Bimodal Silurian and Lower Devonian Volcanic Rock Assemblages in the Machias-Eastport Area, Maine

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By OLCOTT GATES *and* ROBERT H. MOENCH

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Interpretation of chemical data for samples of weakly metamorphosed volcanic rocks of the coastal volcanic belt in southeastern Maine

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METRIC-ENGLISH EQUIVALENTS

[SI, International System of Units, a modernized metric system of measurement]

SI unit		U.S. customary equivalent	
Length			
millimeter (mm)	=	0.039 37	inch (in)
meter (m)	=	3.281	feet (ft)
	=	1.094	yards (yd)
kilometer (km)	=	0.621 4	mile (mi)
	=	0.540 0	mile, nautical (nmi)
Area			
centimeter² (cm²)	=	0.155 0	inch² (in²)
meter² (m²)	=	10.76	feet² (ft²)
	=	1.196	yards² (yd²)
	=	0.000 247 1	acre
hectometer² (hm²)	=	2.471	acres
	=	0.003 861	section (640 acres or 1 mi²)
kilometer² (km²)	=	0.386 1	mile² (mi²)
Volume			
centimeter³ (cm³)	=	0.061 02	inch³ (in³)
decimeter³ (dm³)	=	61.02	inches³ (in³)
	=	2.113	pints (pt)
	=	1.057	quarts (qt)
	=	0.264 2	gallon (gal)
	=	0.035 31	foot³ (ft³)
meter³ (m³)	=	35.31	feet³ (ft³)
	=	1.308	yards³ (yd³)
	=	264.2	gallons (gal)
	=	6.290	barrels (bbl) (petroleum, 1 bbl=42 gal)
	=	0.000 810 7	acre-foot (acre-ft)
hectometer³ (hm³)	=	810.7	acre-feet (acre-ft)
kilometer³ (km³)	=	0.239 9	mile³ (mi³)
Volume per unit time (includes flow)			
decimeter³ per second (dm³/s)	=	0.035 31	foot³ per second (ft³/s)
	=	2.119	feet³ per minute (ft³/min)
Volume per unit time (includes flow)—Continued			
decimeter³ per second (dm³/s)	=	15.85	gallons per minute (gal/min)
	=	543.4	barrels per day (bbl/d) (petroleum, 1 bbl=42 gal)
meter³ per second (m³/s)	=	35.31	feet³ per second (ft³/s)
	=	15 850	gallons per minute (gal/min)
Mass			
gram (g)	=	0.035 27	ounce avoirdupois (oz avdp)
kilogram (kg)	=	2.205	pounds avoirdupois (lb avdp)
megagram (Mg)	=	1.102	tons, short (2 000 lb)
	=	0.984 2	ton, long (2 240 lb)
Mass per unit volume (includes density)			
kilogram per meter³ (kg/m³)	=	0.062 43	pound per foot³ (lb/ft³)
Pressure			
kilopascal (kPa)	=	0.145 0	pound-force per inch² (lbf/in²)
	=	0.009 869	atmosphere, standard (atm)
	=	0.01	bar
	=	0.296 1	inch of mercury at 60°F (in Hg)
Temperature			
temp kelvin (K)	=	[temp deg Fahrenheit (°F)+459.67]/1.8	
temp deg Celsius (°C)	=	[temp deg Fahrenheit (°F)−32]/1.8	

BIMODAL SILURIAN AND LOWER DEVONIAN VOLCANIC ROCK ASSEMBLAGES IN THE MACHIAS-EASTPORT AREA, MAINE

By Olcott Gates and Robert H. Moench

ABSTRACT

Exposed in the Machias-Eastport area of southeastern Maine is the thickest (at least 8,000 m), best exposed, best dated, and most nearly complete succession of Silurian and Lower Devonian volcanic strata in the coastal volcanic belt, remnants of which crop out along the coasts of southern New Brunswick, Canada, and southeastern New England in the United States. The volcanics were erupted through the 600–700-million-year-old Avalonian sialic basement. To test the possibility that this volcanic belt was a magmatic arc above a subduction zone prior to presumed Acadian continental collision, samples representing the entire section in the Machias-Eastport area of Maine were chemically analyzed.

Three strongly bimodal assemblages of volcanic rocks and associated intrusives are recognized, herein called the Silurian, older Devonian, and younger Devonian assemblages. The Silurian assemblage contains typically nonporphyritic high-alumina tholeiitic basalts, basaltic andesites, and diabase of continental character—and calc-alkalic rhyolites, silicic dacites, and one known dike of andesite. These rocks are associated with fossiliferous, predominantly marine strata of the Quoddy, Dennys, and Edmunds Formations, and the Leighton Formation of the Pembroke Group (the stratigraphic rank of both is revised herein for the Machias-Eastport area), all of Silurian age. The shallow marine Hersey Formation (stratigraphic rank also revised herein) of the Pembroke Group, of latest Silurian age (and possibly earliest Devonian, as suggested by an ostracode fauna), contains no known volcanics; and it evidently was deposited during a volcanic hiatus that immediately preceded emergence of the coastal volcanic belt and the eruption of the older Devonian assemblage. The older Devonian assemblage, in the lagoonal to subaerial Lower Devonian Eastport Formation, contains tholeiitic basalts and basaltic andesites, typically with abundant plagioclase phenocrysts and typically richer in iron and titanium and poorer in magnesium and nickel than the Silurian basalts; and the Eastport Formation has rhyolites and silicic dacites that have higher average SiO_2 and K_2O contents and higher ratios of FeO* to MgO than the Silurian ones. The younger Devonian assemblage is represented by one sample of basalt from a flow in red beds of the post-Acadian Upper Devonian Perry Formation, and by three samples from pre-Acadian diabases that intrude the Leighton and Hersey Formations. These rocks are even richer in titanium and iron and poorer in magnesium and nickel than the older Devonian basalts. Post-Acadian granitic plutons exposed along the coastal belt for which analyses are available are tentatively included in the younger Devonian assemblage. The most conspicuous features of the coastal volcanics and associated intrusives are the preponderance of rocks of basaltic composition (< 52 percent SiO_2) in the Silurian assemblage, and the near absence in all assemblages of intermediate rocks having 57–67 percent SiO_2 (calculated without volatiles).

All the rocks are variably altered spilites and keratophyres. The basaltic types are adequately defined, however, by eight samples of least altered basalts having calcic plagioclase, clinopyroxene, and 0.5 percent or less CO_2. The more altered basalts are variably enriched or depleted in Na_2O, K_2O, and CaO relative to the least altered ones. In the silicic rocks no primary ferromagnesian minerals are preserved. The Na_2O and K_2O contents of the silicic rocks are erratic; they are approximately reciprocal, possibly owing to alkali exchange while the rocks were still glassy.

We propose that the coastal volcanic belt extended along an axis of thermal swelling in the Earth's mantle and upward intrusion of partially melted mantle into the sialic Avalonian crust. These processes were accompanied by shoaling and emergence of the belt, and they produced the bimodal volcanism. Tholeiitic basaltic melts segregated from mantle material at rather shallow depths (< 35 km). We are uncertain whether the Silurian basalts and the successively more fractionated older and younger Devonian basalts were produced by separate melting events, or by shallow fractionation of one to form the other. The silicic magmas segregated from sialic crust that was heated and partially melted by the mantle intrusion and its mafic segregations. At first, still-hydrous sialic crust yielded the calc-alkalic rhyolites and silicic dacites of the Silurian assemblage; sparse andesite may have formed by mixing of basaltic and rhyolitic magma. By earliest Devonian time the heated crust was significantly dehydrated and yielded the more potassic, silicic, and iron-enriched older Devonian rhyolitic suite. Available data suggest that the post-Acadian coastal granites are even more enriched in the same components, and may have formed by partial melting of further-dehydrated crust.

The strongly bimodal volcanics of the Machias-Eastport area are unlike known volcanic and plutonic suites that occur above documented subduction zones, where rocks of andesitic composition are typically abundant. Instead, bimodal volcanism implies extensional tectonism, a regime that is supported in the Machias-Eastport area by evidence of Silurian block faulting. The two authors favor somewhat different tectonic regimes, but both authors believe that the results of this study signal a major problem concerning the relations between magmatism and the Acadian orogeny along the coastal volcanic belt, and perhaps elsewhere in the northern Appalachians.

INTRODUCTION

Marine and subaerial metavolcanic rocks of Silurian and Early Devonian age crop out along the coasts of southern New Brunswick in Canada, and of southeastern Maine and eastern Massachusetts in the United States, forming a belt that was bordered by wide tracts of nonvolcanic, predominantly marine clastic deposits of the same age (fig. 1). This belt, called the coastal volcanic belt by Boucot (1968), has been assigned the role of a subduction-related volcanic arc that was active during closure of the presumed proto-Atlantic ocean in Silurian and Devonian time (Bird and Dewey, 1970; McKerrow and Ziegler, 1971; Dewey and Kidd, 1974; Wilson, 1966). However, this assignment was made without the benefit of petrologic data. Whether or not these volcanics are in fact akin to those that occur along any post-Triassic convergent plate boundary is the main question asked in this report. The Machias-Eastport area is a critical one, because it contains the thickest, best exposed, best dated, and most nearly complete succession of Silurian and Lower Devonian volcanic strata in the coastal belt, and probably in the whole Appalachian-Caledonian orogen.

For many years Gates has been mapping in the Machias-Eastport area, and a description and geologic map of the Eastport quadrangle is now available (Gates, 1975). In 1967, Moench began to study mineral deposits in the area. Spurred by the publication of the paper by Bird and Dewey (1970), in 1971 and 1972 we collected typical samples of all the known volcanic rock types that are exposed in the area. Our objectives were to test the Bird-Dewey hypothesis and to establish the nature of volcanic rocks that are associated with mineral deposits of the coastal area. This report presents major oxide data, preliminary minor element data, a summary of petrographic features, and interpretations that focus on tectonic setting.

ACKNOWLEDGMENTS

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REGIONAL PALEOGEOGRAPHIC AND TECTONIC RELATIONSHIPS

Magmas of the coastal volcanic belt probably erupted through the 600–700-m.y. (million years)-old Avalonian basement and its cover of lower Paleozoic platform metasedimentary rocks. Although the actual position of the northwestern margin of the Avalonian terrane has not been delineated precisely, it is at least as far northwest as the line shown in figure 1, drawn mainly on the basis of Naylor's (1975) work. Within the area of the coastal belt, the Silurian and Devonian volcanic suites surely lie above Avalonian rocks.

Eruptions along the coastal volcanic belt that closely preceded those that produced the Silurian assemblage of this paper may be recorded in clasts found in two conglomerates. Volcanic and plutonic clasts are found in Silurian(?) slide conglomerates exposed immediately southwest of the Machias-Eastport area (Gilman, 1966), and in basal polymictic conglomerates of the Silurian Oak Bay Formation of Alcock (1946), exposed a few kilometers north of the Machias-Eastport area (fig. 1; Amos, 1963; Cumming, 1967; Ruitenberg, 1967). These clasts deserve further study to see if they came from a volcanic tract that might have existed in earliest Silurian or before—prior to deposition of the Oak Bay or of the Waweig Formation of Ruitenberg (1967)—within or possibly immediately south of the Silurian and Devonian alinement of the coastal volcanic belt. A possible remnant of such a tract is the Bears Brook Volcanic Group of Late Ordovician(?) age, exposed along the northern coast of Nova Scotia some 400 km northeast of the Machias-Eastport area (fig.1; Boucot and others, 1974).

According to published paleogeographic maps, the Silurian and Early Devonian coastal volcanic belt stands between tracts of approximately synchronous clastic deposits that are almost devoid of volcanic rocks (Boucot, 1968). On the southeast, in northern Nova Scotia (fig. 1), is the Arisaig belt composed of deposits that represent shallow marine and subaerial facies. The area of the Annapolis Valley paleogeographic belt farther south in Nova Scotia was emergent through much of Silurian time, but later in the Silurian and into Devonian time it subsided and received deep marine deposits. Northwest of the coastal volcanic belt are the Fredericton trough and the Merrimack synclinorium, underlain by enormous thicknesses of sparsely graptolitic, probably deep marine deposits of Silurian and Early Devonian age (Pankiwskyj and others, 1976; Osberg and others, 1968; McKerrow and Ziegler, 1971).

The earlier ancestry of the Merrimack synclinorium is shown by the Aroostook-Matapedia belt of conformity between Ordovician and Silurian strata that extends at least from western Maine to Gaspé, Quebec (fig. 1; Pavlides and others, 1968). Elsewhere in the northern Appalachians, Silurian formations rest disconformably or unconformably on Middle Ordovician or older rocks.

Farther northwest are scattered exposures of predominantly Lower Devonian and sparse Silurian vol-

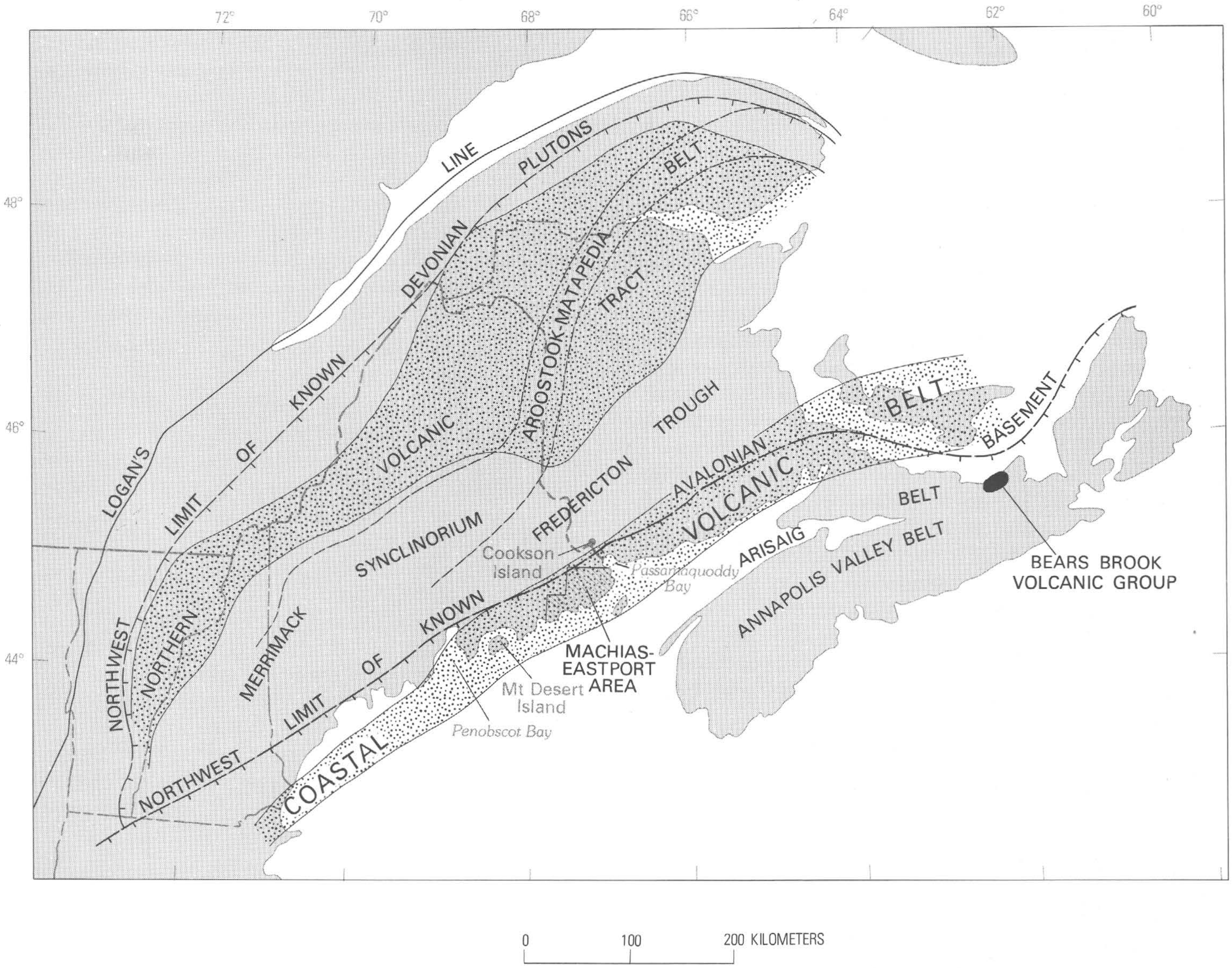


FIGURE 1.—Map of New England and Maritime Provinces showing Silurian and Lower Devonian volcanic tracts and principal paleotectonic features. Names approximately coincide with axes of the features. Coastal volcanic, Arisaig, and Annapolis Valley belts and Bears Brook Volcanic Group modified from Boucot (1968) and Boucot and others (1974, figs. 27, 28). Fredericton trough from McKerrow and Ziegler (1971). Aroostook-Matapedia belt of Taconian conformity from Pavlides, Boucot, and Skidmore (1968, fig. 5-1). Merrimack synclinorium from Osberg, Moench, and Warner (1968). Northern Silurian-Devonian volcanic tract from information on maps of Potter, Jackson, and Davies (1968), and Hussey (1967), and descriptions in Poole, Sanford, Williams, and Kelley (1970), Rankin (1968), Boudette, Hatch, and Harwood (1976, p. 12-20), and other sources. Approximate limit of known Avalonian basement is based on Naylor (1975), Potter, Jackson, and Davies (1968), and Stewart (1974).

canic rocks, forming a poorly defined tract herein called the northern volcanic tract (fig. 1). Volcanics of Ordovician age or older are widely exposed along the same tract. As noted by Rodgers (1970, p. 126, 135-136), however, during the Ordovician the deep marine nonvolcanic Aroostook-Matapedia trough appears to have separated the volcanic belt of northwestern Maine from that of northern New Brunswick. In Early Devonian time the northern tract was an area of shallow seas and volcanic islands. Although most post-Ordovician volcanics of the northern tract are Devonian in age, at least widely scattered Silurian volcanic rocks are found in the Silurian Shaw Mountain Formation in Vermont, in unnamed units in the St. John Valley region of northwestern Maine (Boudette and others, 1976, p. 12-17), and in parts of the Pointe Aux Trembles Formation in the western Gaspé area (Lajoie and others, 1968, p. 627).

STRATIGRAPHY AND STRUCTURE OF THE MACHIAS-EASTPORT AREA

A geologic sketch map (fig. 2) illustrates the main structural features and the general stratigraphic succession in the Machias-Eastport area. Bastin and Williams (1914) originally mapped the Eastport quadrangle, and their formation names are used in this report, with the following changes. Because volcanic rocks are locally abundant in the Quoddy Shale of Bastin and Williams (1914, p. 3), Gates (1975) preferred the name Quoddy Formation, and this usage is adopted herein. The volcanics are most abundant in the upper part of the Quoddy, where it crops out in the Cutler 15-minute quadrangle. The Quoddy of that area was originally called the Little River Formation by Gates (1961, p. 9–23), a name that he discarded in favor of the Quoddy as his mapping progressed into the Eastport quadrangle. Gates (1975) raised to formation status the former Leighton Gray Shale and Hersey Red Shale Members of the Pembroke Formation, and his stratigraphic rank assignment for the names Leighton and Hersey is adopted herein. The former Pembroke Formation is raised herein to group status. Except as noted in the following descriptions, age assignments follow those of Berry and Boucot (1970).

The major structural features of post-Early Devonian age are (1) the large open Cobscook anticline in the Eastport and Gardner Lake quadrangles; (2) the companion Machias syncline, south of Machias; (3) the Lubec fault zone, a belt of sheared and tightly folded rocks of the Eastport and Quoddy Formations; and (4) the Quoddy block, a structural block about 8 km wide and at least 40 km long that lies between the Lubec fault zone and the Fundian fault (fig. 2). The Fundian fault may be the border fault for the Triassic rocks of the Bay of Fundy (Ballard and Uchupi, 1975, p. 1046–1049; Gates, 1969, p. 500). Northwest of the Lubec fault zone, block faulting accompanied the Silurian volcanism, for several faults bring volcanic formations against older rocks and are overlapped by younger Silurian formations (fig. 3). Most of the sedimentary and volcanic rocks are at least weakly metamorphosed and regionally deformed by northeast-trending cleavage. This cleavage and the major folds originated prior to deposition of the Upper Devonian Perry Formation, but the Perry red beds and the folds and cleavage were locally faulted and folded during deposition of the Perry and probably during the Carboniferous.

Rocks assigned to the Quoddy Formation are restricted to the Quoddy structural block (fig. 2), and no correlation of the formation has been firmly established as yet outside the block. The lower part of the Quoddy Formation is composed of dark graptolite-bearing pyritic argillites, shale, siltstone, and thin graded beds of feldspar-rich tuff. The upper part of the Quoddy, exposed mainly in the southern part of the block, contains abundant marine basalts (some pillowed) and keratophyres, as well as local limestone and tuff breccia. Silurian graptolites found in shale and sparse brachiopods found in the coarse limestone and tuff breccia indicate a late Llandovery age for the Quoddy Formation.

The Quoddy Formation occurs as many inclusions and septa engulfed in the Cutler Diabase, a name originally applied by Gates (1961) to complex gabbroic and diabasic intrusions exposed near the town of Cutler. In this report the name "Cutler Diabase" is applied for convenience to the mafic intrusions of the Quoddy structural block. Throughout the block the Cutler is a complex body of multiple emplaced massive and locally layered gabbro and diabase. Some of the diabase appears to have been intruded into the Quoddy Formation when the Quoddy sediments were still soft and water bearing. As a whole, the Cutler is interpreted to represent a subvolcanic complex emplaced mainly in Silurian time, penecontemporaneously with the accumulation of the Quoddy Formation, or only somewhat later. However, the Cutler may have been a source of basaltic lavas that were erupted during the accumulation of the Silurian Dennys, Edmunds, and Leighton Formations, and parts of the Cutler may be as young as Devonian. The Silurian and Lower Devonian formations exposed northwest of the Lubec fault zone are intruded by many dikes, sills, and plutons of diabase (too small to show in fig. 2) that mineralogically and texturally resemble the Cutler of the Quoddy block. As shown later, however, our chemical data suggest that the Cutler is petrologically akin to the Silurian basaltic flows, whereas the sampled diabase sills that intrude the Leighton and Hersey Formations are akin to basalt of the Upper Devonian Perry Formation.

Silurian rocks, very poorly exposed and as yet unnamed, occupy the central part of the Columbia Falls quadrangle and the northern part of the Gardner Lake quadrangle. They include the slide conglomerates described by Gilman (1966), basaltic flows, silicic tuffs and tuff-breccias, and pyritic thinly bedded argillites and siltstones. Graptolites from black shales in the northwestern part of the Columbia Falls quadrangle suggest a late Llandovery to Wenlock age (W. B. N. Berry, written commun., 1962). The black shales are interbedded with silicic tuff-breccias that are in fault

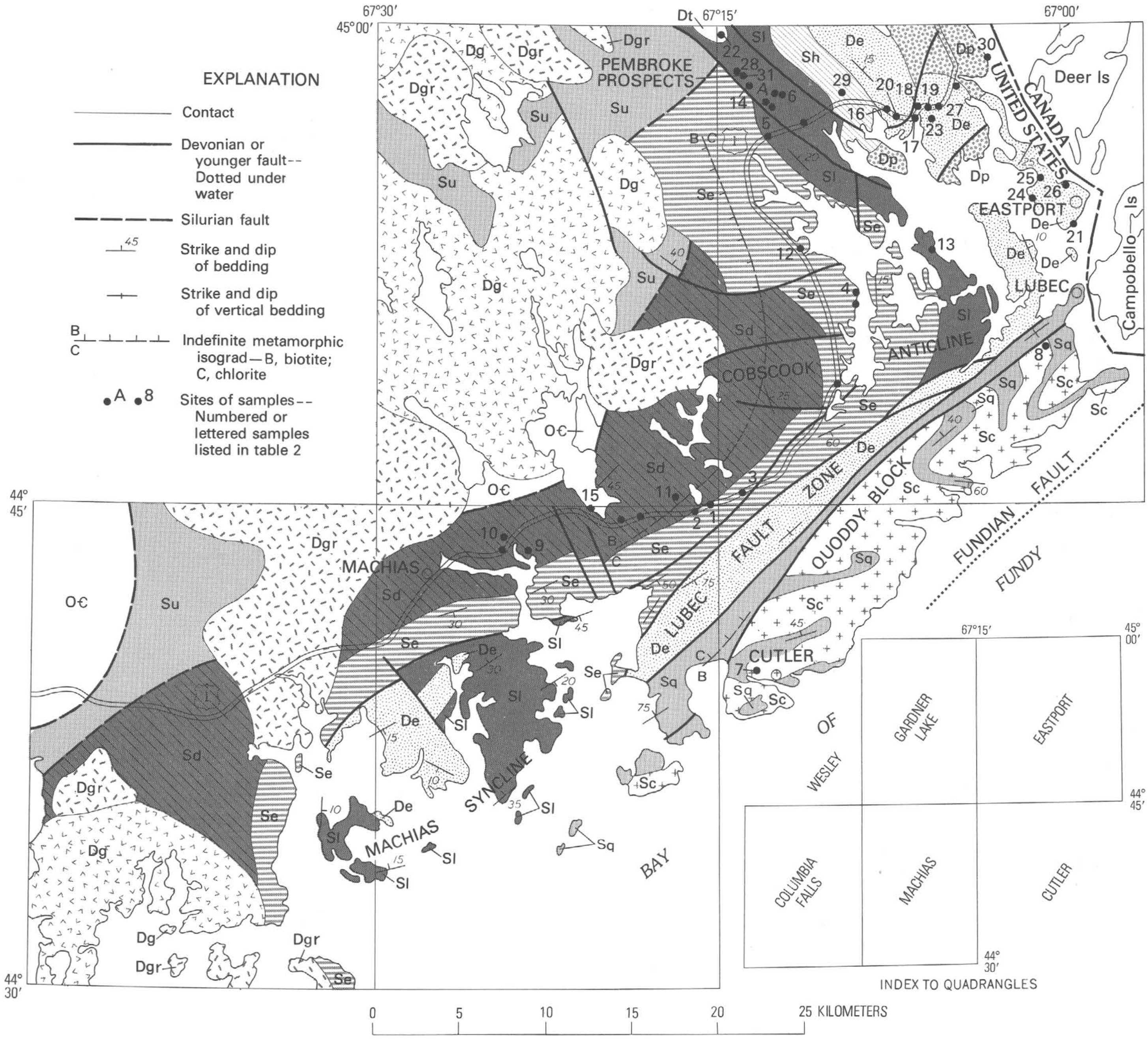


FIGURE 2.—Simplified map of the bedrock geology of the Machias-Eastport portion of the coastal volcanic belt. Simplified from Gates (1961, 1975) and unpublished mapping by Gates and by Richard A. Gilman.

contact with pre-Silurian schist. These unnamed Silurian rocks are labeled Quoddy(?) Formation in figure 3, on the assumption that they correlate with the Quoddy.

The Silurian Dennys Formation, possibly of late Llandovery through Wenlock age, is the basal part of the volcanic sequence in the Cobscook anticline. It consists primarily of basaltic flows, agglomerate, and

EXPLANATION FOR FIGURE 2

Unit symbols (listed in order of increasing age): Dp, Perry Formation; Dgr, granite; Dg, gabbro and diorite; Dt, basaltic andesite of Mount Tom stock; De, Eastport Formation; all of Devonian age. Sh and Sl, respectively Hersey (which may also be Early Devonian age) and Leighton Formations of the Pembroke Group in the Machias-Eastport area; Se, Edmunds Formation; Sd, Dennys Formation; Sq, Quoddy Formation; all of Silurian age. Su, undivided Silurian rocks. Sc, Cutler Diabase of Gates (1961) of Silurian(?) age in the Quoddy block. O€, Ordovician and Cambrian rocks.

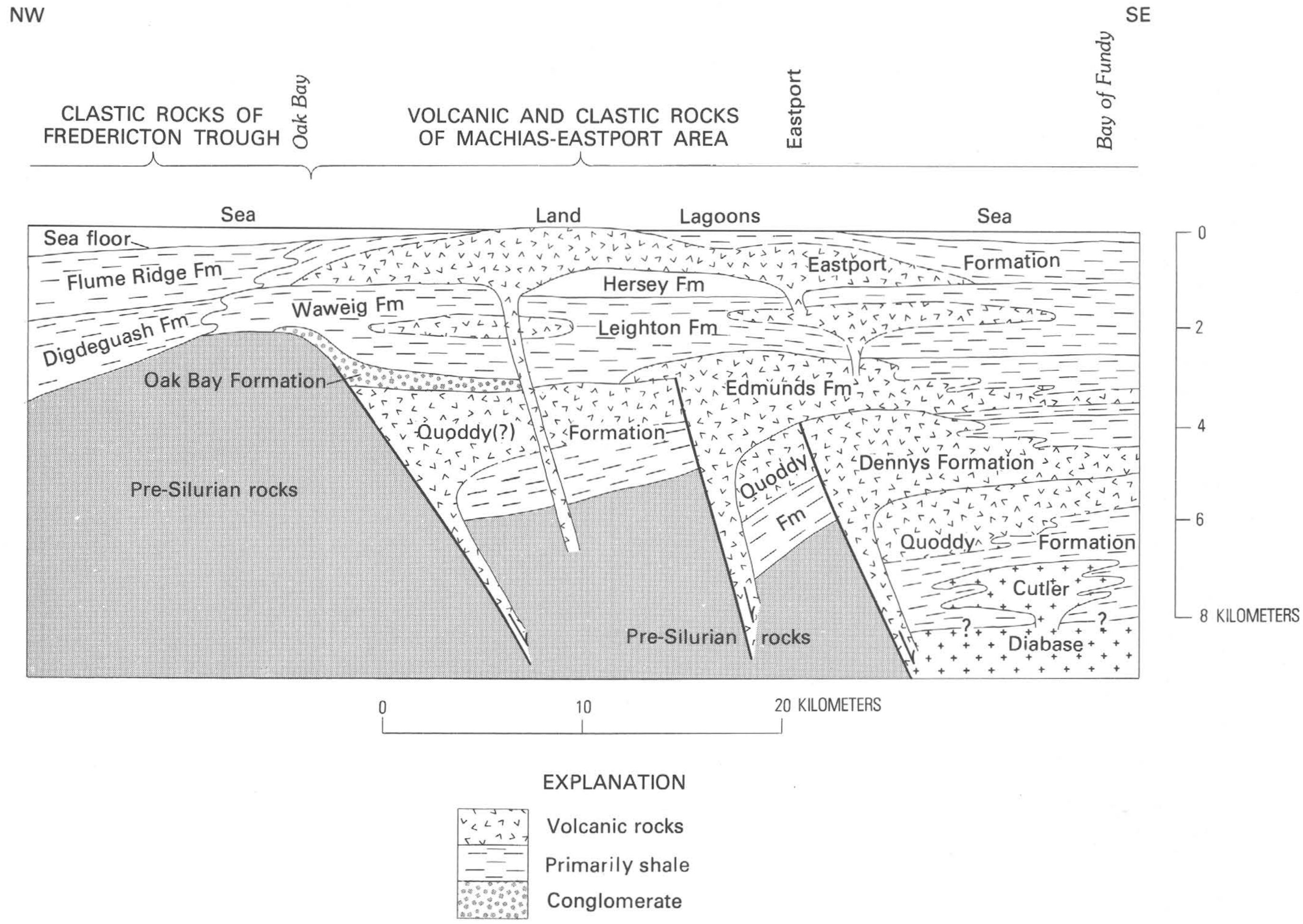


FIGURE 3.—Schematic section across the coastal volcanic belt during late Eastport time, showing relations of Silurian and Devonian formations of the southernmost Fredericton trough and the Machias-Eastport area to one another and to contemporaneous normal faults. Heavy lines, faults; arrows show direction of movement. Solid thin lines, formation contacts, queried where uncertain; dashed lines, gradational boundaries between volcanic and sedimentary parts of formations. Digdeguash and Waweig Formations (both of Silurian age) and Flume Ridge Formation (of Silurian or Early Devonian age) are of Ruitenberg (1967). Correlation of Waweig with the Leighton Formation is from Pickerill (1976).

coarse water-laid bedded tuffs deposited on the slopes of a basaltic volcano. The eruptive center of this volcano is an ellipsoidal mass of basalt and agglomerate in the east-central part of the Gardner Lake quadrangle. The Dennys Formation also contains a linear belt of keratophyric tuff-breccias, breccia pipes, and flow-banded and autobrecciated domes and shallow intrusions. This belt of eruptive centers may have been controlled by a contemporaneous fault zone. The fauna of the Dennys Formation consists of a diversified brachiopod suite together with trilobites, corals, and a few pelecypods.

The Silurian Edmunds Formation, probably mainly of Ludlow age, is made up primarily of silicic green, purple, and maroon coarse tuff-breccia deposited as submarine pyroclastic debris flows or avalanche deposits (Gates, 1975, p. 4–5). As shown by drilling, one graded avalanche deposit in the upper part of the Edmunds is at least 100 m thick. A roughly circular area of very coarse breccia on the border between the Eastport and Gardner Lake quadrangles probably marks the vent that fed the avalanche deposits. The Edmunds Formation also contains a few thin basalt flows and basaltic agglomerates and several lens-shaped domes and shallow intrusions of flow-banded and autobrecciated vitrophyre. The gray to black tuffaceous siltstones and shales of the Edmunds Formation carry a diversified fauna of brachiopods, trilobites, corals, pelecypods, gastropods, ostracodes, and orthoceroids. Watkins and Boucot (1975, p. 254) concluded that the brachiopod fauna indicates a nearshore environment.

The Leighton Formation of latest Silurian (Pridoli) age is composed largely of gray to blue-gray well-bedded and somewhat calcareous siltstones and shales. A few thin dacitic to rhyolitic avalanche tuff-breccias, several thin basalt flows, lens-shaped bodies of basaltic agglomerate, and several domes of dacitic to rhyolitic vitrophyre comprise the volcanic components. Locally, as shown by intensive drilling in a small area, basaltic flows evidently poured in rapid succession into fault-bounded depressions in the sea floor, where they accumulated to thicknesses of 200 m or more. The brachiopod fauna is a restricted shallow-water one (Watkins and Boucot, 1975, p. 254), accompanied by numerous gastropods, pelecypods, ostracodes (Berdan, 1971), and a few trilobites.

The Hersey Formation consists of maroon siltstones and shales and a few nodular limestone beds; it contains no known volcanic rocks. The Hersey pinches out to the southeast, where its stratigraphic position is occupied by shales and volcanic rocks assigned to the Eastport Formation. The Hersey carries a brackish-water fauna of pelecypods, gastropods, and ostracodes. The ostracode fauna suggests that the Silurian-Devonian boundary lies within the Hersey (Berdan, 1971).

The Eastport Formation of Early Devonian age (Gedinne) is a diverse formation composed of basalt flows, coarse basaltic agglomerate, a few dacite and rhyolite tuff-breccia and ash-flow deposits, flow-banded and autobrecciated domes and shallow intrusions of rhyolitic vitrophyre, and gray to maroon siltstones, shales, and minor conglomerate. The fauna is a restricted one of lingulas, pelecypods, and ostracodes (Berdan, 1971). The volcanic rocks of the Eastport Formation erupted partly on land and partly on tidal flats and shallow lagoons, in contrast to the dominantly marine eruptions of the underlying Silurian formations.

During the Acadian orogeny a bimodal suite of gabbro, granitic rocks, and subordinate quartz diorite or diorite, named the Bays-of-Maine Complex by Chapman (1962), intruded the volcanic section and neighboring pre-Silurian rocks along the coastal belt between Penobscot Bay and Passamaquoddy Bay. The complex is not shown in figure 1. The Bays-of-Maine Complex and older rocks were then intruded by granites of the Maine coastal plutons of Chapman (1968). Although field relationships clearly indicate that the coastal plutons are younger, no sharp distinction is seen in the isotopic ages. Granitic rocks assigned to the complex have yielded isotopic ages of about 400 m.y. (Spooner and Fairbairn, 1970; Rb-Sr whole rock and K-Ar biotite); whereas a spectrum of ages greater than 410–340 m.y. has been obtained by the same methods from the coastal granites (Brookins, 1976, table 2). As shown by Brookins (1976), widely disparate ages have been obtained from a single pluton by different methods. Thus, it remains to be seen whether some or all of the coastal plutons are part of the Bays-of-Maine Complex or instead belong to a distinctly younger suite, as favored by Chapman (1968).

The Perry Formation lies on a surface that truncates both the Silurian and Lower Devonian section and the 400-m.y.-old Red Beach Granite of Amos (1963). The Red Beach is a large body that intrudes the Eastport Formation immediately north of the area of figure 2. This granite contributed coarse gravel to the Perry Formation (Amos, 1963; Spooner and Fairbairn, 1970). The Perry is mainly a post-Acadian red bed sequence among which Schluger (1973) has recognized scree, alluvial fan, overbank, and lacustrine facies. Block faulting formed the local basins in which the Perry conglomerate was deposited. One flow of altered basalt is exposed in the Eastport quadrangle. Plant fossils indicate a Late Devonian age (Smith and White, 1905, p. 35).

Though cleaved, the Silurian and Lower Devonian formations are only weakly metamorphosed regionally. Detrital muscovite commonly is preserved in the shales as bent flakes subparallel to bedding. Metamorphic chlorite and muscovite are found most commonly where the rocks are strongly cleaved near faults. As described later, the volcanic rocks are partly to completely altered to mineral associations typical of spilites and keratophyres of greenschist facies or slightly below that metamorphic rank. Prehnite and pumpelleyite—rare on the southeast side of the Appalachians—were found in one specimen from a pre-Acadian(?) diabasic sill that intrudes the Leighton Formation. Hornfels is present along the borders of the principal plutons on the west; metamorphic biotite associated with the hornfels is present in a belt that extends a few kilometers east of the plutons, and in the Quoddy block (fig. 2). Actinolite is restricted to about the same areas. In small areas of sulfide mineralization, some of the rocks are hydrothermally altered.

In summary, the volcanic and associated fossiliferous sedimentary rocks of the Machias-Eastport area record a long history of volcanism, often explosive. Volcanism lasted perhaps 20 m.y. in the Silurian, and a few more million years in Early Devonian time. Marine environments, becoming generally shallower through time, prevailed through the Silurian; in Early Devonian time the volcanics were erupted into shallow lagoons, onto tidal mudflats, and on land. The Eastport Formation represents the beginning of a general emergence of the coastal volcanic terrane that is shown on Boucot's paleogeographic maps (Boucot, 1968, figs. 6–3 to 6–6).

DEFINITION AND PETROGRAPHY OF VOLCANIC ASSEMBLAGES

Volcanic rocks of the Machias-Eastport area divide into a strongly bimodal assemblage of basalts grading to basaltic andesites, for convenience called the basaltic suite, and rhyolites grading to silicic dacites, called the rhyolitic suite (table 1; fig. 4). The only known truly intermediate andesite is a dike that intrudes the Dennys Formation. If the Cutler Diabase were included in the measurements shown in table 1, the volume of the basaltic suite would greatly exceed that of the rhyolitic one.

Because all of the Machias-Eastport rocks are at least mildly metamorphosed, we classify them mainly on the basis of their chemical composition, supplemented by relict primary petrographic features. The whole assemblage is subalkalic, as shown later. With modifications we follow the common Canadian practice of dividing subalkalic metavolcanic rocks into four broad categories: basalt, andesite, dacite, and rhyolite (Irvine and Baragar, 1971; Church, 1975). A plot of our data in Church's diagram (Church, 1975, fig. 8) shows that all samples from the basaltic suite are clearly basalts, despite the presence of as much as 56.5 percent SiO_2. In this report, the term basaltic andesite is used for individual basaltic rocks having more than 52 percent SiO_2, as shown in figure 4. The term rhyolitic suite also is used for convenience, and the term silicic dacite applies to rocks of this suite having 67–70 percent SiO_2. The only sample of andesite, with 62.9 percent SiO_2, might be called dacite, but the analysis plots in the overlapping field for andesites and dacites in Church's diagram, and its cation norm plots in the field for calc-alkalic andesites in figure 7 of Irvine and Baragar (1971). Moreover, the rock has the "motheaten" porphyritic texture that is characteristic of andesites elsewhere.

Norms were calculated for several of the basaltic analyses, but they are used only sparingly in this paper, because at least Fe_2O_3 to FeO ratios and alkali contents have been modified during alteration, even in some rocks that we call "least altered" (as defined later). The norm of one analysis—a sill that intrudes the Leighton Formation—shows a small amount of nepheline, but the other norms are saturated or quartz bearing. The analyses were prepared for norm calculations according to the recommendations of Irvine and Baragar (1971).

TABLE 1.—*Volume by percent of volcanic and hypabyssal intrusive rock types in the Eastport quadrangle, estimated from areas of each type in cross sections; Cutler Diabase excluded*

Formation	Basaltic suite (basalt and basaltic andesite)	Andesite	Rhyolitic suite (rhyolite and silicic dacite)
Eastport	49	0	51
Leighton	58	0	42
Edmunds	2	0	98
Dennys	56	[1]5	39

[1]Dike.

The whole bimodal assemblage is further divisible into three assemblages on the basis of age, relict petrographic features, and chemical composition, herein called the Silurian, older Devonian, and younger Devonian assemblages. The Silurian assemblage comprises the basaltic and rhyolitic suites in the various Silurian formations. The Cutler Diabase of the Quoddy block and the andesite dike that intrudes the Dennys Formation are included in the Silurian assemblage, because their petrologic features and geologic settings suggest a genetic relation to the Silurian volcanics. The older Devonian assemblage contains the basaltic and rhyolitic suites of the Lower Devonian Eastport Formation. These rocks are chemically and petrographically distinct from those of the Silurian formations. Also assigned to the older Devonian assemblage is a plug of porphyritic basaltic andesite (the andesite at Mount Tom of Bastin and Williams (1914)), which intrudes the Leighton Formation and has some of the chemical characteristics of basalts in the Eastport. The basaltic tuff at the base of the Eastport Formation is chemically like the Silurian basalts, but no Eastport-type basalts are known at lower stratigraphic levels, and no Silurian-type basalts are known at higher levels. One of the silicic dacites in the Leighton Formation has chemical characteristics of both the Silurian and older Devonian basalts. With these exceptions, the Silurian and older Devonian volcanic rocks are chemically unlike one another. Most of the compositional shift seems to have taken place during a pause in volcanism represented by the Hersey Formation, and during the transition from marine to subaerial conditions.

The younger Devonian assemblage is defined by the one sample we obtained from a basalt flow in the Perry Formation, but assigned to this assemblage are three sills of comparable chemistry but of probable pre-Perry age that intrude the Leighton and Hersey Formations. The age of the sills is uncertain, but available evidence, including the presence of Acadian cleavage, suggests that they were emplaced after Hersey deposition and prior to Acadian cleaving and metamorphism.

No younger Devonian rhyolites are known. The youngest coastal granites might, however, be silicic companion rocks to the Perry basalt. Of seven chemical analyses of granites that are used in figures 5 and 7, four are from the Tunk Lake pluton (Karner, 1968), which has yielded a preliminary K-Ar age of 357±10 m.y. (Karner, 1974, p. 190), and one is from the Vinalhaven pluton, which has yielded a K-Ar age of 399 m.y. and an Rb-Sr whole rock age of 361±7 m.y. (Brookins, 1976, table 2). If the younger age is the correct one for the Vinalhaven pluton, the approximate 360-m.y. date for the Vinalhaven and Tunk Lake bodies is not much older than the beginning of the Late Devonian. Moreover, the pre-cleavage diabase sills in the Leighton and Hersey Formations must be older than the Perry, and within the broad range of isotopic ages that have been reported for the coastal granites and the granitic rocks of the Bays-of-Maine Complex.

In the following descriptions primary igneous textures and mineralogy are emphasized. Effects of alteration and low rank metamorphism are described later.

SILURIAN ASSEMBLAGE

Most of the basalts and basaltic andesites of the Silurian assemblage display intergranular, subophitic, and ophitic textures. The habit of chlorite, commonly filling intercrystalline pores, suggests formerly porous textures (diktytaxitic) that are common in some tholeiites. A few basalts have a subtrachytic texture of flow-alined laths of plagioclase and grains of augite. Most of the basalts are aphyric. Less common porphyritic basalts have sparsely scattered phenocrysts of plagioclase. Some basalts of the Edmunds and Leighton Formations have sparse phenocrysts of clinopyroxene as well. Olivine is uncommon, but sparse pseudomorphs of saponite(?) after small euhedral phenocrysts of olivine were found in two flows from the Edmunds Formation. Calcic plagioclase, where preserved, exhibits normal gradational zoning from calcic labradorite to sodic labradorite or calcic andesine. The augite is colorless or very pale brown, lacks exsolution lamelli, is only rarely zoned, and shows no evidence of marginal reaction. A few fine-grained intergranular basalts have grains of pigeonite along with augite. Hypersthene is absent. Some flows have small amounts of intergranular potassium feldspar. Accessory minerals are magnetite, ilmenite, sphene, and apatite. Amygdules composed variously of chlorite, quartz, calcite, and epidote are common, particularly at the base and tops of flows. Although many flows overlie or underlie fossiliferous marine siltstones and mudstones, pillows and columnar structures are rare. Most flows are a few to 20 m thick, but some are as much as 100 m thick.

The diabase and gabbro of the Cutler Diabase have essentially the same textures and mineralogy as the Silurian basalts but are coarser grained. In addition, small amounts of ragged green, pale-blue, and colorless amphibole are present in the interstices of some gabbros. One specimen has small amounts of late magmatic deep-brown basaltic hornblende. Small amounts of metamorphic biotite are present in some rocks. In places complex compositional layering and cumulate textures indicate local gravitational fractionation of labradorite, augite, and titaniferous magnetite (Gates, 1961, p. 39–41).

Basaltic tuff-breccias of the Silurian assemblage are a mixture of angular to subrounded fragments of basalt as much as a meter across in a matrix of pumice lapilli, crystals of plagioclase and augite, disaggregated bedded basaltic tuffs, and clasts of siltstone and shale.

Most of the Silurian rhyolites and silicic dacites contain sparse phenocrysts of albite widely scattered through a fine-grained matrix of intergrown albite, quartz, potassium feldspar, and alteration products. Phenocrysts of albite in the silicic domes and flows are euhedral; some are in glomeroporphyritic clots. The phenocrysts in pyroclastic rocks are commonly broken. The albite, having low temperature optics, is commonly dusty with clays and is partially replaced by epidote, or calcite, or both, suggesting that the original plagioclase was more calcic. Alkali feldspar occurs as phenocrysts in a few rhyolites, but more commonly it is intergrown with quartz in lithophysae or in the groundmass. It has disordered and intermediate structural states (Benson orthoclase, Spencer B), suggesting that some primary feldspar has survived metamorphism. Rounded and embayed phenocrysts of quartz occur along with albite in a few of the rhyolitic rocks. Original ferromagnesian minerals are missing, but they may be represented by ragged masses of chlorite and clusters of epidote grains. Accessory minerals are magnetite, leucoxene, and sparse zircons. Flow banding is common. Spherulites and perlitic cracks indicate that many of the silicic rocks were originally vitrophyres. Faint outlines of shards indicate that some of these rocks are tuffs; some may be ash-flow deposits. Evidence of welding, if any, has been destroyed by the metamorphism. Other rhyolitic rocks have a fine-grained granophyric texture or one of interlocking feldspar microlites.

Coarse silicic mixed tuff breccias in the Edmunds and Leighton Formations are composed of boulder-sized blocks and smaller fragments of rhyolites, porphyries, chert, tuffs, basalt, and sedimentary rocks; grains of quartz, albite, and sparse augite; and metamorphic epidote, chlorite, sericite, and carbonate. The sand-sized matrix of some of these deposits is feldspar crystal tuff, containing abundantly scattered broken and euhedral crystals of albite about a millimeter long.

The andesite dike that intrudes the Dennys Formation has euhedral phenocrysts of saussuritized plagioclase, and epidote pseudomorphous after phenocrysts of pyroxene(?). The phenocrysts are set in a felty matrix of ragged blue-green hornblende; laths of dusty albite; scattered grains and spots of chlorite, leucoxene, epidote, and magnetite; and sparse grains of quartz.

OLDER DEVONIAN ASSEMBLAGE

Most of the basalts and basaltic andesites of the Eastport Formation are porphyritic, a significant difference from most of the Silurian basalts. Unaltered phenocrysts of labradorite and augite, some in glomeroporphyritic clots, are set in an intergranular to subtrachytic matrix of the same minerals. Some of the more silica rich basalts and basaltic andesites have a percent or so of intergranular quartz. Small amounts of potassium feldspar are common in the interstices. Chlorite is ubiquitous; epidote or calcite or both may be present. The content of magnetite is at least twice that of the Silurian basalts. The actual iron contents of the older Devonian basalts are somewhat higher also, but the higher magnetite contents are probably more a function of the distinctly lower magnesium contents in the older Devonian basalts. This assumes that iron to magnesium ratios in the pyroxenes are about the same in basalts of both assemblages, but the pyroxenes have not been analyzed. Much of the iron in the older Devonian basalts has been oxidized to hematite, which gives the rocks a maroon color, in contrast to the dark-green or black hues of the Silurian basalts. Many of the older Devonian basalts have red oxidized tops.

The older Devonian silicic rocks contain scattered euhedral phenocrysts of albite, dusty with clays and other alteration products, in a fine-grained matrix. The matrix ranges from devitrified flow-banded glass to fine-grained granophyre. Potassium feldspars occur in small tabular crystals in the groundmass intergrown with quartz, in spherules, in lithophysae, and rarely as euhedral phenocrysts. Some of the potassium feldspars have intermediate structural states (Spencer B, 2 samples)[1], suggesting that some primary feldspar structure has survived metamorphism. One sample has ordered alkali feldspar (maximum microcline), suggesting a secondary origin, in accord with its habit as discrete layers and lenses along flow banding. A few samples contain rounded resorbed phenocrysts of quartz. Ragged masses and wisps of chlorite are the only ferromagnesian minerals. Magnetite, partly or wholly altered to hematite, is more abundant than in the Silurian silicic rocks. A few devitrified vitrophyres of the Eastport Formation contain individual shards and collapsed pumice.

The basaltic andesite at Mount Tom, like most basalt and the basaltic andesite in the Eastport Formation, is porphyritic. Saussuritized phenocrysts of labradorite are set in an intergranular matrix of small euhedral feldspar laths, epidote grains, chlorite, and abundant magnetite. Clots of chlorite and epidote rimmed by an unidentified opaque mineral have the outlines of original pyroxene phenocrysts.

The coarse tuff-breccias, the finer grained tuffs, and the bedded water-laid tuffs consist wholly of rocks and minerals confined to the volcanic pile. Although clasts of pre-Silurian rocks are present in the basal and slide conglomerates in other parts of the coastal volcanic belt, no fragments of metamorphic or plutonic rocks from the presumed underlying Avalonian basement or from the pre-Silurian metamorphic rocks have been found either in the Silurian or Devonian volcanic rocks of the Machias-Eastport area.

YOUNGER DEVONIAN ASSEMBLAGE

The single sample of basalt from the Perry Formation contains sparse small euhedral phenocrysts of argillized labradorite in a fine-grained matrix of lath-shaped argillized calcic andesine, grains of augite, interstitial chlorite, and a few grains of quartz. Some of the quartz grains are round and probably xenocrystic. Magnetite is abundant. The groundmass has fine-grained reddish- to yellowish-brown platy to fibrous mineral (probably saponite), and a few small pseudomorphs of pyroxene containing bastite possibly after orthopyroxene.

Diabase sills that intrude the Leighton and Hersey Formations have a relict ophitic or subophitic texture. The plagioclase is labradorite where unaltered. Magnetite and ilmenite are abundant, and small amounts of potassium feldspar are present in interstices. Apatite is rather abundant, as small rod-shaped crystals that penetrate plagioclase. Trace amounts of quartz were seen. One altered sample (table 2, sample No. 29) from the interior of a sill is coarse grained and composed of albite to sodic oligoclase, prehnite, sunbursts of vividly pleochroic blue-green to straw-yellow pumpelleyite (showing anomalous interference colors), epidote, deep-green chlorite, magnetite, augite, a few spots of calcite, and sparse saponite possibly after olivine.

[1] X-ray studies done by U.S. Geological Survey, under supervision of C. G. Cunningham, Jr. Alkali feldspars (mainly groundmass) were separated from four Silurian and three older Devonian rhyolites; structural states determined by the method of Wright (1968).

SAMPLING

The sites of 44 samples that form the basis of this study are shown in figure 2. Of the 44 samples, 36 were collected from outcrops and roadcuts between Machias and Eastport, and 8 were collected from drill cores in the Pembroke prospect, a small area of epigenetic sulfide mineralization in the Leighton Formation in the northwest corner of the Eastport quadrangle. Sample A is hydrothermally altered basalt from the prospect. Major oxide analyses of 32 samples are listed in table 2, and all analyses, recalculated without volatiles, are displayed in figure 4. Appendix A gives sites and descriptions of samples listed in table 2. Appendix B gives the same information and chemical analyses for all other samples.

Although our samples were not collected in proportion to the relative volumes shown in table 1, we believe that all the major types that define the Silurian and older Devonian assemblages are represented. Four of the seven silicic tuffs shown in figure 4 plot between 67 and 71 percent SiO_2; they have the composition of silicic dacite and low-silica rhyolite. These samples represent mixed tuff breccias in the Edmunds and Leighton Formations, thought to be submarine pyroclastic flow deposits. As such they probably represent the average compositions of the source volcanoes. Our sampling of the younger Devonian assemblage is not adequate. We have one analysis of Perry basalt, and three of diabase sills in the Leighton. Seven analyses from the literature of the coastal granites (Karner, 1968; Dale, 1907) are tentatively included in this assemblage.

ALTERATION

Thin sections show clear evidence of variable spilitic and keratophyric alteration, which produced saussuritized and albitized plagioclase, and also chlorite, epidote, carbonate, and leucoxene after the ferromagnesian and opaque minerals. At least minor changes in chemical composition are inevitable in such rocks, and are shown in fact by the vertical spread of data (especially CaO, Na_2O, and K_2O) in figure 4. Our problem is to find the rocks that have been modified the least. Furthermore, the vitrophyric silicic rocks must have been prone to alkali exchange during hydration (Lipman and others, 1969). In addition, studies of the Pembroke sulfide deposits have shown that hydrothermal alteration may be more intense and widespread than one might expect from casual inspection of outcrops and thin sections. There, a thick sequence of basalts in the Leighton Formation has been greatly enriched in potassium (in feldspar) and manganese (in carbonate and epidote). Data for one sample are shown in table 2 and figure 4 (sample No. A). Without the spectacular manganese contents, these rocks could be mistaken for trachybasalts. Analyses that show more than 0.3 percent MnO and other obviously hydrothermally altered rocks were not included in this study.

The eight large symbols shown in figure 4 represent our least altered basalts and basaltic andesites, and are our "best" analyses. These rocks have recognizable calcic plagioclase, augite, very little calcite, and less than about 0.5 percent CO_2 (table 2, sample Nos. 1, 4, 5, 7, 8, 18, 20, 30). The plagioclase in these rocks may be dusty with alteration products, and the augite is embayed by chlorite. Furthermore, the least altered rocks are variably oxidized, having FeO to Fe_2O_3 ratios of 3.3 to 6.8 in the five marine Silurian basalts, about 1.5 in the two lagoonal or subaerial Eastport basalts, and 0.3 in the single subaerial Perry basalt (table 2). Nonetheless, these rocks are the best guides we have to the original nature of the basalts and the chemical changes that accompanied alteration of the other samples. Because the least altered silicic rocks cannot be defined as rigorously, we have not attempted to identify "best" analyses of dacites and rhyolites.

In figure 4, [2]FeO*, MgO, TiO_2, and P_2O_5 in the Silurian basalts plot within narrowly defined fields that are almost completely separate from the fields for these oxides in the Devonian basalts. This relationship holds regardless of degree of alteration, suggesting that these four oxides were little affected by alteration. This conclusion finds support in Vallance's (1974) study of chemical changes that accompanied the spilitic alteration of Deccan basalt near Bombay, India. There, TiO_2 appears to have been most stable, followed by MgO and total iron (FeO*). Although the oxidation states of iron are extremely variable in our basalts and in the Deccan basalt, the total iron contents evidently are little affected by alteration.

In contrast, the CaO and Na_2O contents evidently have been changed significantly. On the assumption that the CaO and Na_2O contents of the least altered Silurian basalts are primary or nearly so, CaO has been strongly depleted and Na_2O has been enriched in some samples of more altered basalts. Depletion of calcium may have occurred where CO_2 pressure was too low to fix the calcium as calcite in the rocks, for two samples

[2]FeO* = FeO + 0.9 Fe_2O_3 (in weight percent).

TABLE 2.—*Major oxide analyses in weight percent of volcanic rocks of the Machias-Eastport area, Maine*

[Starred site no., least altered basalt, basaltic andesite, and diabase; has at least clinopyroxene and calcic plagioclase; <0.5 percent CO_2. Site Nos. 14 and A, analyses by standard methods by Vertie C. Smith; all other analyses by rapid methods described by Shapiro and Brannock (1962) supplemented by atomic absorption; analyzed by P. Elmore, J. Glenn, R. Moore, H. Smith, and S. Botts, all U.S. Geological Survey. N, no phenocrysts; P, plagioclase in basalts, alkali feldspar in silicic rocks; C, clinopyroxene; O, olivine. Leaders (--), not determined; <, less than]

Assemblage	Silurian															
Formation	Dennys		Edmunds		Leighton		Cutler		Dennys			Edmunds	Leighton		Unnamed	Leighton
Sample No.	★1	2	3	★4	★5	6	★7	★8	9	10	11	12	13	14	15	A
Laboratory No.	D160 372W	W176 692	W176 691	W176 689	W176 686	W178 301	W176 682	W176 680	W176 698	W176 696	D160 371W	D160 373W	D160 380W	D102 345	D160 370W	D102 348
Rock class	Flow	Flow	Flow	Flow	Flow	Flow	Intrusives		Flow	Flow	Flow	Flow	Flow	Flow	Dike	Alt. flow
Phenocrysts	N	N	P	C,O	N	P,C	N	N	P	P	P	P	P	P	P,C?	N
SiO_2	49.7	47.7	50.8	48.9	46.4	50.6	46.8	48.8	73.0	74.2	73.7	71.6	66.3	65.72	62.1	46.61
Al_2O_3	16.6	16.7	15.6	16.6	16.8	15.9	16.3	15.1	15.0	13.2	13.3	14.4	15.9	14.46	16.2	16.25
Fe_2O_3	1.6	3.4	4.1	2.0	2.4	2.8	1.4	1.6	.68	.54	2.0	2.5	.64	1.00	2.1	1.40
FeO	7.0	7.2	5.3	7.5	8.0	5.2	9.5	8.2	1.2	1.6	.84	.80	3.6	3.02	3.8	7.29
MgO	7.7	8.1	6.3	6.6	8.0	5.9	7.4	8.2	.53	.48	.37	.37	.31	1.56	2.8	3.56
CaO	9.2	6.4	7.4	9.1	10.5	9.3	10.0	10.7	1.1	.92	.35	.85	1.8	2.67	5.2	6.77
Na_2O	2.1	3.1	4.4	3.1	2.1	2.8	2.5	2.5	6.4	4.1	4.2	4.0	2.0	4.48	4.0	1.94
K_2O	1.0	1.2	.83	.56	.15	.45	1.1	.72	1.3	3.7	3.9	3.1	5.7	1.70	1.5	4.33
H_2O^+	2.8	3.3	2.8	2.8	3.3	2.5	2.8	2.3	.62	.69	.73	1.2	1.8	1.68	1.1	3.63
H_2O^-	.13	.27	.16	.21	.24	.32	.11	.11	.02	.03	.21	.24	.09	.12	.12	.16
TiO_2	1.3	1.6	1.2	1.2	1.4	1.3	1.5	1.3	.20	.28	.26	.44	.54	.60	.83	1.55
P_2O_5	.25	.22	.15	.19	.15	.37	.25	.22	.02	.03	.03	.09	.08	.18	.21	.20
MnO	.16	.21	.15	.22	.15	.09	.22	.19	.00	.10	.10	.04	.07	.21	.12	1.51
CO_2	.05	<.05	.36	.15	<.05	1.7	.15	<.05	<.05	.06	.01	.30	1.2	2.13	.01	4.55
Cl,F,S	--	.00S	.00S	.00S	.00	--	.08S	.00	.02S	.15S	--	--	--	(.02 Cl, .04 F, .10 S)	--	(.01 Cl, .07 F, .06 S)
Subtotal	--	--	--	--	--	--	--	--	--	--	--	--	--	99.69	--	99.89
Less O	--	--	--	--	--	--	--	--	--	--	--	--	--	.07	--	.06
Total	99.59	99.50	99.55	99.13	99.59	99.23	100.11	99.94	100.09	100.08	100.00	99.93	100.03	99.62	100.09	99.83
Recalculated without volatiles																
SiO_2	51.4	49.7	52.8	51.0	48.3	53.4	48.3	50.0	73.4	74.8	74.4	72.9	68.4	68.7	62.8	51.0
Al_2O_3	17.2	17.4	16.2	17.3	17.5	16.8	16.8	15.5	15.1	13.3	13.4	14.7	16.4	15.1	16.4	17.8
FeO*(FeO+0.9 Fe_2O_3)	8.8	10.7	9.4	9.7	10.6	8.1	11.1	9.8	1.8	2.1	2.3	3.2	4.3	4.1	5.8	9.4
MgO	8.0	8.5	6.5	6.9	8.3	6.2	7.6	8.4	.53	.48	.37	.38	.32	1.6	2.8	3.9
CaO	9.5	6.7	7.7	9.5	10.9	9.8	10.3	11.0	1.1	.93	.35	.87	1.9	2.8	5.3	7.4
Na_2O	2.2	3.2	4.6	3.2	2.2	3.0	2.6	2.6	6.4	4.1	4.2	4.1	2.1	4.7	4.1	2.2
K_2O	1.0	1.3	.86	.58	.16	.48	1.1	.74	1.3	3.7	3.9	3.2	5.9	1.8	1.5	4.7
TiO_2	1.3	1.7	1.3	1.3	1.5	1.4	1.5	1.3	.20	.28	.26	.45	.56	.63	.84	1.7
P_2O_5	.26	.23	.16	.20	.16	.39	.26	.23	.02	.03	.03	.09	.08	.19	.21	.22
MnO	.17	.22	.16	.23	.16	.10	.23	.19	.00	.10	.10	.04	.07	.22	.12	1.7

Assemblage	Older Devonian												Younger Devonian			
Formation	Eastport						Mt. Tom	Eastport					Unnamed		Perry	Unnamed
Sample No.	16	17	★18	19	★20	21	22	23	24	25	26	27	28	29	★30	31
Laboratory No.	W176 671	D160 375W	W176 674	W176 673	W176 672	W176 679	W176 684	W176 675	D160 379W	W176 678	D160 378W	D160 376W	W178 302	W176 683	W176 677	W178 303
Rock class	Tuff	Flow	Flow	Flow	Flow	Flow	Stock	Flow	Tuff	Flow	Flow	Flow	Sills		Flow	Sill
Phenocrysts	N	P	P	P,C	P,C	P	P,C	P	P	N	P	P	N	N	N	P
SiO_2	53.3	45.4	50.4	50.7	53.6	53.5	52.2	67.1	72.4	69.5	74.1	74.9	48.7	47.0	48.9	47.5
Al_2O_3	15.1	18.0	17.2	14.5	16.4	14.8	17.8	13.0	13.9	12.8	12.9	13.2	14.6	13.2	15.8	14.3
Fe_2O_3	3.0	5.4	4.0	6.2	3.8	.85	6.1	4.3	2.7	2.8	1.3	1.7	4.0	3.7	10.8	2.9
FeO	6.0	5.3	6.1	5.5	5.9	10.5	4.2	1.8	.48	2.1	1.7	.28	8.7	10.9	3.4	8.4
MgO	6.6	2.8	5.1	4.1	3.7	2.7	4.3	.43	.23	.37	.15	.04	5.0	5.2	4.8	4.6
CaO	4.4	8.1	7.2	6.0	7.8	4.9	7.3	2.1	.27	1.6	.09	1.20	8.0	9.2	6.7	8.3
Na_2O	2.9	3.4	3.3	4.7	3.1	4.0	3.7	4.7	4.2	2.9	2.8	4.9	3.6	4.2	3.9	2.0
K_2O	1.1	.61	1.5	.32	1.5	.41	.85	3.0	4.5	5.5	5.3	3.5	.77	.12	.70	.77
H_2O^+	3.8	2.5	2.6	2.2	1.7	3.7	1.4	1.1	.70	.80	1.0	.69	2.4	2.0	1.6	3.1
H_2O^-	.75	1.4	.28	.24	.25	.20	.12	.12	.11	.10	.09	.07	.20	.12	.75	.21
TiO_2	1.4	1.7	1.7	2.7	1.4	1.9	1.3	.50	.30	.39	.27	.19	3.1	3.4	2.1	2.6
P_2O_5	.23	.27	.28	.46	.35	.73	.21	.08	.06	.04	.05	.04	.56	.45	.49	.57
MnO	.16	.24	.20	.23	.15	.24	.24	.18	.06	.18	.07	.01	.16	.24	.15	.11
CO_2	1.3	4.2	<.05	2.0	.35	1.4	<.05	1.5	.04	.89	.02	.02	.17	.26	<.05	4.6
S	.00	--	.00	.00	.00	.00	.00	.01	--	.14	--	--	--	.00	.00	--
Total	100.04	99.32	99.86	99.85	100.00	99.83	99.72	99.92	99.95	100.11	99.84	99.74	99.96	99.99	100.09	99.96
Recalculated without volatiles																
SiO_2	56.6	49.8	52.0	53.1	54.9	56.6	53.2	69.1	73.0	70.8	75.1	75.7	50.1	48.1	50.0	51.6
Al_2O_3	16.0	19.7	17.7	15.2	16.8	15.7	18.1	13.4	14.0	13.0	13.1	13.3	15.0	13.5	16.2	15.5
FeO*(FeO+0.9 Fe_2O_3)	9.2	11.1	10.0	11.6	9.5	11.9	9.9	5.8	2.9	4.7	2.9	1.8	12.7	14.6	13.4	12.0
MgO	7.0	3.1	5.3	4.3	3.8	2.9	4.4	.44	.23	.38	.15	.04	5.2	5.3	4.9	5.0
CaO	4.7	8.9	7.4	6.3	8.0	5.2	7.4	2.2	.27	1.6	.09	.20	8.2	9.4	6.9	9.0
Na_2O	3.1	3.7	3.4	4.9	3.2	4.2	3.8	4.8	4.2	3.0	2.8	5.0	3.7	4.3	4.0	2.2
K_2O	1.2	.67	1.6	.34	1.5	.43	.86	3.1	4.5	5.6	5.4	3.5	.79	.12	.72	.84
TiO_2	1.5	1.9	1.8	2.8	1.4	2.0	1.3	.51	.30	.40	.27	.19	3.2	3.5	2.2	2.8
P_2O_5	.24	.30	.29	.48	.36	.77	.21	.08	.06	.04	.05	.04	.58	.46	.50	.62
MnO	.17	.26	.21	.24	.15	.25	.24	.19	.06	.18	.07	.01	.16	.25	.15	.12

of Silurian basalts that have the lowest CaO contents (fig. 4) also have little or no CO_2.

Although the K_2O contents of most of the basalts are too small and variable to tell much about possible enrichment or depletion, potassium may have been strongly depleted in two samples (table 2): sample 5, a least altered Silurian basalt with 0.16 percent K_2O, and sample 29, a more altered younger Devonian diabase with 0.12 percent K_2O. These K_2O contents are one-third to one-eighth that of the other basalts or diabases of their respective assemblages. Both samples also have exceptionally small amounts of barium and rubidium, as shown for sample 5 in table 3. Although these low abundances might be primary, it seems more likely that potassium, rubidium, and barium were selectively removed.

In the rhyolitic rocks of both assemblages, Na_2O and K_2O contents are extremely erratic (fig. 4). High Na_2O contents are typically accompanied by low K_2O contents, however, so that the total alkali contents are much less variable. This approximately reciprocal relationship may express alkali exchanges that took place while the rocks were still glassy.

Although none of the sampled rocks were truly closed systems during alteration, there is little evidence of massive chemical changes that would significantly affect the identification of a rock from its chemical analysis. Andesites were not changed to rocks that we now call basalts or rhyolites, or vice versa. Our confidence in the validity of the major oxide analyses is strengthened by the minor-element data, which as shown later have remarkably consistent minor-element signatures within each assemblage and with pristine basalts of other parts of the world.

VOLCANIC PETROLOGY

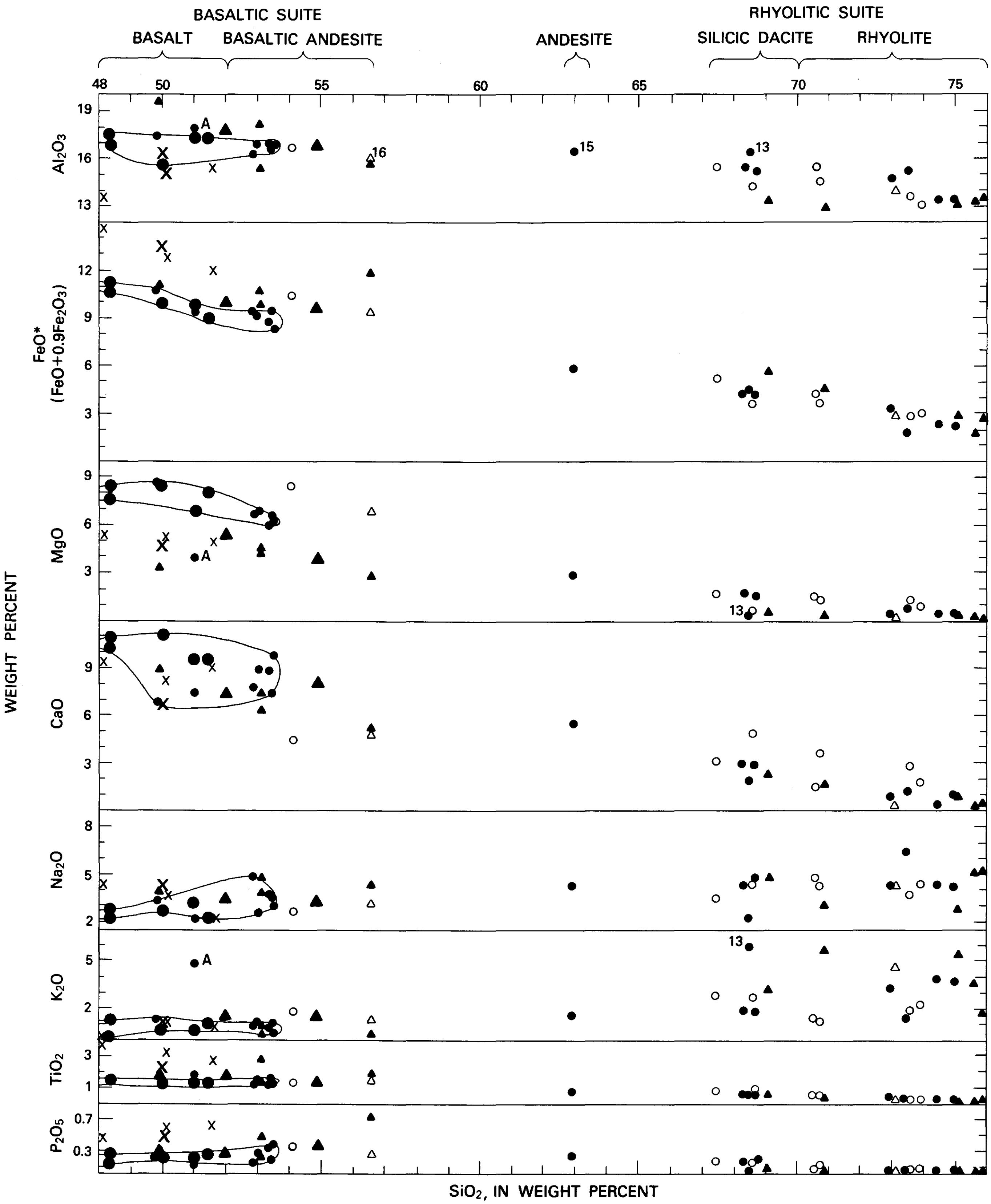
The bimodal distribution of the volcanic rock types and their major chemical features are shown in figures 4–7. The Silurian and older Devonian assemblages are distinguished by almost consistently different FeO^*/MgO, FeO^*/SiO_2, and MgO/SiO_2, and contents of MgO and total alkalis in both the basaltic and rhyolitic suites. Basalt in the Perry Formation and the diabase sills in the Leighton and Hersey Formations, and the tentatively included coastal granites (figs. 5, 7) comprise a third compositionally distinctive bimodal suite.

Figure 5 shows alternative boundaries between alkaline and subalkaline or tholeiitic basaltic rocks. We favor Irvine and Baragar's line (1971) for the Machias-Eastport rocks, because it yields the simpler classification (almost all subalkaline), and because the line of Macdonald and Katsura (1964) does not divide the Machias-Eastport rocks in a compositionally meaningful way. This preference is supported by data on the oxides and minor elements that Floyd and Winchester (1975) and Winchester and Floyd (1976) considered to be immobile during alteration, namely: P_2O_5, TiO_2, niobium, yttrium, and zirconium. According to criteria established by these authors, almost all the Eastport-Machias basalts are clearly tholeiitic. The younger Devonian basalts are partial exceptions, for they may be classed as alkalic on the basis of their high contents of TiO_2 and P_2O_5, and high P_2O_5 relative to zirconium; or they may be classed as tholeiitic on the basis of low contents of niobium relative to yttrium. These relationships may be seen when our data from table 3 are plotted in various diagrams of Winchester and Floyd (1976) and Floyd and Winchester (1975) that utilize all the listed immobile elements. Although the older and younger Devonian basalts have higher niobium contents than the Silurian basalts (table 3), alkalic basalts elsewhere typically have at least twice as much niobium as the 14 ppm (parts per million) niobium in sample 30 (table 3), a younger Devonian basalt. (See Engel and others, 1965, table 2; Lipman and Moench, 1972, table 1.)

Figure 6 is the commonly used AFM diagram, and figure 7 is the type of diagram used by Kuno (1968, fig. 4, 16–18) to illustrate the variation of major oxides relative to solidification index, or the amount of MgO that shows in an AFM diagram. In figure 7 the variations of FeO^*, TiO_2, and SiO_2 relative to solidification index effectively illustrate the compositional evolution of both the basaltic and rhyolitic suites of all three age assemblages.

Table 3 summarizes minor-element data. In this report these data are used only for comparative purposes, and further interpretations are deferred until other analyses are completed.

Pearce and Cann (1973) prepared three diagrams that are intended to permit one to identify the tectonic setting of a suite of basalts on the basis of their minor-element contents; specifically, titanium, zirconium, yttrium, and strontium. These diagrams do not appear to be appropriate for identifying the tectonic setting of the basalts of the Machias-Eastport area. The main problem, also recognized by Gottfried, Annell, and Schwarz (1977, p. 106, fig. 6), is the lack of adequate data on a wide range of continental tholeiites. For example, data for the Columbia River Basalt Group (McDougall, 1976, tables 1–3) and for basalts of the


BASALTIC SUITE
BASALT
BASALTIC ANDESITE
ANDESITE
RHYOLITIC SUITE
SILICIC DACITE
RHYOLITE
48 50 55 60 65 70 75
Al_2O_3
FeO^* $(FeO+0.9Fe_2O_3)$
MgO
CaO
Na_2O
K_2O
TiO_2
P_2O_5
WEIGHT PERCENT
SiO_2, IN WEIGHT PERCENT
A
13
15
16

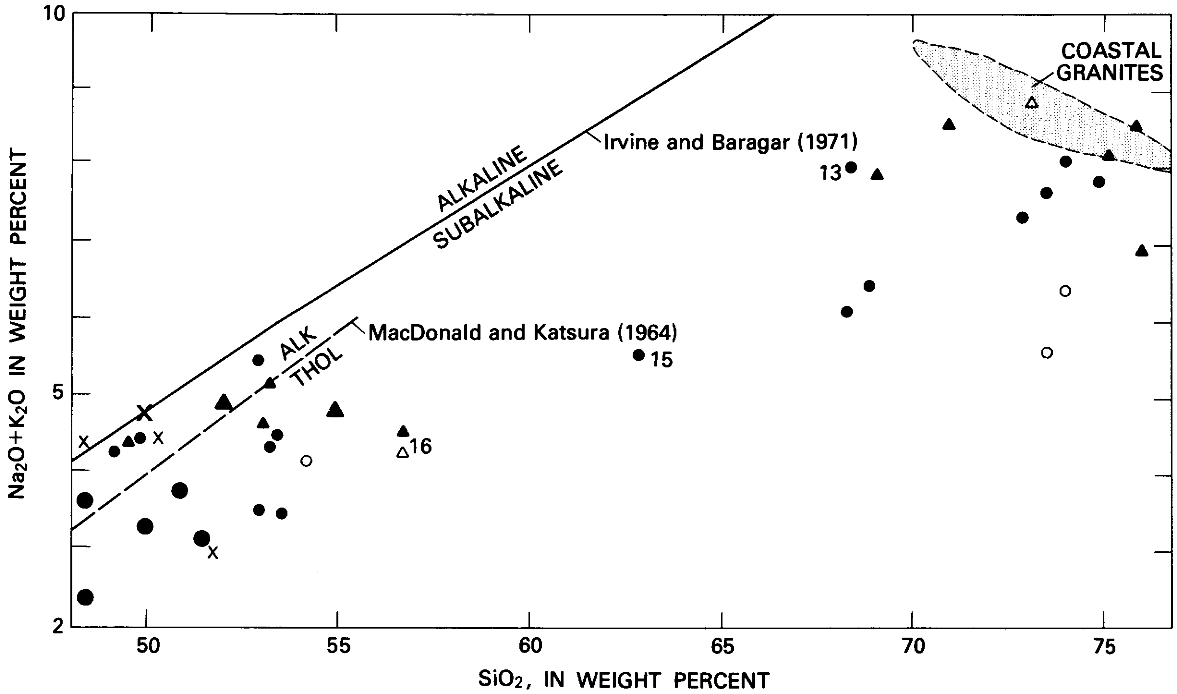


FIGURE 5.—Alkali-silica variation diagram. Field of coastal granites encloses four analyses from the Tunk Lake pluton (Karner, 1968), and one each from the Jonesboro pluton at Jonesboro, the Vinalhaven pluton on Hurricane Island, and an unnamed pluton on High Island in southwestern Penobscot Bay (Dale, 1907). Large symbol, least altered basalts. Open symbol, volcaniclastic rocks; all others, lava rocks. Circle, Silurian assemblage; triangle, older Devonian assemblage; X, younger Devonian assemblage. Samples 13, 15, and 16 (table 2) are labeled.

Rio Grande depression (Lipman, 1969; Lipman and Mehnert, 1975)—all clearly continental tholeiites—plot variously in the fields for ocean-floor basalts, low-potassium tholeiites of island arcs, and calc-alkalic basalts in Pearce and Cann's (1973) diagrams. The diagrams provide, however, a convenient way for comparing minor-element associations in different groups of basalts. For example, in their diagrams the available data for basalts of the Rio Grande depression plot closely with our data for the Silurian basalts of the Machias-Eastport area. The remarkable similarity of these basaltic rocks of widely different age and setting is shown also by the major oxide data listed in table 4.

◀ FIGURE 4 (facing page).—Harker diagram showing major oxides, recalculated without H_2O and CO_2. Large symbol, best analyses of least altered basalts. Open symbol, volcaniclastic rocks, including four analyses of mixed tuff breccias between 67.5 and 71 percent SiO_2. All others, lava rocks. Circle, Silurian assemblage; triangle, older Devonian assemblage; X, younger Devonian assemblage. Samples 13, 15, and 16 (table 2) are labeled. Sample A, hydrothermally altered Silurian basalt from the Pembroke prospect. Envelopes enclose samples of Silurian basalts.

Figure 8 shows average major-oxide and minor-element data for least altered basalts of the Machias-Eastport area on the Harker-type diagrams of McDougall (1976, figs. 5, 6) for basalts of the Columbia River Group. These diagrams provide a convenient way of showing how minor-element signatures change sympathetically with changes in major-oxide composition in the Silurian to older and younger Devonian progression. The diagrams also show a striking similarity that exists (in direction, not amount) between these changes and those that accompany the Columbia River progression, despite obvious differences in tectonic setting. All basalts of the Machias-Eastport area are much more aluminous than those from the Columbia River area, but the differences in FeO*, MgO, CaO, TiO_2, P_2O_5, and the minor-element contents of the somewhat magnesian Silurian basalts, of the silicic older Devonian basalts, and of the younger Devonian basalts (exceptionally rich in iron and titanium), are remarkably similar to the differences between the Picture Gorge, lower, and middle basalts of the Yakima Subgroup.

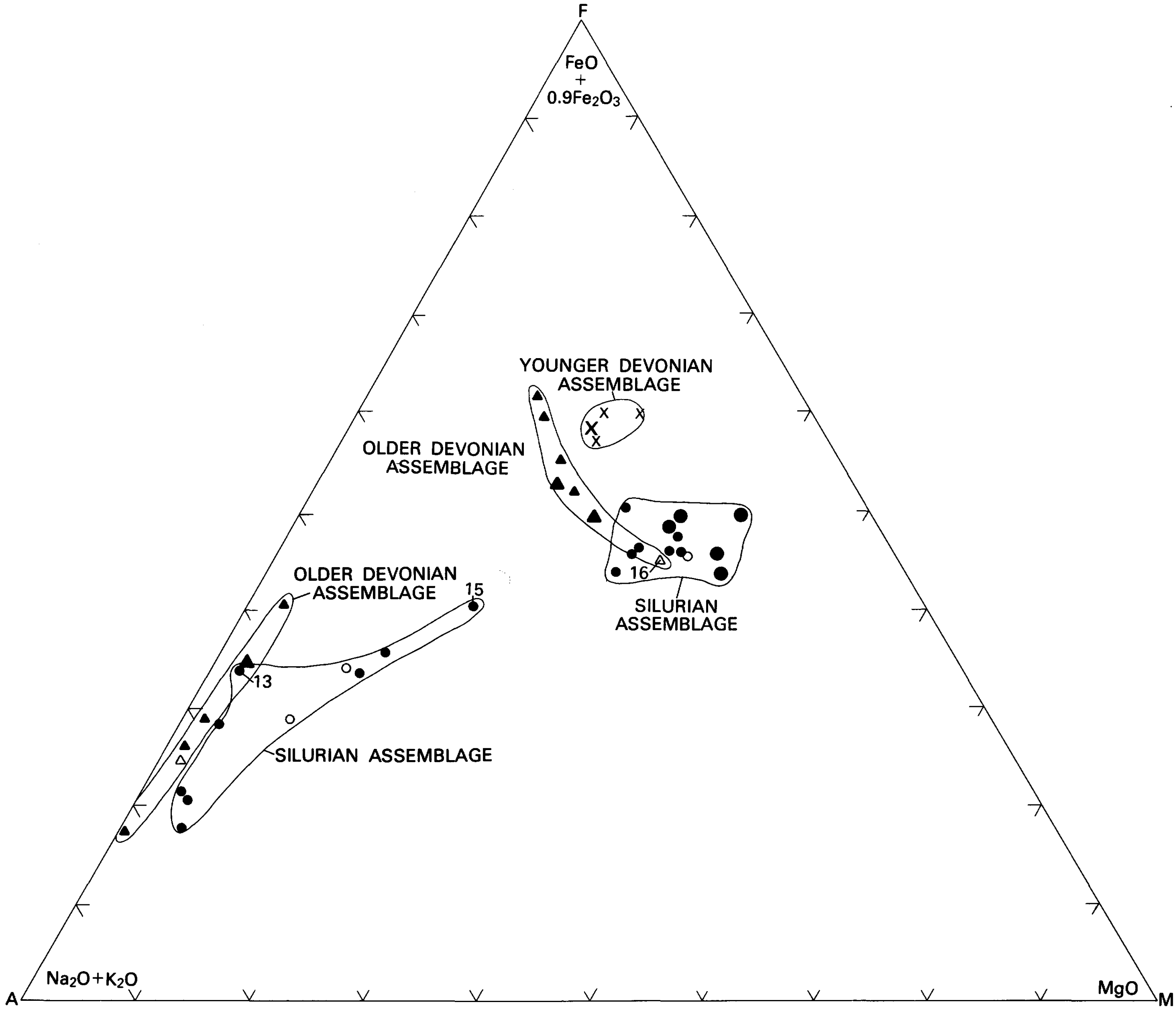
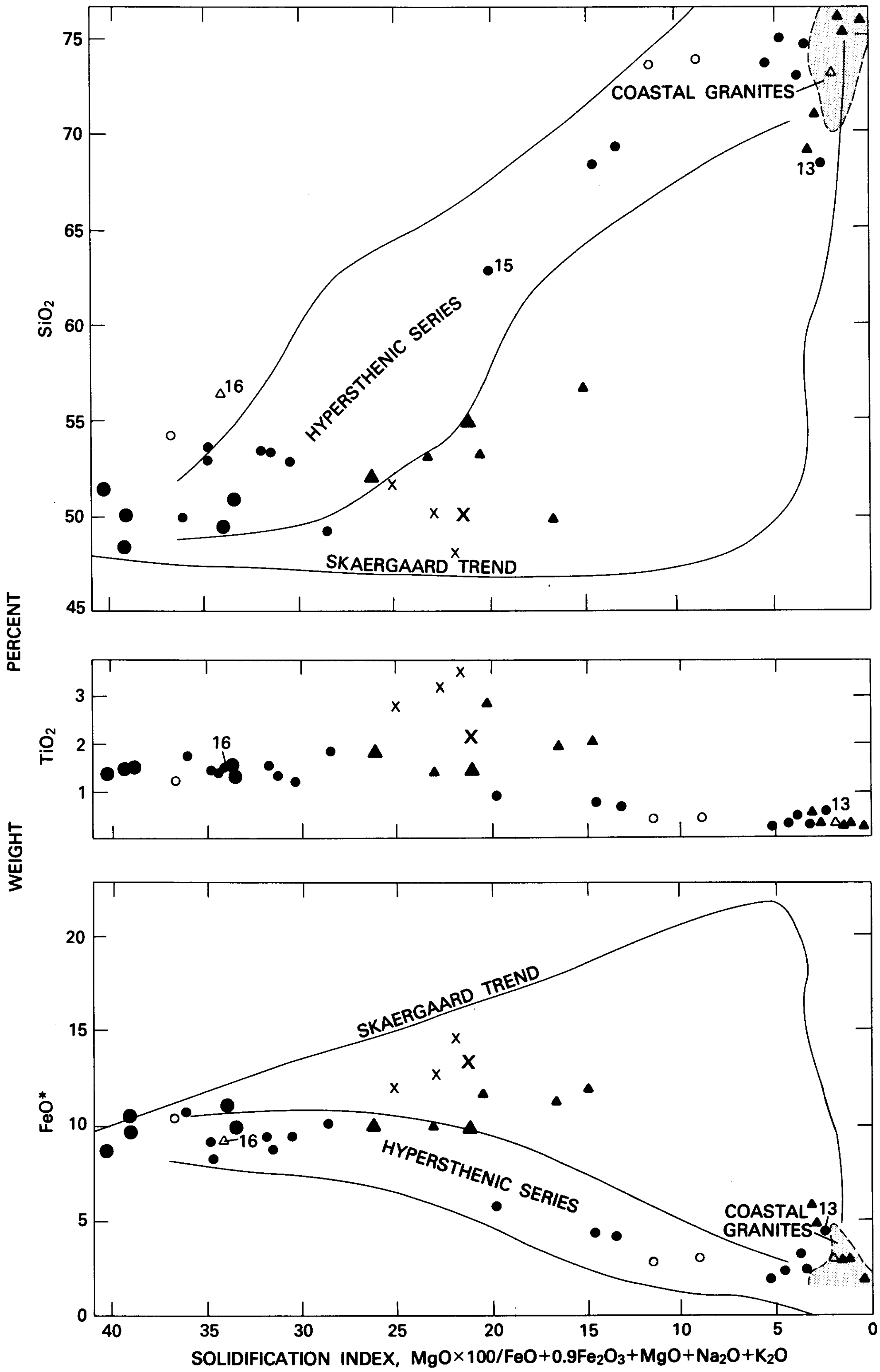


FIGURE 6.—AFM diagram (weight percent basis). Large symbol, least altered basalts. Open symbol, volcaniclastic rocks; all others, lava rocks. Circle, Silurian assemblage; triangle, older Devonian assemblage; X, younger Devonian assemblage. Samples 13, 15, and 16 (table 2) are labeled.

FIGURE 7 (facing page).—Variation of SiO_2, TiO_2, and FeO* (total iron as FeO) relative to solidification index (weight percent basis). Approximate boundaries of hypersthenic field in Japan from Kuno (1968, figs. 16, 17). Skaergaard trend from Wager and Brown (1968, tables 4, 9, 10). Field of coastal granites encloses four analyses from the Tunk Lake pluton (Karner, 1968), and one each from the Jonesboro pluton at Jonesboro, the Vinalhaven pluton on Hurricane Island, and an unnamed pluton on High Island in southwestern Penobscot Bay (Dale, 1907). Large symbol, least altered basalts. Open symbol, volcaniclastic rocks; all others, lava rocks. Circle, Silurian assemblage; triangle, older Devonian assemblage; X, younger Devonian assemblage. Samples 13, 15, and 16 (table 2) are labeled. ▶



75
70
65
60
55
50
45
SiO2
COASTAL GRANITES
HYPERSTHENIC SERIES
SKAERGAARD TREND
16
15
13
3
2
1
TiO2
16
13
PERCENT
WEIGHT
20
15
10
5
0
FeO*
SKAERGAARD TREND
HYPERSTHENIC SERIES
COASTAL GRANITES
16
13
40
35
30
25
20
15
10
5
0
SOLIDIFICATION INDEX, MgO×100/FeO+0.9Fe2O3+MgO+Na2O+K2O

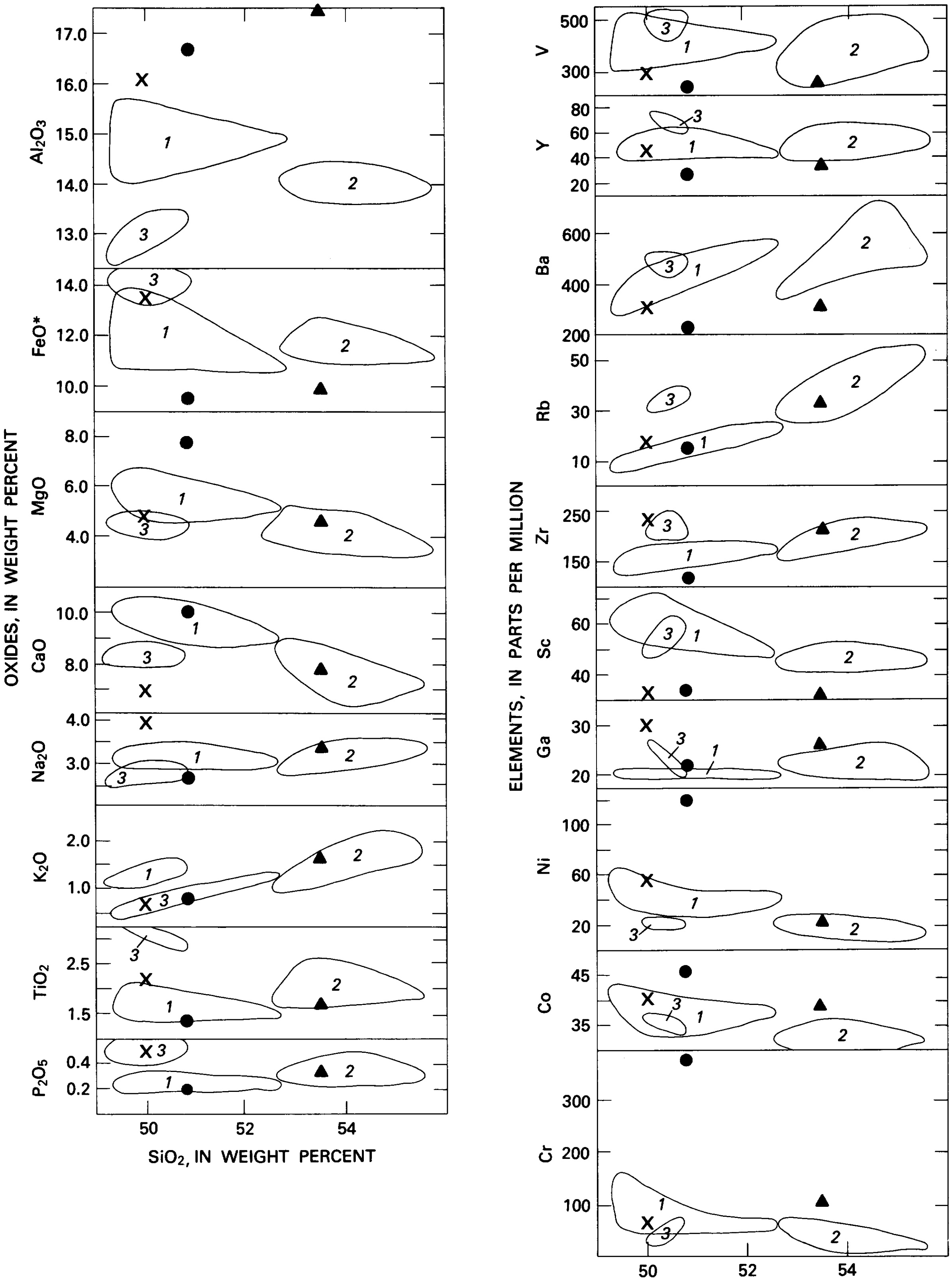


FIGURE 8.—Major-oxide and minor-element data for least altered basalts of the Machias-Eastport area compared with data of McDougall (1976, figs. 5, 6) for the Columbia River Basalt Group.

TABLE 3.—*Selected and average minor-element data on volcanic rocks*

[Starred sample Nos., average of several values. N, looked for but not detected; leaders (--), not looked for; <, less than. Numbers in parentheses, number of samples for which data are available. Data in parts per million except SiO_2 and K_2O, in percent (from table 2). In all samples, Sr and Rb detected by X-ray fluorescence analyses. In all samples, U detected by delayed neutron determinations. All samples, except samples 13 and 15, analyzed for Th, La, Yb, Ba, Co, Cr, Cs, Hf, Sb, Sc, Ta, and Zr by instrumental neutron activation. For samples 13 and 15, Th detected by delayed neutron determinations. For samples 13 and 15, La, Yb, Ba, Co, Cr, Cs, Hf, Sb, Sc, Ta, and Zr detected by semiquantitative emission spectrographic analyses by computerized techniques. In all samples, Be, Ga, Nb, Ni, V, Y, Ag, Mo, Pb, Sn, and Zn detected by semiquantitative emission spectrographic analyses by computerized techniques. Analysts: X-ray fluorescence analyses by W. P. Doering; delayed neutron determinations by H. T. Millard, Jr., and D. A. Bickford; instrumental neutron activation analyses by R. J. Knight and H. T. Millard, Jr.; semiquantitative emission spectrographic analyses by computerized techniques by A. F. Dorzapf, supplemented by visual method by J. L. Harris, J. D. Fletcher, B. W. Lanthorn. All analysts, U.S. Geological Survey]

Rock type	Basalt			Basaltic andesite	Basalt	Andesite	Rhyolite	Dacite	Dacite	Rhyolite
Age assemblage	Silurian		Older Devonian		Younger Devonian	Silurian		Older Devonian		
Sample No.	★1,4,8	5	18	20	30	15	★9,10,11,12	13	★23,25	★26,27
SiO_2	50.8	48.3	52.0	54.9	50.0	62.9	73.9	68.4	69.5	75.4
[1]K_2O	.77	.16	1.6	1.5	.72	1.5	3.0	5.9	4.4	4.5
[1]Sr	516	374	472	375	550	412	140	85	62	38
[1]Rb	15	2	35	29	16	47	74	158	128	144
[1]U	.40	.23	.76	1.25	1.12	1.92	3.17	5.26	3.05	4.64
[1]Th	1.77	.75	2.24	4.01	3.18	9.17	11.7	22.3	13.5	15.6
[1]La	15.0	7.77	15.2	24.9	27.4	50	39.7	100	72.7	133
Yb	2.12	2.17	2.66	2.95	2.83	3	4.87	15	10.8	8.59
[1]Ba	227	84.8	290	330	307	300	554	1,000	676	636
Co	46.1	55.8	43.4	32.5	39.9	20	2.42	20	1.27	1.01
Cr	380	345	162	47.3	58.0	50	20.4	5	16.6	17.6
Cs	1.24	.83	2.7	1.41	1.77	--	1.25	--	.65	.98
Hf	2.84	2.19	4.47	4.72	4.39	N	8.60	N	18.7	10.7
Sb	.23	1.34	.63	.40	2.31	N	.99	N	.89	1.25
Sc	33.5	34.2	30.8	28.2	32.3	30	9.53	30	6.57	12.8
Ta	.26	.11	.45	.52	.83	--	1.04	--	2.49	1.79
[1]Zr	115	85.7	194	222	231	150	325	1,000	802	443
Be	<1	<1	1.5	1.9	1.8	1	2.4	2	6.9	3
Ga	22	23	28	24	30	20	19	30	46	25
[1]Nb	4.3(2)	4	9.6	6.0	14	7	8.5	30	22.	25
Ni	120	172	41	11	55	50	6.1	70	2.8	13
V	233	300	200	300	300	150	12.(3)	3	12.	15
Y	28	32	31	36	45	30	57	150	177	100
Ag	.34(2)	.29	.31	.21	.47	N	<0.1	N	.35	N
Mo	4.3	6.2	4.0	<1.5	5.4	3	2.7(1)	5	2.8	N
Pb	6.2	7	6.1	5.3	14	15	15	20	16	10
Sn	9.5(2)	<3.2	7.9	7.9	15	N	5.9(2)	N	10	N
Zn	127(2)	129	117	116	169	N	36.(2)	N	141	N

[1]Elements or oxides of elements that are strongly excluded from rock-forming minerals of the Earth's mantle; called excluded or incompatible. Others are included in mantle minerals; called included or compatible elements (Green and Ringwood, 1967, p. 174, 175; Jamieson and Clarke, 1970).

EXPLANATION FOR FIGURE 8

◀ From oldest to youngest: *1*, Picture Gorge Basalt; *2*, lower basalt, and *3*, middle basalt of the Yakima Basalt Subgroup; all of the Columbia River Basalt Group. Machias-Eastport data, from oldest to youngest: dot, average of three Silurian basalts (sample Nos. 1, 4, 8); triangle, average of two older Devonian basalts (sample Nos. 18, 20); X, younger Devonian basalt (sample No. 30); all data in tables 2 and 3.

SILURIAN ASSEMBLAGE

In major-oxide and minor-element composition and in the absence of a transition to abundant andesites, the Silurian basalts may be called high-alumina tholeiites of continental character. Olivine tholeiites and quartz tholeiites are represented. The basalts are not strongly fractionated, for many are nonporphyritic, and FeO* to MgO ratios are rather uniform. This characterization is based mainly on the paucity of andesites, for many similarities can be seen in the composition of calc-alkalic orogenic basalts, high-alumina continental tholeiites, and the Silurian basalts. All the examples shown in table 4 plot within Kuno's field for high-alumina basalts (Kuno, 1960; 1968, fig. 1). On the basis of its major-oxide composition alone, the Silurian basalt of sample 5 (table 2, recalculated without volatiles) is indistinguishable from the average ocean floor tholeiite basalt of Engel, Engel, and Havens (1965, table 3). The only conspicuous differences between these two and all the others are the low K_2O contents and the high TiO_2 contents, particularly in comparison with the calc-alkalic basalts. As shown by Pearce and Cann (1973, fig. 2), most calc-alkalic basalts have less than about 7,500 ppm titanium, whereas the Silurian basalts contain 7,500 to nearly 10,000 ppm titanium. The TiO_2 content alone, however, is not a sure indication of tectonic association of basalts.

The data on minor elements indicate that the Silurian basalts are not akin to oceanic tholeiites or tholeiites of island arc or back-arc settings, but no sharp distinction can be drawn from these data between the Silurian basalts, calc-alkalic basalts, and some continental basalts. The Silurian basalts contain more potassium and far greater abundances of the whole suite of excluded minor elements (listed and defined in table 3) in comparison with oceanic tholeiites. (Compare table 3 with Jakes and Gill, 1970, table 1; Jamieson and Clark, 1970, table 2; Engel and others, 1965, tables 1, 2; Kay and others, 1970, table 4.) Data on rare-earth elements are particularly diagnostic. The Silurian basalts have 7.8–18.5 ppm lanthanum and lanthanum to ytterbium ratios that range at least from 3.5 to 8, indicating significant enrichment in the light rare-earth elements (table 3, average La and Yb given for sample Nos. 1, 4, 8). These abundances are not out of line with rare-earth element data for calc-alkalic basalts, but they stand in contrast with the small lanthanum abundances and low lanthanum to ytterbium ratios that are characteristic of ocean floor, island arc, and back-arc tholeiites (Jakes and Gill, 1970; Jakes and White, 1972, table 2B; Hart and others, 1972; Kay and others, 1970). Abundances of the included minor elements, on the other hand, are not conspicuously different. In diagrams of Miyashiro and Shido (1975), which utilize titanium, vanadium, chromium, and nickel, the Silurian basalts plot consistently with the ocean floor tholeiites—but so do the most basaltic calc-alkalic rocks.

Petrologists commonly distinguish calc-alkalic from tholeiitic rocks on the basis of alkali-enrichment versus iron-enrichment respectively (Miyashiro, 1974), but as noted by Irvine and Baragar (1971, p. 529), this distinction is not always sharply defined. The standard AFM diagram may be misleading if used uncritically. In figure 6, for example, the area for the Silurian basalts bulges slightly toward A, suggesting an incipient calc-alkalic trend. This bulge probably is an expression of metasomatic sodium-enrichment, how-

TABLE 4.—*Silurian basalts from the Machias-Eastport area compared with high-alumina tholeiites and calc-alkaline basalts from other regions*

[Data in weight percent]

	Silurian assemblage		Tholeiitic basalts			Calc-alkalic basalts		
	Machias-Eastport area		Northern New Mexico Rio Grande depression	Ocean floor	Greenland Skaergaard chill border	Northern California Warner basalt	Japan	Papua
Reference No.	1A	1B	2	3	4	5	6	7
No. of analyses	4	1	19	10	1	1	1	1
SiO_2	50.2	48.3	50.9	49.94	48.71	49.20	48.10	50.79
Al_2O_3	16.7	17.5	16.3	17.25	17.44	17.16	16.68	16.45
FeO*	9.9	10.6	11.2	8.71	9.48	10.28	11.24	8.45
MgO	7.7	8.3	7.4	7.28	8.73	7.88	8.89	9.05
CaO	10.1	10.9	8.9	11.86	11.53	11.45	10.48	9.60
Na_2O	2.65	2.2	3.0	2.76	2.40	2.58	2.51	2.92
K_2O	.83	.16	.64	.16	.25	.23	.46	1.08
TiO_2	1.35	1.50	1.2	1.51	1.19	.89	.73	1.06
P_2O_5	.24	.16	.16	.16	.10	.09	.15	.21
MnO	.21	.16	.16	.17	.16	.17	.54	.12

SOURCES OF DATA

1. A, average four least altered basalts; B, sample No. 5 (table 2).
2. Lipman and Mehnert (1975, table 1, col. 12).
3. Engel, Engel, and Havens (1965, table 3, col. 1).
4. Kuno (1968, table 2, col. 7; recalculated without volatiles).
5. Kuno (1968, table 2, col. 6; recalculated without volatiles).
6. Kuno (1968, table 2, col. 5).
7. Jakes and Smith (1970, table 2, col. 1; recalculated without volatiles).

ever, for it is composed entirely of basalts that do not qualify as least altered. An alkali-enrichment trend is shown also in Aoki's AFM diagram for basalts of the Rio Grande depression (Aoki, 1967, fig. 5), but this trend is formed by one alkali andesite from a cone that is younger than the basalts of the Servilleta Formation (the most voluminous upper Cenozoic basalts in the northern part of the depression) and by three alkalic olivine basalts that may have their source outside the depression (Lipman, 1969, p. 1349). In Aoki's AFM diagram, all the tholeiites plot within a small area that shows no obvious trend one way or the other. Thus, in view of these and the foregoing considerations, the only valid distinction between high-alumina tholeiites and calc-alkalic basalts is the absence or presence respectively of a transition to abundant andesites. In the absence of such a transition, we conclude that the Silurian basaltic suite is tholeiitic. Its large abundance of excluded minor elements identifies the suite as continental.

Most analyses of the Silurian rhyolitic suite and the andesite dike plot along a typical calc-alkaline trend in the AFM diagram (fig. 6), and within the hypersthenic series of Kuno (1968) in figure 7. With the exception of sample 13, K_2O contents in rocks of the rhyolitic suite are rather low (table 2; fig. 4). Contents of K_2O and Na_2O tend to be roughly reciprocal, suggesting that alkali exchange took place while the rocks were still glassy (Lipman and others, 1969). As shown in figure 4, most of the Silurian rhyolites are more aluminous than those of the older Devonian rhyolitic suite.

The analysis of one sample of silicic dacite in the Leighton Formation (table 2, sample No. 13) plots with the older Devonian silicic dacites in figures 4–7, expressing the high content of total alkalis, and the high FeO* to MgO ratio in this sample. This rock appears to have characteristics of both the Silurian and older Devonian assemblages. Its alumina content is high, actually higher than any of the other Silurian rhyolites; it also has the highest K_2O and lowest Na_2O contents of both rhyolitic suites. Minor-element abundances in sample 13 are exceptional, but they are most comparable to those of the older Devonian rhyolitic suite (table 3). The cobalt and nickel contents of sample 13 are comparable to those of the andesite.

In summary, the Silurian assemblage divides into a suite of tholeiitic high-alumina basalts of continental character, and a suite of calc-alkalic rhyolites and silicic dacites and one known andesite. Although this association may seem incongruous, Irvine and Baragar (1971, p. 529) pointed out that tholeiitic basalts and calc-alkalic silicic rocks are in fact closely associated in some areas, as in the Yellowknife volcanic belt of Canada. If calc-alkalic andesites of Silurian age were much more abundant than they are in the Machias-Eastport area, the whole Silurian assemblage would not be unlike the calc-alkalic volcanics of the Cascade Range. The same reasoning applies, however, to the basalts of the Rio Grande depression.

OLDER DEVONIAN ASSEMBLAGE

The older Devonian basaltic suite is clearly tholeiitic, according to Irvine and Baragar's criteria (fig. 5), and it has predominantly tholeiitic abundances of immobile minor elements, as discussed previously. As shown in figure 6, these basalts clearly define an iron-enrichment trend. The older Devonian basalts and basaltic andesites have a wider range and higher average SiO_2 content than the Silurian ones, and distinctly more FeO*, TiO_2, P_2O_5, and Na_2O, but less CaO and MgO. Thus, FeO* to MgO ratios are generally higher than those of the Silurian suite. Among the included minor elements, chromium and nickel contents range widely but are distinctly less abundant in the older Devonian basaltic suite (table 3). Other differences in minor-element signatures are shown in figure 8. Petrographically, the older Devonian basalts and basaltic andesites, typically having abundant magnetite and phenocrysts of plagioclase, appear to represent derivative magmas. The low-magnesium and low-nickel contents indicate that olivine fractionated from the magmas.

In contrast, the basaltic tuff at the base of the Eastport Formation has chemical characteristics of the Silurian basalts (table 2, sample No. 16; figs. 4–7), except for its high SiO_2 and low CaO contents, which (since it is a tuff) might be a result of contamination by quartz-bearing sediments, and its low CaO content, probably a result of calcium-depletion during alteration. This basaltic tuff is directly overlain by a basaltic flow (table 2, sample No. 20) having a high FeO* to MgO ratio, a high P_2O_5 content, and petrographic features and the minor-element signature of the older Devonian basalts (table 3). No basalts like those of the Silurian assemblage are known higher in the section, and no Eastport-type basalts are known lower in the section. Among the basalts, therefore, a shift toward iron-enriched basaltic magmas evidently took place abruptly between eruptions of the basal tuff and the next overlying flow of the Eastport. This shift closely followed the volcanic hiatus represented by the Hersey Formation and accompanied the general trend toward shoaling and emergence of the area of the coastal volcanic belt.

Our six samples of older Devonian rhyolites and silicic dacites have 69–75.7 percent SiO_2. The average SiO_2 content of these rocks is distinctly higher than that of the Silurian rhyolitic suite, even if the Silurian andesite and the mixed tuff breccias are excluded from the average. The older Devonian rhyolitic suite also has distinctly higher FeO* to MgO ratios, higher average K_2O and total alkali contents, and distinctly lower alumina contents (figs. 4-7).

Figure 7 illustrates the contrast between the Silurian and older Devonian rhyolitic suites to best advantage. Whereas all of the Silurian suite, except sample 13, conforms to the calc-alkalic hypersthenic series of Kuno (1968), the older Devonian rhyolitic suite plots along a trend that diverges only slightly from that of the strongly tholeiitic Skaergaard trend. Significant differences between the Silurian and older Devonian rhyolitic suites are seen also in the minor-element signatures (table 3). The older Devonian rocks are poorest in strontium, but richest in the other excluded minor elements.

YOUNGER DEVONIAN ASSEMBLAGE

The flow and sills of the younger Devonian assemblage are iron- and titanium-rich tholeiitic basalts of strongly continental character. The four samples have 48-51.5 percent SiO_2, distinctly lower than most of the older Devonian basalts. The higher FeO*, TiO_2, and P_2O_5 contents of these rocks are higher than those of most basalts of the Eastport, but FeO* to MgO ratios are about the same (table 2; fig. 4). In figure 5 one analysis plots barely in the alkaline field of Irvine and Baragar (1971). This analysis (table 2, sample No. 29) has a trace of nepheline in the norm, possibly because its Fe_2O_3 content is too low. According to criteria established by Floyd and Winchester (1975), the abundances of immobile elements have characteristics of both alkalic and tholeiitic basalts, owing to the high TiO_2 and P_2O_5 contents (common in alkalic basalts) and low niobium contents (common in tholeiitic basalts). In the AFM diagram the four samples plot within a small area closer to the FM side than do the analyses of older Devonian basalts, and in figure 7 they plot closer to the Skaergaard trend.

The younger Devonian basalts and the two least altered older Devonian basalts have rather comparable minor-element signatures that are quite different from the basaltic Silurian signature (table 3; fig. 8). In the younger, magnesium and nickel contents are low, as in the older Devonian basalts, indicating that olivine fractionated from the magma.

Available analyses of granitic plutons of the coastal belt plot within the small areas that are shown in figures 5 and 7. As shown in figure 5, these granites have generally higher total alkali contents—owing mainly to higher K_2O—than the older Devonian and Silurian rhyolitic suites. In figure 7 the area of the granites is closest to the Skaergaard trend. Thus, in all the silicic rocks of all three assemblages, the most conspicuous changes from the older to younger suites are toward higher K_2O contents, toward higher average and more restricted SiO_2 contents, and toward increasingly tholeiitic crystallization trends. Unfortunately, absence of published analyses of the Bays-of-Maine Complex prevents determination of whether or not the rocks of this complex, intermediate in age between the older Devonian assemblage and the younger coastal granites, share this trend.

SUMMARY AND ORIGIN

The most conspicuous feature of the volcanic suite in the Machias-Eastport area is the andesite gap. Within the fossiliferous Silurian and Lower Devonian sequence, sedimentary beds and volcanic rocks of widely contrasting mafic and silicic composition are complexly interstratified. Plutonic rocks further emphasize the bimodal distribution of igneous rock compositions in the Bays-of-Maine Complex (Chapman, 1962; Pajari, 1973) and evidently throughout New England as well (Wones, 1976). Major intrusives exposed in and near the Machias-Eastport area are the Cutler Diabase (considered a subvolcanic mafic complex related to the Silurian assemblage of volcanics), and the Bays-of-Maine Complex, intruded in turn by the coastal granites (tentatively considered the silicic end member of the younger Devonian assemblage). Bimodal magmatism thus seems to have been time-persistent in the Silurian and Devonian before and possibly during and after the Acadian orogeny. Whether it was characteristic of the whole northern Appalachians for this time remains to be ascertained. Although andesites of this age are in fact abundant locally (Shride, 1976; Williams and Gregory, 1900; Howard, 1926), descriptions in most available reports seem to emphasize the predominance of basaltic and rhyolitic rocks. Andesites are described in all the principal reports on other parts of the coastal volcanic belt, but no chemical analyses have been published. It remains to be determined whether these andesites are akin to those of typical subduction-related magmatic arcs, or instead are like the porphyritic iron- and titanium-rich silicic basalts and basaltic andesites of the Eastport Formation; and, for example, the lower basalts of the Yakima Subgroup of the Columbia River Group (fig. 8; Waters, 1961; Wright and others, 1973; McDougall, 1976).

Chemically and petrographically, basalts of the Machias-Eastport area have characteristics of continental tholeiites, in accord with the likelihood that they were erupted through the Avalonian sialic crust. Moreover, as time passed the basaltic lavas became more continental in character, in a manner that seems analogous to the Columbia River progression (fig. 8), changing from the rather magnesian Silurian lavas to the silicic older Devonian basalts and basaltic andesites, variably enriched in iron and titanium and depleted in magnesium and nickel, and then to the younger Devonian basalts, which also are most enriched in iron and titanium and in several of the excluded minor elements. The silicic magmas also changed, starting with calc-alkalic types and ending with more potassic and more silicic magmas having the greatest abundances of excluded minor elements (table 3), and a closer alinement to the Skaergaard trend (figs. 6, 7). These changes appear to have continued across the time of the Acadian orogeny, for the available analyses of the coastal granites show even closer alinement to the Skaergaard trend. The most conspicuous shift toward iron-enrichment was abrupt; it closely followed a volcanic hiatus represented by the Hersey Formation, and it accompanied the general emergence of the coastal volcanic belt in earliest Devonian time. The younger Devonian basalts evidently erupted both before and after the formation of the Acadian cleavage. Thus, the compositional shift was fully developed in both the basaltic and rhyolitic suites before the Acadian. It was in reverse, moreover, to the changes that mark the transition from immature to mature island arcs, according to Miyashiro (1974).

Nicholls and Ringwood (1973) have shown that partial melting of ultramafic upper mantle under water-saturated conditions can yield quartz tholeiites and olivine tholeiites at depths as great as 70 km and 100 km, respectively. Under dry conditions the origin of such magmas and the fractionation of olivine from them are restricted to much shallower depths: no more than about 15 km for quartz tholeiites, and 35 km for high-alumina basalts (Green and Ringwood, 1967; Green and others, 1967) or perhaps high-alumina tholeiites like those of the Silurian assemblage. The most favorable tectonic setting for deep origins under hydrous conditions is in the wedge-shaped mantle that lies below an island arc. By definition the resulting tholeiitic basalts are arc tholeiites—poor in titanium, magnesium, nickel, and chromium relative to abyssal tholeiites (Jakes and Gill, 1970), and quite unlike any basalts of the Machias-Eastport area, which are of continental character. Shallow origins thus seem to be required for basalts of the Machias-Eastport area.

A scheme that we currently favor postulates thermal expansion of the mantle, and diapiric intrusion into the sialic crust along the trend of the coastal volcanic belt. These processes were accompanied by shoaling and emergence of the belt, and they produced the bimodal volcanism. At depths that may have been significantly less than 35 km, high-alumina tholeiitic magma segregated from the partially melted mantle diapir. If the crust was in fact much thinner than 35 km, it was probably thinned or fragmented by extension. The fact that the older and younger Devonian basalts are greatly depleted in magnesium and nickel relative to the Silurian ones indicates that large amounts of olivine fractionated from the parent. We are not certain, however, that the Silurian basaltic magma was in fact the parent of the Devonian magmas. All three types may have had another parent; or, alternatively, each type might represent separate melting events. These questions remain for future consideration.

According to our scheme, heat furnished to the crust by the mantle diapir caused partial melting, resulting in the silicic magmas. At first, in Silurian time, melting yielded calc-alkalic rhyolites and silicic dacites from deformed and metamorphosed but still hydrous, largely pelitic sedimentary material. Sparse andesite magma might have formed by mixing of basalt and rhyolite, known to occur at least locally elsewhere (Eichelberger, 1974). By earliest Devonian time the heated crust was partly dehydrated; partial melting produced more silicic and more potassic rhyolitic magmas that solidified along iron-enrichment trends, in accord with experimental evidence. (See Wyllie, 1973, fig. 8.) The shift toward iron-enrichment is probably an expression of lower oxygen fugacities that inhibited the early crystallization of magnetite (Kennedy, 1955; Osborn, 1962) or amphibole (Boettcher, 1973; Cawthorn and O'Hara, 1976). We are unable to explain, as yet, the close correspondence between the emergence of the coastal volcanic belt and the shift toward iron-enrichment that is shown by both the basaltic and rhyolitic suites; but an important factor undoubtedly was the progressive dehydration.

TECTONIC IMPLICATIONS

In documented post-Triassic plate tectonic settings, it is well known that fundamentally basaltic or strongly bimodal basalt-rhyolite igneous suites are characteristic of continental regions undergoing plate separation and extension; whereas, most suites along convergent plate boundaries are more or less unimodal, having a wide spectrum of igneous rock compositions (Martin and Piwinskii, 1972; Miyashiro, 1974, 1975; Lipman and others, 1972; Christiansen and Lipman, 1972; and many others). In extensional settings only very locally is andesite the predominant rock type; typically, it is greatly subordinate to more mafic and silicic rocks, and commonly andesite is absent. In convergent settings andesite is rarely absent; commonly, it is the predominant rock type. Exceptions to these rules should be noted. Bimodal or even trimodal volcanic suites occur locally in convergent settings, as in some individual volcanoes of the Cascades (McBirney, 1968, 1969) and on individual islands of the Lesser Antilles (Brown and others, 1977, fig. 2); but andesite is abundant in these suites. The Newberry volcano of the east side of the Cascade Range is strongly bimodal, composed largely of basalt, but having about 30 percent rhyolite and dacite and only 5 percent andesite in the immediate vicinity of the caldera (Higgins, 1973). Interestingly, the Newberry and the rather similar Medicine Lake Highland volcanoes (Condie and Hayslip, 1975) are on the western margin of a region of great extent that is known to be undergoing extension, possibly in a relationship analogous to extensional basins behind island arcs (Karig, 1971; Christiansen and Lipman, 1972; McDougall, 1976). The primitive Kermadec arc seems to have a bimodal suite composed of tholeiitic basalt and sparse silicic dacite (Brothers and Martin, 1970; Brothers and Searle, 1970). Unlike the coastal volcanic belt, the Kermadec arc is underlain by a thin oceanic crust; and its tholeiitic basalts have only small abundances of excluded minor elements (Miyashiro, 1974; Jakes and Gill, 1970). While these exceptions must be taken into account, the association of regionally extensive, time-persistent, strongly bimodal volcanism with extensional tectonism in post-Triassic settings seems to be a general rule that should apply to ancient orogenic belts. Pending further studies elsewhere along the coastal volcanic belt, we believe that the bimodal suites of the Machias-Eastport area express extensional tectonism in Silurian and Devonian time. The coastal belt does not seem to be the remains of a volcanic arc above a subduction zone, as proposed by McKerrow and Ziegler (1971) and Dewey and Kidd (1974).

The presence of calc-alkalic silicic rocks in the Silurian assemblage requires explanation, for such rocks are most common in volcanic arcs above subduction zones (Miyashiro, 1975). Though uncommon in extensional settings, calc-alkalic rocks are in fact known to occur there: in parts of the Karroo dolerites, in the British Tertiary (Miyashiro and Shido, 1975, p. 267), and in the Bushveld Complex (Walker and Poldervaart, 1949, fig. 35). According to our scheme for the origin of the volcanics in the Machias-Eastport area, the calc-alkalic Silurian rhyolitic suite was produced by partial melting of still-hydrous sialic crust; whereas, the tholeiitic older Devonian rhyolitic suite and the younger Devonian granites were produced by partial melting of dehydrated crust. If this model is correct, the presence of calc-alkalic silicic rocks does not necessarily identify a subduction-related magmatic suite.

If the coastal volcanic belt is not the remains of a subduction-related volcanic arc, then what is it? Conceivably, the bimodal Machias-Eastport volcanism took place in an extensional area behind an andesitic arc, as suggested by McDougall (1976) and others for the Columbia River Basalt Group, but if so, where is the arc? From presently available information, no major belt of andesitic volcanics of Silurian or Early Devonian age can be identified in the northern Appalachians. We have no definite answers that we can agree upon.

Gates (1978) proposed that during the Late Ordovician or earliest Silurian time the spreading center of the Cambrian and Ordovician proto-Atlantic was subducted beneath the northwest margin of the Avalonian continental plate. This brought to a halt spreading and subduction in the region of the present Merrimack synclinorium, and left a remnant linear basin, the Fredericton trough, which subsequently filled with Silurian and Lower Devonian clastics. The subducted spreading center powered the extensional block faulting and bimodal volcanism of the Machias-Eastport area and perhaps, but yet to be demonstrated, the entire coastal volcanic belt. Renewed compression during the Acadian orogeny squeezed the magmas that had fed the volcanoes upwards into the overlying volcanics to form the Bays-of-Maine Complex, a bimodal plutonic complex. The normal faults that formed the Perry terrestrial alluvial basin tapped subcrustal magmas for the Perry basalts.

Moench agrees that the proto-Atlantic ocean did not close completely during the Taconian orogeny, as shown by the Aroostook-Matapedia belt of Taconian conformity (fig. 1; Pavlides and others, 1968). He believes, however, that the thick prism of marine sediments of the Merrimack portion of the belt of conformity accumulated in a deep extensional fault trough that was tectonically active through Late Ordovician, Silurian, and Early Devonian time (Moench, 1970; Moench and Pankiwskyj, 1978). During the Silurian the axis of the trough evidently shifted from the Aroostook-Matapedia belt to the present alinement of the Merrimack synclinorium and Fredericton trough (fig. 1). Subsidence continued along this new alinement while contemporaneous block faulting, bimodal volcanism, shoaling, and emergence took place along the coastal volcanic belt. According to Moench, the coastal volcanic belt was a tract of thermal inflation and arching that lay directly above an axis of mantle upwelling, whereas the deep Merrimack-Fredericton seaway coincided with an active extensional fault trough that lay along the northwestern flank of the tract of arching.

Both the trough and the arch were expressions of tectonic extension that prevailed through the Silurian and Early Devonian.

But did mantle upwelling end with the onset of the Acadian orogeny? Although Acadian deformation in New England was compressional, little evidence has been found so far—provided our conclusion that the coastal volcanic belt is not the remains of an andesitic arc is correct—that the orogeny was preceded by subduction during the Silurian and Early Devonian, leading to continental collision. Moench sees no major chemical differences in the available data—admittedly too meager for definite conclusions—between the coastal volcanics and the New Hampshire Plutonic Series. Both are strongly bimodal; the silicic member of New Hampshire plutonics is calc-alkalic tonalites to granites having about the same compositional range as the rhyolitic suite of the Silurian assemblage. Moench proposes, therefore, that the coastal volcanism, and perhaps the more sporadic volcanism of the northern belt, were forerunners of the far more extensive and voluminous magmatism that resulted in the syn-Acadian and post-Acadian New Hampshire plutons and batholiths. The process of mantle upwelling, segregation of basaltic magma, and partial melting of sialic crust to produce the silicic magmas was the same before, during, and shortly after the Acadian. Because the process began earliest along the coastal volcanic belt, the crust was dehydrated earliest there, resulting in the shift from calc-alkalic to tholeiitic magma types well before the Acadian. The calc-alkalic New Hampshire Plutonic Series northwest of the coastal volcanic belt, on the other hand, represents partial melting of predominantly pelitic material that was still hydrous in the Devonian.

Both authors agree on the essential conclusions that the Merrimack synclinorium and the Fredericton trough do not represent a former trench along a Silurian and Early Devonian subduction zone and that the coastal volcanic belt is not the remains of an andesitic arc above a subduction zone.

Firm conclusions regarding the tectonic setting of the entire southeastern margin of the New England and Maritime Appalachians during the Silurian and Devonian obviously cannot be made from this petrologic study of a single small area. We have found few published investigations of the chemistry of Silurian and Lower Devonian volcanic rocks elsewhere in either the coastal volcanic belt or the northern belt (fig. 1). Yet, one of the best clues we have to ancient plate tectonic regimes lies in comparisons of the chemistry of their magmatic products with the chemistry of magmatic products of current plate tectonic regimes. Our conclusions disagree with published models for the Appalachians. We hope that this disagreement will spur others to make more thorough studies in the New England and the Maritime Appalachians to further test the Wilson cycle model as applied to Silurian and Early Devonian time and the Acadian orogeny.

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APPENDIX

APPENDIX A

[Samples listed in table 2: Sites on 7½-minute quadrangles and Gardner Lake 15-minute quadrangle, and sample descriptions. Mineral abbreviations: Q, quartz; Ksp, K-feldspar; Alb, albite; Oli, oligoclase; Pc, calcic plagioclase; Lab, labradorite; Byt, bytownite; Cpx, clinopyroxene; Aug, augite; Pig, pigeonite; Ol, olivine; Amp, amphibole; Hb, hornblende; Ac, actinolite; Cht, chlorite; Bi, biotite; Mu, muscovite; Sct, sericite; Sap, saponite; Op, opaques; Mt, magnetite; Il, ilmenite; Leu, leucoxene; Hem, hematite; Py, pyrite; Sph, sphene; Ru, rutile; Pr, prehnite; Pu, pumpellyite; Ep, epidote; Ca, calcite; Zr, zircon; Ap, apatite; Sp, sphalerite]

Sample No.	Description
1	Machias Bay quadrangle; roadside outcrop U.S. highway 1, approx. 0.16 km (0.1 mi) east of Indian Lake. Dennys Formation. Basalt flow, massive, aphyric, relict dictytaxitic texture. Minerals: Aug, Byt, Cht, sparse Ep, Ac, Mt, Leu, Ksp.
2	Machias Bay quadrangle; roadside outcrop U.S. highway 1, approx. 0.3 km (0.2 mi) west of Indian Lake. Dennys Formation. Basalt flow, massive, aphyric with sparse Ca-Ep amygdales. Minerals: Aug, Alb, Cht, sparse Ksp, Ep, Sct, Ac, Op, trace Ca.
3	Whiting quadrangle; roadside outcrop U.S. highway 1 about 2.4 km (1.5 mi) east of Indian Lake. Edmunds Formation. Massive aphyric basalt flow with relict dictytaxitic texture. Minerals: Alb, Aug, Cht; scattered Ksp, Mt, Ep, and trace of Ca.
4	Whiting quadrangle; outcrop on west shore of Whiting Bay, 1 km (0.6 mi) azimuth N. 78° E. of summit of Littles Mountain, Cobscook Bay State Park. Edmunds Formation. Basalt flow with small phenocrysts of Aug and saponitized Ol, and sparse Cht–Ca amygdales. Minerals: Pc (dusty with clay and saussuritic alteration), Ol, Aug, Cht, minor Sap, Ep, Ru, Ca, Ksp.
5	Pembroke quadrangle; roadside outcrop U.S. highway 1; 0.8 km (0.5 mi) azimuth N. 75° W. from summit of Oak Hill. Leighton Formation. Massive aphyric basalt flow with inconspicuous secondary foliation; relict ophitic texture. Minerals: Pc, Aug, Cht, minor Ru, Leu, Ep, Sap.
6	Pembroke quadrangle; outcrop in woods 0.5 km (0.3 mi) N. 70° E. of Big Hill summit. Leighton Formation. Massive aphyric basalt flow with inconspicuous secondary foliation; small phenocrysts of Pc and Aug. Minerals: Pc, Aug, Cht, Ca, minor Ep, Mt, Leu, and Sct.
7	Cutler quadrangle; quarry 1.6 km (1 mi) west of Cutler village. Cutler Diabase. Coarse relict ophitic texture with scattered Ep pods, avoided in sampling. Minerals: Pc, Pig, brown Hb, blue-green and colorless Amp, sparse brown Bi, minor Il, Cht, Ep, and sparse Ca.
8	West Lubec quadrangle; quarry at NE. end of Ellis Hill. Cutler Diabase. Coarse ophitic. Minerals: Pc, Aug, pale green to colorless Amp, Bi, Cht, minor Il, Leu, Sph, Ep, and unidentified white mica.
9	Machias Bay quadrangle; outcrop on State route 191, 1.6 km (1 mi) south of East Machias. Dennys Formation. Gray flow-banded felsite with inconspicuous secondary foliation; 5 percent Alb phenocrysts in dense xenomorphic granular matrix. Minerals: Alb, Q, white mica, minor Cht, Mt, Bi, and Ep.
10	Machias quadrangle; roadside outcrop on U.S. highway 1 about 1.5 km (0.9 mi) SW. of East Machias. Dennys Formation. Felsite with about 5 percent phenocrysts of Alb in a dense xenomorphic granular matrix. Minerals: Q, Alb, Ksp, minor Bi, Cht, sparse Sct, and traces of Ca and Py.
11	Gardner Lake 15′ quadrangle; SE. cor.; roadside outcrop on U.S. highway 1, 0.8 km (0.5 mi) east of Indian Lake. Dennys Formation. Pale-red felsite with sparse blocky phenocrysts of alkali feldspar (partly replaced by Ksp) in interlocking matrix. Minerals: Q, Alb, Ksp, and traces of Mt, Ap, and metamorphic Bi.
12	Pembroke quadrangle; roadside outcrop on U.S. highway 1, 1.2 km (0.75 mi) south of Hobart Stream. Edmunds Formation. Grayish-red felsite with 5–10 percent albite phenocrysts in a matrix of interlocking feldspars and Q, in part trachytic. Minerals: Q, Alb, Ksp, minor Cht, Mt, trace of Ca.
13	Eastport quadrangle; outcrop on hill east of road, 1.6 km (1 mi) south of Denbow Point on Denbow Neck. Leighton Formation. Gray felsite with amygdales filled with Cht, Sct, and Ca, and a few grains of Py and Sp. Major minerals are Q, Ksp, and Alb.
14	Pembroke quadrangle; drill core from Pembroke prospect; hole S–67, 1.2 km (0.75 mi), azimuth N. 55° W. of summit of Big Hill; approx. 2.6×2.6-cm (1×1-in.) fragments taken at 1.5-m (5-ft) intervals between 98 and 134 m (320 and 440 ft) below collar. Represents lower part of lenticular flow in Leighton Formation. Pale-gray mottled to banded felsite with 10–20 percent of small Alb phenocrysts. Minerals: Q, Alb, minor Cht, and Ca, and sparse Sct.
15	Machias Bay quadrangle; roadside outcrop about 0.8 km (0.5 mi) west of Gardner Lake and 1 km (0.6 mi) east of Whiting town line. Andesite dike that cuts Dennys Formation. Dark gray, dense, nonfoliated. Minerals: Alb (containing Ep), Q, ragged Hb, minor Ksp, and Op.
A	Pembroke quadrangle; drill core from Pembroke prospect; hole A-8, 0.3 km (950 ft), azimuth N. 80° E. of summit of Big Hill; approx. 2.6 × 2.6 cm (1 × 1 in.) fragments taken at 3-m (10-ft) intervals between 61 and 91 m (200 and 300 ft) below collar. Represents upper part of thick, hydrothermally altered flow sequence in Leighton Formation. Dark-gray, dense, massive altered basalt; has scattered amygdales mainly filled with green Cht, some with Q, Ca. Minerals: Alb, Sct, Ca (probably Mn-bearing), Il, Leu, and sparse Cpx, Ep.
16	Pembroke quadrangle; roadside outcrop on U.S. highway 1 about 0.3 km (0.2 mi) NW. along road from east border of quadrangle. Basaltic tuff at base of Eastport Formation; angular clasts as much as 1 cm across of porphyritic, dense, and scoriaceous basalts and sparse clasts of silty mudstone; matrix is quartz-bearing feldspathic tuff. Minerals: Alb, Cht, Ca, Sct, Sph, Ksp.
17	Eastport quadrangle; roadside outcrop on U.S. highway 1 about 1.6 km (1 mi) east of west quadrangle border. Eastport Formation. Basalt flow with abundant phenocrysts of Alb. Minerals: Alb, Cht, Ca, Il, Hem; pseudomorphs of Ca and Cht after Cpx.
18	Eastport quadrangle; roadside outcrop U.S. highway 1 about 2.3 km (1.4 mi) east of west quadrangle border. Eastport Formation. Basalt flow with abundant phenocrysts of Lab as much as 6 mm across. Minerals: argillized Lab, Aug, Cht, Mt, Sph, Ksp.
19	Eastport quadrangle; roadside outcrop U.S. highway 1 about 2.4 km (1.5 mi) east of west border of quadrangle. Eastport Formation. Flow above that of sample 18; dense basalt with small phenocrysts of feldspar and Aug in a trachytic matrix. Minerals: Alb, Cht, Aug, Mt, Ep, Sph, Ca.

Lab. No.	Description
W176693	Machias Bay quadrangle; roadside outcrop U.S. highway 1, 1.6 km (1 mi) SW. of northern quadrangle boundary. Dennys Formation. Large sample of gray mixed tuff breccia; felsites and scattered dark-gray clasts in feldspar-rich clastic matrix. Minerals: Alb, Ksp, Q, Bi, Sct, Cht, Ep. Analyses: 71.7 Si, 13.3 A, 0.69 Fe2, 2.1 Fe, 1.1 M, 2.7 C, 3.7 N, 1.8 K, 0.92 H, 0.06 h, 0.39 T, 0.08 P, 0.10 Mn, 0.40 CO.
W176690	Whiting quadrangle; roadside outcrop U.S. highway 1, 2.6 km (1.6 mi) north of Whiting. Edmunds Formation. Mixed tuff breccia; angular clasts as long as 2 cm of felsites in matrix of feldspar crystal tuff. Minerals: Alb, Q, minor Ep, Cht, Sct, Op, Ca. Analyses: 69.5 Si, 14.3 A, 2.6 Fe2, 1.3 Fe, 1.2 M, 3.5 C, 4.0 N, 1.1 K, 1.4 H, 0.11 h, 0.51 T, 0.10 P, 0.10 Mn, 0.22 CO, 0.00 S.
W176688	Whiting quadrangle; outcrop on west shore of Whiting Bay approx. 61 m (200 ft) south of site of sample No. 4 (App. A). Edmunds Formation. Mixed tuff breccia; angular to rounded clasts of felsites in matrix of feldspar crystal tuff. Minerals: Alb, Q, minor Cht, Sct, Ep, Op, Ksp. Analyses: 65.4 Si, 14.8 A, 2.8 Fe2, 2.4 Fe, 1.6 M, 2.9 C, 3.3 N, 2.7 K, 1.7 H, 0.16 h, 0.76 T, 0.16 P, 0.13 Mn, 1.2 CO, 0.00 S.
W176687	Pembroke quadrangle; roadside outcrop U.S. highway 1 at corner near Dennysville-Pembroke town line. Edmunds Formation. Mixed tuff breccia; felsites and darker volcanics in matrix of crystal tuff. Minerals: Alb, minor Ksp, Q, Cht, Sct, Ca, Op. Analyses: 64.9 Si, 13.3 A, 2.4 Fe2, 1.2 Fe, 0.57 M, 4.6 C, 4.2 N, 2.5 K, 1.4 H, 0.13 h, 0.62 T, 0.13 P, 0.20 Mn, 3.5 CO, 0.00 S.
W176685	Pembroke quadrangle; roadcut U.S. highway 1, 0.65 km (0.4 mi) west of West Pembroke junction. Edmunds Formation. Mixed tuff breccia; unsorted angular clasts of felsites, and a few silty mudstones in a matrix of feldspar crystal tuff. Minerals: Alb, Q, Cht, Sct. Analyses: 68.9 Si, 15.0 A, 0.88 Fe2, 3.2 Fe, 1.5 M, 1.5 C, 4.7 N, 1.2 K, 2.1 H, 0.13 h, 0.5 T, 0.08 P, 0.08 Mn, 0.25 CO, 0.06 S.
D102344	Pembroke quadrangle; same site as sample No. 14 (App. A); approx. 2.6×2.6-cm (1×1-in.) fragments taken at 1.52-m (5-ft) intervals between 61 and 98 m (200 and 320 ft) below collar. Represents middle of thick lenticular flow in Leighton Formation. Analyses: 65.04 Si, 14.65 A, 0.74 Fe2, 3.47 Fe, 1.70 M, 2.85 C, 4.13 N, 1.67 K, 2.02 H, 0.17 h, 0.62 T, 0.16 P, 0.23 Mn, 2.14 CO, 0.01 Cl, 0.04 F, 0.22 S.
W178306	Pembroke quadrangle; same site as sample No. 14 (App. A); single 2.6×5-cm (1×2-in.) specimen taken 114 m (375 ft) below collar. Analyses: 64.7 Si, 14.4 A, 0.50 Fe2, 2.5 Fe, 1.7 M, 4.8 C, 3.7 N, 1.5 K, 1.9 H, 0.15 h, 0.52 T, 0.22 P, 0.24 Mn, 3.5 CO.
D160374W	Pembroke quadrangle; same site and basalt flow as sample No. 20 (App. A). Analyses: 52.4 Si, 16.8 A, 3.4 Fe2, 5.8 Fe, 4.0 M, 7.8 C, 2.7 N, 1.4 K, 2.0 H, 0.26 h, 1.6 T, 0.35 P, 0.17 Mn, 0.75 CO.
D160377W	Eastport quadrangle; roadside outcrop State route 190, 0.65 km (0.4 mi) south of Perry. Eastport Formation. Reddish-brown felsite; spherulitic and intergrown blades of alkali feldspar, intergranular Q, and scattered phenocrysts of Alb as long as 3 mm. Minerals: Alb, Ksp, Q, spots Hem-dusted Cht, trace Zr. Analyses: 74.5 Si, 13.2 A, 2.1 Fe2, 0.84 Fe, 0.16 M, 0.43 C, 5.0 N, 1.7 K, 0.74 H, 0.08 h, 0.20 T, 0.03 P, 0.06 Mn, 0.22 CO.

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Sample No.	Description
20	Pembroke quadrangle; roadside outcrop U.S. highway 1 at east border of quadrangle. Eastport Formation. Basaltic flow above basal Eastport tuff (sample 16); euhedral phenocrysts of Pc and Aug. Minerals: Pc, Sct, Aug, Cht, Mt, sparse Ca.
21	Eastport quadrangle; outcrop on south shore of Buckman Head, Moose Island, Eastport, Eastport Formation. Bulbous body that intrudes shale, evidently penecontemporaneously: finely porphyritic basalt. Minerals: Alb, Cht, Ca, Sph, Leu.
22	Pembroke quadrangle; outcrop at south end of Mount Tom, about 1.6 km (1 mi) NW. of Ayers Junction. Stock of porphyritic basaltic andesite that intrudes the Leighton Formation; blocky argillized Lab phenocrysts 3–5 mm across in a trachytic matrix. Minerals: Lab, Cht, and Ep (partly pseudomorphous after Cpx), abundant Mt, and sparse Ksp.
23	Eastport quadrangle; roadside outcrop on U.S. highway 1 about 2.9 km (1.8 mi) east of west quadrangle border. Eastport Formation. Flow-banded felsite with alternating layers of spherulitic and interlocking bladed feldspar and Q; sparse blocky alkali feldspar phenocrysts. Minerals: Ksp, Alb, Q, minor Mt, Cht, and Ca.
24	Eastport quadrangle; outcrop on west shore of Moose Island, 1.2 km (0.75 mi) north of Shackford Head. Eastport Formation. Rhyolitic tuff with clasts of pale-red felsite as much as 1 cm long in a dense gray matrix; conspicuously foliated; matrix composed of smaller felsites and Alb crystals. Minerals: Q, Alb, Ksp, Cht, Hem.
25	Eastport quadrangle; roadside outcrop on State route 190 at Redoubt Hill, Moose Island. Eastport Formation. Grayish-red flow-banded felsite; interlocking blades of alkali feldspar closely intergrown with Q. Minerals: Q, alkali feldspar, minor Ca, Mt, sparse Cht, Hem, Py.
26	Eastport quadrangle; outcrop on State route 190, Moose Island in Eastport, 1.6 km (1 mi) SE. of Redoubt Hill. Eastport Formation. Flow-banded felsite with sparse 1-mm phenocrysts of Alb in a dense matrix of Q, Ksp, sparse Cht, and Op.
27	Eastport quadrangle; roadside outcrop on U.S. highway 1 about 2.4 km (1.5 mi) south of town of Perry. Eastport Formation. Grayish-red flow-banded felsite with spherulitic and interlocking textures. Minerals: Q, Alb, Ksp, minor Op, and accessory Zr.
28	Pembroke quadrangle; drill core from hole S–51, Pembroke prospect; hole is 0.7 km (0.42 mi) azimuth N. 58° W. from Big Hill summit. Diabase sill that cuts the Leighton Formation: approx. 2.6×5-cm (1×2-in.) fragment taken 105 m (344 ft) below collar; middle of 24-m (80-ft) thick sill. Relict diabasic texture. Minerals: Alb, Cht, Aug, Ep, Ksp, Q (1.6 percent), Il, Mt, Py, Ap, Ac, Ca.
29	Pembroke quadrangle; roadcut on U.S. highway 1 near SE. end of Pennamaquan Lake. Diabase sill that cuts the Hersey Formation. Coarsely ophitic diabase from center of sill. Minerals: Aug, Alb-Oli, Cht, trace of brown Hb, minor Ep, Pr, Pu, and Sap.
30	Eastport quadrangle; outcrop on shore of Passamaquoddy Bay, 0.8 km (0.5 mi) north of Gleason Point. Perry Formation. Brownish-gray dense basalt with sparse 3–5-mm phenocrysts of plagioclase in a trachytic matrix. Minerals: argillized Pc, Aug, Mt, Hem, sparse amygdales with Q and Cht.
31	Pembroke quadrangle; drill core from hole S–51, 0.7 km (0.42 mi), azimuth N. 58° W. of Big Hill summit. Diabase sill that cuts the Leighton Formation; approx. 2.6×5-cm (1×2-in.) fragment taken from a thin sill at 17 m (55 ft) below the collar. Relict diabasic texture; clear Lab corroded by Ca and Sct. Minerals: Lab, Cht, Ca, Sct, Mt, Il, sparse Py.

APPENDIX B

[Samples not listed in table 2 or numbered in figure 2: sites on 7½-minute quadrangles, sample descriptions, chemical analyses, Samples D102344, D102347 analyzed by standard methods by Vertie C. Smith; all others by rapid methods by P. Elmore, J. Glenn, R. Moore, H. Smith, S. Botts, U.S. Geological Survey. Mineral abbreviations: Q, quartz; Ksp, K-feldspar; Alb, albite; Oli, oligoclase; Pc, calcic plagioclase; Lab, labradorite; Byt, bytownite; Cpx, clinopyroxene; Aug, augite; Pig, pigeonite; Ol, olivine; Amp, amphibole; Hb, hornblende; Ac, actinolite; Cht, chlorite; Bi, biotite; Mu, muscovite; Sct, sericite; Sap, saponite; Op, opaques; Mt, magnetite; Il, ilmenite; Leu, leucoxene; Hem, hematite; Py, pyrite; Sph, sphene; Ru, rutile; Pr, prehnite; Pu, pumpellyite; Ep, epidote; Ca, calcite; Zr, zircon; Ap, apatite; Sp, sphalerite. Oxide abbreviations: Si, SiO_2; A, Al_2O_3; Fe2, Fe_2O_3; Fe, FeO; M, MgO; C, CaO; N, Na_2O; K, K_2O; H, H_2O^+; h, H_2O^-; T, TiO_2; P, P_2O_5; Mn, MnO; CO, CO_2. Oxides measured in weight percent]

Lab. No.	Description
W176695	Machias Bay quadrangle; roadside outcrop U.S. highway 1, 0.8 km (0.5 mi) east of Gardner Lake. Dennys Formation. A 10-in block basaltic tuff in basaltic agglomerate; clasts of altered scoriaceous and massive basalts in fine-grained clastic matrix of basaltic composition. Minerals: Alb, Ep, Cht, Bi, and Amp. Analyses: 51.8 Si, 15.9 A, 2.5 Fe2, 7.7 Fe, 8.0 M, 4.2 C 2.4 N, 1.6 K, 3.9 H, 0.09 h, 1.2 T, 0.34 P, 0.15 Mn, <0.05 CO, 0.01 S.
D102347	Pembroke quadrangle. Drill core, Pembroke prospect; hole E–4, 0.76 km (0.47 mi), azimuth S. 55° W. from Big Hill summit. Sample is 2.6×2.6-cm (1×1-in.) fragment taken every 1.5 m (5 ft) from 62.5 to 78 m (205 to 255 ft) below collar; represents several basaltic flows. Leighton Formation. Massive basalt with evenly scattered amygdales (Q, Ca, Cht) and inconspicuous pervasive secondary foliation. Minerals: Cht, Ca, Alb, minor Sct, Ep, Sph. Analyses: 48.39 Si, 15.13 A, 0.91 Fe2, 7.85 Fe, 5.91 M, 6.50 C, 3.14 N, 0.95 K, 4.18 H, 0.24 h, 1.38 T, 0.17 P, 0.25 Mn, 4.63 CO, 0.01 Cl, 0.03 F, 0.03 S.
W178304	Same site and rock type as D102347. Single 2.6×5-cm (1×2-in.) fragment at about 62.5 m (205 ft); least altered available. Leighton Formation. Analyses: 47.8 Si, 15.2 A, 0.00 Fe2, 7.8 Fe, 5.4 M, 8.0 C, 3.2 N, 0.70 K, 3.9 H, 0.30 h, 1.2 T, 0.29 P, 0.18 Mn, 5.4 CO.
W178307	Same site as sample No. A (App. A). Single 2.6×5-cm (1×2-in.) fragment at about 229 m (750 ft). Least altered available. Leighton Formation. Dense aphyric basalt; inconspicuous secondary foliation. Minerals: Pc, Alb, Aug, Cht, Amp, Ep, Ca, minor Leu, Ru, Sct. Analyses: 50.0 Si, 15.9 A, 1.4 Fe2, 7.4 Fe, 6.3 M, 8.4 C, 2.4 N, 0.96 K, 3.9 H, 0.23 h, 1.3 T, 0.26 P, 0.23 Mn, 1.7 CO.
W176697	Machias quadrangle; roadcut U.S. highway 1, 1.5 km (0.9 mi) south of bridge at East Machias. Dennys Formation. Mixed tuff breccia; clasts of many felsites in a clastic matrix of alkali feldspars, Q, and small felsites. Minerals: Q, Alb, Ksp, Bi, and Mu (metamorphic), minor Ca, Cht, Ep. Analyses: 73.2 Si, 13.0 A, 0.77 Fe2, 2.3 Fe, 0.92 M, 1.8 C, 4.3 N, 2.1 K, 0.90 H, 0.03 h, 0.39 T, 0.08 P, 0.11 Mn, 0.16 CO, 0.20 S.