristics of chlorite in greenstones of the North Haven Formation suggest that those rocks have been subjected to two metamorphic events, whereas the mafic rocks of the Castine Formation have been recrystallized in a single event. The mineral assemblages observed in all of these rocks are compatible with the pumpellyite-actinolite subfacies.

Cann (1969), Pearce and Cann (1973), Vallance (1974), Dostal and Strong (1983), and Murphy and Hynes (1986) have documented changes in the original chemistry of volcanic rocks by metamorphic processes. Almost all major and trace elements can migrate under different sets of conditions. The processes of albitization, chloritization, and epidotization indicate the complexity and the diversity of possible chemical changes.

A major problem in studying ancient volcanic rocks such as those in the coastal belt of Maine is to obtain chemical parameters that are unaffected by halmyrolysis, metamorphism, and/or weathering and serve as a guide to their original compositions. This problem can never be solved satisfactorily. However, to minimize the effects of weathering, we have chosen for chemical analysis only samples that showed no evidence of weathering. Samples were also examined in thin section to determine the extent to which the original mineralogy was recrystallized to metamorphic minerals. It must be noted that all of the samples exhibited a degree of new mineral growth, but only the least recrystallized were chemically analyzed. In addition, two criteria were employed to assess how well the chemical data reflects the original compositions. In one of these criteria, proposed by Irvine and Baragar (1971), rocks with $H_2O + CO_2 > 2.5$ weight percent are considered to be chemically altered. In our analyses the sum of H_2O and CO_2 was determined by loss on ignition, and, consequently, could be understated. In any case, many of the analyses do not meet this test. In the second criterion, the weight percent of CaO is compared to the sum of those of $Na_2O + K_2O$. Erratic and low concentrations of CaO relative to erratic and high concentrations of $Na_2O + K_2O$ suggest lime depletion and/or alkali enrichment (Pamic, 1974; Vallance, 1974). Many of our analyses show these relationships, again indicating that they have been chemically altered.

The major element oxide data for the volcanic rocks analyzed in this study are shown in Table 1, and the solid symbols in Figure 6 represent what we interpret to be the least altered compositions of basalt and basaltic andesite. Diagnostic criteria to identify chemical alteration in felsic rocks are less clear, and therefore, no attempt was made to identify the least altered felsic rocks in Figure 6.

CHEMICAL PETROLOGY OF THE VOLCANIC ROCKS

General Statement

Major element analyses for the least altered volcanic rocks are presented in Table 1. Eighteen analyses are from the North Haven Formation, and 45 are from the Castine Formation. The analyses represent the important lithologies that constitute these formations, but the number of analyses for each lithology should not be considered to be statistically related to their abundances. Sample locations are plotted in Figure 3b. North Haven Formation

Basalts, high alumina basalts, and basaltic andesites (nomenclature of Taylor, 1969) constitute >90% of the rocks of the North Haven Formation; most of the remainder are rhyolites and dacites. Cation abundances indicate that nearly half of these basalts are olivine and hypersthene normative, whereas the others are olivine and nepheline normative. According to the normative classification of Irvine and Baragar (1971) these basalts are undersaturated and alkaline, but because many samples show some evidence of alkali mobility during alteration, their normative mineralogies may be suspect. If spilitization was part of the alteration process, alkali enrichment would increase the amount of normative plagioclase and, thereby, lock additional silica up in the plagioclase. This depletion of the total silica tends to produce undersaturation in at least some of the remaining normative minerals.

Major element oxides are plotted on Harker-type variation diagrams (Fig. 6). The preponderance of basalts and basaltic andesites (SiO_2 <55%), the lack of intermediate rocks (SiO_2 = 55-62%) and the paucity of siliceous rocks (SiO_2 >62%) are evident from these diagrams. Many basalts have high concentrations of Al_2O_3, MgO, Na_2O, and K_2O, and low concentrations of CaO relative to the basaltic averages posted in Cox et al. (1979). These concentrations, along with the scatter of these oxides, suggest a degree of alteration of the samples, possibly involving spilitization. The concentration of major elements in the two felsic rocks are comparable to the average oxides from their Cenozoic counterparts, although SiO_2 is higher by nearly 3 weight percent in the rhyolite, and Al_2O_3 is lower by nearly

TABLE 1. WHOLE-ROCK MAJOR ELEMENT OXIDE ABUNDANCES.

$FeO^* = FeO + 0.9/Fe_2O_3$; $Mg\# = [MgO/(MgO+FeO^*)] \times 100$. Fe_2O_3/FeO standardized at 0.25; B, Br, E, Gs (G also), and LS represent Butter, Barred, Eagle, Great Spruce Head and Little Spruce Head, respectively.

North Haven Formation

	E33	E123	E151	E151C	E251	E372	E443	E462	E482
SiO_2	49.3	47.7	51.1	54.7	48.9	47.6	47.7	49.8	47.9
Al_2O_3	16.2	13.4	21.5	18.9	15.3	17.2	15.9	15.6	14.4
FeO*	9.1	10.6	6.3	5.6	10.1	8.7	10.0	9.7	10.0
MgO	7.3	14.1	2.8	3.9	8.0	8.3	9.7	6.9	10.0
CaO	6.2	4.4	4.7	3.1	8.0	6.6	3.9	6.4	7.6
Na_2O	4.6	3.3	5.2	8.3	3.6	4.6	3.8	3.0	2.8
K_2O	1.0	0.4	3.3	0.3	0.7	0.6	1.8	2.2	1.3
TiO_2	1.7	1.2	0.9	0.8	1.3	1.4	1.3	1.4	1.2
LOI	2.5	2.8	1.7	3.3	2.2	3.7	3.5	2.2	2.4
Total	97.9	98.2	97.5	98.9	98.1	98.7	97.6	97.2	97.6
FeO*/MgO	1.2	0.8	2.3	1.4	1.3	1.1	1.0	1.4	1.0
Mg#	44.5	57.1	30.7	41.1	44.2	48.8	49.2	41.5	50.0
Rock type	Hi-Al Bas.	Bas.	Hi-Al Bas.	Hi-Al Bas. Andes	Bas.	Hi-Al Bas.	Bas.	Bas.	Bas.

	E513	E572	E582	E593	E623†	E632	E642	E664	E681
SiO_2	48.9	48.6	47.5	48.3	48.1	48.7	66.8	74.6	48.0
Al_2O_3	16.0	15.6	17.0	17.5	16.6	16.0	13.5	13.3	18.4
FeO*	9.9	9.5	9.6	9.4	9.2	9.7	5.3	1.4	9.8
MgO	5.2	7.4	7.0	7.3	8.3	8.6	2.8	0.3	8.9
CaO	5.1	5.9	7.0	7.4	8.7	7.7	0.2	0.0	5.1
Na_2O	5.9	4.2	4.8	4.2	3.5	4.0	4.7	3.6	3.8
K_2O	1.0	0.7	0.5	0.7	0.4	0.3	2.3	3.2	0.6
TiO_2	1.9	1.7	1.8	1.5	1.3	1.1	0.2	0.1	1.5
LOI	2.9	3.3	2.4	2.8	2.6	2.1	2.1	0.9	3.3
Total	97.4	96.9	97.6	99.2	99.0	98.5	98.1	97.4	99.4
FeO*/MgO	1.9	1.3	1.4	1.3	1.1	1.1	1.9	4.7	1.1
Mg#	34.4	43.8	42.2	43.7	47.4	47.0	34.6	17.6	47.6
Rock type	Hi-Al Bas.	Bas.	Hi-Al Bas.	Hi-Al Bas.	Hi-Al Bas.	Hi-Al Bas.	Dac.	Rhyol.	Hi-Al Bas.

Castine Formation

	LS1051A	LS1071	LS1091	G-2†	Gs-2†	Gs-2	Gs3	Gs292	Gs1104	Gs1124	Gs1151	Gs1161
SiO_2	41.7	42.4	46.5	47.9	51.9	50.9	45.6	46.7	66.8	53.4	57.1	68.1
Al_2O_3	17.1	20.8	17.2	15.9	15.0	15.6	15.4	16.7	16.0	18.8	15.3	12.7
FeO*	14.0	11.1	10.9	10.0	9.2	9.5	10.8	10.7	2.5	9.4	7.7	5.5
MgO	1.9	4.2	9.1	6.3	4.8	5.0	6.5	5.3	0.4	4.1	6.2	2.4
CaO	9.0	5.5	4.5	9.3	7.9	6.5	9.3	8.0	0.2	1.6	1.6	2.4
Na_2O	4.8	4.6	3.9	3.6	5.7	4.6	2.8	5.4	5.4	6.7	5.1	1.7
K_2O	6.5	4.3	1.2	0.8	0.2	0.5	0.5	0.2	5.4	0.5	0.1	4.1
TiO_2	1.8	1.1	1.7	1.6	2.3	1.9	1.7	2.0	0.2	1.0	0.9	0.6
LOI	2.5	6.0	3.2	3.4	3.0	2.5	2.5	2.9	1.2	2.7	3.4	1.6
Total	99.3	100.0	98.2	100.0	101.0	97.0	97.7	97.9	98.1	98.2	97.8	99.1
FeO*/MgO	7.4	2.6	1.2	1.6	1.9	1.9	1.7	2.0	6.3	2.3	1.2	2.3
Mg#	11.9	27.5	45.5	38.6	34.0	34.3	37.6	33.1	13.8	30.3	44.6	30.3
Rock type	Hi-Al Bas.	Hi-Al Bas.	Hi-Al Bas.	Bas.	Bas.	Bas.	Bas.	Hi-Al Bas.	Dac.	Bas. Andes	Low-K Andes	Rhyo-Dac.

† indicates U.S.G.S. duplicate analyses.

TABLE 1. (CONTINUED)

$FeO^* = FeO + 0.9/Fe_2O_3$; $Mg\# = [MgO/(MgO+FeO^*)] \times 100$. Fe_2O_3/FeO standardized at 0.25; B, Br, E, Gs (G also), and LS represent Butter, Barred, Eagle, Great Spruce Head and Little Spruce Head, respectively.

Castine Formation

	Gs1164	Gs1192	Gs1201	Gs1231	Gs1251	Gs1252A	Gs1271	Gs1272	Gs1301C	Gs1352A	Gs1361
SiO_2	74.4	54.2	48.1	69.9	49.7	70.2	70.8	72.2	71.2	74.0	49.7
Al_2O_3	12.8	18.9	15.6	12.1	14.9	14.2	14.6	14.4	14.0	12.1	16.3
FeO*	0.9	7.4	10.2	4.0	9.8	3.2	3.0	2.3	3.2	3.6	9.8
MgO	0.7	4.7	8.5	0.3	5.2	0.5	0.5	0.8	2.0	0.4	5.3
CaO	0.4	0.1	6.1	2.0	8.6	0.5	1.0	0.1	0.1	0.2	4.8
Na_2O	5.1	0.3	4.7	4.1	4.9	8.8	7.3	6.8	3.9	6.2	5.3
K_2O	6.7	9.3	0.2	3.0	1.2	0.5	3.3	0.6	2.2	0.2	1.1
TiO_2	0.1	0.2	1.7	0.2	2.1	0.3	0.2	0.2	0.2	0.2	2.2
LOI	0.8	2.7	2.9	1.3	2.7	–	1.4	1.0	2.1	2.5	3.0
Total	101.9	97.8	98.0	97.0	99.1	98.2	102.6	98.4	98.9	99.4	97.5
FeO*/MgO	1.3	1.6	1.2	13.3	1.9	6.4	6.0	2.9	1.6	9.0	1.9
Mg#	43.8	38.8	45.5	7.0	34.7	13.5	14.2	25.8	38.5	10.0	35.1
Rock type	Rhyol	Hi-K Bas. Andes	Gabbro	Rhyol	Bas.	Rhyol	Rhyol	Rhyol	Rhyol	Rhyol	Hi-Al Bas.

	Gs1362	Gs1384	Gs1421	Gs1425	Gs1213B	Gs2145	GsX	B-1†	B-2†	B-2	B-3†
SiO_2	57.8	73.3	46.4	70.8	62.8	66.6	64.9	52.3	45.1	45.5	47.4
Al_2O_3	15.3	13.5	14.7	13.1	20.1	16.6	15.1	15.4	16.1	15.7	16.6
FeO*	8.6	0.2	11.9	2.7	1.3	2.0	5.4	9.3	10.6	11.1	10.3
MgO	1.3	0.2	7.2	1.4	1.5	0.2	1.7	4.8	6.3	6.4	6.4
CaO	3.0	0.4	8.0	0.9	0.2	0.1	1.4	7.9	9.7	9.6	10.9
Na_2O	6.0	6.3	3.7	4.1	9.7	3.9	6.5	5.5	3.8	3.5	3.1
K_2O	1.0	2.5	1.1	2.7	0.7	8.2	0.5	0.3	0.3	0.3	0.3
TiO_2	1.1	0.7	2.2	0.6	0.8	0.2	0.8	2.1	2.1	2.0	1.8
LOI	3.9	0.5	3.0	1.2	1.2	0.5	1.4	2.5	4.5	2.2	3.1
Total	97.9	97.6	98.2	97.5	98.3	98.3	97.7	101.0	99.0	96.3	101.0
FeO*/MgO	6.6	1.0	1.7	1.9	0.9	10.0	3.2	1.9	1.7	1.7	1.6
Mg#	13.1	50.0	37.7	34.1	53.6	9.1	23.9	34.0	37.3	36.6	38.3
Rock type	Andes	Rhyol	Bas.	Rhyol	Dac.	Dac.	Dac.	Bas.	Hi-Al Bas.	Bas.	Hi-Al Bas.

	B-3	B742	B752	B781A	B811	B834	B883	B922	Br964	Br1035	Br3651A
SiO_2	47.3	50.8	44.7	49.7	68.6	71.9	77.3	73.9	74.1	50.1	49.9
Al_2O_3	16.1	14.5	16.2	15.8	14.5	13.1	11.7	12.1	12.1	16.3	15.7
FeO*	10.2	9.6	14.6	11.6	2.8	3.7	1.1	2.9	3.0	9.5	10.6
MgO	6.1	4.4	4.9	4.8	0.2	0.4	0.2	0.1	0.3	3.2	5.4
CaO	10.8	8.5	9.5	6.6	0.2	0.1	0.1	0.1	0.2	5.7	6.9
Na_2O	2.7	5.4	6.1	5.1	4.5	4.7	2.8	5.4	4.7	5.6	5.1
K_2O	0.2	0.3	0.5	0.4	5.0	3.0	3.1	3.3	2.3	4.6	0.5
TiO_2	1.6	2.0	3.5	2.6	0.2	0.3	0.1	0.2	0.3	2.6	2.0
LOI	2.0	3.1	2.5	2.7	2.6	1.1	0.9	1.2	1.3	3.3	1.8
Total	97.0	98.6	102.6	99.3	98.6	98.4	97.3	99.1	98.2	100.9	98.5
FeO*/MgO	1.7	2.2	3.0	2.4	14.0	9.3	5.5	29.0	10.0	3.0	2.0
Mg#	37.4	31.4	25.1	29.3	6.7	9.8	15.4	3.4	9.1	25.2	33.8
Rock type	Hi-Al Bas.	Bas.	Hi-Al Bas.	Gabbro	Rhyol	Rhyol	Rhyol	Rhyol	Rhyol	Hi-Al Bas.	Bas.

† indicates U.S.G.S. duplicate analyses.

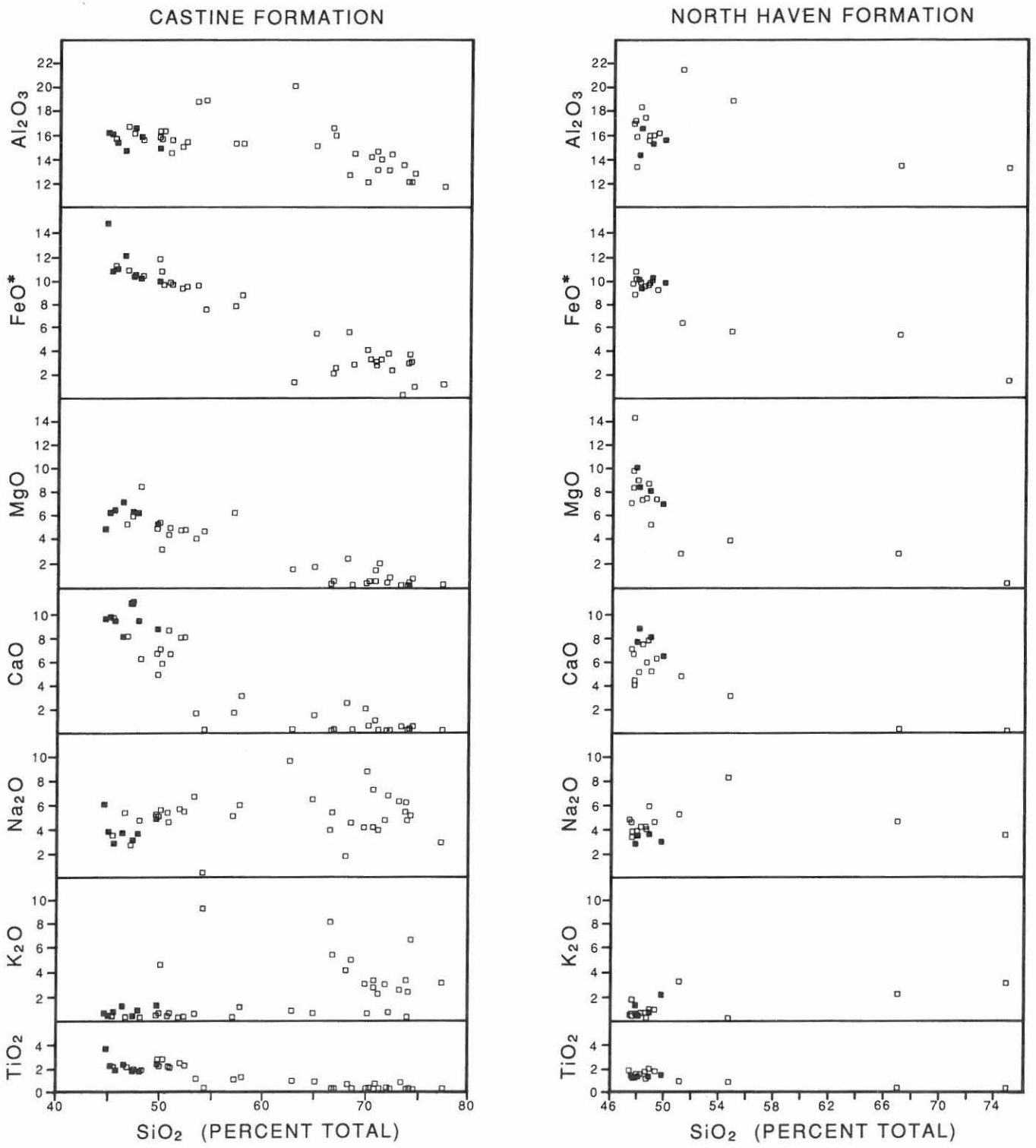


Figure 6. Harker-type variation diagrams for volcanic rocks in the North Haven and Castine Formations. Solid symbols represent least altered analyses.

the same amount in the dacite. CaO values for both of these felsic rocks are comparatively low, perhaps due to Ca depletion.

Mg-numbers (Mg# = [MgO/(MgO + FeO*)] x 100) for basalts of the North Haven Formation (Table 1) vary between 17.6 and 57.1. According to the criteria of Frey et al. (1979), these values indicate that most of these rocks are considerably evolved relative to primitive basalts (Mg-number = 68-75), probably due to fractionation of olivine and pyroxene.

Castine Formation

Chemical analyses of samples from the Castine Formation include basalts and basaltic andesites (~30%) and dacites and rhyolites (~70%). Although few andesites were found in this study, Smith el al. (1907) report andesite on the south shore of the island of North Haven, Shride (1976) described a thick section of andesites from the southern end of the belt in Massachusetts, and Bouley (1978) provides chemical data that indicates the presence of andesite near Castine, Maine. Numerous agglomerates were not chemically analyzed.

Cation abundances indicate that the majority of basalts and basaltic andesites are hypersthene normative and, therefore, alkaline (Irvine and Baragar, 1971). Most of the rhyolites and dacites are corundum normative compared to the rhyolite and dacite averages of Cox et al. (1979). However, alkali enrichment is also suspected in these rocks, and as a result their norms should be viewed with caution.

Major element oxide data are presented in Harker-type variation diagrams in Fig. 6. These diagrams indicate the bimodal character of the formation with a large number of basalts and basaltic andesites (SiO_2 <55%), a paucity of andesites (SiO_2 = 55-62%) and a majority of dacites and rhyolites (SiO_2 >62%). The basalts have a high concentration of Na_2O coupled with a degree of scatter for SiO_2, CaO, and alkalis. These relationships are taken to imply alteration of the original basaltic compositions by alkali enrichment. The concentration of TiO_2 is also high compared to basaltic averages (Chayes, 1975). Because of the relative immobility of TiO_2 during alteration (Pearce and Cann, 1973), the high TiO_2 must reflect magmatic abundances. In the dacites and rhyolites the concentration of Na_2O is also anomalously high and the alkalis have considerable scatter. Approximately 50% of the silicic rocks analyzed have sufficiently high concentrations of alkalis to be labeled alkali dacites or alkali rhyolites. Both potassic and sodic dacites and rhyolites are represented, but the sodic types predominate. These high alkali concentrations may be due to alkali enrichment, which may account for the low concentrations of CaO in these silicic rocks relative to the Cenozoic averages of Chayes (1975).

The Mg-numbers for the majority of the basalts are in the intermediate range (25.1 - 53.6) as compared to primitive basalts (Frey et al., 1979). These values indicate at least moderate fractionation of the parent magma and/or possible interaction with crustal materials. One sample from Little Spruce Head Island has an anomalously low Mg-number of 11.7.

Geochemical Comparison of the North Haven and Castine Formation Volcanic Suites

A major difference between the bimodal volcanic suites is that the North Haven Formation is dominated by mafic rocks with only minor occurrences of felsic rock, whereas the Castine Formation is dominated by felsic rocks with subordinate mafic varieties. Furthermore, the Castine Formation contains large amounts of agglomerate and tuff, and the North Haven Formation contains only limited amounts of these rocks.

Because felsic volcanic rocks are very sparsely represented in the North Haven Formation, only the mafic volcanic rocks are discussed in the following chemical comparisons. Referring to Table 1, SiO_2 shows a much broader range in the mafic volcanic rocks of the Castine Formation (41.7 - 54.2 wt%) compared to that in the North Haven Formation (47.5 - 54.7 wt%). Average TiO_2 concentrations are higher in the Castine Formation (1.89±0.60 wt%) than in the North Haven Formation (1.37±0.31 wt%). Al_2O_3 is less abundant in the Castine Formation than in the North Haven Formation, and a significant portion of the volcanic rocks of the North Haven Formation are high alumina basalts. MgO concentrations are slightly greater in the North Haven Formation, and FeO* levels for both formations are nearly the same. Accordingly, the FeO*/MgO values for the Castine Formation are somewhat greater than those for the North Haven Formation; on the other hand, the Mg-numbers are larger for the mafic volcanic rocks of the North Haven Formation. Although the concentration of CaO is greater in the mafic volcanic rocks of the Castine Formation than in those of the North Haven Formation, and the average concentrations of alkalis is uniformly high in both formations, these undoubtedly have been affected by alteration and do not reflect original magmatic values.

The marked differences in (1) the relative abundances of the major rock types in each suite, (2) the relative abundance of felsic tephra in each suite, and (3) the average TiO_2 concentration in the basalts in each suite suggest that the two volcanic suites represent different magmatic conditions.

Magmatic Lineage and Tectonic Affinity

In this section various discrimination diagrams are presented and discussed in an attempt to fix the magmatic lineage and tectonic setting of these rocks.

An alkalis-FeO*-MgO triangular plot (Fig. 7) is commonly used to establish the differentiation path of comagmatic igneous rocks. In the case of volcanic rocks, the parent magma is thought to be a basalt having a field as indicated near the FeO*-MgO sideline. Two differentiation paths have been established which describe the manner in which the chemistry of the parent magma is changed by the process of crystallization: the tholeiitic trend and the calc-alkalic trend. The tholeiitic trend, path A in Figure 7, moves away from the parent magma toward the FeO* apex, and at some large FeO*/MgO value turns toward the alkali apex.

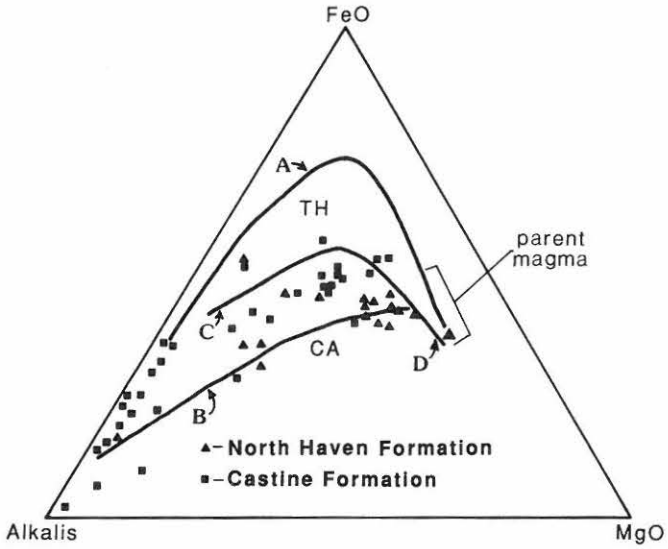


Figure 7. AFM diagram for volcanic rocks in the study area. Triangles and squares represent the North Haven and Castine Formations respectively. Line A represents a tholeiitic differentiation trend and line B represents a calc-alkaline trend. Discriminiation line C-D is after Irvine and Baragar (1971).

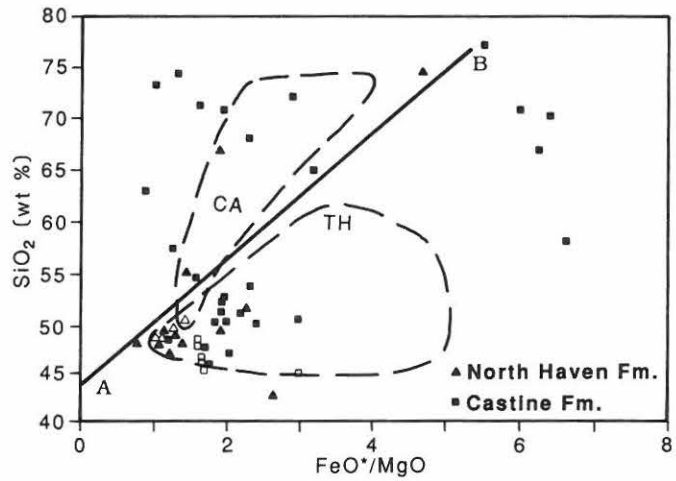


Figure 8. FeO*/MgO versus weight percent SiO_2 variation diagram for the volcanic rocks in the study area. Symbols as in Fig. 6. After Miyashiro (1974).

This trend is thought to be typical of the crystallization of rift-type volcanic rocks or some immature arcs. The calc-alkalic trend moves more directly from the parent compositions toward the alkali apex, as illustrated by path B in Figure 7. This trend is thought to be more common for the crystallization of island arc and Andean-type lavas. The heavy line C-D in Figure 7 separates the tholeiitic and the calc-alkaline field.

The compositions of samples from the North Haven and Castine Formations are plotted in Figure 7. Most of the samples lie in the calc-alkaline field, but because the rocks of both formations are thought to have been chemically altered, particularly with respect to the alkalis, the validity of this diagram may be questioned. However, the concentrations of the alkalis cannot be higher than 2 or 3%. The adjustments to the positions of the compositional points in Figure 7 must be made in a direction away from the alkali apex, approximately parallel to the line separating the tholeiitic and the calc-alkaline fields over the left half of the diagram. These arguments would not greatly change the distribution of compositional points in relation to line C-D. Those compositional points nearer the FeO*-MgO sideline would be displaced toward the area of the parent magma. Thus, we conclude that on this diagram the compositional points representing both the North Haven and the Castine Formations suggest a calc-alkaline trend.

Miyashiro (1974) has suggested the use of the SiO_2-FeO*/MgO plot to determine the differentiation paths of volcanic rocks. He argues that these parameters are less affected by alteration than would be those used in the alkalis-FeO*-MgO diagram. This conclusion is supported by the work of Vallance (1974) on the Deccan basalts, in which he showed that FeO*/MgO and SiO_2 were only slightly affected by spilitization. Miyashiro (1974) plotted several suites of volcanic rocks on this diagram and demonstrated that calc-alkaline suites plotted along a SiO_2 enrichment trend, whereas tholeiitic suites plotted along an FeO enrichment trend. These two trends are overlaid on Figure 8. The solid line (A-B) purportedly separates calc-alkaline from tholeiitic compositions, but it should be noted that this diagram does not satisfactorily differentiate the two suites below 50 wt% of SiO_2, and it is only at intermediate and higher concentrations of SiO_2 that the effects of differentiation are evident. The compositions of samples from the North Haven and the Castine Formations plot mainly within the field showing tholeiitic trends. A large number of basalts, however, plot in a part of the diagram where discrimination between the two suites is poor. In addition, the absence of any rocks of intermediate composition makes it difficult to establish a differentiation trend.

Both Figures 7 and 8 assume that the chemical characteristics of the rocks plotted on them are related by a differentiation process, and to the extent that this condition is not met, these diagrams may lack their stated significance. The proportions of basaltic to felsic rocks in the North Haven Formation does allow them to be related through differentiation, but even here the absence of intermediate rocks casts some doubt that they represent a true differentiation series. In the case of the Castine Formation, the preponderance of felsic rocks over basalts and the lack of intermediate rocks almost certainly precludes their being related by a differentiation process. This rock series must have a large component of crustal material that skews the compositions toward the felsic end of the compositional spectrum. For these reasons, we do not regard the trends on these diagrams to represent compelling arguments about the compositional lineage of these rocks.

The mineralogy of the pyroxenes is more definitive. Kuno (1968) regarded his hypersthenic and pigeonitic series as repre-

TABLE 2. TRACE AND RARE-EARTH ELEMENT DATA FROM SELECTED BASALTIC SAMPLES IN EAST PENOBSCOT BAY (U.S.G.S. UNPUBLISHED DATA). CONCENTRATIONS IN PARTS PER MILLION (ppm).

	E623	Gs-2	G-2	B-1	B-2	B-3
Ba	87	45	80	37	43	26
Nb	5	8	1	6	5	7
Rb	7	5	<5	<5	5	5
Sr	377	276	225	255	258	355
Zr	113	176	159	175	179	150
Y	29	32	30	32	34	31
Ti	6,589	13,777	9,584	12,579	12,579	10,782
Co	41.6	38.0	42.8	37.7	42.2	42.7
Cr	237	189	38.3	190	195	157
Cs	0.36	<0.4	0.47	<0.4	0.27	<0.4
Hf	2.47	3.53	3.22	3.57	3.80	2.93
Rb	11	<20	13	<20	<20	<20
Sb	1.91	0.6	<0.9	0.52	<0.9	0.70
Ta	0.22	0.54	0.69	0.55	0.50	0.33
Th	0.34	0.56	0.48	0.60	0.61	0.33
U	<0.4	<0.5	0.25	<0.5	<0.4	<0.4
Zn	77	81	81	79	96	90
Sc	34.4	39.7	34.8	39.6	35.4	42.7
La	4.36	8.4	9.51	8.9	8.9	6.6
Ce	13.3	21.8	23.1	20.9	24.7	18.3
Nd	15	16	17	22	15	18
Sm	3.05	3.97	3.60	3.87	4.7	3.82
Eu	1.24	1.41	1.29	1.42	1.75	1.55
Gd	5.4	6.4	4.6	<2	5.4	<6
Tb	0.77	0.88	0.68	0.83	1.01	0.87
Tm	0.38	0.5	0.4	0.5	0.5	0.30
Yb	3.12	3.04	2.18	2.88	3.27	3.10
Lu	0.447	0.429	0.319	0.447	0.495	0.446

Ba – Y analyses by X-Ray Spectroscopy
Ti analysis by Atomic Absorption Spectrophotometry
Co – Lu analyses by Instrumental Neutron Activation

senting volcanic suites of the calc-alkaline and tholeiitic series, respectively. According to the conclusions of Kuno (1968), the presence of monoclinic pyroxene and the absence of orthorhombic pyroxene in the basalts from the North Haven and Castine Formations puts them in the pigeonitic series and classifies them as tholeiitic. As noted by Miyashiro (1974), there are cases where this mineralogic definition disagrees with the chemical definitions.

The concentration of TiO_2, because of the immobility of this oxide during alteration, has been used as a discriminant of tectonic setting of tholeiites (Pearce and Cann, 1973). In addition, Pearce (1974) has reported mean concentrations of TiO_2 for various suites of mafic rocks interpreted to have certain tectonic settings as follows: ocean-floor tholeiites = 1.42 wt%, calc-alkaline mafic volcanic rocks = 1.07 wt%, and continental rift basalts = 2.47 wt%. Feiss (1982) has suggested that TiO_2 concentrations of 1.0 - 1.3 wt%, or less, in mafic rocks are typical of subduction zones. Taken at face value, the mean TiO_2 concentration of the samples taken from the North Haven basalts (1.37 wt%) compares most favorably to that of Pearce's ocean-floor tholeiite, and the mean of samples from the Castine Formation (1.89 wt%) compares most favorably to that of Pearce's mean value for continental rift basalts.

Trace and rare-earth element abundances and abundance ratios have been used by numerous researchers to define the tectonic setting of volcanic suites (e.g. Frey et al., 1968; Schilling, 1969; Pearce and Cann, 1973; Wood et al., 1979b; Frey, 1980; Brooks and Coles, 1980). To the extent that magmatic processes are controlled by tectonic conditions, the trace and rare-earth element abundances of volcanic suites may be used to infer their tectonic setting. In addition, the immobility of trace and rare-earth elements make them especially useful as guides to magmatic processes that operated in ancient volcanic suites.

Trace and rare-earth elements for six basaltic samples were analyzed by the U.S. Geological Survey laboratory in Reston, Virginia. The analytical data are presented in Table 2. One analysis is from the North Haven Formation and five are from the Castine Formation. The data presented here are too few to establish any convincing interpretations regarding magmatic or tectonic conditions. However, as more trace and rare-earth element data become available, the accumulated data base may better establish magmatic trends and tectonic settings. In order

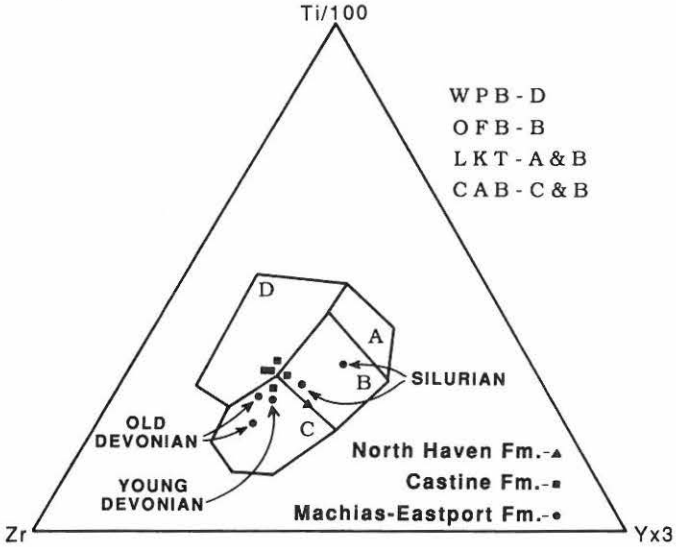


Figure 9. Discrimation diagram using Ti, Zr, and Y. Within-plate basalts (WPB), low-potassium tholeiites (LKT), ocean-floor basalts (OFB) and calc-alkaline basalts (CAB) plot in fields as indicated above. After Pearce and Cann, (1973). Triangle, squares, and circles represent North Haven and Castine Formations, and rocks from the Machias-Eastport area (Gates and Moench, 1981), respectively.

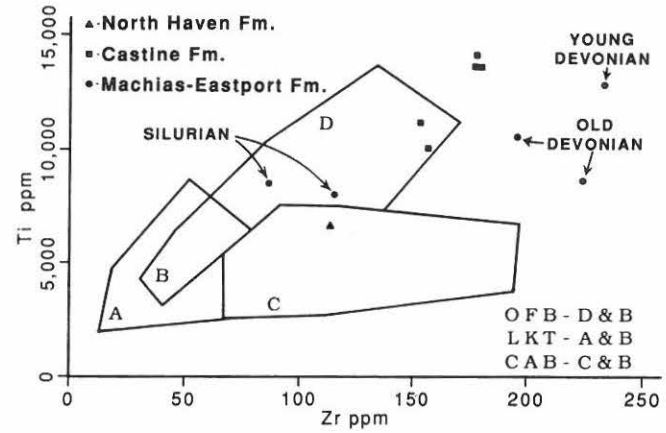


Figure 10. Discrimination diagram using Ti and Zr. Symbols and labels are as in Figure 9. After Pearce and Cann (1973).

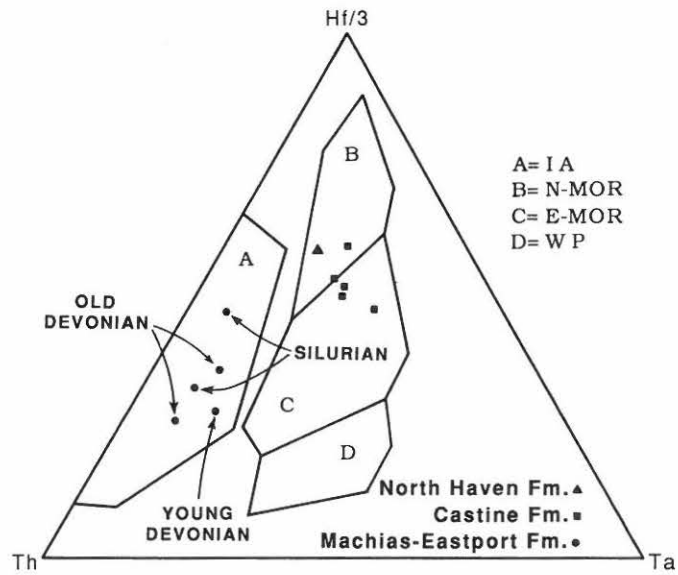


Figure 11. Discrimination diagram for basalts using Hf, Th, and Ta. Island arc (IA), normal MOR (N-MOR), enriched MOR (E-MOR), and within-plate (WP). Symbols as in Fig. 9. After Wood et al. (1979a).

to augment our data base, the diagrams that follow include the trace and rare-earth element analyses presented by Gates and Moench (1981).

Pearce and Cann (1973) outline a procedure for using discrimination diagrams involving the elements Ti, Zr, and Y to discriminate amongst various tectonic settings. First, they utilize the Ti/100-Zr-3Y diagram to determine whether within-plate basalts are represented. Figure 9 shows the positions of the analyses presented here and those reported by Gates and Moench (1981). The analysis from the North Haven Formation plots near the boundary between fields B and C. Most of the analyses from the Castine Formation lie in field D, but close to its junction with fields B and C, and one analysis each lies in fields B and C. The five samples reported by Gates and Moench (1981) fall into fields B and C. Field B was designed to contain ocean-floor basalt, low-potassium tholeiite, and calc-alkaline basalt. Field C was drawn on the basis of calc-alkaline basalt, and field D is purported to contain within-plate basalt.

Pearce and Cann (1973) then use the Ti-Zr diagram only if within-plate basalts are not represented. Although within-plate basalts are represented in Figure 9, their positions on the diagram are very near the fields for ocean-floor and calc-alkaline basalts. For this reason we present data from the study area along with data from Gates and Moench (1981) for the Machias-Eastport area on a Ti-Zr diagram (Fig. 10). The one analysis from the North Haven Formation plots within the field of calc-alkaline basalt, two analyses from the Castine Formation plot within the field for ocean-floor basalt, and the remaining analyses from the Castine Formation plot outside any of the three fields represented. Three of the analyses presented by Gates and Moench (1981) also plot outside of the fields delineated by Pearce and Cann (1973). This diagram does not successfully fix the tectonic setting of the basalts from the coastal volcanic belt.

Wood et al. (1979a) utilized a diagram based on the abundances of Hf, Th, and Ta to differentiate between rocks generated in different tectonic settings (Fig. 11). They distinguished normal oceanic ridge basalt, enriched oceanic ridge basalt, within-plate basalt, and basalt generated at destructive plate margins. The one analysis from the North Haven Formation plots in the field for normal oceanic ridge basalt, whereas the analyses from

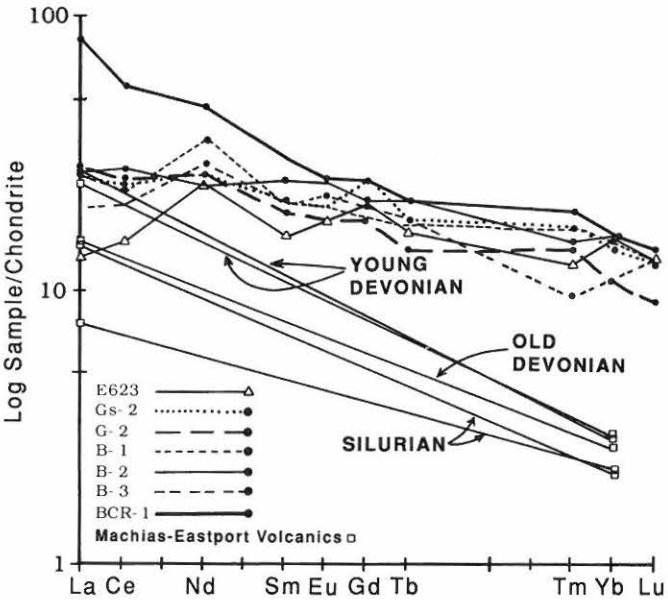


Figure 12. Chondrite-normalized rare-earth element diagram. Values normalized to data of Haskin et al. (1968). Data for La and Yb from Machias-Eastport area (Gates and Moench, 1981) are connected with straight lines. Symbols as in Fig. 9.

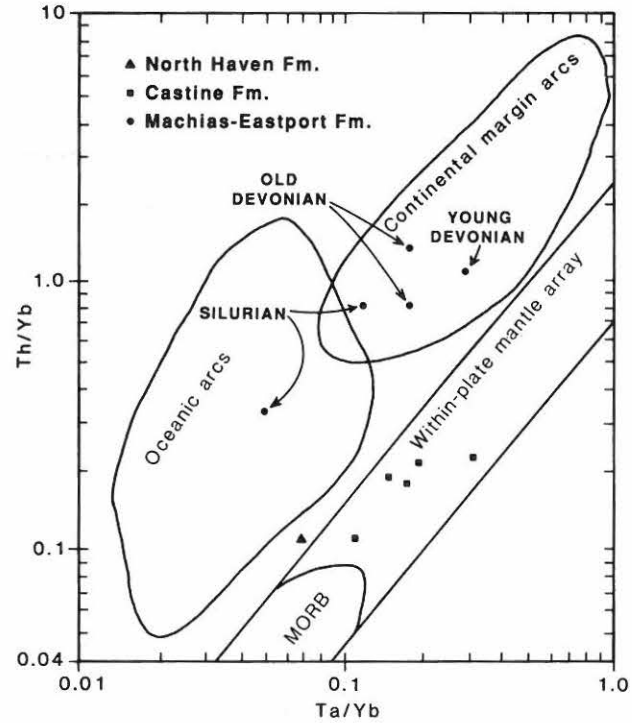


Figure 13. Th/Yb-Ta/Yb diagram showing distribution basalts from the North Haven Formation, Castine Formation, and the Machias-Eastport area (Gates and Moench, 1981). Symbols as in Fig. 9. Adapted from Condie (1986).

the Castine Formation plot in the fields of normal oceanic ridge and enriched oceanic ridge basalts. The data of Gates and Moench (1981) plot in the field for island arcs.

Rare-earth element data for the six basalts from Penobscot Bay are plotted in Figure 12 on a chondrite-normalized diagram. The single analysis from the North Haven Formation displays a very irregular, slightly depleted light rare-earth element pattern with La/Yb equal to 0.84. Individual rare-earth element concentrations range between 12.6 and 25 times chondrite values. In general, the pattern of slightly depleted light rare-earth elements and the observed chondrite-normalized values are similar to those for ocean-floor basalts reported by Schilling (1969) and Frey (1980).

The five rare-earth element analyses from the Castine Formation display mild light rare-earth element enrichment patterns relative to chondrites and have chondrite-normalized La/Yb values ranging between 1.29 and 2.64 (Fig. 12). Individual concentrations of rare-earth elements range between 9.9 and 36.5 times chondrite values. These mildly enriched rare-earth element patterns are similar to those for both continental tholeiitic basalt (Herrmann et al., 1974; Frey, 1980; and Dupuy and Dostal, 1984) and calc-alkaline basalt and andesite (Peccerillo and Taylor, 1976; and Garcia, 1978). The lack of any Eu anomaly in these basalts indicates that fractional crystallization of plagioclase was not an important factor in their differentiation history.

Gates and Moench (1981) supplied data on the abundance of La and Yb for five basalts from the Machias-Eastport area. These chondrite-normalized values are shown as individual points on Figure 12. The Machias-Eastport rocks show greater La enrichment relative to Yb compared to the basalts of this study. La concentrations for the younger Devonian and one of the older Devonian basalts are within the range of La concentrations in the Castine Formation. The basalts from this study have higher Yb concentrations than any of the basalts studied in the Machias-Eastport area. Gates and Moench (1981) observed that the high values for La and Yb and the relatively high La/Yb values (3.5 to 8) in the basalts from Machias-Eastport are similar to those for calc-alkaline basalts, but they are unlike those characteristic for ocean-floor, island-arc, and back-arc tholeiites.

In the Th/Yb-Ta/Yb diagram (Condie, 1986) presented as Figure 13, the analysis from the North Haven Formation plots outside all fields. It should be noted, however, that its position lies fairly close to the fields for oceanic arc and within-plate basalts. The analyses from the Castine Formation all plot in the field for within-plate basalts. Four basalt analyses from the Machias-Eastport area (Gates and Moench, 1981) plot in the field for continental arcs and one analysis plots in the field for oceanic arcs.

On the MORB-normalized incompatible element diagram shown in Figure 14, a pronounced negative Rb anomaly, negative Nb anomalies, and overall light incompatible element depletion are evident for the basalt analyses from the North Haven Formation. The five basalt analyses from the Castine Formation show approximately similar trends for the lighter elements, but,

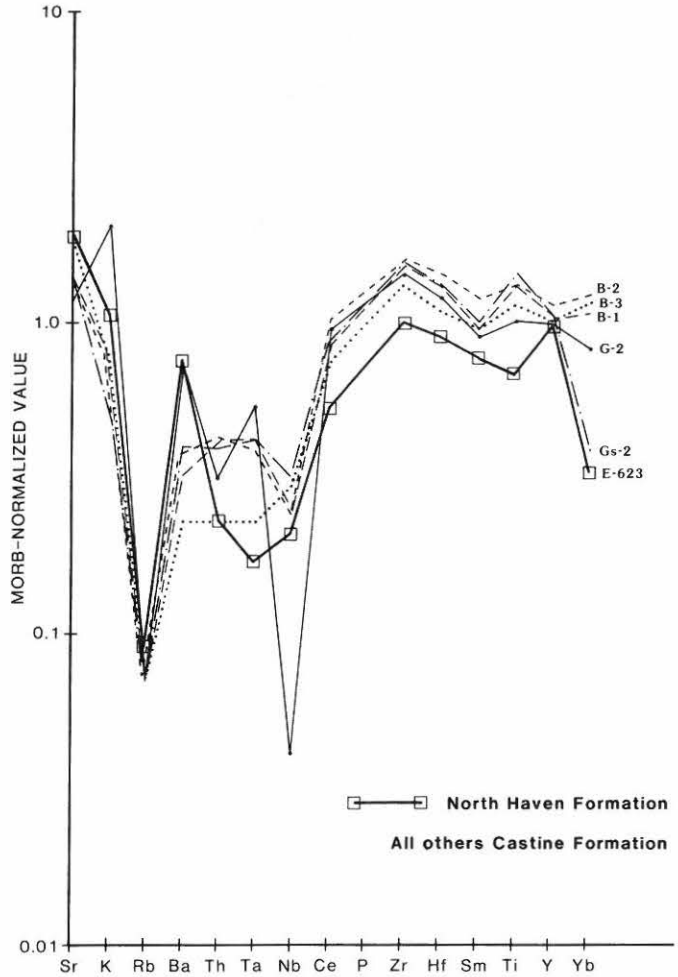


Figure 14. MORB-normalized incompatible element distributions for basalts from the study area. Symbols as in Fig. 9. Data normalized using averaged data for MORB basalts in Wood et al. (1979b).

generally, Nb is more depleted than either Th or Ta. The heavier elements (Ce to Yb) are in general equal to or slightly enriched compared to the MORB incompatible element abundances. In all of the six analyses presented, enrichment of Sr and K relative to the other light incompatible element may be related to secondary chemical alteration discussed earlier.

A strong negative Ta-Nb anomaly is thought to be characteristic of calc-alkaline basalts at immature arcs (Atherton et al., 1985; Condie, 1986). This feature is evident in the incompatible element distribution for the analysis from the North Haven Formation. While Ta-Nb depletion is evident in the basalts from the Castine Formation, no strong negative anomaly is apparent. This contrasts the strong negative Ta-Nb anomaly observed by Hon and Thirlwall (1985) in the Silurian and Devonian Newbury volcanic rocks of Massachusetts. They cite this feature as one piece of evidence indicating that the volcanism in this area occurred in an island arc environment. It should be noted that we have not compared their actual data to those data presented in Figure 14.

GEOLOGICAL CONSTRAINTS

North Haven Formation

The disproportionate abundance of mafic over felsic volcanic rocks in the North Haven Formation is consistent with oceanic basalt or basalts of a young island arc. A large number of the basalts are pillowed; therefore, they must have been deposited subaqueously. The proportion of felsic material is consistent with an origin by partial melting of basalt (Gibson, 1969) or by differentiation of a parent basaltic magma (Yoder, 1973). Yoder has calculated that a basaltic magma could yield by differentiation up to 20% of its original volume as felsic rocks. Production of such relatively minor amounts of felsic material in a continental setting appears unlikely since the anatexis of crustal material would result in a greater abundance of silicic rocks than are present (Battey, 1966; McBirney, 1969).

Castine Formation

The voluminous felsic volcanic rocks in the Castine Formation are inconsistent with an origin by differentiation from basalts, and their abundance must mean that they have at least in part been derived by partial fusion of continental crustal material. This contention is supported by the initial Sr^{87}/Sr^{86} value of 0.7079±0.0015 reported by Brookins et al. (1973) for the Castine Formation. Further support for this conclusion comes from the observation of dikes of Castine volcanic rocks cutting the Islesboro sequence which is interpreted to form part of the cover sequence of the Avalon basement. Many of the basalts are pillowed, suggesting subaqueous deposition, but felsic flows are characterized by lapilli tops, perlitic fractures, and columnar joints, features that suggest a terrestrial environment. A large portion of the volcanic rocks in the Castine Formation are agglomerates and tuffs which are characteristic of arc-type volcanism (Gill, 1983). Although no andesites are present in the area of this study, they have been reported within the Silurian-Lower Devonian volcanic rocks of the coastal belt from Castine and the island of North Haven in Maine and from the Newbury volcanic rocks in Massachusetts. Our present knowledge of the regional proportions of basalt, andesite, dacite, and rhyolite in the coastal belt is not good.

SUMMARY AND CONCLUSIONS

The North Haven Formation lies unconformably beneath a sedimentary unit that in turn is overlain by the Silurian-Lower Devonian volcanic rocks. The age of the North Haven Formation is not well fixed; possible ages range from Precambrian to Ordovician. Both units are metamorphosed to pumpellyite-actinolite subfacies of the low greenschist facies. The North Haven

Formation is polydeformed, whereas the Castine Formation is not.

The North Haven Formation consists mainly of basalts. The pillowed nature of some of these basalts suggests a subaqueous origin. Felsites make up less than 10% of the formation, and the proportion of basalt to felsite suggests that the felsites may be differentiation products of basalts in an oceanic environment (i.e., away from continental crust). Because rocks of intermediate compositions are absent and the felsites are sparse, they cannot be used to establish a differentiation trend. However, SiO_2-FeO*/MgO diagrams for the basalts and the presence of only a monoclinic pyroxene suggest a tholeiitic composition.

The TiO_2 contents of the basalts in the North Haven Formation are in the range of typical ocean-floor basalts. However, most of the other major element and trace element data that we have do not distinguish unequivocally among the possible tectono-magmatic settings for the formation. Hf/3-Th-Ta data suggest ocean-floor basalts and the rare-earth element data have similarities to those for ocean-floor basalts. A negative Ta-Nb anomaly in these rocks suggests that they may be part of an immature oceanic arc.

The Castine Formation contains a preponderance of felsic volcanic rocks, much felsic tephra and water-laid volcanic conglomerates, and a smaller amount of basalt, some of which is pillowed. Features related to the cooling of these volcanic rocks suggest mixed terrestrial and subaqueous deposition. The abundance of felsites mitigates against their origin by simple differentiation of basalt but suggests that much of the felsite must have originated by partial melting of continental crustal material. This origin for the felsites indicates that the Castine Formation must have been deposited on continental crust and rules out oceanic origins. Two origins are possible: continental rift and Andean-type arc. The chemistry is far from definitive in discriminating between these two cases. Because it is unlikely that the felsites are differentiation products of basalt, they cannot be used in alkalis-FeO*-MgO or SiO_2-FeO*/MgO diagrams to establish lineage trends. In those diagrams the basalts alone do not establish a trend, and they must be regarded as essentially tholeiitic. The TiO_2 concentrations of the basalts are intermediate between those typical of ocean floor basalts and basalts found in continental rifts. The rare-earth element data are not definitive in determining a tectonic setting, showing similarities to both continental rift tholeiites and calc-alkaline basalts and andesites. The trace element discrimination diagrams that are most successful in classifying the basalts suggest that they were generated in a within-plate environment. Due to the large amount of felsic rocks present in the area and an inferred continental basement for the region, we interpret this to be an ensialic rift. The large amount of agglomerate in the Castine Formation and the existence of andesites in the outlying areas may contradict this conclusion and suggest that the Castine Formation and its associated volcanic rocks in the coastal volcanic belt in general may have formed in an Andean-type plate margin.

To further advance the understanding of the tectono-magmatic character of the coastal volcanic belt in Massachusetts, Maine, and New Brunswick, additional research should focus on expanding the geochemical data base for the volcanic rocks within this belt. The major element oxides, trace elements, and rare-earth elements for the basalts and andesites along the entire volcanic belt will be key to identifying their tectonic setting. Chemical analyses of the Silurian-Devonian andesites and associated basalts that occur on North Haven Island in Penobscot Bay, Maine, and near Newbury, Massachusetts, would appear to be the most logical next phase of research.

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