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Robert G. Marvinney, State Geologist

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Author: *Olcott Gates*

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Editors' Preface

In 1992, Olcott Gates brought to the Maine Geological Survey a preliminary draft of the Geologic Map of North Haven and Vinalhaven Islands. The 1992 draft included unit outlines and structural symbols, a brief explanation of major rock units, three cross sections, and a schematic diagram. At that time, the Maine Survey could not produce color maps in-house. Due to the large expense of color press runs, it was important that each map be in its final form before going to publication. With this in mind, Ollie returned to the islands to clarify parts of the map with complex geologic relationships. In the spring of 1998 he brought to the Maine Survey an updated version of the map with much more detail, especially around the Thorofare. The 1998 draft included unit outlines and structural symbols, a complete and detailed explanation of units, and a narrative description of the geologic history with literature references. By this time, the Maine Survey had developed the capability to publish color maps in-house, allowing the publication process to be more flexible and inexpensive, and allowing photographs to be included directly on the map sheet. He discussed with MGS staff the layout of the map sheet, and the sorts of information he wanted to show on it. He did not bring cross sections with him at that time, because there were still some problems that he had not resolved to his satisfaction. In addition, there was a possibility that laboratory analyses then in progress might be able to determine the age of certain rocks, clarifying their relationships.

Unfortunately, Ollie passed away in July of 1999 before revisions were completed. His wife, Jane, gave materials related to the map to the Maine Geological Survey. These materials included a hand-drafted map (little changed since 1998), two drafted cross sections, seven field notebooks, dozens of field maps of various sizes and quality, and various scraps of paper and mylar with sketches of possible contacts and cross-section configurations, replete with erasures, multiple lines, and even some white-out. Most importantly, a text file was saved on his computer with a lengthy detailed explanation of units, description of structural geology, acknowledgments, references, explanation of symbols, and geologic history. The geologic history included numbered references to photographs which were set aside in a set of plain white envelopes.

Although these materials collectively included all the types of information we had discussed putting on the map sheet in 1998, it soon became clear to us that Ollie had not quite finished ironing out all the details. In particular, there were several places where the text made reference to things that were not on the draft of the map we thought to be the most recent. The cross sections did not quite match the map in a few places. And the explanation of units in his computer file did not include a key to the letter symbols shown on the map. None of the materials after the 1992 version were dated, so we could not be sure in all cases which changes were the most recent. Fortunately, Ollie had been discussing his ideas with other geologists, through letters and on field visits to the islands. These other geologists supplied information that proved crucial to us in matching map units with the explanation, and in deciding which of the interpretations was the most recent. Some of the information they provided is reproduced in appendices to this report. In the fall of 2000, a mockup of the map was reviewed by D. B. Stewart, R. A. Wobus, and R. A. Wiebe who pointed out several of our errors and made substantive comments for which we thank them.

On the final map, Geologic Map 01-352, we have taken cross sections C-D and E-F from Ollie's original drawings. Cross section A-B and the Schematic Diagram were taken from his 1992 draft and modified slightly to conform with the map changes. As much as possible, relationships described in his text were taken to be authoritative, since the text presents an internally consistent interpretation. Consequently, we modified the map and cross sections to conform with his written descriptions. In editing the map and compiling the other information displayed on the map sheet, we were forced to abbreviate the descriptions of rock units and omit some discussion because of space limitations. The purpose of this report is to present Ollie's complete text, from which the map explanation was derived. The brief Introduction is ours. At certain places we have edited the text to make it consistent with what we think is Ollie's most recent interpretation. Most changes are simple, such as changing the name of a fault, but in some instances the original meaning is not entirely clear, as in the nature of the contact between the Seal Cove and Perry Creek formations. In such cases, we have done our best to infer his meaning, and have inserted numbers in brackets [ ] that refer to appended Notes which explain our uncertainty. This may allow other geologists to glean subtleties from his own words that were not apparent to us.

In the end, the points of uncertainty turn out to be minor in comparison with the fundamental soundness of the map. This is an excellent piece of geologic mapping that has significantly improved our understanding of an important and complex part of the Maine coast. It stands as an impressive final installment in Ollie's series of contributions to Maine geology.

Henry N. Berry IV and Robert G. Marvinney
Maine Geological Survey
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Bedrock Geology of North Haven and Vinalhaven Islands

by
Olcott Gates

edited by
Henry N. Berry IV and Robert G. Marvinney

INTRODUCTION

This report accompanies Geologic Map 01-352, Bedrock Geology of North Haven and Vinalhaven Islands. The bulk of the report describes rock units in more detail than could be shown on the map itself. In addition, it offers justification for some of the relationships illustrated on the map, such as the ages of units and their cross-cutting relationships. A table of geochemical analyses representative of the major volcanic rock units is presented, as well as new paleontologic findings.

ACKNOWLEDGMENTS

I am indebted to Arthur J. Boucot, Oregon State University, and J. M. Berdan, U.S. Geological Survey, for identification of my fossil collections from Calderwood Point, Calderwood Island, and Greens Island (Appendix IV). Philip H. Osberg of the University of Maine at Orono helped me in the field with the Calderwood Formation. At my request, David B. Stewart of the U.S. Geological Survey, Washington D.C. made a critical and very helpful review of an earlier version of the map.

I am also indebted to Walter A. Anderson, former State Geologist, and to the other members of the Maine Geological Survey for their unending patience and generous cooperation. The Maine Geological Survey financed the field work during summers part time from 1988 to 1992, and the cost of geochemical analyses. Finally, my wife Jane, also a geologist, has given me field, logistic, editorial, and moral support for half a century.

EXPLANATION OF UNITS

PLUTONIC ROCKS

Mississippian? Devonian?

The assignment of this age to the plutonic rocks is based on a single Rb-Sr age. Brookins (1976, p. 137) reported a Rb-Sr whole rock age for **Dcg** of 353 ± 7 Ma (corrected using the new Rb decay constant of 1.42 x 10^{-11} yr.), Tournaisian (Early Carboniferous) by the Geological Society of America Time Scale (Palmer, 1983)[*1]. The uncertainty of 7 Ma allows for a Devonian age as well. However, other granitic and gabbroic plutons in the coastal Maine belt have isotopic ages in the Silurian-Devonian time interval (Hogan and Sinha, 1989; Hill and Abbott, 1989; Stewart and others, 1988; West and others, 1992) and in some cases, zircon and $^{40}Ar/^{39}Ar$ ages are older than Rb-Sr ages. The Deer Isle granite, which bears a lithologic resemblance to the Vinalhaven coarse-grained granite, has a zircon date of 371 Ma (Stewart, 1998) which is Devonian. Until a reliable zircon date is available, a Devonian age is assumed, to simplify the map symbol (D).

ap Aplite dike.

Dcg Coarse-grained biotite-hornblende granite and quartz-monzonite with a few mantled feldspars. Enclaves and cognate inclusions are rare. On the basis of chemical analyses Mitchell and Rhodes (1989) classified **Dcg** as I-type crustal, minimum melt with some chemical characteristics of anorogenic A-type. Interior of pluton has not been mapped.

Dfg Fine-grained biotite granite. Roof phase of **Dcg**.

Dqd Granodiorite, quartz-diorite. Biotite, hornblende, remnant pyroxene. Includes a dike near Mullen Head.

Dg Gabbro and diabase. Minor diorite. Olivine and pyroxene varieties. Chemical analyses (Mitchell and Rhodes, 1989) indicate a range of compositions. High MgO (8.9-11.8 wt %) gabbros are thought to have accumulated olivine and plagioclase crystals; medium to low MgO (4.1-7.5 wt %) gabbros show evidence of fractionation and contamination by the neighboring granite.

~ ~ Granitic and gabbroic magma mingling zone. Stoped blocks of gabbro, Silurian sedimentary rocks, and pre-Silurian schists are intruded by granitic and diabasic dikes and bounded by dikes consisting of diabase pillows with chilled margins in a matrix of granitic rock. These pillow dikes result from the mingling of basaltic and granitic magma whose differences in viscosity and temperature prevented mixing and the consequent chemical and physical homogenization (Mitchell and Rhodes, 1989, give a brief literature review). The mingling zones indicate intrusion by **Dqd**, **Dfg**, and **Dcg** into an overlying gabbro pluton [*2] which contained stoped blocks of schist (resembling rocks of the Ellsworth Formation) and of unfoliated, contact metamorphosed Silurian rocks including one with Silurian brachiopods (A. J. Boucot letter, 1/31/1990), **Su(f)**, on Greens Island southwest of Vinalhaven. The gabbro blocks cut by granitic and diabasic dikes represent crystallized parts of the gabbro pluton. The pillow basalt - granitic dikes include those with nested pillows separated by thin granitic material, the result of sinking of the pillows which squeezed out the host granitic magma, and those consisting of broken pillows and angular basalt fragments in a granitic matrix. In these the basalt pillows cooled, became brittle, and were broken apart by differential movement of the increasingly viscous host granitic magma. The mingling of the two magmas indicates that parts of the gabbro pluton were still liquid or continued to be fed when intruded by the granitic magma. The circular outline of **Dcg** and associated rocks and the steep to vertical, sharp contacts suggest that the **Dcg** and **Dfg** pluton was emplaced by cauldron subsidence of which intrusion of the gabbro pluton was the initial phase [*2]. Mitchell and Rhodes (1989) report on a detailed geochemical study of the mingling zone.

Dpg Quartz-perthite granite of Otter Island. Devonian age uncertain.

d Diabase dike. Predominantly with northerly trends. Older than **Dcg**, **Dfg**, **Dqd**.

qp Quartz porphyry northwest of Vinalhaven on Dogfish Island, and dikes elsewhere. Of uncertain age. Some are composite with diabase dikes.

r Rhyolite dike, of uncertain age.

METAMORPHOSED PLUTONIC ROCKS

Ordovician? Cambrian?

OЄg Hornblende gabbro. Hornblende laths form strong lineation. Intrusive into **Єcs** [*3].

STRATIFIED AND VOLCANIC ROCKS

Devonian

Vinalhaven Rhyolite

Brookins (1976, p. 138) reported a Rb-Sr whole rock age for the Vinalhaven Rhyolite of 381 ± 6 Ma (corrected), Middle Devonian by the GSA Time Scale (Palmer, 1983). In the absence of a more accurate zircon age, the Vinalhaven Rhyolite is thus assigned to the Devonian. Based on the uncorrected Rb-Sr age and some poorly preserved ostracodes from Fish Head (Seal Cove Formation of this paper) [*4], Brookins and others (1973) assigned an Early Devonian age to the Vinalhaven Rhyolite, a more likely age as **Dvr** overlies **DSp** along a transitional contact [*5].

The Vinalhaven Rhyolite consists of several lithologic units all derived from a siliceous magma that cooled rapidly to glass, subsequently devitrified and hydrothermally altered to greenschist grade. Felsic or mafic phenocrysts are sparse. Its rhyolite classification awaits completion of chemical analyses [*6]. Spherulites in the flow-banded units occur commonly near contacts with underlying bedded rocks from which water vapor was probably derived. The formation probably represents the remnants of a small volcanic eruption center.

Dvr2 Flow-banded rhyolite with autobreccia. Crystallite concentrations mark flow bands. This unit rests on several of the older units, locally along erosional unconformities, and is interpreted as a remnant of a late dome or flow. It overlies the Perry Creek fault and may have been erupted along it. (See Schematic Diagram on the map sheet for presumed relationships.) [*7]

Dvb Coarse, hydrothermally altered rhyolite breccia. Much perlite, possibly due to eruption into a lake in which **Dvt** was deposited.

Dvtb Coarse, crudely bedded to massive crystal, lithic tuff-breccia. A variety of rhyolitic fragments. Reworked coarse tephra.

Dvt Thinly bedded fine-grained tuff. Waterlaid, possibly in a lake.

Dvw Welded vitric, crystal lithic tuff devitrified and altered. Base not welded. A massive unit without internal variations both in outcrop and thin-section. At Fox Rocks it is perhaps 200 meters thick, but thins abruptly along Perry Creek and then pinches out below a unit of **Dvr** [*8]. The initial eruption, which deposited the thin layer now exposed along Perry Creek overlying **DSp**, was followed by subsidence during which **Dvw** continued erupting along or was emplaced against the contemporaneous Fox Rocks fault that offsets the underlying rocks [*9].

Dvr Rhyolite. A complex unit of flow-banded rhyolite, several varieties of autobreccia and mixed breccia. Base is a coarse autobreccia that overlies a once soft maroon tuff-breccia deformed by the basal autobreccia. Spherulites, indicated by black circles on the map, are common above bedded (once wet?) **DSp** rocks. Local perlite. Interpreted to be multiple flows but locally is intrusive into soft **DSp** rocks.

At its base, the Vinalhaven Rhyolite is transitional with the Perry Creek Formation. Red and tan mudstones and siltstones like those of the Perry Creek Formation are mapped within it. It is marked by the first appearance of flow-banded rhyolite in angular to subrounded fragments up to 0.5 meters in size in a coarse-bedded tuff-breccia along with varying amounts of clasts of once glassy feldspathic rocks, tuffaceous siltstones, and a few of basalt. Accompanying rocks in the transition zone are described below as part of the Perry Creek Formation.

Devonian-Silurian

Perry Creek Formation (new name)

This formation underlies the Vinalhaven Rhyolite along a transitional contact perhaps with some local erosion. The Perry Creek and Seal Cove formations apparently overlie the Thorofare Andesite, but the nature of the contact is hidden beneath the Thorofare. Because the stratigraphic interval between **DStrt** and **DSvd** is approximately constant, it may be that the contact is depositional. The map, alternatively, postulates a fault, the Thorofare fault, between the Vinalhaven Diabase and the Thorofare Andesite because a significant part of the Seal Cove Formation appears to be missing [*10].

DSp Near the mouth of Perry Creek above the Vinalhaven Diabase, the Perry Creek Formation is overlain by the basal tuff-breccia of the Vinalhaven Rhyolite along an irregular contact and grades downward through fluvially deposited feldspathic tuffs, tuff-breccias, and pebble conglomerates to laminated and thinly bedded mudstones and argillite like those at Smith Point [*11]. Along the shore from Browns Head to Crockett Cove, the bedded rocks consist largely of rhyolitic tuff-breccias and bedded tuffs, and tuffaceous mudstones and siltstones. Thick coarse massive tuff-breccias, cross-bedding, cut-and-fill, and lensing of different rock types suggest that the Perry Creek Formation portrays increasingly violent approaching volcanism, largely rhyolitic, accompanied by steepening stream gradients and increasingly frequent debris flows.

Vinalhaven Diabase

The Vinalhaven Diabase is a sill within the Perry Creek and Seal Cove Formations [*12]. It was intruded largely into still soft maroon mudstones and siltstones that, locally on the east side of Browns Head and south of Perry Creek, resulted in inclusions of maroon muds and a vesicular top east of Browns Head and a hydroclastite of basalt fragments in a red matrix (**DSvdb**) south of Perry Creek, and hence probably intruded at shallow depth soon after deposition of enclosing **DSp** rocks. However, since the siltstones and mudstones of the Perry Creek Formation were still soft when the basal tuff-breccia of the Vinalhaven Rhyolite was deposited, the Vinalhaven Diabase may be younger than the former. Internal contacts and small faults suggest that parts of the sill are a complex of multiple intrusions. At Fish Head and Crockett Cove it appears to have changed its intrusion horizon [*13].

DSvd Diabase and basalt. Primary mineralogy consists of labradorite, clinopyroxene, and magnetite in a fine-grained intergranular texture. The dominant diabase has xenocrysts of quartz bordered by pyroxene or hornblende and of unidentified feldspar with a once melted interior within a thin rim of clear plagioclase. Other facies include strongly porphyritic, vesicular, and felty textures. Most of the diabase is hydrothermally altered to chlorite, epidote, and saussuritized plagioclase with some remnant clinopyroxene.

DSvdb Breccia of amygdular (chlorite and calcite filled) basalt locally with maroon interstitial hematite. It overlies and was intruded by **DSvd**. Interpreted as a remnant of a hydroclastite (peperite) resulting from intrusion of **DSvd** into very wet muds.

Seal Cove Formation (new name)

DSsc Along the Thorofare beneath the Vinalhaven Diabase, the Seal Cove Formation [*14] is largely maroon tuffaceous mudstone, feldspathic sandstone, and thinly bedded tan argillite. Beneath the **DSvd** sill, to Smith Point and southwest along the shore, the Seal Cove Formation consists of laminated and thinly bedded mudstones and siltstone with fine-scale cross-bedding, flame structures, and soft sediment deformation. Southwest along the shore towards the contact with **Dcg**, these fine-scale structures become increasingly obscured by contact metamorphism to hornfels, producing granular epidote, quartz, calcite, tremolite, and fine-grained biotite. Near Smith Point several less metamorphosed beds have unidentifiable small fossils, probably ostracodes. A shoal exposed at low tide in Seal Cove has beds like those at Smith Point [*15]. As yet unnamed ostracodes at Fish Head resemble those in the Hersey and Eastport Formations of probable Gedinnian age in the Eastport area (Brookins and others, 1973). My hand lens examination suggests that ostracodes found in a low-tide exposure of variegated siltstone and argillite beneath the **DSvd** near Browns Head are probably the same [*16].

DSsct Bedded tuffs [*17].

DSsctb Tuff-breccias. Locally contains small, pink feldspars or coarse chlorite clots with white rims. Some coarse conglomerates and tuff-breccias similar to rocks interbedded with and intruded by **DSta** [*17].

<u>Thorofare Andesite</u>

The Thorofare Andesite underlies the Seal Cove Formation with its probable Gedinnian ostracodes. In the Cox Cove area the Thorofare Andesite overlies a section of Ames Knob Formation ranging in age through most of the Silurian, and includes blocks of fossiliferous Ames Knob rocks within it [*18].

The various flows, breccias, agglomerates, and shallow intrusions have a common mineralogy. The least altered samples have blocky plagioclase phenocrysts with complex oscillatory zoning in the oligoclase-labradorite range, euhedral phenocrysts of clinopyroxene, and magnetite in a pilotaxitic groundmass of plagioclase microlites, commonly showing felty texture, and small euhedral phenocrysts of clinopyroxene, commonly altered to chlorite and hematite. There are a few pseudomorphs of olivine. Locally, particularly near the base, the andesite contains irregular amygdules of chlorite and quartz. Most of the andesitic rocks are very hydrothermally altered to saussuritized plagioclase, calcite, epidote, chlorite, leucoxene, clay, and hematite. Pyroxene is altered to chlorite and hematite. Hematite colors much of the andesite maroon. It replaces groundmass minerals and the original pyroxenes, forms veins and the matrix of breccias, penetrates the margins of andesite blocks, and colors interstitial muds in some breccias. Hot oxidizing hydrothermal solutions must have pervaded much of the andesitic pile.

The Thorofare Andesite is a complex volcanic pile in which individual lithologic units are discontinuous, are both intrusive and extrusive, and include isolated lenses of bedded tuff-breccia and fine-grained tuffs as well as several blocks of fossiliferous Ames Knob Formation. The following units are not listed in stratigraphic order.

DSta Green, purple, gray, and maroon andesite with conspicuous plagioclase phenocrysts and locally flow-banded. Some are clearly intrusive into the volcanic pile. Others with chlorite and quartz amygdules are interpreted as flows.

DStab Purple to maroon andesite breccias and agglomerates particularly prominent on Stimpsons Island and to a lesser extent on Calderwood Point. Includes unmapped **DSta**. Angular to subrounded blocks up to a meter in diameter in a highly oxidized siliceous matrix locally of mudstone. Some breccias are oligomict of andesite blocks only. Others are polymict incorporating large blocks of andesite, bedded round-pebble polymict andesitic conglomerate, tuffaceous cross-bedded sandstone, bedded tephra, and fossiliferous **Sak** rocks. Some lenses of **DStt** and **DStrt** are in sedimentary contact with **DStab** and are overlain and cut out by **DStab** or **DSta**. The oligomict breccias are probably autobrecciated flows. The polymict breccias and agglomerate with hematitic mud interstices are debris flows or lahars mixing various surface rocks including agglomerate blocks violently erupted from a vent.

DStrt A rhyolite vitric tuff of shards, collapsed pumice, and scattered broken quartz and plagioclase crystals. It is overlain by andesite at Telegraph Point and on the Dumpling Islands, and is not the top of the formation.

DStt Tuff, argillite, maroon siltstone, and mudstone. Lapilli tuffs with occasional larger blocks up to a meter across. Bedded tuffs, massive tuffs, amygdaloidal lavas with mud inclusions [*19]. The **DStt** on the Sugar Loaves is very coarsely bedded polymict agglomerate of andesite boulders, cobbles, and pebbles of andesite.

DSl Intrusive latite on Babbidge Island. Oligoclase phenocrysts in a quartzo-feldspathic devitrified matrix [*20].

The Thorofare Andesite is a remnant of an andesitic volcano, but most of the critical contacts with other units are concealed beneath the Fox Islands Thorofare and Carver Cove. The only exposed contact of any length is in the Ames Knob and Cox Cove area. There from west to east successively the Thorofare Andesite rests on gray fossiliferous limey shale along a sheared contact dipping to the south; a lens of shale occurs within andesite breccia; andesite apparently intrudes highly folded dark gray siltstone with distorted brachiopods; and andesite overlies vitric tuff along a sheared contact dipping south. On the west shore of Waterman Cove, andesite overlies and also apparently intrudes highly folded shale. Faulting associated with the Cox Cove fault further complicates the contact. Emplacement of the Thorofare Andesite was accompanied by folding and faulting of the underlying Ames Knob Formation and intrusion along the contact.

The Thorofare Andesite on the islands of the Little Thorofare consists largely of various block agglomerates and breccias that enclose, intrude between, and have sheared contacts with blocks of distorted Ames Knob Formation on Burnt, Stimpsons, and Calderwood Islands. On Calderwood Island siliceous limestone with a probably Llandovery to Wenlock (Silurian) age fauna (A. J. Boucot letters 2/6/91; 3/7/91; see Appendix IV) of brachiopods, corals, bryozoa, and *Tentaculites* is faulted against quartzite and quartz pebble conglomerate, maroon siltstone, bedded tuff, rhyolitic tuff like that on Burnt Island (identical to the vitric tuff beneath andesite at Ames Knob) and folded argillite all assumed to be Silurian. Contacts are highly sheared and many are cut off by intrusive **DSta**. Similarly along the north shore of Burnt Island a shear zone bounds **Sakt**, but does not continue into andesite. The **Sak(f)** block on Stimpsons Island is of Pridolian age (Brookins and others, 1973) and thus younger than that on Calderwood Island although it appears to be structurally lower. On the northwest shore of Calderwood Neck a much distorted and broken block of Ames Knob shale, **Sak(f)**, enclosed by **DStab** has a scrappy fauna of undiagnostic brachiopods and *Tentaculites* which is Silurian (A. J. Boucot letter 3/1/91) and perhaps resembling the fauna on Stimpsons Island (J. M. Berdan letter 9/1/89). (See Appendix IV for excerpts of Boucot and Berdan letters.)

The Thorofare Andesite built a partly subaerial, partly marine volcanic pile in the Late Silurian to Early Devonian Ames Knob shallow sea. The Lower Silurian block on Calderwood Island and its conglomerate and bedded tuffs may comprise a remnant of the Ames Knob Formation through which the Thorofare Andesite initially erupted. Eruption into water explains the extensive brecciation as the lavas chilled. Debris flows were partly subaerial and partly submarine, lubricated by silts, muds, and seawater. Blocks of bedded tephra, stream gravels, sandstones, siltstones, and mudstones are remnants of ash falls, stream sediments deposited on subaerial flanks of the pile, and perhaps mudflat silts and muds that were isolated and engulfed by blocky flows, debris flows, and intrusive sills and dikes as the volcanic pile grew accompanied by fluctuating shallow marine and subaerial conditions on its flanks. Circulation of seawater heated by the erupting andesite produced the very extensive hydrothermal alteration and strong oxidation. The massive agglomerates and breccias, the abundant intrusive andesite, and the blocks of **Sak**, the youngest of which is on Stimpsons Island and structurally below the older one on Calderwood Island, suggest that the Thorofare Andesite of the Little Thorofare area is a partially collapsed vent. Cross section E-F speculatively illustrates this idea. The maroon sands, silts, and muds of the Seal Cove Formation [*21] continue the shallow water and mudflat deposition after the andesitic volcanism ceased in the Early Devonian.

Silurian

Ames Knob Formation

The abundantly fossiliferous Ames Knob Formation ranges in age from late Llandovery through Pridoli (Brookins and others, 1973), which for almost a century has served as a bench mark date in the Penobscot Bay area. Smith (1896) and Smith and others (1907) described the marked difference in metamorphism and structure between the highly deformed North Haven Greenstone and the much less deformed and very fossiliferous Ames Knob Formation, and noting the conglomerate between them (**Scg**), concluded that the two were separated by a period of regional metamorphism and erosion. The Silurian fossils (Niagaran according to Smith) served to divide the rocks of the Penobscot Bay area into metamorphosed Ordovician or older rocks on one hand and Silurian Ames Knob and younger rocks on the other. Today the episode of metamorphism and deformation would be identified as the Taconian orogeny.

Sak Gray, maroon, tan shale, siltstone, limestone, pebble conglomerate, bedded tuffaceous sandstones, and a thin rhyolite shardy tuff. The exposed section suggests deposition in shallow water. The type section along the shore northwest of Ames Knob is folded and faulted. Map units in which fossils have been discovered are indicated by an **(f)**. Although the fauna spans the Silurian from late Llandovery through Pridoli, much section has probably been lost. The occurrences as blocks in the Thorofare Andesite are described above.

Sakt Vitric tuff. Shards, collapsed pumice fragments, and perlite fragments exposed east of Cox Cove and on Burnt and Calderwood Islands [*22].

Scg Basal conglomerate of **Sak**? Angular to subround clasts of the underlying **Ꞓnh** and of bull quartz in a hematitic matrix. It is a colluvium deposit that along its base contains blocks of the immediately underlying North Haven Greenstone. It is in fault contact with the rest of the Ames Knob Formation. It shares the strong foliation of **Ꞓnh** including flattening of clasts. Its proximity is the only evidence that it may be the basal conglomerate of the Ames Knob Formation [*23].

Polly Cove Formation (new name)

The Polly Cove Formation occupies the same stratigraphic and structural position as the Ames Knob Formation, but it is given a different formation name because of differences in lithology, a lack of fossils, and problematic facies relationship to the Ames Knob Formation.

Spct Gray argillite, shale, siltstone, pebble conglomerate, feldspathic bedded tuff, and massive tuff-breccia. Folded and faulted. Hornfelsed near **Dcg**. The bedded tuffs west of Vinalhaven on Green Island and Green Ledge are also assigned to the Polly Cove Formation.

Spcr White-weathering, vitreous, black rhyolite [*24].

Spca Hornfelsed siliceous argillite and calc-silicate. A basal bedded quartz grit lens rests unconformably on the Calderwood Formation.

<u>Undifferentiated Silurian Rocks</u>

These lithologic units are assigned to the Silurian because they are unfoliated and of greenschist facies where not contact metamorphosed.

Su Stoped blocks of contact metamorphosed unfoliated bedded argillite and siltstone in **Dcg** and **Dg**. Block labeled **Su(f)** on Greens Island has Silurian brachiopods (A. J. Boucot letter 1/31/1990; see Appendix IV).

Sut Tuffaceous and argillaceous rocks on Roberts and Hay islands.

Sur Rhyolite intruding **Sut** argillite on Roberts and Hay islands.

Sub Basalt, diabase, and basaltic breccias on Brimstone Island.

Sup Flow-banded plagioclase porphyry on the Brimstone Islands.

Pre-Silurian (Cambrian?)

These formations are foliated, regionally metamorphosed rocks and hence presumed to be older than the Ames Knob Formation. The formations below are not listed in stratigraphic order as their stratigraphic relations to each other are not known [*25].

<u>Calderwood Formation</u>

Foliated blastomylonitic rocks metamorphosed to epidote amphibolite grade. Brown and oxidized biotite associated with late cracks. Except for some possible lapilli in the schist units, pillows in the basalt units, and remnant textures in the latite sill, the mineralogy and textures of the original rocks have been obliterated. In thin section many of the rocks resemble recrystallized mylonites, perhaps part of a broad shear zone. Almost all of the Calderwood Formation is exposed on Calderwood Neck, but Calderwood schists also crop out on a small island northwest of Big White Island, west of Vinalhaven. The pre-Silurian age is based on strong foliation and unconformable contact with **Spca**. Rocks lithologically like the Calderwood Formation have not been found elsewhere in coastal Maine, and its relation to the North Haven Greenstone is unknown.

Ꞓca Quartz amphibolite. Includes a foliated gabbro.

Ꞓcs Quartz-biotite-actinolite schist. Augen of granular quartz and actinolite in a granular quartz matrix. Originally chert, argillite, and siliceous volcanic rocks. Locally pyritic.

Ꞓcl Metalatite sill with sheared margins. Plagioclase phenocrysts in matrix of fine-grained granular quartz, K-feldspar, biotite.

Ꞓcb Sheared pillow basalt on Ash Tree Point. Nesting and vesicular tops suggest younging to the northwest.

Ꞓcp Foliated plagioclase porphyry on Widow Island. Assigned to the Calderwood Formation based only on its foliation and geographical position.

<u>North Haven Greenstone</u>

Ꞓnh Pillow basalts, basaltic tuffs, carbonaceous schist, conglomerate. Highly altered to clays, chlorite, calcite, actinolite, tremolite, leucoxene, iron ores. Only ghosts of original textures remain. Strongly sheared with flattened pillows and mineral streaking and pillow elongation which plunge steeply southwest. Tops indicators such as pillow nesting indicate most dips are to the south and southeast. Structure is a monocline repeated by northeast-trending faults of uncertain age, but assumed to be pre-Silurian because they are parallel to the trends of shearing foliation in the greenstone. To the northeast, the North Haven Greenstone underlies Oak Island and Grass Ledge, and continues on strike to Eagle Island (Pinette and Osberg 1989). Similar rocks are reported by Stewart (1998) as part of the Ellsworth Formation in Deer Isle, implying a probable Cambrian age for the North Haven Greenstone. Pinette and Osberg (1989) conclude that their geochemistry indicates an in-plate origin. The following rock types of inland outcrops too sparse to map with continuity and shoreline exposures too small to differentiate are designated by letter symbols: (g) greenstone, undifferentiated; (p) pillow lava; (q) granular quartz veins common in fault zones; (qc) quartz-carbonate-pyrite veins; (rp) "rotten" pyritic rock, most commonly associated with sheared rocks. In addition, the following units are mapped.

a Argillite.
cg Polymict rhyolite, latite, basalt pebble conglomerate lenses.
gb Gabbro, some unsheared.
sc Black, mylonitic schist.
sd Sheared diabase and gabbro.

Ꞓnhl Latite and rhyolite tuff-breccias, chloritic tuffs, and pillow lavas at Pulpit Harbor and Bartlett Harbor and as lenses in **Ꞓnh** elsewhere.

Fish Point Formation (new name)

Ꞓfp Slightly foliated recrystallized graywacke, devitrified rhyolite, conglomerate of rhyolite pebbles, and sheared limestone on Fish Point and ledges, and highly sheared pyritic feldspar porphyry on the west shore of Waterman Cove. In fault contact with **Ꞓnh** along the Waterman Cove fault and probably with Calderwood Formation along the presumed Cox Cove fault [*26].

Pre-Silurian

Undifferentiated Pre-Silurian Rocks

pSs Crinkly mica schists with quartz lenses and veins, foliated amphibolite, and minor quartzite resembling rocks of the Ellsworth Formation. Occurs in stoped blocks in the granite-gabbro mingling zone and as a roof pendant in the gabbro of the Barley Hill area.

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WHOLE ROCK GEOCHEMISTRY

Bimodal volcanism including abundant rhyolites associated with fossiliferous Silurian sedimentary and volcanic rocks has been described in the coastal volcanic belt eastward as far as the Eastport area and New Brunswick. However, no andesitic volcanism like that of the Thorofare Andesite nor rocks like those of the Calderwood Formation have been described elsewhere within the belt. The petrogenetic and structural place of the Thorofare Andesite and its associated structural blocks in the coastal volcanic belt remains to be solved.

Chemical analyses for the major rock units are presented in Table 1 [*27]. Sample locations are indicated on maps in Appendix V.

TABLE 1. Chemical analyses of rocks from North Haven and Vinalhaven Islands. Major elements reported in weight percent. Fe_2O_3= total iron, assuming all Fe is converted to Fe^{3+} during ignition. L.O.I. = Loss on ignition to 1050 °C. Trace elements in parts per million, except TiO_2 in weight %. Detection limits for trace elements as follows: TiO_2 0.01%; Th and Pb 10 ppm; all others 5 ppm. n.d.=not determined. Analyses performed by X-ray fluorescence spectroscopy at the Regional Geochemical Center, Department of Geology, St. Mary's University, Halifax, Nova Scotia, except FeO and CO_2 determined by the Technical University of Nova Scotia.

	North Haven Greenstone and Fish Point Formation					Thorofare Andesite							
Sample	G85	G117	G179	G183	G346	G121	N30	N40B	N42	N118	N99	VH67A	N270G
SiO_2	51.06	45.49	46.50	47.26	73.89	69.77	60.20	57.15	57.50	58.56	49.98	66.06	76.88
Al_2O_3	13.42	16.06	14.80	14.73	13.39	9.03	16.52	17.77	16.84	16.52	18.33	15.50	11.99
Fe_2O_3	12.20	12.32	12.08	13.56	2.36	8.82	6.96	7.75	8.52	7.79	9.24	6.77	1.26
MgO	3.12	6.43	6.91	6.77	0.70	0.67	3.09	3.99	3.56	3.25	2.78	0.54	0.24
CaO	6.86	7.63	8.90	8.02	0.06	0.65	6.18	3.21	7.01	6.65	6.27	2.92	0.65
Na_2O	5.60	3.20	3.58	3.75	4.43	2.89	2.60	3.36	2.52	2.57	4.62	4.15	3.38
K_2O	0.54	1.44	0.69	0.07	3.37	2.81	2.01	2.32	2.11	2.11	1.19	3.18	3.53
TiO_2	3.13	2.97	2.80	2.78	0.42	0.21	0.81	0.76	0.80	0.82	1.00	0.52	0.14
MnO	0.22	0.17	0.20	0.21	0.03	0.17	0.14	0.15	0.15	0.12	0.23	0.07	0.02
P_2O_5	1.55	0.32	0.60	0.32	0.05	0.03	0.14	0.10	0.11	0.14	0.16	0.15	0.02
L.O.I.	2.70	4.60	2.70	2.90	0.70	4.80	1.80	4.10	1.40	1.60	7.40	0.50	1.50
Total	100.39	100.63	99.76	100.38	99.42	99.83	100.45	100.67	100.53	100.12	101.19	100.35	99.61
FeO	9.16	9.02	8.96	9.89	n.d.	6.96	3.90	4.50	4.83	4.23	1.97	2.33	n.d.
CO_2	0.60	0.98	0.07	0.28	n.d.	4.71	0.30	0.90	0.16	0.24	3.94	0.21	n.d.
Ba	44	424	179	11	376	164	331	372	344	381	260	531	465
Rb	10	14	<5	<5	17	34	50	89	63	56	40	95	139
Sr	181	480	480	331	50	11	222	294	205	219	248	205	55
Y	91	27	42	30	151	626	31	24	26	31	30	50	29
Zr	354	156	244	169	1094	5312	167	123	133	165	147	223	96
Nb	19	15	18	13	51	440	8	6	8	8	9	11	12
Th	<10	<10	<10	<10	10	40	<10	<10	<10	<10	<10	<10	20
Pb	<10	<10	<10	<10	<10	10	10	<10	10	16	<10	18	11
Ga	19	17	20	16	28	49	17	14	15	18	19	17	7
Zn	125	86	95	94	57	151	80	75	81	76	59	46	38
Cu	8	36	53	45	5	8	16	5	23	22	8	7	<5
Ni	5	59	52	60	<5	<5	16	22	10	17	14	<5	5
TiO_2	2.92	2.79	2.40	2.70	0.44	0.20	0.74	0.84	0.78	0.75	0.97	0.50	0.15
V	167	374	280	379	<5	<5	140	211	195	154	155	29	7

Cr	<5	68	147	146
5	<5	44	35	8
50	9	6	11	

North Haven Greenstone: G85 - Pillow lava, Mackerel Point, North Haven (N.H.); **G117** - Pillow lava, east shore of Waterman Cove, N.H.; **G179** - Diabase, head of Southern Harbor, N.H.; **G183** - Pillow lava, head of Southern Harbor, N.H.; **G346** - Rhyolite tuff, north shore of Pulpit Harbor, N.H.

Fish Point Formation: G121 - Rhyolite, Fish Point, N.H.

Thorofare Andesite: N30 - Andesite, north side of golf course, N.H.; **N40B** - Andesite, close to contact, north side of Ames Knob, N.H.; **N42** - Andesite, Ames Knob, N.H.; **N118** - Andesite, golf course hill; **N99** - Andesite, oxidized, north side of the Thorofare, N.H.; **VH67A** - Andesite, south of Swimming Pool, Vinalhaven (V.H.); **N270G** - Rhyolite vitric tuff, Telegraph Point, N.H.

TABLE 1. Chemical analyses of rocks from North Haven and Vinalhaven Islands (continued).

	Vinalhaven Diabase			Vinalhaven Rhyolite					Calderwood Formation			Widow Island porphyry
Sample	V90	V104	N51	VH119	VH121	VH124	VH145	VH377	VH3	VH9	VH12	WI1
SiO_2	55.97	55.05	50.53	76.79	74.17	75.47	74.17	73.65	60.98	64.71	60.24	59.50
Al_2O_3	14.74	15.62	16.29	12.75	13.65	13.60	13.59	13.32	13.83	12.30	14.30	18.32
Fe_2O_3	7.97	7.50	9.52	0.94	1.51	1.64	1.88	2.87	8.50	10.47	7.86	5.00
MgO	5.11	3.58	7.39	0.07	0.11	0.10	0.27	0.42	1.98	3.53	2.37	0.47
CaO	8.71	7.48	8.38	0.24	0.37	0.58	0.71	0.65	5.64	1.93	4.67	1.87
Na_2O	2.63	2.92	3.09	6.01	4.12	4.05	4.03	3.58	1.58	1.14	6.26	6.23
K_2O	1.81	1.77	0.97	1.51	5.00	3.46	3.93	4.06	5.11	3.92	1.58	5.70
TiO_2	1.06	1.20	1.30	0.10	0.11	0.10	0.17	0.21	0.92	0.58	1.22	0.51
MnO	0.14	0.13	0.17	0.02	0.03	0.10	0.04	0.11	0.12	0.10	0.20	0.14
P_2O_5	0.17	0.21	0.10	0.01	0.04	0.00	0.02	0.03	0.17	0.04	0.20	0.14
L.O.I.	2.20	4.80	2.10	0.60	0.10	0.40	0.80	0.70	1.20	1.60	1.50	1.80
Total	100.53	100.25	99.85	99.05	99.21	99.50	99.62	99.60	100.04	100.33	100.40	99.68
FeO	5.23	4.90	6.83	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
CO_2	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Ba	205	213	130	199	382	312	364	308	310	191	113	197
Rb	50	59	40	40	158	187	148	159	101	75	12	42
Sr	423	332	250	29	21	18	48	29	269	233	87	174
Y	35	37	35	75	65	71	67	58	337	371	149	51
Zr	139	141	129	165	174	176	197	182	3378	2295	1148	757
Nb	5	8	<5	12	14	12	14	13	224	122	56	78
Th	<10	<10	<10	14	14	16	14	15	21	18	12	<10
Pb	<10	14	<10	<10	<10	<10	14	<10	14	<10	<10	10
Ga	16	18	14	14	17	16	15	15	66	66	33	33
Zn	68	65	72	7	7	18	23	28	75	81	109	51
Cu	34	18	53	<5	<5	<5	6	<5	13	5	5	9
Ni	35	28	85	<5	6	<5	<5	5	<5	6	<5	<5
TiO_2	0.98	1.17	1.31	0.10	0.10	0.10	0.17	0.23	0.75	0.62	1.10	0.48
V	173	177	193	5	<5	<5	12	17	<5	<5	75	<5

Cr		134	103	191	7
10		12	9	18	<5
<5		6	<5		

Vinalhaven Diabase: **V90** - Diabase sill, south shore of the Thorofare, V.H.; **V104** - Diabase intruding mud, west of Browns Head, V.H.; **N51** - Diabase dike, east shore of Browns Cove, N.H.

Vinalhaven Rhyolite: VH119 - Breccia fragment in breccia along base of rhyolite, V.H.; **VH121** - Flow-banded rhyolite along road near radio tower, V.H.; **VH124** - Breccia on hill northwest of end of Long Cove, V.H.; **VH145** - Welded tuff near base, east shore of Crockett Cove, V.H.; **VH377** - Welded tuff, near top of Middle Mountain, V.H.

Calderwood Formation: VH3 - Quartz amphibolite, on shore east of Polly Cove, V.H.; **VH9** - Schist, east shore of Carver Cove, V.H.; **VH12** - Latite, on shore northwest of Salt Works Cove, V.H.; **WI1** - Porphyry, Widow Island.

Editors' Notes

[*1] The absolute ages assigned to the Geologic Time Scale are continually revised as new information becomes available. In the text, Gates has used the 1983 G.S.A. time scale of Palmer. On the map, we show a portion of the geologic time scale using revisions recommended by R. D. Tucker and W. S. McKerrow (Canadian Journal of Earth Sciences, 1995, v. 32, no. 4, p. 368-379).

[*2] In 1996, Ollie Gates introduced the geology of Vinalhaven to Robert A. Wiebe of Franklin and Marshall College. Wiebe was particularly interested in the relationships between granite and gabbro, especially in the mingling zones that Ollie had mapped. Based on his prior experience in similar igneous complexes at Pleasant Bay and on Mt. Desert Island, Maine, Wiebe formulated a model of the Vinalhaven pluton in which the granite magma chamber was intruded by gabbro, and rocks near the south and east margins of the granite were near the base of the magma chamber. Wiebe brought a group of students to Vinalhaven in the summer of 1998 to study igneous features in several small areas to test and refine this model.

It is not clear to the editors to what extent Ollie had adopted these new interpretations. The model described in the manuscript, that the granite intruded an overlying gabbro, had been developed by Ollie before 1996, mainly to account for the angular blocks of gabbro in the granite concentrated toward the east margin of the pluton, and the large area of metamorphic rock near Barley Hill which he interpreted as a roof pendant. He thought these had sunk into the granite magma, and therefore must have come from higher levels. He obviously did agree that the textures described by Mitchell and Rhodes (1989) indicated commingling of mafic and granitic magmas, and his statement that gabbro "continued to be fed" after the granite magma had intruded is entirely consistent with Wiebe's model of mafic replenishments. Comments to the editors in 2000 by Wiebe and R. A. Wobus (Appendices II and III), who had been having ongoing discussions with Ollie, suggest that their observations had impressed upon him that there was more commingling of magmas than he had originally thought. At the same time, it is not clear to the editors whether he had abandoned the idea that the eastern side of the pluton was near the roof of the magma chamber. As Weibe points out, Ollie had not drawn any cross sections through the pluton that might have illustrated his interpretation. Furthermore, we are not sure just when Ollie wrote the present manuscript. So we have decided to retain Ollie's text, even though it may not reflect his most recent thinking.

[*3] Gates had listed this unit under the Calderwood Formation in his explanation.

[*4] Gates's manuscript assigned the Fish Head locality to the Perry Creek Formation, but his map clearly shows it to be in the Seal Cove Formation. In fact, his manuscript does not separate the Seal Cove Formation from the Perry Creek Formation at all; rocks of both formations are included in the Perry Creek. The editors believe this to indicate that the map was revised to divide the Seal Cove Formation from the Perry Creek Formation after the manuscript had been written. Therefore, general references in the manuscript to the "Perry Creek Formation," we have replaced with "Perry Creek and Seal Cove formations"; and specific references to the lower part of the "Perry Creek Formation," as in the case of the Fish Head locality, we have replaced with "Seal Cove Formation" to agree with the map and with Ollie's 1998 written communication to Bud Wobus (see Appendix I).

[*5] The argument presented here is that the Vinalhaven Rhyolite is not substantially younger than the Gedinnian? (Early Devonian) fossils at Fish Head, and therefore is more likely Early Devonian than Middle Devonian as the Brookins (1976) Rb-Sr age would indicate. This argument relies on the fact that the contact between the top of the Perry Creek Formation and the base of the Vinalhaven Rhyolite is transitional, implying no time gap. Also implicit in the argument is the interpretation that the fossils are in the Perry Creek Formation. But separating the Seal Cove Formation from the Perry Creek Formation after the manuscript was written (see note 4), means that the Fish Head fossil locality is now assigned to the Seal Cove Formation. In the Geologic History (see map), Gates suggests that uplift and erosion may have occurred after deposition of the Seal Cove Formation. In that case, the argument that the fossils and the Vinalhaven Rhyolite are close in age may be less compelling.

[*6] The geochemical analyses presented in Table 1 include samples from the Vinalhaven Rhyolite, which are classified as rhyolite on standard geochemical classification diagrams (see note 27). This sentence in the text suggests it was written before Ollie had interpreted the geochemical analyses.

[*7] One of the uncertainties on the map is whether a definite age sequence can be determined among the flow units in the Vinalhaven Rhyolite. On Gates's 1992 draft map, all flow units were labeled "Dvr" even though it was apparent that they were not all the same age. His schematic diagram clearly shows a younger dome of Dvr cutting through an older unit of Dvr; and the explanation on the 1992 draft says about the Vinalhaven Rhyolite "The above units not in order of age. Dvw underlain and overlain by Dvr." On that draft, the Perry Creek fault is drawn through the length of Perry Creek and through the length of Crockett Cove, but it does not continue across the intervening land. Instead, a continuous unit of Dvr spans the region where the fault would be projected. This relationship implies that the Perry Creek fault was buried beneath the rhyolite flow, as stated in the text. At some time after 1992, Gates had relabeled this area between Perry Creek and Crockett Cove Dvr2, apparently to indicate that it was younger than other units of Dvr. However, on the 1998 draft, the Perry Creek fault was drawn continuously through the rhyolite to connect with the fault in Crockett Cove (as shown on the final map). Interestingly, the fault was drawn through the old Dvr2 lettering that had been only partly erased. By this new interpretation, the unit that had been Dvr2 was now divided by the fault into northwestern and southeastern parts, with all units labeled Dvr. The map explanation, however, lists two units of rhyolite flows. Unfortunately, no unit labels were given, but the younger unit is described as a "late dome or flow," while the older unit is described as being transitional with the Perry Creek Formation at its base. Furthermore, one is listed above the welded tuff unit Dvw and the other is listed below it in the explanation. Together, we take these indications to mean that the unit northwest of the fault, which rests on the Perry Creek Formation, is the older unit, and the unit southeast of the fault, which rests above the welded tuff unit, is the younger unit. On a separate paper copy of the map, Ollie has labeled some of the units Dvr2 and others Dvr1 in a way that is consistent with this interpretation and consistent with the cross sections. While we don't know for certain when he labeled that paper copy, we have followed it here in labeling the younger unit Dvr2. We decided not to label the older units Dvr1 because not all of them were labeled on the paper copy, and they may well be of different ages. Therefore the older units, most of which rest below Dvw, are labeled simply as Dvr, allowing that several flow units and intrusive units of various ages are probably included.

[*8] The manuscript at this place says "pinches out below Dvr1," but the map unit to which it apparently refers is labeled only Dvr. Since we have decided not to use Dvr1 on the map (see note 7), we have substituted "beneath a unit of Dvr."

[*9] The Fox Rocks fault was not labeled on the draft map. It is clear from context to which fault it refers.

[*10] This is another place where Ollie had considered two interpretations to account for the apparent change in breadth of the Seal Cove Formation from Seal Cove to Fish Head. By one interpretation, the thinning to the northwest was caused by uplift and erosion of the Seal Cove Formation before deposition of the Perry Creek Formation producing an angular unconformity. This interpretation is described in the Geologic History. The other interpretation, illustrated on the map and cross sections, calls for the Thorofare fault to cut out the lower part of the Seal Cove Formation under the Thorofare. The Thorofare fault was not shown on the 1992 draft map, and it was not described in the map explanation, so it appears to the editors that it was a recent interpretation. The editors have inserted the last sentence in this paragraph to reflect the map interpretation. We think, however, that Ollie would still favor an unconformity beneath the Perry Creek Formation, in addition to truncation of the lower Seal Cove Formation along the Thorofare fault.

[*11] The rocks at Smith Point are now assigned to the Seal Cove Formation. This sentence may be describing the stratigraphic section from the Vinalhaven Rhyolite down through the Perry Creek Formation into the Seal Cove Formation (see note 4).

[*12] The original manuscript read "... a sill within the Perry Creek Formation," but the diabase intrudes near the contact between the Perry Creek and Seal Cove Formations as indicated on the map and cross sections (see note 4).

[*13] On the southeast side of Crockett Cove, the diabase intrudes below the Perry Creek-Seal Cove contact, within the Seal Cove Formation (see note 4).

[*14] In the original manuscript, this paragraph was included under the Perry Creek Formation. The editors have substituted Seal Cove Formation in this paragraph for Perry Creek Formation (see note 4).

[*15] The location of this shoal is not known to the editors.

[*16] The location of this low-tide exposure is not known to the editors. It may be below the Fish Head locality. The map does not indicate a mappable unit of Seal Cove Formation beneath the Vinalhaven Diabase southwest of Fish Head on Browns Head.

[*17] Units DSsct and DSsctb were indicated on the map, but no description was given. Their descriptions have been taken from Ollie's field notes.

[*18] The implication is that Seal Cove fossils above and Ames Knob fossils below bracket the Thorofare Andesite to Late Silurian-Early Devonian in age.

[*19] Unit DStt was indicated on the map, but the only description was for rocks on the Sugar Loaves. The rest of the description was taken from Ollie's field notes.

[*20] Description taken from 11/1/97 letter from Ollie to Peter Garrett, Waterville, Maine.

[*21] Seal Cove Formation has been substituted here where the manuscript has Perry Creek Formation. (See note 4)

[*22] Units of Sakt were not delineated on the mylar draft map. They were shown, however, on a paper copy of the map that Ollie had modified with a pen and white-out. The locations of units labeled Sakt on that modified copy correspond to the locations described in the text. On previous drafts these units of tuff were assigned to the Thorofare Andesite as unit DSttb.

[*23] On Ollie's 1992 draft map, this unit is described as "Basal conglomerate of Sak," yet the 1998 draft manuscript is much more equivocal. We think that he came to doubt the longstanding view of Smith and others (1907) that the conglomerate was part of the Ames Knob Formation. The features he describes show that the conglomerate has little in common with the Ames Knob Formation. Perhaps because Smith and others had included it with the Ames Knob, he still allows for that possibility. Even though it is listed in the explanation under the heading of Ames Knob Formation, Ollie did not assign it a symbol such as Sakc, which would be the conventional way to indicate a unit within a formation.

[*24] The unit Spcr appears on both the 1992 and 1998 draft maps, yet is omitted from the explanation. The unit description is taken from Ollie's field notes, which suggest the "r" stands for rhyolite.

[*25] Ollie had designated the age of these units as "Pre-Silurian" since the beginning of the mapping project, an age range which is required by the fact that the metamorphism which affects them does not affect the Silurian and younger rocks. We have added the slightly more restrictive "Cambrian?" designation because of Ollie's stated belief that some of these units probably correlate with the Ellsworth Formation east of Penobscot Bay, for which a Cambrian age has recently been determined (Stewart, 1998).

[*26] The fault referred to in the manuscript as the Cox Cove fault was labeled as the Fish Point Ledge fault on the 1998 mylar. It is not clear to us why one name should be preferred over the other, so we have chosen to use Cox Cove fault. By this we do not mean to imply any particular age relationship between the Waterman Cove fault and the Cox Cove fault. Indeed, in his text concerning Structural Geology (see map), Ollie interprets the two faults to have been active at the same time.

[*27] While Ollie collected the samples and obtained the chemical analyses, the editors do not know the extent to which he had analyzed the results. We have taken the

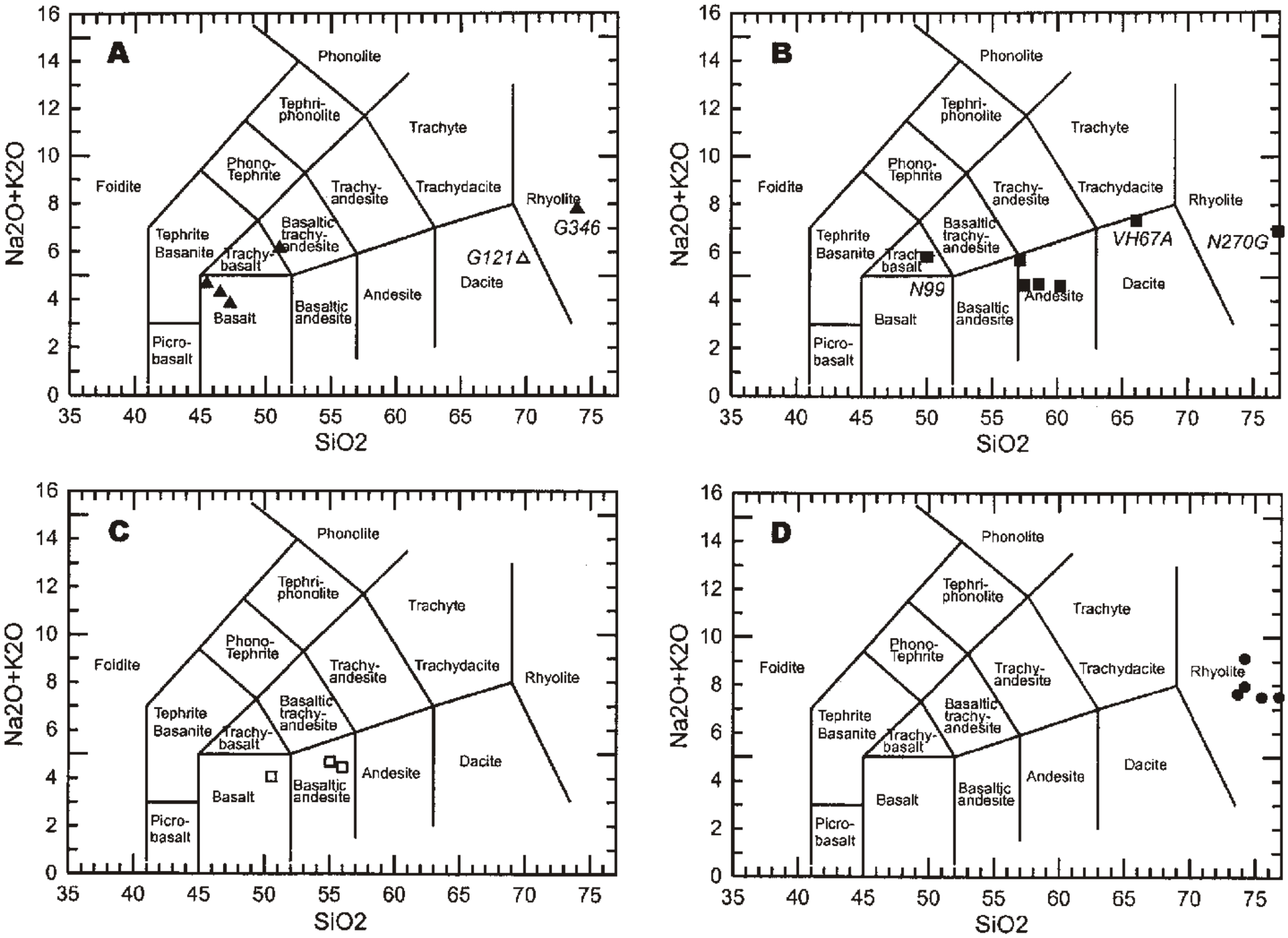


Figure 1. Geochemical classification of analyzed samples according to the SiO_2 vs. Na_2O+K_2O plot of LeBas and others (1986). Plotted by formation: A. North Haven Greenstone, including a rhyolite (G346) from the latite member (Ꞓhnl), and a dacite (G121) from the Fish Point Formation. B. Thorofare Andesite, including a rhyolite vitric tuff (N270G). C. Vinalhaven Diabase. D. Vinalhaven Ryolite.

liberty of plotting the geochemical data on standard diagrams as a way to present the data. Figure 1 shows an SiO_2 vs. alkalis (Na_2O+K_2O) classification plot after Le Bas and others (1986)[1]. For the North Haven Greenstone (Figure 1A) the mafic lavas plot generally as basalt, the sample from the latite member at Pulpit Harbor (G346) is rhyolite, and the sample from the Fish Point Formation (G121) is dacite. For the Thorofare Andesite (Figure 1B), four samples plot as andesite, one (VH67A) as dacite, and a vitric tuff at Telegraph Point (N270G) is rhyolite. Sample N99, plots in the field of trachybasalt, but the sample is described as "oxidized," so it might not represent a magmatic composition. The Vinalhaven Diabase samples (Figure 1C) plot as basalt to basaltic andesite, and the Vinalhaven Rhyolite samples (Figure 1D) plot clearly in the rhyolite field (see note 6).

Two discriminant diagrams, shown in Figures 2 and 3, compare the analyzed rocks with rocks formed in modern tectonic environments based on certain trace element compositions. Figure 2 shows the manganese, titanium, and phosphorous proportions of the mafic rocks in comparison with rocks in various modern oce-

[1]Le Bas, M. J., LeMaitre, R. W., Streckeisen, A., and Zanettin, B., 1986, A chemical classification of volcanic rocks based on the total alkali-silica diagram: Journal of Petrology, v. 27, p. 745-750.

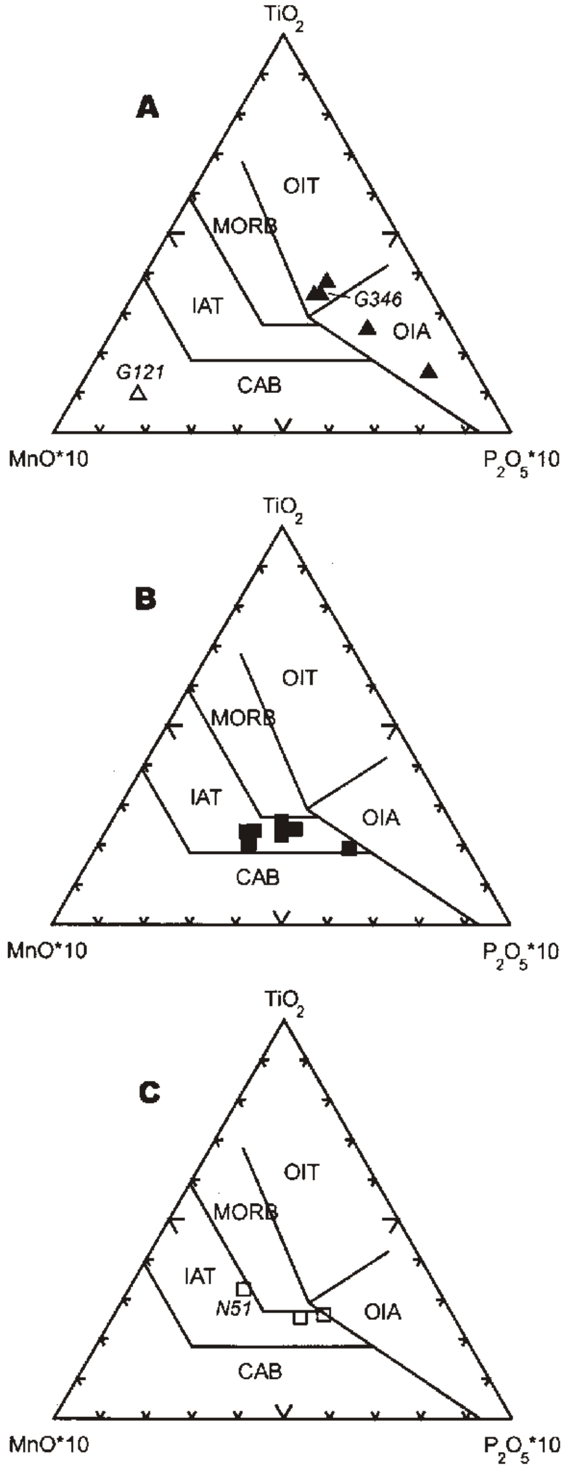


Figure 2. Tectonic setting of analyzed samples according to the MnO(x10)-TiO_2-P_2O_5(x10) plot of Mullen (1983). Fields show typical values for ocean island tholeiites (OIT), ocean island andesites (OIA), mid-ocean ridge basalts (MORB), island arc tholeiites (IAT), and calc-alkaline basalts (CAB). Samples are plotted by formation: A. North Haven Greenstone, including a rhyolite (G346) from the latite member, and a dacite (G121) from the Fish Point Formation; B. Thorofare Andesite; and C. Vinalhaven Diabase.

anic environments according to Mullen (1983)[2]. The North Haven Greenstone samples (Figure 2A) plot in the fields of ocean island volcanics, consistent with the interpretation of Pinette and Osberg (1989), and supporting Ollie's view of eruption on the Cambrian ocean floor (see Geologic History on the map sheet). The North Haven samples are are distinct from the Thorofare Andesite (Figure 2B) and Vinalhaven Diabase (Figure 2C), which plot in the field of island arc rocks, suggesting they formed along a convergent plate boundary related to a subduction zone.

Figure 3 shows Y+Nb vs. Rb compositions for the felsic rocks in comparison with fields of granite in various modern tectonic environments according to Pearce and others (1984)[3]. The North Haven Greenstone (G346) and Fish Point (G121) samples plot in the field of ocean ridge granites. The rhyolite from the Thoro-

[2] Mullen, E. D., 1983, MnO/TiO_2/P_2O_5: a minor element discriminant for basaltic rocks of oceanic environments and its implications for petrogenesis: Earth and Planetary Science Letters, v. 62, p. 53-62.

[3] Pearce, J. A., Harris, N. B. W., and Tindle, A. G., 1984, Trace element discrimination diagrams for the tectonic interpretation of granitic rocks: Journal of Petrology, v. 25, p. 956-983.

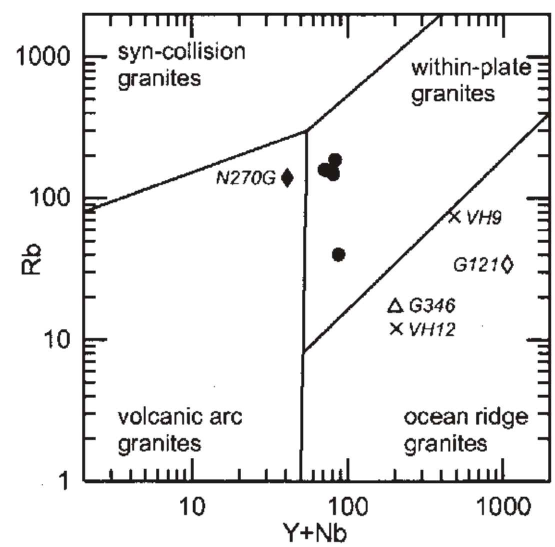


Figure 3. Tectonic discrimination diagram for the rhyolites and dacites based on Y+Nb vs. Rb after Pearce and others (1984). Rhyolite (G346) from the North Haven Greenstone, dacite (G121) from the Fish Point Formation, latite (VH12) and dacite (VH9) from the Calderwood Formation plot in the field of ocean ridge granites. Rhyolite tuff (270G) of the Thorofare Andesite plots in the field of volcanic arc granites. All five rhyolites (circles) of the Vinalhaven Rhyolite plot in the field of within-plate granites.

fare Andesite (sample N270G) plots as a volcanic arc granite. Rhyolites from the Vinalhaven Rhyolite plot in the field of within-plate granites. Thus, the felsic rocks from the three formations are distinct from one another and consistent with the setting indicated for the mafic rocks in Figure 2.

An array of trace elements is displayed in "spider diagrams" in Figure 4. Spider diagrams show the trace element abundances of the analyzed rocks in comparison with the abundances of the same elements in typical mid-ocean ridge basalt (MORB), here using the values of Pearce (1983)[4]. As does Figure 3, these diagrams show that rocks from within a unit are similar, and rocks from different units are chemically distinct from each other.

The samples from the Calderwood Formation, including one sample (WI1) from Widow Island, are plotted on chemical diagrams in Figure 5. The four samples scatter across the dacite, trachyandesite, and trachyte fields of the SiO_2 vs. alkalis (Na_2O+K_2O) classification plot (Figure 5A). The plot of Mullin (1983) suggests a volcanic arc setting (figure 5B), whereas the felsic rocks (VH9, VH12) suggest an oceanic setting (Figure 3). The spider diagram (Figure 5C) shows a consistent pattern among the four samples, with similarities to the felsic rocks (G346 and G121) of the North Haven Greenstone (Figure 4A), particularly with respect to the relatively high values of niobium (Nb) and zirconium (Zr). Some of the scatter displayed in the major element diagram (Figure 5A), and the apparent

[4]Pearce, J. A., 1983, Role of sub-continental lithosphere in magma genesis at active continental margins, *in* Hawkesworth, C.J., and Norry, M. J. (editors), Continental basalts and mantle xenoliths: Shiva Publishing Co., Cheshire, U.K., p. 230-250.

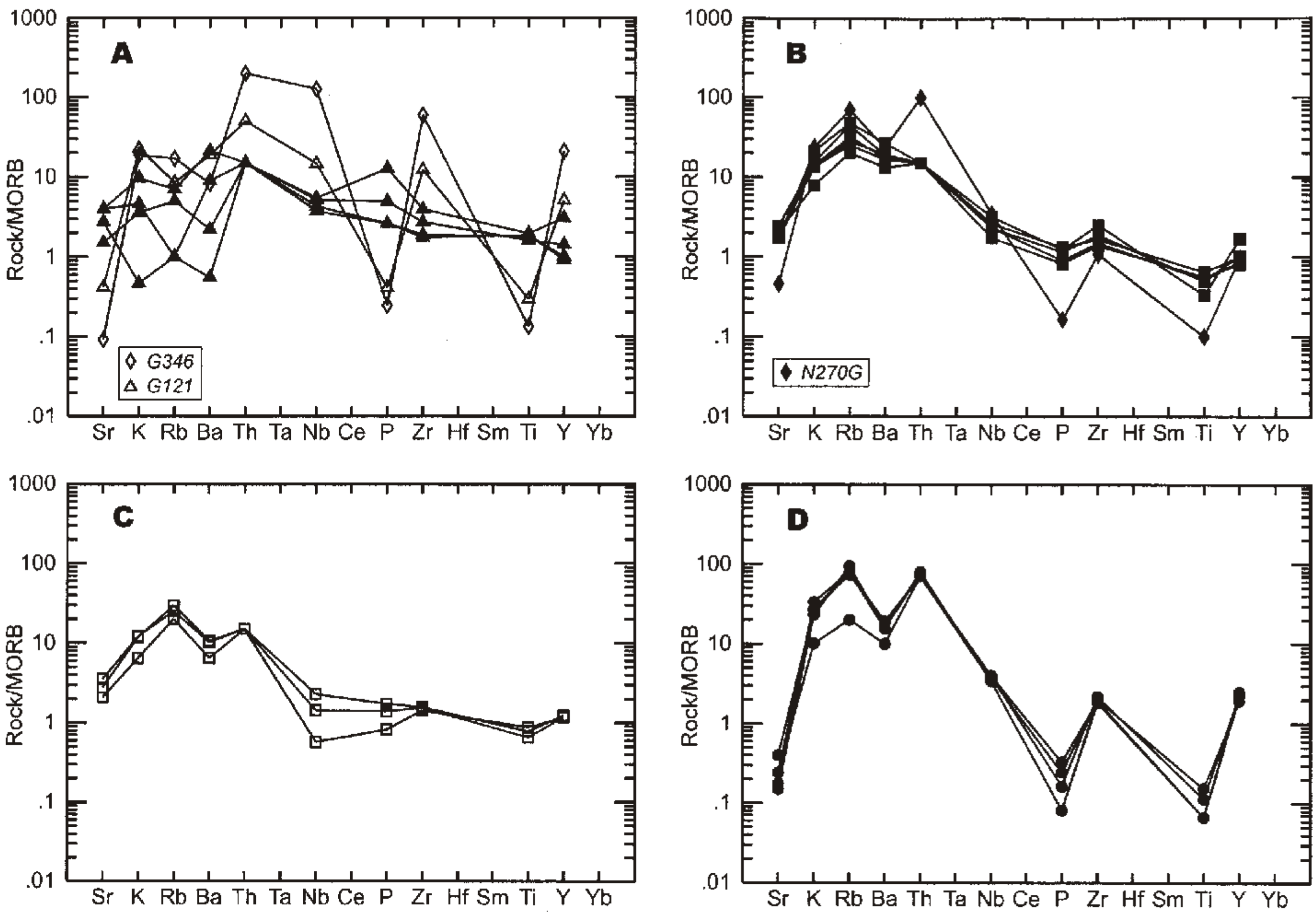
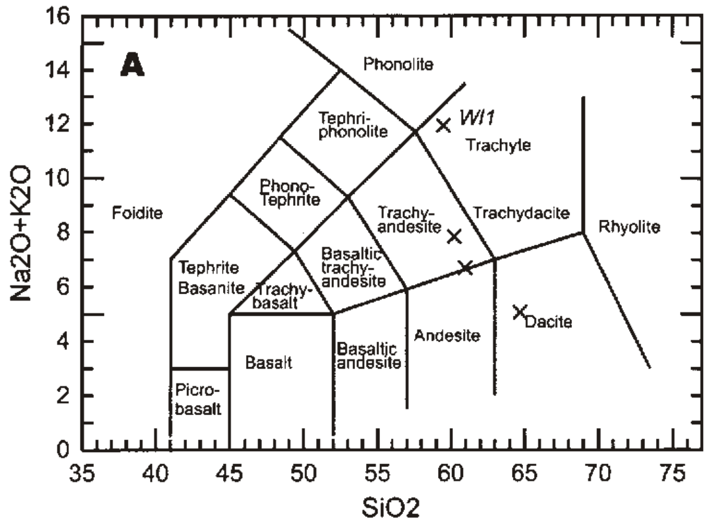
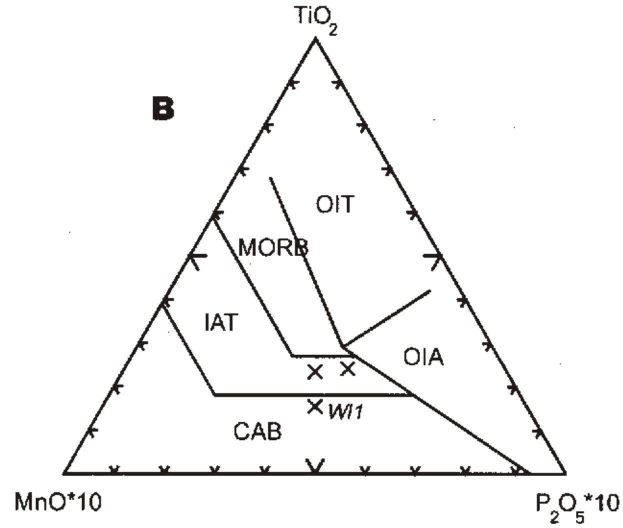


Figure 4. Spider diagrams of analyzed samples normalized to MORB using values of Pearce (1983). Plotted by formation: A. North Haven Greenstone, including a rhyolite (G346) from the latite member, and a dacite (G121) from the Fish Point Formation; B. Thorofare Andesite, including a vitric rhyolite (N270G); C. Vinalhaven Diabase; and D. Vinalhaven Rhyolite.





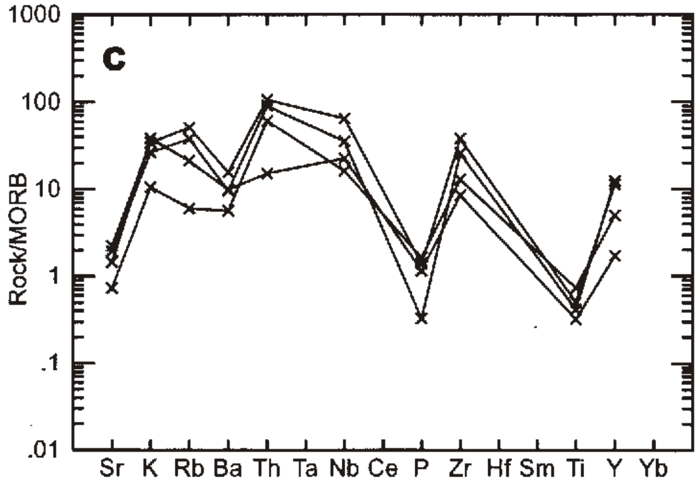


Figure 5. Geochemistry of three samples from the Calderwood Formation and one from Widow Island (WI1). A. Classification according to the Na_2O+K_2O vs. SiO_2 plot of LeBas and others (1986). B. Tectonic setting for the less silicic rocks (SiO_2<63%) according to the MnO(x10)-TiO_2--P_2O_5(x10) plot of Mullin (1983). C. Spider diagram normalized to MORB using values of Pearce (1983).

inconsistency in tectonic setting between Figures 3 and 5B may reflect chemical changes during metamorphism.

[*28] The manuscript refers to "David B. Stewart (personal communication)." The editors have substituted the reference to Stewart's map, which contains the information, but was published only a short time before Gates's death.

APPENDIX I

Partial stratigraphic column, hand-written by Ollie Gates for Bud Wobus, 7/27/1998

Silurian-Devonian

<u>Perry Creek Formation</u>

SDp Bedded maroon, purple, white vitric, crystal, lithic tuffs, tuff-breccia and interbedded tuffaceous siltstone, pebble conglomerate. Coarse breccias of flow-banded rhyolite signal beginning of rhyolitic volcanism.

<u>Seal Cove Formation</u>

SDsc Red, maroon, green, purple shales, siltstones, and sandstones - Along shore south of Smith Point hornfelsed towards granite contact.

<u>Thorofare Andesite</u>

SDta Green, purple, tan porphyritic andesite sills, dikes and flows.

SDtab Purple to maroon andesite breccias. Angular to rounded blocks up to a meter in highly oxidized siliceous matrix locally of mudstone. Breccia locally engulfs inclusions of round-pebble andesitic conglomerate, sandstones and fossiliferous Silurian (Ames Knob) sediments. Interpreted as rubbly andesite flows, debris flows, avalanche deposits.

SDttb Mixed andesitic-rhyolitic polymictic tuff breccias.

SDl Intrusive latite on Babbidge Island.

Silurian

<u>Ames Knob Formation</u>

Sak Gray, maroon, tan shale, siltstone, limestone, pebble conglomerate, and bedded lithic tuffs. Llandovery to Pridolian fauna. Includes blocks in SDta.

Scg Basal conglomerate of Sak? Angular to subround clasts of underlying pSnh in hematitic matrix. Colluvium deposit?

<u>Polly Cove Formation</u>

Spct Gray argillite, shale, pebble conglomerate, feldspathic tuff, much folded and faulted.

Spca Siliceous argillite. Bedded quartz grit lens unconformable on Calderwood Fm.

APPENDIX II

Letter Excerpt from Reinhard A. Wobus to Henry Berry, 10/12/2000

... You have done an excellent job of portraying Ollie's map and of representing what I believe were his ideas about the area. I know you want to keep this Ollie's map in spite of some of the new ideas that have developed since he put it together. I'm sorry we were unable to convince him about several things related to the Vinalhaven granite—e.g., basaltic/gabbroic magma intruded a granitic mush more than the other way around. And the age question of what are likely co-magmatic hybrid plutonic and volcanic rocks remains unanswered, although we ought to have some good zircon dates at some point. [Ollie's] caveat in the [text] about the likely unreliability of Brookins' Rb-Sr ages is good.

Our work in the volcanics verifies Ollie's mapping and generally supports his stratigraphy and interpretations, though the portrayal of the welded tuff unit of the Vinalhaven rhyolite in the schematic cross section seems implausible; a welded tuff (a subaerial unit) wouldn't drape around a subsided cauldron block as shown.

APPENDIX III

Letter Excerpt from Robert A. Wiebe to Henry Berry, 10/26/2000

... The only thing that I found troubling was the retention of his [Gates's] early plutonic interpretations. I thought, though I could be wrong, that he realized that the depositional features (particularly, the pipes, I thought, impressed him) associated with the gabbroic rocks required that the eastern and southern sides of the pluton must really be the floor of the chamber, not the roof as he originally preferred. The occurrence of the volcanics on the NW margin of the intrusion certainly lends strong support to this notion. It seems apparent, then, that [the large area of metamorphic rocks at] Barley Hill is not a "roof pendant" but simply more large stoped blocks, just like those seen along the coast. It also seems likely, looking at his attitudes on the metamorphic rocks, that that area of metamorphic rocks is likely to be many separate blocks sitting within the gabbro/diorite.

APPENDIX IV

Letter excerpts from J. M. Berdan and A. J. Boucot to Olcott Gates, 1989-1991

Excerpt 1: J. M. Berdan to Jane and Ollie Gates, September 1, 1989

"Well, I have taken a preliminary look at the collection from Calderwood Point, Vinalhaven Island, and although they look good in the hand, under the microscope they are not so hot. The slabs have molds and casts of chonetid, rhynchonellid and spiriferid brachiopods, some pelecypods, bryozoans, beyrichiid ostracodes, crinoid columnals, etc., but nothing that is identifiable even generically. However, the general association is like that reported from Stimpsons Island by Brookins, Berdan and Stewart (GSA Bull., v. 84, p. 1619-1628, May, 1973), and I have a hunch that this may be the same stuff. I think that you probably have a copy of the GSA paper, but am enclosing a copy of the original report to Dave Stewart, which you may not have. As you will see from the enclosed report, the collections from Stimpsons Island were not very good, either."

[Note written on bottom in Ollie's hand: "Inclusion in Thorofare Andesite on Calderwood Point."]

Excerpt 2: A. J. Boucot to Ollie Gates, January 31, 1990

"Your little box arrived safely, and has been unduly unwrapped! The material is, as you know, kind of scrappy. BUT, when everything is taken into consideration I would have to conclude that it's probably of Silurian age, and probably Upper Silurian. The "logic" is as follows: 1) in the Coastal Belt the youngest marine, pre-Acadian fossils known are earliest Devonian (Gedinnian stuff from the Eastport Fm. and equivalents); 2) your hornfels yielded fragments of a rhynchonennid [sic*] (the kind of thing I commonly refer to as "<u>Camarotoechia</u>"), and a finely costellate chonetid that is similar to materials I've called <u>Protochonetes</u> in the past (such as your Leighton Shale Coll. No. 17086). Chonetids don't come in worldwide until the latest Ordovician (Anticosti only), and don't become common until the later Llandovery (later Lower Silurian). So...sounds like you have something that would probably be pre-Pembroke Fm. type fauna (some of that fauna is known on North Haven, a locality of Dave Stewart's that I collected some time ago). I suspect that you might be able to match your stuff up if you got back to North Haven and worked in the pre-Pembroke Formation type faunas."

[* rhynchonellid]

[Note written on bottom in Ollie's hand: "Inclusion in mingling zone on Greens Island"]

Excerpt 3: Ollie Gates to A. J. Boucot, October 4, 1990

"I found another new fossil occurrence, this time on Calderwood Island east of North Haven. It appears to be from a large block of well-bedded limestone and argillite in the Thoroughfare [sic] Andesite, perhaps a slump block within a caldera. It is a very scrappy collection because the limestone beds are thin, have weathered into small valleys between the argillite beds, and the whole block is somewhat hornfelsed. It is of mostly small horn corals, bryozoa, and a few brachs, not typical of many Silurian collections I have made over these many years. It would take a real expert to get the age even in the ball park, so I'm asking if you would mind taking a look at it. I don't really expect any results but it is worth a try."

Excerpt 4: A. J. Boucot to Ollie Gates, February 6, 1991

"Figured I'd better write you to "confirm" what we just said over the phone! NF-178, Calderwood Island, certainly looks Upper Llandovery to early Wenlock to me (and more likely Llandovery) because of the smooth pentamerinid. It's the kind of thing we used to always call <u>Pentamerus oblongus</u>, but since with your somewhat scrappy collection I couldn't make out whether or not there is any trilobation I'd probably call it "<u>Pentamerus</u>" today to indicate a smooth pentamerinid with discrete brachial lamellae (no median septum as in <u>Pentameroides</u>). I'll call Bill Oliver on Friday and see if I can con him into looking at your corals (which are not all that bad, although maybe coming from me that doesn't mean too much).

"NF 60 will need some acid work—all I could see on the weathered surfaces are nondescript rhynchonellid brachs. Wouldn't dare say much about age based on them."

[Note written on bottom in Ollie's hand: "Calderwood Island **Sak**"]

Excerpt 5: A. J. Boucot to Ollie Gates, February 13, 1991

"The Stimpson's Point [sic*] material is CERTAINLY much younger than your Calderwood Point collection. <u>Quadrifarius</u> is still a Pridoli-Geddinian age item (and abundant <u>Salopina</u> are known from coastal Acadia mostly in the Pridoli (including Arisaig, Nova Scota). So...guess you still have a real headache."

[*Stimpsons Island]

Excerpt 6: A. J. Boucot to Ollie Gates, March 1, 1991

"As far as I can see your #56, Calderwood Point collection has lots of a chonetid, probably a protochonetid, a Howellella, a "Carmartotoechia" [sic] type rhynchonellid, a dalmanellid (rare, and I'm not sure of its identitiy), a trilobite scrap or two, and lots of Tentaculites. The small Howellella suggests a C_3 (Llandovery) - Pridolian or even earlier Gedinnian age span—that's about all I could say. Ecologically I would guess for pretty shallow water, nearshore, subtidal conditions (lots of crinoidal debris), in about the B.A. 2 position in view of the overall abundance of Tentaculites, rhynchonellids and the chonetid. Sorry that I can't be more helpful.

.

.

.

"P.S. Got NF 60 out of the acid—only recovered an uncinuloid rhynconellid that could be anywhere from C_3 into the Devonian—not much help. Coming from where it does I guess its most likely to be Silurian, and pre-Pembroke in age, i.e., pre-Pridolian, but that's a guess based on local biostrat."

[Note written on bottom in Ollie's hand: "Calderwood Point. **Sak** inclusion in andesite"]

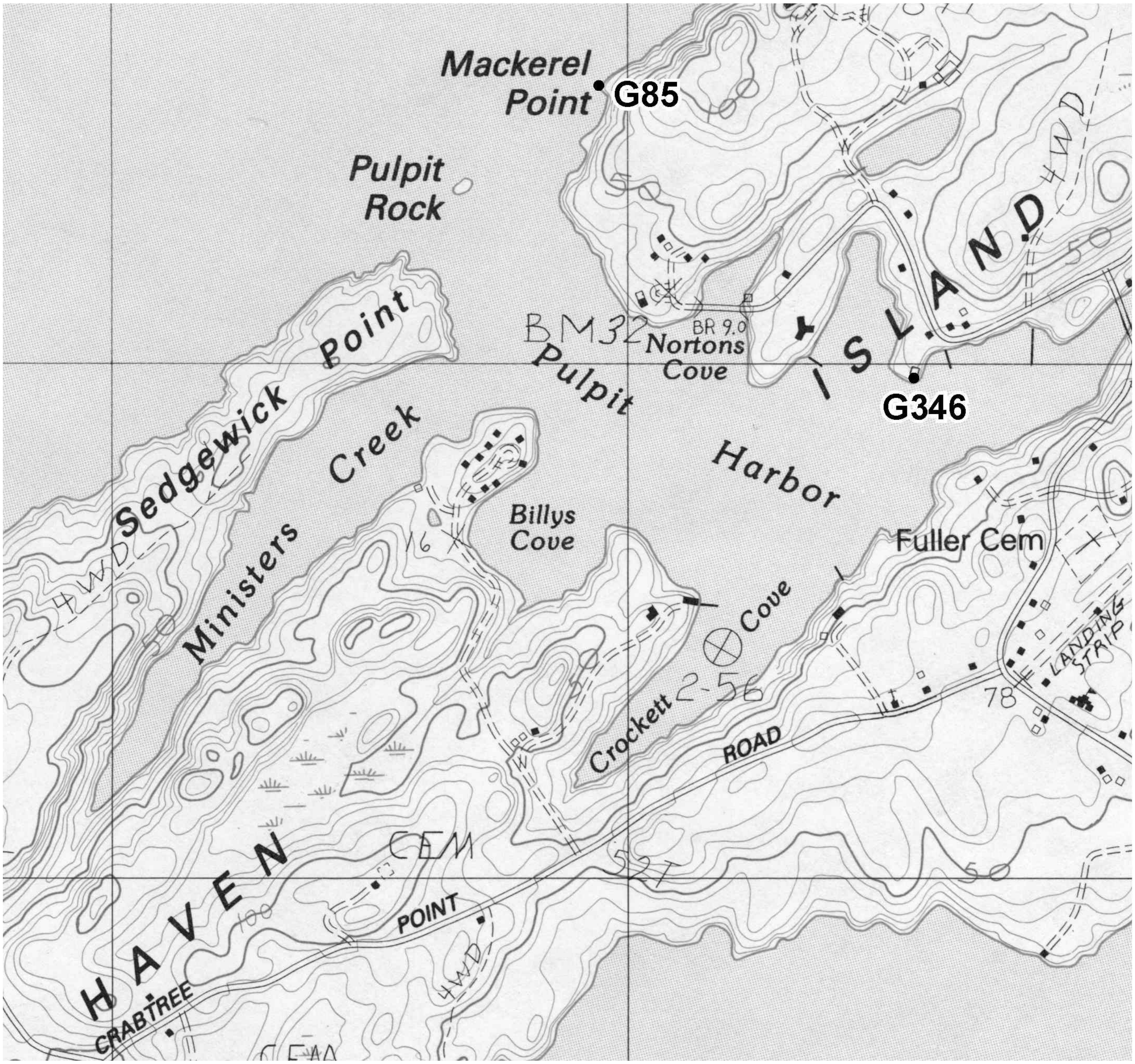
Excerpt 7: A. J. Boucot to Ollie Gates, March 7, 1991

"Bill Oliver called me yesterday about the corals from NF 178. All he could see were overall of "Silurian" type, with Tryplasma being the only generically identifiable item. So...the best that can be said is that the corals are permissively consistent with the brac story (i.e., the Pentamerus from NF 178? indicates an Upper Llandovery or maybe even earlier Wenlock age). NF 60 only has a sphaerirhynchid brac, as I said earlier, which doesn't help in the relative age business very much.

"If it's practical next summer I would suggest that you recollect NF 178 in a big way—blocks rather than small hammer type samples (get out the old sledge, crowbar and cold chisels). With a hunderd pounds or so of blocks I can try to get a more extensive brac collection, and also get better corals (Bill would like to have them for reference purposes—this is really the first Silurian coral locality in the Coastal Silurian from St. John to Boston—could be eventually important for biogeographic purposes when we know more abouth the corals)."

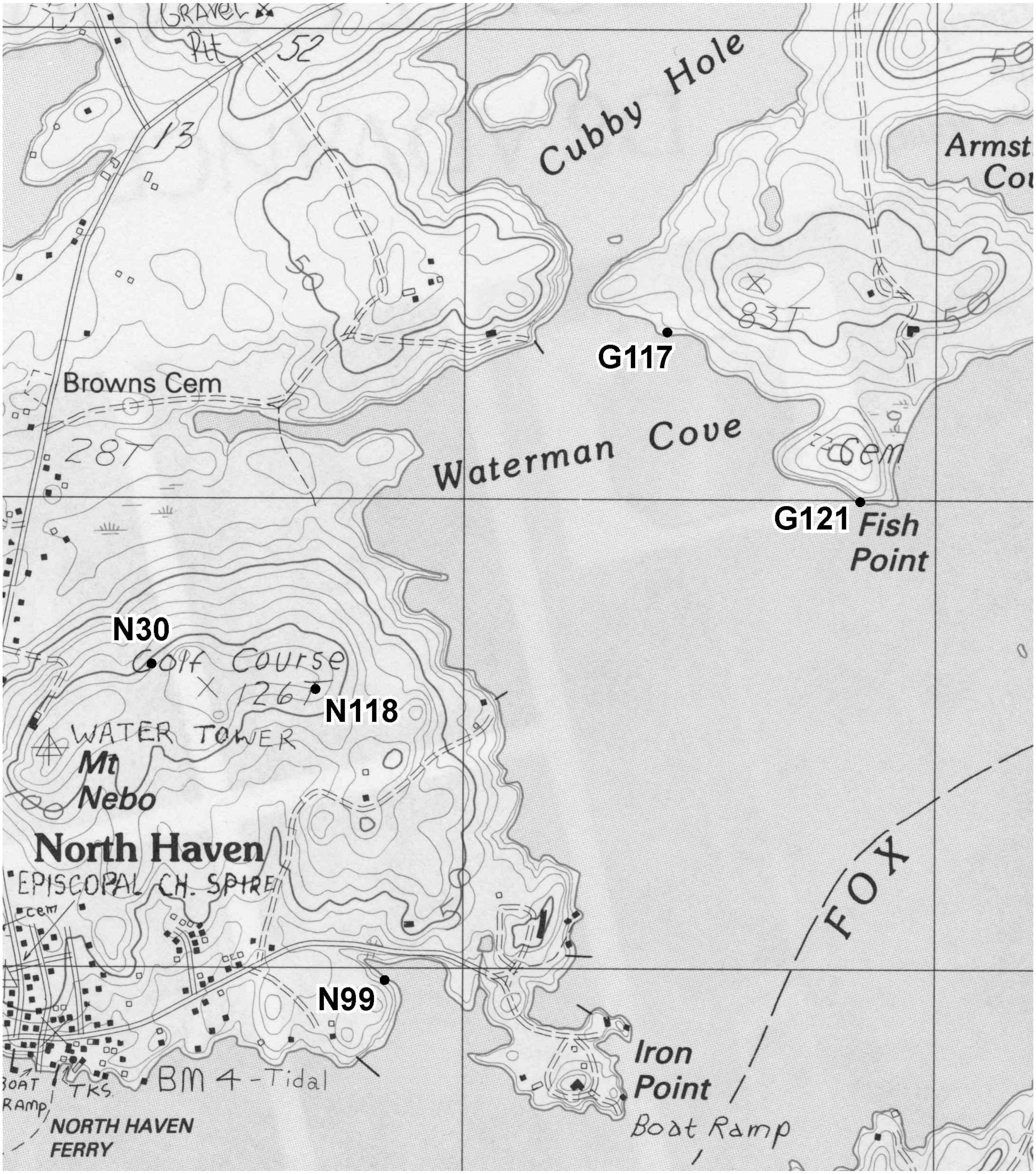
[Note written on bottom in Ollie's hand: "Calderwood Island **Sak**"]

APPENDIX V
Location maps for samples whose geochemistry is reported in Table 1.

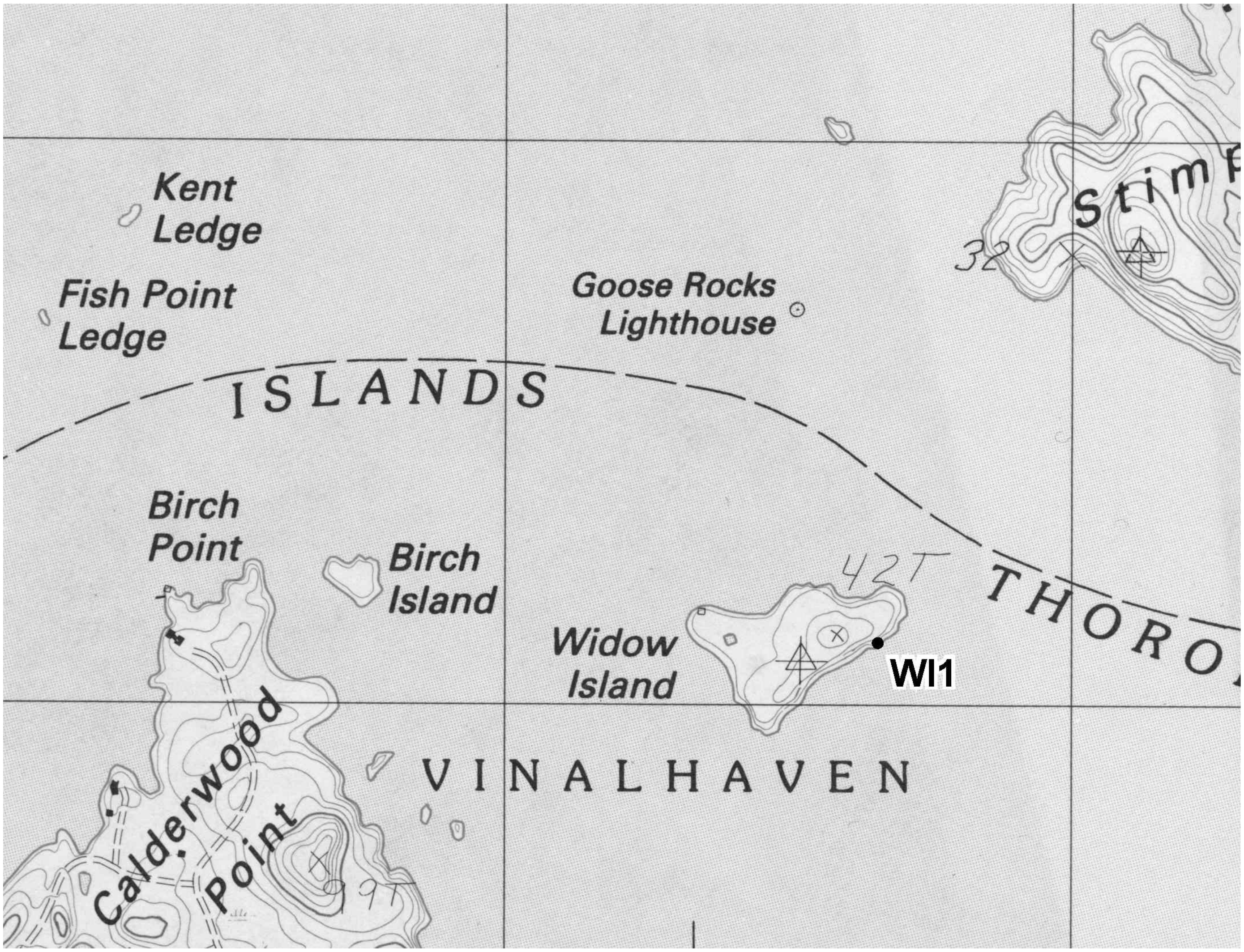


Map A-1. An enlarged portion of the North Haven West 1:24,000 quadrangle. **North Haven Greenstone: G85** - Pillow lava, Mackerel Point, North Haven; **G346** - Rhyolite tuff, north shore of Pulpit Harbor, North Haven.

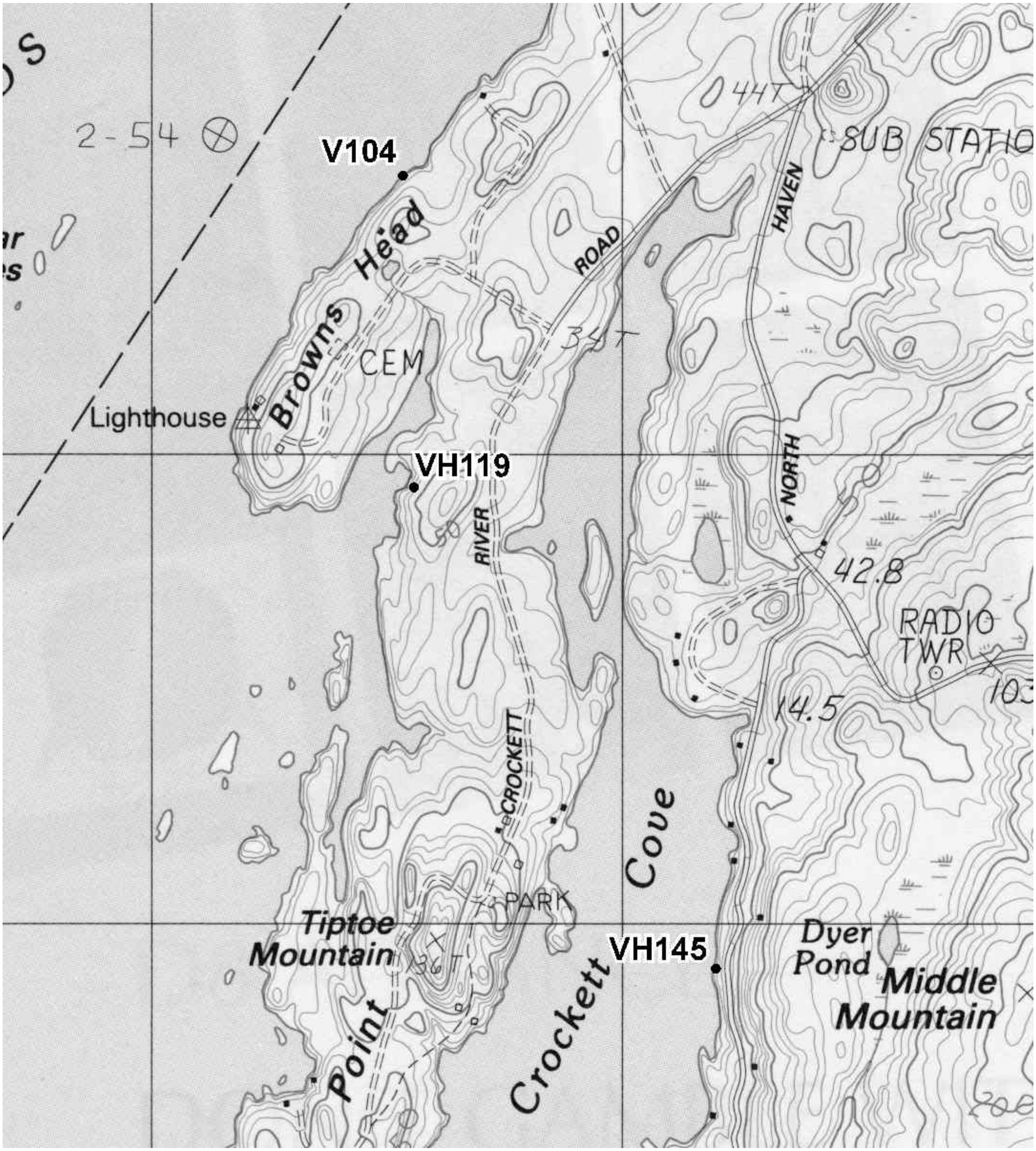
Map A-2. An enlarged portion of the North Haven West 1:24,000 quadrangle. **North Haven Greenstone: G179** - Diabase, head of Southern Harbor, North Haven; **G183** - Pillow lava, head of Southern Harbor, North Haven. **Thorofare Andesite: N40B** - Andesite, Close to contact, north side of Ames Knob, North Haven; **N42** - Andesite, Ames Knob, North Haven; **N51** - Diabase dike, east shore of Browns Cove, North Haven; **N270G** - Rhyolite vitric tuff, Telegraph Point, North Haven.



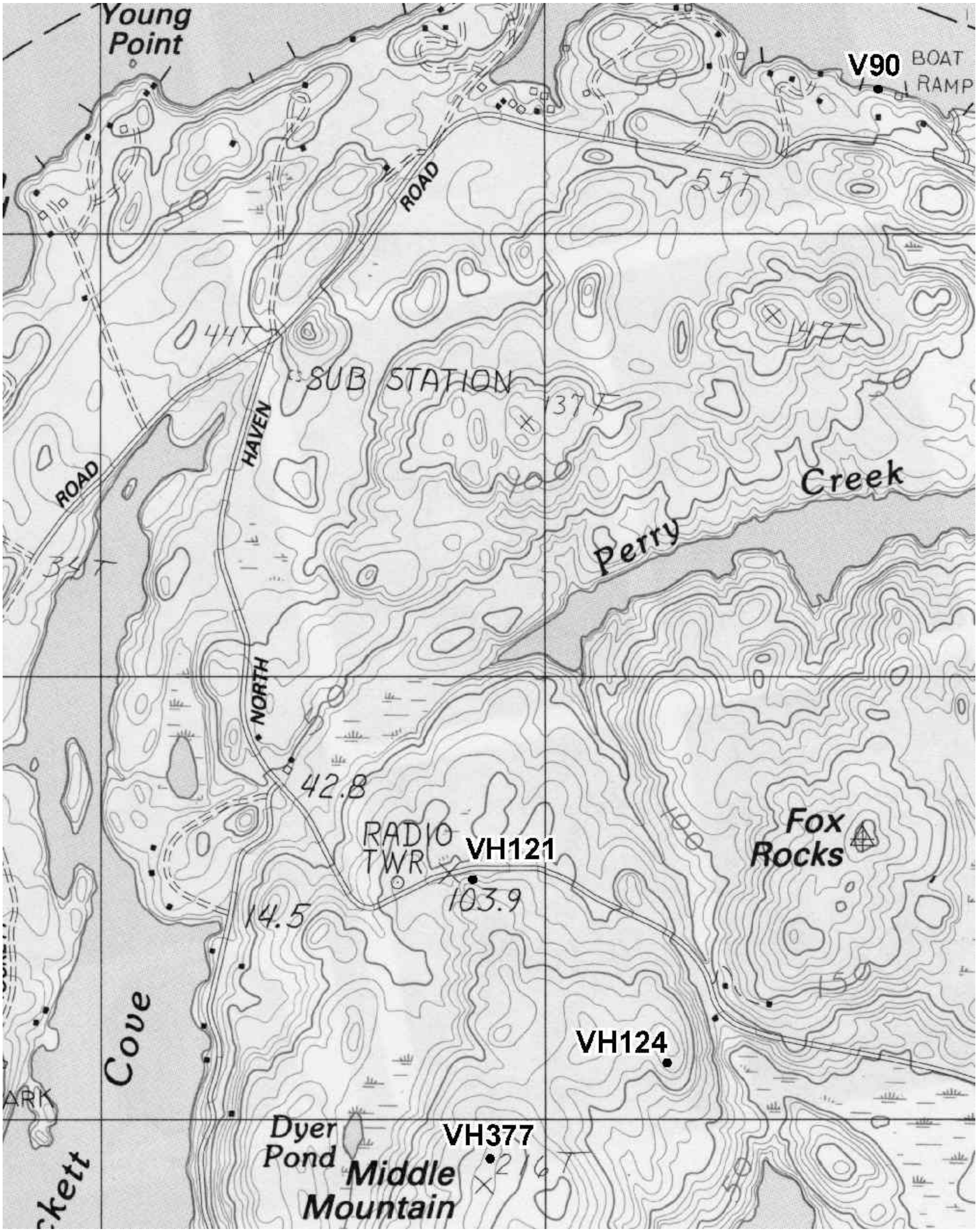
Map A-3. An enlarged portion of the North Haven East 1:24,000 quadrangle. **North Haven Greenstone: G117** - Pillow lava, east shore of Waterman Cove, North Haven. **Fish Point Formation: G121** - Rhyolite, Fish Point, North Haven. **Thorofare Andesite: N30** - Andesite, north side of golf course, North Haven; **N99** - Andesite, oxidized, north side of the Thorofare, North Haven; **N118** - Andesite, golf course hill, North Haven.



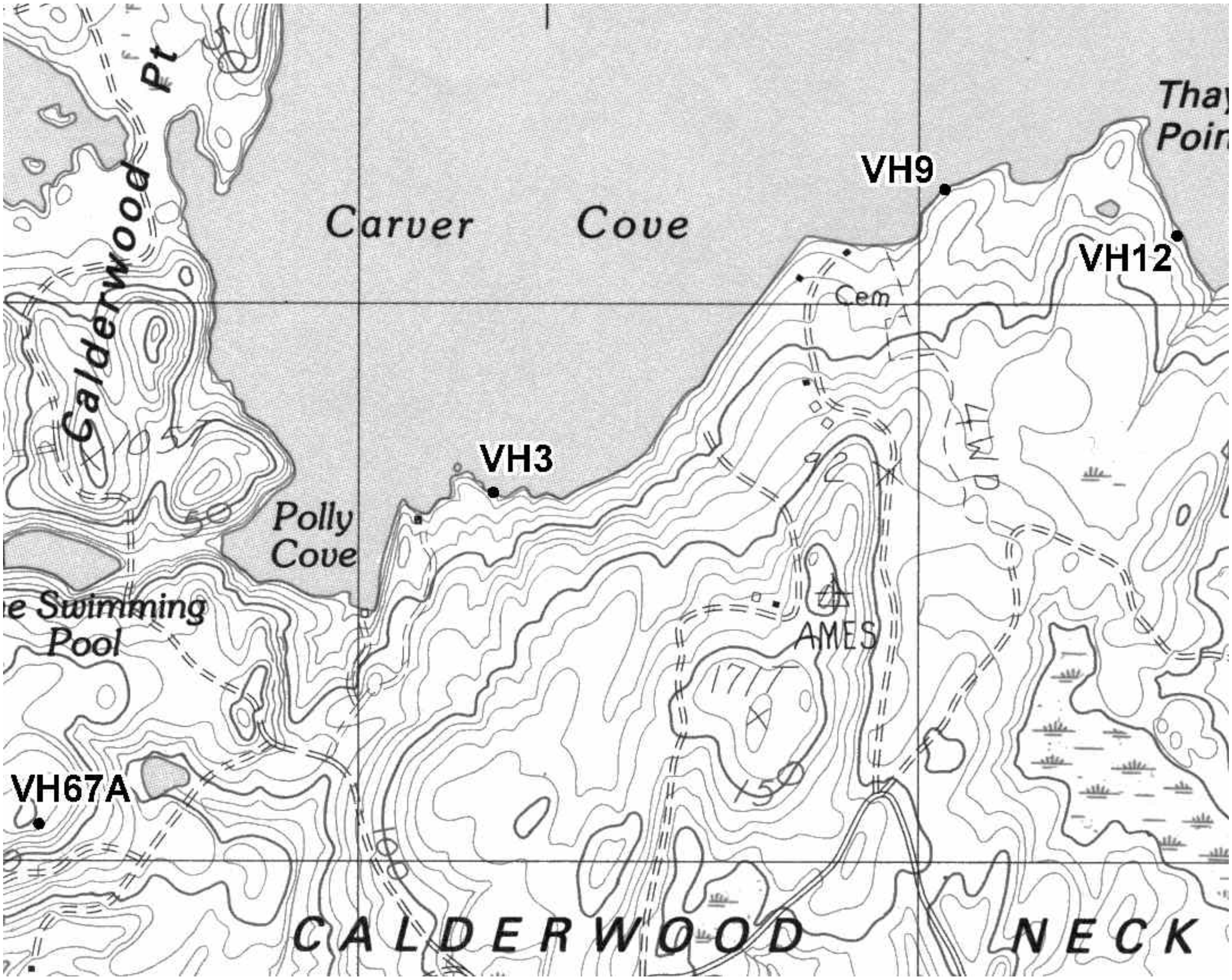
Map A-4. An enlarged portion of the North Haven East 1:24,000 quadrangle. **Calderwood Formation: WI1** - Porphyry, Widow Island.



Map A-5. An enlarged portion of the Leadbetter Island 1:24,000 quadrangle. **Vinalhaven Diabase**: **V104** - Diabase intruding mud, near Browns Head, Vinalhaven. **Vinalhaven Rhyolite: VH119** - Breccia fragment in breccia along base of rhyolite, Vinalhaven; **VH145** - Welded tuff near base, east shore of Crockett Cove, Vinalhaven.



Map A-6. An enlarged portion of the Leadbetter Island 1:24,000 quadrangle. **Vinalhaven Diabase: V90** - Diabase sill, south shore of the Thorofare, Vinalhaven; **Vinalhaven Rhyolite: VH121** - Flow-banded rhyolite along road west of radio tower, Vinalhaven; **VH124** - Breccia on hill northwest of end of Long Cove, Vinalhaven; **VH377** - Welded tuff, near top of Middle Mountain, Vinalhaven.



Map A-7. An enlarged portion of the Vinalhaven 1:24,000 quadrangle. **Calderwood Formation: VH3** - Quartz amphibolite, on shore east of Polly Cove, Vinalhaven; **VH9** - Schist, east shore of Carver Cove, Vinalhaven; **VH12** - Latite, on shore northwest of Salt Works Cove, Vinalhaven. **Thorofare Andesite: VH67A** - Andesite, south of Swimming Pool, Vinalhaven.