

Commingle Gabbroic and Granitic Magmas in the Northern Bays-of-Maine Igneous Complex, Calais Area

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ABSTRACT

Field evidence from the northeastern end of the Bays-of-Maine Igneous Complex shows that coeval mafic and felsic magmas intruded the region during the Devonian. An intrusive complex of diabase pillows in a matrix of granite underlies an extensive region south of Calais, Maine, including much of the area occupied by the Baring portion of the Moosehorn National Wildlife Refuge. The mafic component displays a variety of contact features including: (1) fine-grained, quenched margins, pillowed form, with sharp boundaries against the granite matrix; (2) medium-grained, non-quenched margins, pillowed form, with diffuse contacts against the granite matrix; and (3) angular, brecciated fragments set in granite matrix, with either sharp or diffuse contacts with granite matrix. In some areas, the pillowed complex forms dikes within gabbro bodies.

The abundance of well-preserved pillows suggests that relatively little blending or homogenization of the basalt and rhyolite occurred at the level of outcrop exposure. Hence, we prefer the term "magma commingling" as used by Mitchell (1986) and Mitchell and Rhodes (this volume), rather than "magma mixing" for the event recorded in this area. When the basalt and rhyolite were juxtaposed, the viscosity of the basalt rose to a value higher than that of the rhyolite matrix, and a variety of pillow-matrix boundary types developed. Many pillows exhibit granite-healed, planar fractures, demonstrating a final, brittle stage in the evolution of the pillow-matrix system, before final crystallization of the matrix.

This bimodal basalt-rhyolite magmatism in the Bays-of-Maine Igneous Complex mimics the compositional features found in the Siluro-Devonian coastal volcanic belt and provides additional support for the hypothesis that these two major igneous complexes in coastal Maine are related.

INTRODUCTION

In this report we describe field relationships which indicate extensive commingling of felsic and mafic magmas near Calais, Maine, at the northeastern end of Chapman's (1962) Bays-of-Maine Igneous Complex. These observations derive from ongoing field studies in the Calais 15' quadrangle (Ludman and Hill,

1986, in prep.) and in the adjoining Devils Head, Red Beach, and Robbinston 7.5' quadrangles (Abbott, 1977, 1986).

The Bays-of-Maine Igneous Complex (Chapman, 1962) is an assemblage of granite and gabbro plutons extending from Penobscot Bay northeastward into New Brunswick. According

TABLE 1. SUMMARY OF PUBLISHED AGES (Ma) FROM THE CALAIS, MAINE, REGION.

	Rb-Sr	K-Ar	Reference
Red Beach granite	385 ± 6 ^a		3
Red Beach granite	393 ^b	415, 409 (bio.)	1
Charlotte granite	404 ^b	414 (bio.)	1
Meddybemps granite	375 ^b	412, 361 (bio.)	1
St. George pluton	386 ± 20 ^c	399 (hbl.)	5
(New Brunswick)		393 (bio.)	
St. Stephen gabbro		418 (hbl.)	6
		360 (bio.)	
Eastport Fm. volcanics	399 ± 3 ^c		2
(intruded by Red Beach granite)			
Pocomoonshine Lake gabbro		431 ± 24 (hbl.)	4

^aRb-Sr mineral isochron.^bRb-Sr mica age.^cRb-Sr whole rock age.All ages recalculated from the original sources using the new decay constants for ⁸⁷Rb and ⁴⁰K from Steiger and Jaeger (1977).

References: (1) Faul et al., 1963; (2) Fullagar and Bottino, 1970; (3) Spooner and Fairbairn, 1970; (4) Westerman, 1972, 1973; (5) Pajari et al., 1974; (6) Wanless et al., 1973.

to Chapman (1962), the mafic magmatism preceded the felsic magmatism. In contrast, Mitchell (1986) and Mitchell and Rhodes (this volume) cited evidence for coexisting rhyolitic and basaltic magma at the southwestern end of the complex (Vinal-haven Island). We report similar observations from the north-eastern end.

The Bays-of-Maine Igneous Complex is predominantly Devonian in age, although some of the gabbro may be Silurian. Table 1 summarizes the geochronological data published for rocks in the Calais area.* Westerman (1972, 1973) reported an age of 431 ± 24 Ma for hornblende from the Pocomoonshine Lake gabbro in the Big Lake 15' quadrangle immediately west of our study area. In the Calais area (Fig. 1), the Red Beach granite (Amos, 1963; Abbott, 1986) intrudes the Eastport Formation of early Devonian or younger age (Berdan, 1971) and is in turn unconformably overlain by the Upper Devonian Perry Formation (Amos, 1963; Schluger, 1973; Abbott, 1986). Fullagar and Bottino (1970) obtained an age of 399 ± 3 Ma for the Eastport Formation, dominated by data for the rhyolites. Spooner and Fairbairn (1970) reported a Rb-Sr whole rock "age" of approximately 392 Ma, obtained by combining data for the Charlotte granite, Meddybemps granite, and the Red Beach granite (Fig. 1), onto a single diagram. Faul et al. (1963) reported K-Ar ages of 414 Ma for the Charlotte granite, 412 and 361 Ma for the Meddybemps granite, and 415 and 409 Ma for the Red Beach granite. Spooner and Fairbairn (1970) determined a Rb-Sr mineral isochron age of 385 ± 6 Ma for the Red Beach granite.

*All ages cited have been recalculated from the original references using the new decay constants suggested by Steiger and Jaeger, 1977. The conversion factors published in Dalrymple (1979) were used to correct all K-Ar ages.

It is clear from inspecting Table 1 that additional work is needed to clarify the ages of plutons in the Calais area - a conclusion that is not new to workers in this region. The Eastport Formation (399 Ma) is intruded by both the Charlotte granite and the Red Beach granite, hence the recalculated K-Ar ages for those plutons (409-415 Ma) are too old, if the Rb-Sr age for the Eastport Formation is correct. Although the field evidence we describe below suggests that mafic and felsic magmas coexisted during at least part of the Devonian, the uncertainty in ages precludes addressing questions such as the length of time during which gabbroic magmas were injected into the crust, and whether there are genetic links between the gabbroic plutonism and the granitic magmatism in toto.

PETROLOGY OF COMMINGLED PLUTONIC UNITS

Amos (1963) subdivided the plutons in the Calais area into seven units: (1) norite and gabbro; (2) diorite; (3) the Baring granite; (4) the Meddybemps granite; (5) the Charlotte granite; (6) the granite of Magurrewock Lakes; and (7) the Red Beach granite. Our field studies indicate that extensive commingling

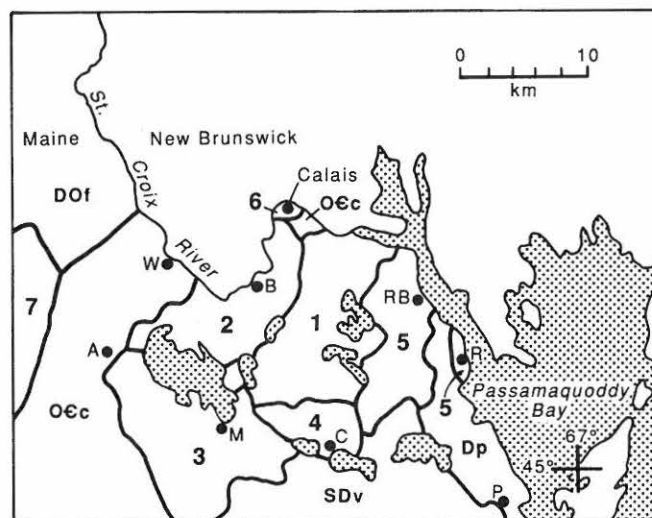


Figure 1. Generalized geologic map of the Calais area, Maine after Osberg et al. (1985). Plutonic units: (1) Zone of extensive magma commingling, approximately coincident with the "diorite" unit of Amos (1963). This unit contains gabbro, diorite, granodiorite, dikes, and irregular zones of diabase pillows in a granite matrix, and mixed rocks of hybrid composition which are not easily separable, even at map scales greater than 1:24,000. (2) Baring granite. (3) Meddybemps granite. (4) Charlotte granite. (5) Red Beach granite. (6) St. Stephen gabbro. (7) Pocomoonshine gabbro. Not shown: small bodies of the granite of Magurrewock Lakes. Sedimentary and volcanic rock units: (OCc) Cookson Fm. (SDv) Maine coastal volcanics: Eastport, Edmunds, Leighton and Quoddy Formations. (DOF) Flume Ridge Fm. (Dp) Perry Fm. Geographic locations: (A) Alexander; (B) Baring; (C) Charlotte; (M) Meddybemps; (P) Perry; (R) Robbinston; (RB) Red Beach; (W) Woodland. Areas with dot pattern = lakes.

has occurred between mafic and felsic magma. The evidence comes mostly from Amos' (1963) diorite unit, which we have incorporated into our map unit 1 (Fig. 1). This unit is extremely heterogeneous, consisting of (1) gabbro (plagioclase with $An > 50$); (2) diorite (plagioclase with $An < 50$); (3) granodiorite; (4) dikes and irregular zones of diabase pillows in a granitic matrix; and (5) mixed rocks of hybrid composition. The granitic rocks in this unit are most likely related to the Baring granite. We emphasize that all of these compositions are contained within the composite unit labeled "1" on Figure 1; a description of each of the units follows. For more detailed field relations, see the maps in Abbott (1986) and Ludman and Hill (in prep.).

Gabbro

A wide range of gabbroic compositions occurs in the Calais region, including olivine gabbro, norite, anorthositic norite, hypersthene gabbro, hornblende gabbro, and leucogabbro (Amos, 1963; Westerman, 1972, 1973; Coughlin, 1983). The gabbros generally contain plagioclase (An_{70-40}), hornblende, augite, orthopyroxene, biotite, magnetite, sphene, and apatite. Some samples contain either olivine or quartz \pm orthoclase. Secondary chlorite, sericite, and epidote also occur. Generally, the gabbro is homogeneous in outcrop scale although locally, rhythmic bedding is well-developed, as at Staples Mountain in the Calais quadrangle (Coughlin, 1983; Ludman and Hill, 1986, in prep.) and at Pocomoonshine Mountain in the Big Lake quadrangle (Westerman, 1972, 1973). We have found that areas shown on Amos' (1963) map as "norite-gabbro" generally contain a distinctive, porphyritic gabbro with buff to tan plagioclase phenocrysts up to 4 cm in diameter.

Diorite

Diorite (*sensu stricto* - plagioclase $< An_{50}$) is the predominant mafic plutonic component within the Calais quadrangle. The diorite lacks olivine, and clinopyroxene occurs as relict cores in hornblende grains, rather than as the discrete grains which occur in the gabbro bodies. Except for a few olivine-rich gabbros, the color index of many of the diorites is as high as that in some gabbro. The diorites are predominantly plagioclase-hornblende-biotite-bearing rocks; the hornblende:biotite ratio varies from >1 to <1 . Interstitial quartz occurs in some diorites. In some areas, a distinctive foliated diorite with igneous laminations of hornblende-rich and feldspar-rich bands occurs. These occur in discontinuous, isolated outcrops in the Calais quadrangle (Ludman and Hill, in prep.).

Granodiorite

Granodiorite, within unit 1 of Figure 1, occurs primarily in northeast-southwest elongate bodies that intruded gabbro. The granodiorite is intruded by the Red Beach granite, Charlotte granite, and smaller bodies of biotite granite. The last of these

belong to Amos' (1963) granite of Magurrewock Lakes. Typically, the granodiorite contains plagioclase (An_{50-29}), hornblende, biotite, quartz, perthite, magnetite, and apatite. Chlorite, epidote and sericite are secondary minerals. This unit displays gradational compositional variations over a wide range, from diorite and quartz diorite to granite.

At the southwest end of the Bays-of-Maine Igneous Complex, Mitchell (1986) noted that local patches of granodiorite were formed by mixing between basaltic pillows and the surrounding rhyolite matrix. He suggested that large, homogeneous granodiorite plutons, which intrude the felsic-mafic pillowed complex, might have formed by more efficient blending of the two compositions at depth.

Mixed Rocks

The mixed rocks unit of Abbott (1986), within unit 1 of Figure 1, consists of rounded to angular inclusions of gabbro, with smaller proportions of diabase pillows (see following description and Figs. 3, 6). The inclusions and diabase pillows are set in a dioritic to granitic matrix of variable composition. Where the volume percent of inclusions or the degree of disaggregation of the inclusions is great, the color index of the rock is high. Fragments of gabbro range in size from centimeters up to hundreds of meters, while the diabase pillows are usually less than 30 cm in size, but can reach 2 m or more. The rocks form a continuum from essentially inclusion-free granodiorite to essentially homogeneous gabbro. At one extreme, the unit might best be described as brecciated gabbro; at the other, as granodiorite with sporadic inclusions of gabbro. Consequently, the placement of the contact between the mixed rocks and the gabbro, and that between the mixed rocks and the granodiorite is somewhat subjective.

There are two modes of occurrence of this mixed rock unit: (1) as a border facies of the granodiorite intrusions, and (2) as isolated patches in the gabbro. The second mode of occurrence may represent apophyses of the first in the fractured roofs of subjacent bodies of granodiorite. The different areas of granodiorite exposed at the surface may all be parts of a single body.

Pillow Diabase

Diabase is found sporadically throughout the northern part of the area, where it is integrally related to gabbro, granite, and granodiorite. Within our study area, diabase occurs only as pillows or fragmented inclusions in an intermediate or felsic host. Dikes or other intrusive forms of diabase have not been observed to crosscut any of the gabbroic or granitic bodies in the area.

The diabase pillows have a variety of forms and a wide range of sizes up to several meters. The shapes include (1) simple well-rounded pillows (Fig. 2a); (2) crenated pillows, outward-pointing lobes alternating with inward-pointing cusps (Figs. 2b,

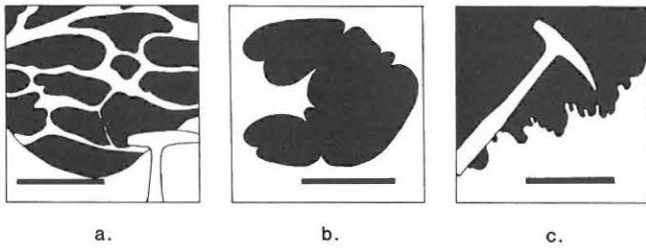


Figure 2. Nature of the boundary between diabase pillows and surrounding granite matrix. (a) Simple, well-rounded diabase pillows. (b) Crenate pillow. (c) Margin of an amoeboid pillow. Scale bar is 25 cm.

3, 4); (3) amoeboid pillows, outward-pointing lobes alternating with inward-pointing lobes (Fig. 2c); and (4) angular inclusions (Fig. 5). For each type of inclusion the margins may be sharp or diffuse. The composition of the surrounding material becomes more mafic as the margins of the pillows become more diffuse. The simple, well-rounded pillows commonly occur in aggregates in which the pillows have been deformed against one another (Fig. 2a). This deformation suggests that the diabase was plastic when it was in contact with the felsic host.

The proportion of the matrix varies substantially, regardless of the pillow type, from isolated pillows in an otherwise homogeneous felsic matrix to more than 90% pillows. In the latter case, the pillows tend to have coalesced, perhaps by gravity settling, such that most of the interstitial felsic magma has been expelled. Commonly, all that remains of the matrix is a thin film between pillows and anti-crenated volumes of felsic rock (inward-pointing lobes alternating with outward-pointing cusps).

Fine grained, thin (2 to 5 mm) rinds on the simple and crenate pillows have been interpreted to result from quenching. These rinds are predominantly composed of fine grained, brown-pleochroic biotite. Although similar biotite is present in the interiors of the pillows, it is much less abundant than hornblende. These relationships suggest some degree of chemical exchange across the mafic/felsic interface.

We have no evidence to indicate which component (felsic or mafic) was emplaced into the crust first. The basalt was quenched to form diabase pillows, whose initial shapes would be controlled by the surface tension of the congealing mafic magma against the surrounding felsic magma. This would produce the simple, rounded pillows. The crenate shapes may represent deformed pillows, or pillows that were frozen in the process of subdividing. The amoeboid pillows would indicate a more fluid interdigitation of the two magmas. The absence of quenched margins on the amoeboid pillows suggests that the felsic host for these pillows was unusually hot compared with the felsic magma which encased the simple and crenate pillows.

Many diabase pillows have been intruded along narrow fractures by the felsic matrix, presumably at a time when the pillows were essentially crystallized, but the matrix was still fluid (Fig. 3a). The angular diabase inclusions probably represent the fragments of more thoroughly fractured pillows (Fig. 5).

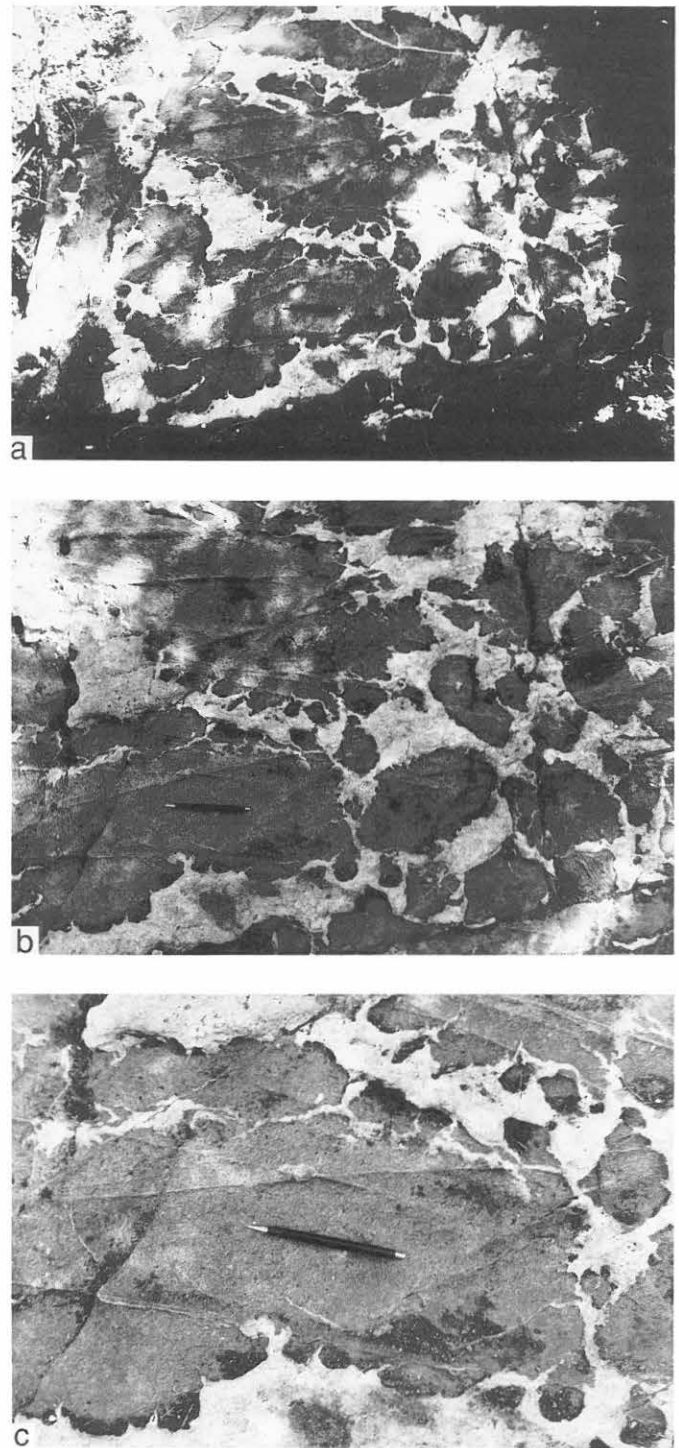


Figure 3. Pavement exposure of pillowed diabase in granite matrix, east of junction of South Ridge Trail and Beaver Trail, Moosehorn National Wildlife Refuge. Pencil is in the same position in each photo. (a) Note fractured pillow at top, healed by matrix granite. (b) Note presence of both cusped (pillowed) and angular (brecciated) diabase blocks. (c) Close-up of pillowed diabase. The diabase at this locality exhibits quenched margins at granite contacts. However, the dark shading in the photo is caused by pine needles accumulated in the depressions left by weathering of the less resistant diabase. Silicified joints which crosscut the diabase were more resistant to weathering.

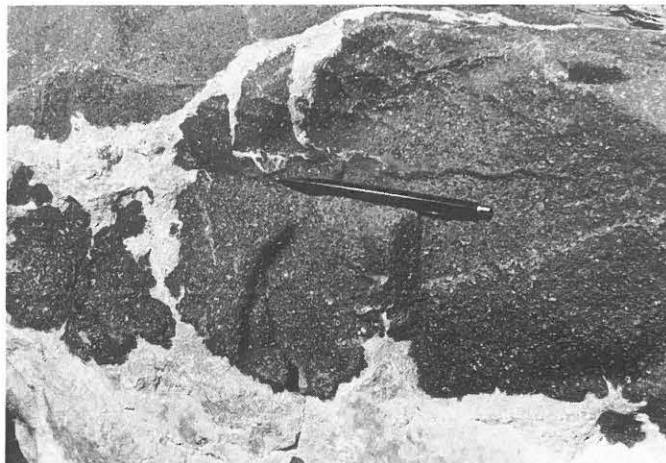


Figure 4. Plagioclase-phyric diabase pillow in granite matrix, Snare Meadow, Moosehorn National Wildlife Refuge. Pencil for scale. Dark rind in diabase at granite contact marks the quenched margin of the pillow. Note evidence near the pencil tip for fracture and rotation of the diabase pillow while the granite could still flow.

Angular gabbro fragments are commonly medium-grained equigranular immediately adjacent to the granite contacts; they show no evidence of quenching.

Diabase pillow complexes, i.e., diabase plus felsic matrix, locally constitute dikes, rarely exceeding 4 meters in width, in the gabbro. Angular fragments of gabbro are also present in the granodiorite matrix of these dikes and the walls are rarely exposed. Figure 6 is a sketch map of one side of a diabase pillow dike. The dike trends north-south and is zoned with respect to the proportion of diabase pillows. There is a swarm of north-south-trending diabase pillow dikes cutting the gabbro immediately south of Vose Pond.

Diabase pillows as well as angular fragments of gabbro also characterize the mixed rocks associated with the granodiorite unit. It may be that the diabase pillow dikes are simply apophyses of these mixed rocks. If so, then, in accordance with Mitchell's (1986) model, the whole of the granodiorite may be a well-homogenized hybrid of the diabasic magma and a granitic magma, with the diabase pillows being preserved only where quenched along the margins of the granodiorite (mixed rocks) and in dikes.

Baring Granite

The Baring granite (unit 2 on Fig. 1) is a medium to coarse grained biotite \pm hornblende granite. Most samples have a seriate texture and contain quartz, plagioclase with minor zoning (An₂₆₋₂₃ cores, An₂₁ rims), perthitic microcline, biotite, hornblende, apatite, zircon, and opaque minerals. Allanite occurs in some samples, and myrmekitic intergrowths occur in some, but not all specimens. Generally, outcrops of Baring granite are massive and medium to coarse grained. Locally,

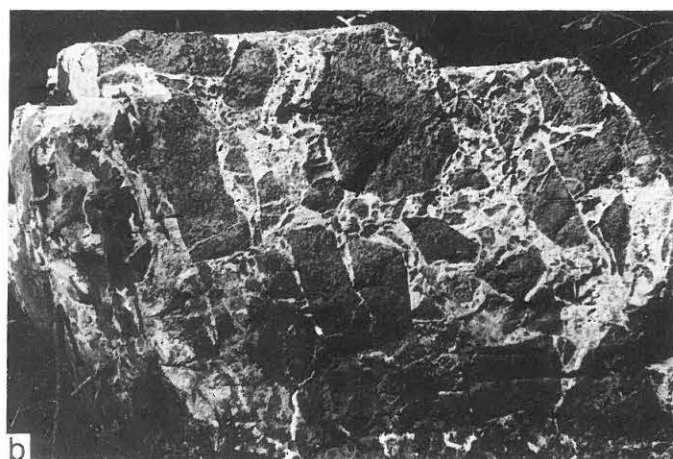
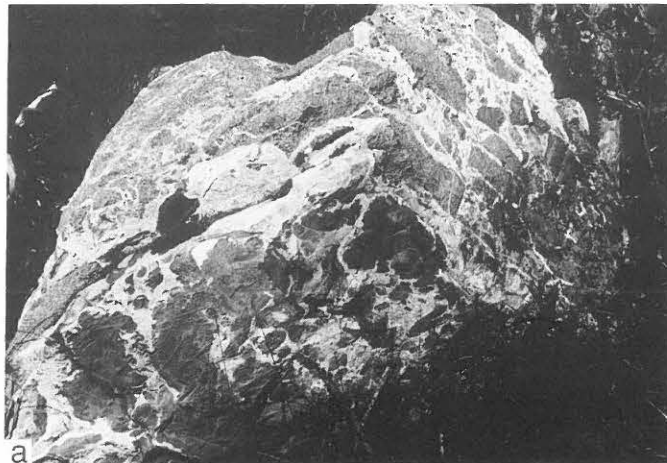


Figure 5. Two sides of a single, 1.5 m float block along the Beaver Trail, near Mahar Flowage, Moosehorn National Wildlife Refuge. (a) Pillowed and brecciated diabase in granite matrix. (b) Primarily brecciated diabase fragments in granite matrix. The large octagonal fragment at top-center, as well as the two rectangular fragments below it, can easily be located in the upper-right face of the block in Fig. 5a.

there are coarse grained, porphyritic variants with alkali feldspars to 2-3 cm. A quenched, porphyritic facies, which we interpret as part of the Baring granite, with rapakivi mantling and inclusions of basalt blebs occurs locally adjacent to the diabase pillow zones.

Where the granite occurs as thin lenses or septa in the pillowed diabase or mixed rocks zones, the percentage of hornblende is noticeably higher than in outcrops of homogeneous granite. This effect is most strongly developed in outcrops which contain pillows or breccia fragments with diffuse boundaries. In other locations, particularly adjacent to diabase pillows which display very sharp, quenched margins against the granite, the granite is finer grained than normal Baring granite and contains an unusually low proportion of mafic minerals. The fine grain size of the matrix granite indicates a greater nucleation rate compared with normal Baring granite.

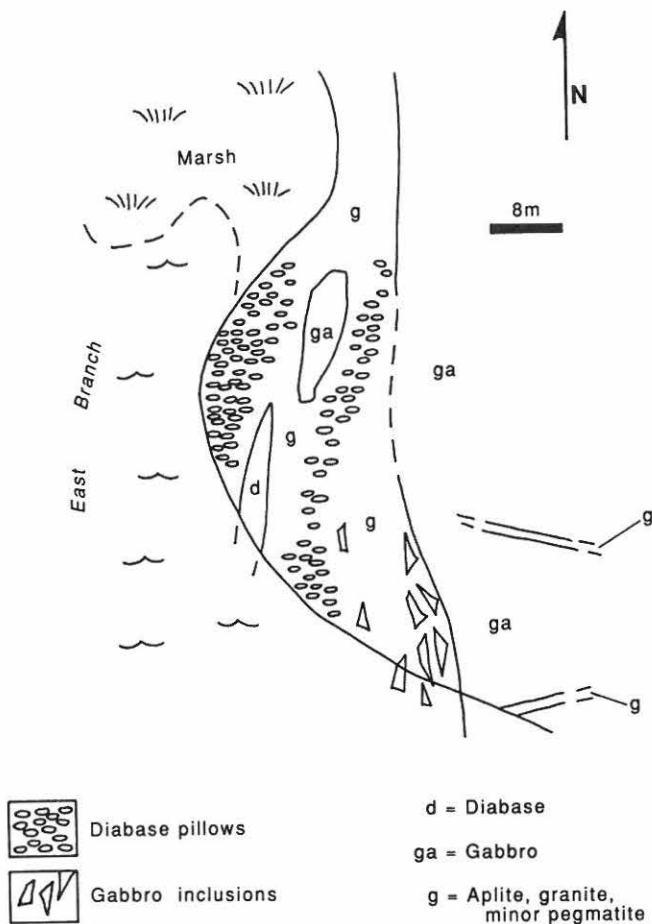


Figure 6. Map of east wall of a dike containing diabase pillows. The pillow complex is exposed on the east bank of East Branch, approximately 1 km. northeast of Vose Pond. Scale bar is 8 m.

The relative dearth of mafic minerals in the granite suggests either (1) that nucleation of quartz and feldspars was enhanced while nucleation of biotite and hornblende was suppressed at the (higher temperature? dryer?) contacts with the molten diabase; or (2) that some or all components needed to stabilize hydrous silicates (OH?) were effectively removed from the granite magma at the contact, presumably by diffusion into the "chilled" (800 - 1000°C ?) diabase pillow. We note (1) that scattered amygdulites filled with quartz, biotite, and hornblende occur in some, but not all, of the quenched diabase pillows; and (2) the quenched margins of the diabase pillows are predominantly composed of fine-grained biotite - in contrast to the pillow interiors, where the predominant mafic silicate is hornblende.

DISCUSSION

In recent years, volcanologists have shown that eruptions from chemically zoned or stratified magma chambers are not uncommon in the geologic record (Hildreth, 1981; Bacon, 1986).

There can be no doubt that juxtaposition of two magmas occurs and could be preserved in the plutonic regime as well (Reid et al., 1980; Reid and Eichelberger, 1981; Whalen, 1985; Mitchell, 1986; Mitchell and Rhodes, this volume; Whalen and Gariépy, 1986). The ellipsoidal to amoeboid forms and the presence of quenched margins in diabase pillows set in granite matrix demonstrate that magma commingling has been preserved over a wide outcrop area in the Calais region. The common observation of sharply-defined margins on the diabase pillows in the Calais area (Fig. 4) demonstrates that no substantial degree of mixing (or blending) of the two compositions has occurred at the present level of erosion. It is quite likely, however, that some degree of elemental and isotopic exchange has occurred across the pillow:matrix interface. The biotite-rich pillow rims and the increased hornblende content of some pillow-matrix granite compared with normal Baring granite in areas free of inclusions attests to local hybridization between the two magmas.

The textural preservation of the pillowed complex may derive from relatively rapid cooling at shallow depth. We discuss below the possibility that some of the magmatism recorded in the adjacent Silurian-Devonian coastal volcanic belt may be related to that which formed the Bays-of-Maine plutonic complex. If so, the lack of andesite compositions in the bimodal basalt-dacite/rhyolite volcanic suite of the Eastport Formation (Gates and Moench, 1981) also attests to limited mixing.

The presence of angular or brecciated inclusions of one igneous rock type in another is often taken to indicate a greater age for the type which forms the inclusions. We have observed a number of outcrops which contain both amoeboid pillows and brecciated fragments; indeed, in many cases, thin granite veins continuous with and indistinguishable from the granite inter-pillow matrix cut undoubted pillows into angular fragments (Fig. 3). Hence, these results suggest that not all angular inclusions within a plutonic matrix need predate the host. For those outcrops of Baring granite with abundant angular gabbroic inclusions, but lacking convincing evidence for pillows (such as those exposed along Rte. 1 approximately 1 km south of Rte. 9), extensive geochemical and mineralogical studies will be needed to relate the brecciated fragments to either known pillowed complexes or to gabbros which may predate the Baring granite - gabbro intrusive complex (J. Jerinski, Ph.D. dissert. in progress, Virginia Tech. Univ.).

Physical Conditions during Magma Commingling

Abbott (1977, 1987) estimated that the Red Beach granite, the youngest of the Acadian granites in the area, was emplaced at a depth of 0.8 - 1.5 km. Hill (Ludman and Hill, in prep.) summarized geochemical evidence which suggests that the Baring granite, Charlotte granite, Meddybemps granite, and granite of Magalloway Lakes are of similar origin, and have some mineralogical and geochemical features akin to A-type granites (Loiselle and Wones, 1979). Abbott (1987) related

some of these, specifically the Charlotte granite and the granite of Magurrewack Lakes, to the Red Beach granite. Whalen (1986) described A-type granites related to the St. George batholith in New Brunswick, of similar age to the granites in the Calais area and immediately northeast of our study area. At the southern end of the Bays-of-Maine complex, on Vinalhaven Island, Mitchell and Rhodes (this volume) report granite with some A-type affinities commingled with basaltic pillows in virtually the same field associations as those we describe from the northern end of the complex.

Clemens et al. (1986) reported 1 kb melting experiments on an A-type granite; for 1% dissolved water, the solidus temperature is about 875°C, and the liquidus temperature is over 1000°C. The granite that Clemens et al. (1986) studied became water-saturated at about 4% H₂O for the 1 kb pressure of the experiments. Assuming that these results are relevant to the Baring granite, they indicate that the granite would have been at relatively high temperatures at the time of mixing with the basalt to form the pillowed complexes.

Thompson (1974) summarized the results of melting experiments on a variety of basalts from Skye, whose compositions may be analogous to those of the parent magmas which formed the gabbros in the Calais area. Liquidus temperatures vary between approximately 1160 - 1260°C, depending on the basalt composition; solidus temperatures are not as well constrained, but are at or below 1050°C. The common occurrence of plagioclase-porphyritic gabbro in the Calais area, and the occasional presence of distinct plagioclase phenocrysts (Fig. 4), coupled with the absence of olivine or pyroxene phenocrysts in the quenched diabase pillows, is compatible with shallow crystallization of a relatively Fe-rich magma under hydrous conditions (see data summarized for Skye and Snake River Plain lavas in Thompson, 1972). The abundance of amphibole and late crystallization of biotite in many gabbro samples supports crystallization under hydrous conditions. Temperatures in the range of 1200 - 1150°C are indicated by these relationships (Thompson, 1972).

In his summary of structural studies in the plutonic Queriguit Complex, Marre (1986) discussed contact relationships between mafic inclusions and felsic host rock which are similar to the crenate and amoeboid pillows and brecciated fragments we observe in the Calais area. He noted that, for inclusions (Marre's "enclaves") such as our crenated pillows with an oak-leaf-shaped outline (Fig. 2b), the material of greater viscosity forms rounded lobes while the material of lower viscosity fills the sharp embayments. Our simple and crenate pillows (Fig. 2a, 2b) would develop when the viscosity of chilling basalt was somewhat greater than that of the felsic matrix. If the viscosities of the mafic and felsic magmas were more closely matched, the amoeboid boundaries of Figure 2c featuring smoothly interdigitating lobes without any sharp embayments, would develop. The amoeboid texture in Figure 2c may develop preferentially along the boundaries of larger basaltic masses, which would have a greater thermal mass than small basalt pillows, allowing the

basalt to retain higher temperatures and a lower viscosity for a longer period of time.

The inferences we have drawn from our field observations about the relative viscosities in the mafic and felsic components are in apparent conflict with experimental viscosity data. Crystal-free basalt at 1200°C has a significantly lower viscosity, approximately 2 to 3 log(poise) units (Murase and McBirney, 1973), than rhyolite at 1000°C. The viscosity of rhyolite with 10% dissolved water at 1000°C is approximately 4 log(poise) units, vs. approximately 8 for rhyolite with 1% dissolved H₂O at the same temperature (Shaw, 1965).

Two effects may provide the means to reverse the normal difference in viscosity between mafic and felsic magmas, and to explain our field observations. First, the viscosity of crystallizing basalt increases rapidly with increasing phenocryst content, especially when crystallization exceeds 20% (Shaw et al., 1968). Upon mixing, the hotter basalt and cooler rhyolite will approach thermal equilibrium; crystallization of the basalt will accelerate while the rhyolite may locally become superheated. Second, because the viscosity of a magma is inversely related to its temperature, the viscosity of the basalt will increase and the viscosity of the rhyolite will decrease at the interface between the two magmas. Together, these effects must be sufficiently large to reverse the normal viscosity contrast between magmas of basaltic vs. rhyolitic composition, in order to explain our observations as well as those of Mitchell (1986), Mitchell and Rhodes (this volume), Whalen (1985), and Whalen and Gariépy (1986).

Although some of the angular breccia fragments in the pillowed outcrops may represent preexisting mafic wall rocks intruded by the Baring granite, the presence of fractured pillows in many of the same outcrops can only be reconciled with brecciation of the congealing mafic component soon after the mixing event. The textures indicate that, upon mixing, the basalt coalesced into pillows with chilled margins. The pillows deformed plastically to form the range of shapes shown in Figure 2. Due to their greater solidus temperature, crystallization in the pillows proceeded more rapidly than in the granite matrix. Eventually, some pillows fractured while the granite was still molten. Marre (1986) noted that it is difficult to generate fractures within more viscous inclusions by transmitting stress through surrounding, less viscous matrix, and appealed to earthquake shocks traversing the pluton. Perhaps thermal stresses in radially cooling pillows could overcome the tensile strength of the crystallizing diabase body. The implied volume increase of the brecciated fragments could easily be accommodated if the surrounding, less viscous felsic magma was still largely or partly molten.

In some areas, the interpillow granite is relatively fine-grained and nearly devoid of mafic silicates. Although we have no data for the water contents of the granite or of the diabase pillows, it is likely that the basalt had a lower (OH) content than the rhyolite at the time they were juxtaposed. It is possible that the rhyolite may have lost (OH) to the pillows by diffusion across

the interface. This effect could explain the dearth of hydrous silicates in these fine-grained granite zones and may explain the biotite-rich selvages of quenched pillows.

Regional Implications

Gabbro, diabase, and basalt occur throughout the Silurian-Devonian coastal volcanic belt, indicating a long-standing source of basaltic magma from Early Silurian to Early Devonian time (Gates, 1975). Felsic volcanic rocks also occur throughout the sequence (Bastin and Williams, 1914; Gates, 1975). Gates and Moench (1981) noted that the coastal volcanic belt is essentially a bimodal basalt-dacite/rhyolite suite, and tentatively suggested that the adjacent Bays-of-Maine Igneous Complex might be genetically related, more likely to the Eastport Formation bimodal volcanism than to the Silurian bimodal suite (O. Gates, pers. commun., 1987). Our work at the northeastern end of this complex, and that of Mitchell (1986) and Mitchell and Rhodes (this volume) at the southwestern end, provides compelling evidence that mafic and felsic magmas were coeval in the Bays-of-Maine Igneous Complex. Geochemical studies are in progress by us, by Mitchell, and by Jerinski (Ph.D. dissert., Virginia Tech. Univ.) on various aspects of the Bays-of-Maine

Igneous Complex which will permit further comparison with the eruptive suite in the coastal volcanic belt.

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