Introduction

The problem of the contemporaneous association of mafic and more silicic magmas has fascinated and puzzled petrologists from the very beginnings of our science (e.g., Bunsen, 1851; Harker, 1904; Holmes, 1931; Wagner and Bailey, 1953; Walker and Skelhorn, 1966; Yoder, 1973). This association has more recently been linked to a growing consensus that magma reservoirs are compositionally zoned and that they are periodically invaded, or replenished, by magmas of a different composition. Evidence comes both from the geological record (e.g., Wilcox, 1954; Bailey et al., 1976; McBirney and Noyes, 1979; Hildreth, 1981; Irvine et al., 1983; Morse, 1986; McBirney et al., 1987; Wiebe, 1987; Bacon and Drury, 1988) and from experimental and theoretical fluid dynamic studies (e.g., Chen and Turner, 1980; Turner, 1980; Huppert and Turner, 1981; Huppert et al., 1982a, b, 1984a, b; Spera et al., 1986). There are two basic models, both of which may be currently active to some de-
On the one hand, cooling and crystallization of an initially homogeneous melt (perhaps aided by wall-rock assimilation or melting) is thought to lead to density stratification, separating compositionally distinct, and possibly zoned, magmas (e.g., McBirney, 1980; McBirney et al., 1987). Alternatively, injection of compositionally distinct magmas into an evolving magma reservoir may lead either to mixing and homogenization, or to the formation of density stratified layers (e.g., Wiebe, 1974a,b; Huppert and Sparks, 1980; Huppert et al., 1984a,b; Sparks and Huppert, 1984; Huppert, 1986; Wiebe, 1987, 1991).

Recent studies in fluid dynamics have produced many models exploring the interaction of two or more fluids differing in composition, temperature, density and viscosity. Many of these attempt to mimic the development of zoned magma bodies and the effects of magma replenishment (Sparks and Sigurdsson, 1977; Huppert and Sparks, 1980; Huppert and Turner, 1981; Huppert et al., 1982a,b, 1984a,b; Wiebe, 1987; Oldenburg et al., 1989). Although exposed evidence supporting these inferred relationships has remained elusive, Wiebe (1974a,b, 1991) has provided several examples which indicate that the plutonic expression of replenished or invaded magma chambers may not be as rare as we think. In this paper, we describe a sequence of layered gabbroic and dioritic rocks from the Coastal Maine Magmatic Province which we believe to be a repetitive, sill-like invasion of basaltic magma onto the cumulate floor of an evolving, more silicic chamber. Here we concentrate largely on field, textural, and overall chemical relationships leading to this interpretation. In subsequent work we will deal more fully with the chemical, isotopic and thermal evolution of this body.

Geologic setting

The Coastal Maine Magmatic Province (Hogan and Sinha, 1989), previously called the Bays-of-Maine Igneous Complex (Chapman, 1962a), contains a bimodal association of over 100 mafic and granitic plutons. They intrude pre-Devonian metasedimentary and metavolcanic rocks and range in age from early Silurian to early Carboniferous, which in turn are thought to rest unconformably on Precambrian basement gneisses (Stewart et al., 1986). Previous studies report that many of the mafic and felsic plutons were related in both time and space and provide detailed field and petrologic evidence of commingling and mixing of magmas (Chapman, 1962b, 1970; Taylor et al., 1980; Mitchell, 1986; Stewart et al., 1988; Hill and Abbott, 1989; Chapman and Rhodes, 1990; Wiebe, 1991). The granite-gabbro-diorite rocks of the Isle au Haut Complex are situated at the southernmost exposed sequence of the province, on the island of Isle au Haut, 8 km south of Stonington, Maine and Deer Isle. To the north is the Deer Isle pluton and to the east the Swans Lake pluton. The geological units of the Isle au Haut Igneous Complex as named by Hogan and Sinha (1989) were originally mapped by Smith et al. (1907); much later followed a more detailed petrographic study of the plutonic units (Luce, 1962). The complex is composed mainly of an homogeneous 390 Ma granite (28 km²) (Pb/U ages by R.W. Luce, pers. commun., 1987) intruding older silicic volcanic rocks to the west, with a layered 413 Ma gabbro-diorite-quartz monzodiorite complex (51 km²) forming the eastern third of the island and the small islands and ledges to the east (Fig. 1). Most of the mafic units on the island proper are diorites. A granitic intrusion that differs in composition from the western Isle au Haut granite crops out on small islands to the east of the mafic complex and field evidence indicates that it may have been emplaced contemporaneously with the layered gabbros of the mafic complex. We have found no direct field evidence for comagmatic interaction of the western Isle au Haut granite with the mafic rocks, and suspect that it has a younger intrusive relationship given the pre-

![Fig. 1. Location and generalized geologic map of the lithologic units which comprise the Isle au Haut Igneous Complex, Maine.](image-url)
Fig. 2. Geologic map and cross section (vertical exaggeration 4x) of the composite layering of Gabbro-Diorite units and Granites exposed on Eastern Head peninsula and Eastern Ear island.

Petrography and chemistry of the layers

All samples from the layered complex are holocrystalline, hypidiomorphic granular in texture. Grain sizes range from very fine-grained to moderately coarse-grained in the gabbros and medium- to coarse-grained in the diorites. Modal analyses of selected samples from each of the layers were obtained by counting 1500 points. These are presented in Table 1 and are plotted according to the IUG classification scheme of Streckeisen (1973) in Figure 3. We have systematically collected and analyzed in detail the five gabbroic and five dioritic layers across the exposed sequence along the southern coast. Major- and trace-element concentrations were obtained by XR (Norrish and Chappell, 1967; Norrish and

<table>
<thead>
<tr>
<th>Sample</th>
<th>AA2</th>
<th>A1</th>
<th>B3</th>
<th>C3</th>
<th>D1</th>
<th>E4</th>
<th>F4</th>
<th>G4</th>
<th>H6</th>
<th>I1</th>
<th>F10 (Pipe)</th>
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<td>48.4</td>
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<td>50.2</td>
<td>56.7</td>
<td>42.4</td>
<td>48.4</td>
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<td>-</td>
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<td>11.2</td>
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<td>Quartz</td>
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<td>-</td>
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<td>17.1</td>
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<td>-</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.1</td>
<td>0.1</td>
<td>-</td>
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<td>Zircon</td>
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<td>0.2</td>
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<tr>
<td>Rutil</td>
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</table>

Fig. 3. Sketch of aerial photograph shows alternating sequence of layers exposed along the southern shoreline of East Head.

TABLE I

Modal analysis of a representative sample from each layer (1500 counts, 1/3 mm interval)
and coarse hash marks. respectively. All contacts are the 'Isle au Haut Granite at 358 m are shown by the coast of Eastern Head showing the clearly exposed succession. All five layers are hornblende gabro from the lowest layer through the uppermost layer (Fig. 5). They range between 40 and 50 modal percent plagioclase which is zoned from An$_{40}$ cores to An$_{25}$ rims. Plagioclase crystals near diorite contacts are clear laths from core to rim. Away from these contacts the crystals tend to be lightly to moderately corroded, commonly with resorbed cores. The nature of these crystals, obviously in disequilibrium with their surroundings, may be the result of volatiles possibly introduced into the gabbro by the more hydrous dioritic units. The rims are almost everywhere clear. Except for one sample from the lowest unit (A), none of the gabbroic units contains alkali feldspar or quartz.

The predominant mafic mineral is a subhedral to anhedral paragenetic hornblende (nomenclature according to Leake, 1978), poikilitic with plagioclase, which ranges from 17 to 54 modal percent. The hornblende cores are pleochroic light yellow to dark brown and rimmed by a pleochroic yellow to dark bluish-green variety. The cores of many of the hornblendes are strongly altered and may be relict clinopyroxene. Biotite and titanomagnetite commonly rim the hornblende and occasionally are intergrown with it. Accessory minerals consist almost exclusively of apatite, but zircon and sphene are present, albeit infrequently, as very late-stage phases. Epidote and chlorite (which may be quite abundant) are sporadically present as alteration products.

At the lowermost contacts, the gabbros are fine grained and have intergranular textures. Away from the contacts, the texture changes from subophitic to ophitic and can be broadly described as a framework of interlocking crystals or cumulates (Irving, 1982). A few of the units show fine rhythmic layering. Compositely, the gabbroic units are theolitic and show limited chemical variations (Table 2). They resemble within-plait theolities according to the classifications of Pearce and Cann (1973) and Meschede (1986) and are restricted to the normal subalkaline series of Pecceirollo and Taylor (1976) as shown in Figure 6. Plotted on an AMF diagram (Fig. 7), the gabbros are largely consistent in composition. Departures from the group can be ascribed to physical mixing and hybridization which appear to have been restricted only to a thin region between gabbro I and quartz monzodiorite H and within the mixed zone of quartz diorite D. The gabbros are relatively uniform in both compatible and incompatible elements within each unit and throughout the stratigraphic succession (Fig. 8).

Diorites

In contrast with the gabbros, the dioritic units are structurally homogeneous and display neither layering, chilled margins, nor textural variations among the five layers. Modally and chemically, however, the layers change upwards from quartz diorites (layers AA and B) to quartz monzodiorites (layers D, F and H) increasing in quartz and alkali feldspar concentrations with successive layers (Fig. 4). All units are ophitic.

Plagioclase makes up 44 to 63 modal percent of the dioritic units and is zoned normally from An$_{40}$ cores to An$_{25}$ rims. The grains are nearly as corroded as those from the gabbroic units to core to rim variations appear as abrupt. Alkali feldspar is interstitial and also present as a very late-stage rim to plagioclase, but on in layers B and above. With increasing stratigraphic height, alkali feldspar becomes more abundant as a cumulus phase. Late-stage, interstitial anhedral quartz increases in amount with stratigraphic height, though not as dramatically as does the alkali feldspar.

The dominant mafic phase is again hornblende, but it is endenitic in composition. As the gabbros, the hornblendes are zoned, from a brown core to a green rim. Biotite commonly intergrown with (or replaces) the hornblende, rims it, and also forms an interstitial member. Titanomagnetite rims both the mafic phases. There is also actinolite which may be the alteration product of pyroxene.

Accessory minerals include late-stage sphen, zircon, rutile and substantial apatite in some samples. Epidote and iron oxide staining are present as secondary minerals.

At Eastern Head, the dioritic units show n
The evolving calc-alkaline trend (Fig. 7). In contrast, the pipes contain concentric, consisting almost entirely of albite with local concentrations of coarse plagioclase-rio laths and mm equant hornblende crystals. Local concentrations of coarse plagioclase-pegmatitic crystals occur as irregular, radially scattered patches throughout the unit. In the adjacent EX. The pipes differ from their associated diorites in composition and texture. Most are pegmatic, consisting almost entirely of albite with interstitial concentrations of secondary actinolite and epidote. Larger pipes are closer in texture and composition to the underlying dioritic unit. Chemically, the pipes have syenitic affinities, but are strongly depleted in many elements that are abundant in the diorites (e.g., K2O and Ba. Table 2). Unfortunately, a more detailed quantitative analysis of the pipes suffers the inherent problems associated with sampling very coarse-grained and pegmatic bodies.

<p>| Table 1: Average major and trace element compositions for each layer |
|--------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|</p>
<table>
<thead>
<tr>
<th>Layer</th>
<th>AA gabbro</th>
<th>B quartz diorite</th>
<th>C gabbro</th>
<th>D quartz m dior.</th>
<th>E gabbro</th>
<th>F quartz m dior.</th>
<th>G gabbro</th>
<th>H quartz m dior.</th>
<th>I gabbro</th>
<th>F pipe average</th>
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<td>Majors</td>
<td>AA gabbro</td>
<td>B quartz diorite</td>
<td>C gabbro</td>
<td>D quartz m dior.</td>
<td>E gabbro</td>
<td>F quartz m dior.</td>
<td>G gabbro</td>
<td>H quartz m dior.</td>
<td>I gabbro</td>
<td>F pipe average</td>
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<td>1.10</td>
<td>1.08</td>
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<td>71.76</td>
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<td>10.64</td>
<td>11.96</td>
<td>11.52</td>
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<td>11.96</td>
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<td>11.01</td>
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Table 2: Major and trace element compositions for each layer

Fe2O3t = Total iron as Fe2O3
M dior. = monzonodiorite.

Fe2O3t = Total iron as Fe2O3
M dior. = monzonodiorite.

![Fig. 6. Composition of the gabbros and dioritic units on the K2O-SiO2 diagram; boundaries of arc tholeiite, calc-alkaline, and high-K calc-alkaline series of Peccerillo and Taylor (1976).](#)

Relationship of the layered gabbro-diorite units

**Gabbros overlying diorite units**

The southernmost exposures on Isle au Ha reveal an alternating layered sequence of diorites sentu lato and five gabbros (units A - I) dipping to the west (Fig. 3). The gabbro units range in thickness from 7 to 106 m, their bases, they have very fine-grained contacts, approximately 4-5 cm thick, which appear to have chilled against the underlying dioritic units. Immediately above this chill zone, the grain size progressively coarsens on 5 m to a coarse gabbro with 6 mm plagioclase laths and 11 mm equant hornblende crystals. Local concentrations of coarse plagioclase-pegmatitic crystals occur as irregular, radially scattered patches throughout the unit.

At the interface of the gabbro and the underlying diorite units are lobate, cuspate stru...
Fig. 8. Letters represent average incompatible and compatible element compositions (wt.%) versus stratigraphic height for samples in the alternating layered series. Average composition ignore obvious effects of hybridization at some boundaries. Gabbros are layers A, C, E, G, and H; dioritic layers (shaded) are -AA, B, D, F, and H. Boundary between layers shown as solid horizontal line.

Fig. 9. Photograph and sketch of the contact between gabbro I overlying monzodiorite H. Contact shows cup "load cast" structures and pipes intruding into the gabbro. Provide strong evidence for the gabbro chilling against the dioritic units, and for sinking largely molten "pillows" into the underlying diorite.

The gabbro. They are very fine grained, with chilled margins, and are texturally and chemically identical to the fine-grained margins of the gabbro from which they were detached. Both the "load cast structure" of the chilled gabbroic contact and the chemistry and texture of these "pillows" with their adjacent contacts provide strong evidence for the gabbro chilling against the dioritic units, and for sinking largely molten "pillows" into the underlying diorite.

At the same interfaces, fingers or pipes of the dioritic unit penetrate upwards in the gabbro unit for several meters (Fig. 5).
These fingers and pipes plunge 53°, E9°S, a direction which coincides with the poles to the planes of the layered units (Fig. 10) and further confirms that the magma layers were originally horizontal when emplaced.

The pipes are cylindrical in form and tend to be spaced about 1-1.5 m apart. The gabbro has chilled against the pipes for tens of centimeters above the diorite-gabbro contact. The pipe diameter tends to increase from about 8 cm to as much as 50 cm with increasing height in the gabbro (15 m). Occasional conduits over 1.6 m in diameter have been found. With increasing height in the gabbro unit, the frequency of the pipes decreases and the contact of the dioritic pipes with the gabbro becomes more diffuse. At higher levels, xenoliths of the gabbro occur within the dioritic pipes. These xenoliths include hybrid compositions as well as gabbro. The ultimate fate, and relationships of these dioritic pipes to the uppermost part of the thicker gabbro layers, is not fully understood. With thinner gabbro layers (e.g., layers C and E), the pipes can be traced almost entirely to the overlying dioritic layer without any indication of tapering or mixing in the gabbro. We cannot tell from field relationships whether they amalgamate to form the overlying dioritic layer, breach the top of the gabbro magma to become resorbed into an overlying liquid, or eventually diffuse and mix with the gabbro.

The occurrence of pipes has been described before, both from the Channel Islands and from the British Tertiary Province (Elwell, 1958), where inclined pipes intrude overlying layers (Elwell et al., 1962; Buscher et al., 1985). These authors concluded, as we do here, that the pipes reflect the invasion of an overlying magmatic layer by a contrasting magma composition. However, they attributed the inclination of the pipes to displaceable flow of the magma into which the pipes intruded. The pipes we find in the layered sequence show no evidence of post-intrusive displacement or deformation.

Dioritic layers overlying gabbroic layers

The dioritic units range in thickness from 7 to 24 m. Contacts where dioritic units overlie gabbros have several types of relationships. At stratigraphically higher levels, the contacts are somewhat diffuse and wispy over a restricted area. As opposed to gabbro overlying diorites, no penetration of one unit into the other is apparent and the gabbros and quartz monzodiorites do not appear to interact away from the contact. With lower units, however, the contacts can be obscured by physical mixing and hybridization. In the case of the dioritic unit D and the underlying gabbro C, the contact between the units is indistinct and some samples assigned to unit D show more maFiC and hybrid compositional characteristics. Figure 11 presents an idealized summary of the different relationships observed at the outcrop.

The conclusions to be drawn from these field and textural relationships are inescapable. The gabbros and underlying diorites represent coexisting, compositionally distinct, layered magmas. The fingers or pipes provide compelling evidence that the diorites, or some component of the diorite, were liquid and intruded molten gabbros. The chilled margins of the gabbros reinforce this conclusion and indicate that the temperature contrast between the magmas effected the crystallization of the gabbro against the diorite. It is also evident that the magmas were gravitationally unstable and were attempting to overturn. Moreover, during crystallization of the gabbro, a downward sinking of gabbroic lobes into the underlying diorite eventually detached as isolated pillows. Owing to the more viscous nature of the diorite, the pillows were unable to descend far into the overlying diorite.

The fingers and pipes plunging 53°, E9°S, a direction which coincides with the poles to the planes of the layered units (Fig. 10) and further confirms that the magma layers were originally horizontal when emplaced.
upwards from chilled bases of melanodiorite to leucodiorite where it is in contact with another chilled melanodiorite. This type of layering occurs only in the lower and upper diorite sequences through a 60 m vertical section at le Nez (southeastern Jersey), which is composed of diorite-gabbro-diorite layers. The layered diorite complexes of the Channel Islands also appear to have formed contemporaneously with the emplacement of granitic bodies. Several authors describe different origins to these layers. Elwel et al. (1960, 1962) explained the layering as formed by the invasion of ultrabasic magma which remelted and remobilized a solid veined diorite. Bishop and French (1982) and Bishop and Key (1983) attribute the same field relationships to metamorphism of a solid layered gabbro by the emplacement of the granitic bodies. In contrast to these interpretations, Topley and Brown (1984) attribute the layering within the dioritic units to primary igneous origins. A spirited discussion and reply has outlined the latter two arguments (Topley and Brown, 1984, and reply). Having seen the layered units in the Channel Islands (M.C.), we believe that the relationships on Isle au Haut, and our interpretation of their origin, can also be applied to this igneous complex.

Resolving the gravitational instability of coexisting magmas

The field and textural relationships of the gabbroic and dioritic layers clearly show liquid-liquid contacts. This interpretation, however, introduces the apparent contradiction of a denser gabbroic liquid overlying less dense diorite magma, a portion of which must also have been liquid. If both the gabbro and diorite were simultaneously largely liquid, a Rayleigh-Taylor instability would develop and both layers should completely or largely overturn through pipes and conduits to solidify in a stable diorite-over-gabbro configuration. The contact relationships outlined earlier illustrate many of these features, but apparently were arrested or frozen during the process of overturning. This apparent paradox may, however, be resolved through a simple examination of the density contrast between the layers.

Figure 12 shows schematically the contact relations of gabbro overlying diorite. A temperature for the gabbro of 1130°C is estimated using the thermometer developed by Helz and Thornber (1987) for Kilauea Iki Lava Lake. This estimate is in general agreement with experimentally determined melt temperatures for basaltic magmas with similar overall compositions (e.g., Grove et al., 1982). The temperature of the dioritic melt is more difficult to establish. We estimated the temperature of the quartz monzodiorite using analogous glass compositions from Grove et al.'s (1982) experimental work on the Medicine Lake Highlands at 1000°C. Although this estimate may be somewhat high, the densities of the gabbro and quartz monzodiorite magmas, calculated using the method of Bottiinga and Weill (1970), are obtained using these temperature estimates and the composition of the chilled gabbro contact and the composition of the uppermost quartz monzodiorite in contact with the gabbro. This procedure yields estimated densities in the gabbro and quartz monzodiorite liquid of 2.75 and 2.59, respectively. Clearly, if both the gabbro and quartz monzodiorite were liquid, the density contrast and resulting gravitational instability would require that both liquids overturn entirely. The higher temperature of the gabbro would superheat the overturning pipes and accentuate this process, as evident from the density contrast of the pipe versus the gabbro. Field evidence shows that although the process was initiated it did not go to completion. Therefore, the diorite could not have been wholly liquid when invaded by the gabbroic liquid. If, however, the quartz diorite and quartz monzodiorites were solid, or largely solid, then this density anomaly would no longer be sufficient to cause the units to overturn.

Figure 12 shows the same relationship, but with a liquid gabbro overlying a dioritic liquid mush. The density contrast with a solid-liquid contact is, in this case, stable. Moreover, a relatively stable relationship should exist when a liquid gabbro overlies a quartz diorite or quartz monzodiorite crystalline mush containing 10% interstitial liquid or less.

Discussion

The chemical variations of the respective layers, combined with the clear field and textural evidence summarized above, have led us to conclude that the composite layering is the plutonic expression of a periodically replenished, or invaded, evolving magma body containing coexisting gabbroic and more silicic magmas (Chapman and Rhodes, 1990). If, however, both gabbroic and dioritic layers were simultaneously liquid (as the field and textural evidence seem to imply) their respective relationship of gabbro overlying diorite gravitationally unstable and should not survive; both layers should completely overturn. Furthermore, repeating this inherently unstable process many times, as the alternant succession of dioritic and gabbroic layers quest, simply stretches credulity. The apparent paradox of a less dense dioritic liquid beneath a denser gabbroic liquid can be resolved if the underlying dioritic layer represents cumulatively solidified, forming the floor of evolving dioritic, or perhaps more silicic magma body (Fig. 12). As this body cools it crystallizes, it is invaded by a pulse of gabbro magma that intrudes, sill-like, between denser crystal mush of the cumulate floor and the overlying less dense magma (Fig. 1). Wiebe (1974a, b) describes a similar example from Cape Breton Island, of a floored diorite pluton invaded by successive pulses of gabbro magma. The pipes represent the residuum interstitial fluid within the cumulate crystallization mush, which collects beneath the gabbro owing to compaction and deformation of cumulate floor. This residual fluid, heated the gabbro, and now gravitationally unstable will penetrate the overlying gabbroic liquid forming the pipes. This must occur before gabbro can solidify to form an impenetrable cap. The fact that the pipes are preserved plies that the gabbroic magma was not vigorously convecting following emplacement. Some fluid dynamic models would predict that a quiescent crystallization history is unlikely (Marsh, 1989).

The overlying dioritic chamber would be perched by the invasion of the gabbroic. It would vigorously convect, and would crystallize further until the ponded gabbro cooled and largely solidified. We envisage this new floor to the evolving chamber forming the substratum onto which the diorite magma would continue to crystallize, then forming a new floor of crystal mush.
Invasions of gabbroic magma, as outlined above, would provide the alternating composite layers exposed on Isle au Haut, and explain the systematically varying compositions of the dioritic layers interrupted by the homogeneous compositions of the gabbros. If the crystallization rate of the diorite floor was relatively uniform, then the variable thickness of the diorite layers reflects the intrusion rate of the gabbroic magma, which appears to have diminished gradually with time. We see little evidence for mixing between the layers except in very restricted environments (e.g., hybridized xenoliths within some pipes and an incomplete and thin layer between gabbro I overlying quartz monzodiorite II).

In this model, we do not know the parental composition of the magma crystallizing in the chamber with any certainty. Unlike the invading gabbro, where we have chilled margins and pillows to define the composition, we see only the cumulate products of crystallization within the chamber, which range from quartz diorite proper to quartz monzodiorite. At present, we have two working hypotheses that require further testing:

(a) In the simplest case, the magma in the pluton is broadly silicic, perhaps evolving from quartz diorite to quartz monzonite as it cools and crystallizes. The diorite cumulates that form the floor of the chamber are the product of this differentiation. In essence this is a closed system, except for the periodic intrusion of the gabbroic sill, which, although expected to create thermal perturbations in the chamber, appear to have had only minimal compositional effect through mixing, hybridization or diffusion. In this regard, the conclusions of Sparks and Marshall (1986) may be appropriate. That is, the mafic to felsic ratio may be too low, and thermal equilibrium may occur before significant chemical diffusion can take place. The cooled gabbroic sill simply becomes too viscous to facilitate mixing. We would expect this ratio to be low with a basaltic liquid periodically invading a much larger more felsic reservoir. It is possible that the Isle au Haut granite could represent the upper part of such a magma body, that has been down faulted into its present position juxtaposed with the lower, inverted mafic part of the pluton.

(b) Our second hypothesis is essentially open-system assimilation-fractional crystallization process (e.g., McBirney, 1980; Paolo, 1981; Watson, 1982; Grove et al., 1988). The initial composition of the magma in the pluton may well have been gabbro probably related to the magma that continues to invade and periodically replenish the magma reservoir. Assimilation of crustal material, as the magma cooled, crystallized, and was further replenished, could lead to progressions in the composition of the magma, as well as zoning of the magma body (McBirney, 1980). The progressive change with stratigraphic height from layered gabbro, through diorite, to quartz monzodiorite cumulates the floor of the magma chamber would therefore be a reflection of this continuing process. Melting of crust by the invading basal magma might result in pulses of contemporaneous granitic melts invading the magma body to produce a hybrid magma, thereby accelerating the differentiation process. The granite exposed to the east is possibly contemporaneous with the layered gabbro and diorite and could be an example of this type of process.

Conclusion

We believe that the composite mafic layering exposed on Isle au Haut is the plutonic equivalent of a periodically replenished, or invaded evolving magma reservoir. Moving down the succession of layers provides “snapshots” of its magmatic development that can be explored geochemically and petrologically. Our own investigations in the Coastal Maine Magmatic Province and field excursions to the Channel Islands lead us to believe that this process should in fact be quite common in provinces which show a bimodal association.
silicic and mafic magmas. Moreover, a review of the literature suggests us that, although largely unrecognized as such, there may be numerous examples of the effects of episodic invasion or replenishment in the plutonic environment (e.g., Elwell, 1958; Elwell et al., 1962). Chapman, 1962a; Blake et al., 1965; Walker and Skelhorn, 1966; Butcher et al., 1985; Parsons and Becker, 1987; Hill, 1988; Stewart et al., 1988; Vernon et al., 1988; Mitchell and Rhodes, 1989).

Acknowledgements

Introduction

Scanning electron microscopy (SEM) analysis of pyroclastic fragments is widely used in volcanological studies, particularly in the field of eruptive phenomena connected with magma–water interaction.

An exhaustive review of hydrovolcanism can be found in Sheridan and Wohletz (1983), and we will refer to their definitions in the following. Particularly, we will use “hydromagnetism” as a general term for an explosive process involving the contact between magma and external water, while “phreatomagnetism” always referring to events where the external water have a surely phreatic origin.

The criteria for recognizing deposits belonging to hydromagnetic phases by scanning electron microscopy are illustrated in numerous papers (Walker and Croasdale. 1972; Heikinheimo, 1984).

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Morphologic features of juvenile pyroclasts from magmatic or phreatomagmatic deposits of Vesuvius

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ABSTRACT


Three eruptive sequences of historical and recent activity of Vesuvius were carefully studied using scanning electron microscopy analysis techniques. The aims of this study was to characterize and distinguish deposits from magmatic and phreatomagmatic eruption phases.

The sample pretreatment methods from previous authors were reviewed and a washing technique was checked, making it possible to obtain easily examinable samples without modifying their morphologic features.

In each stratigraphic sequence the samples were examined and their shape, typology of vesulation, and state of glass (edge modification by abrasion, alteration, presence of aggregates, secondary minerals and coatings) were analyzed and described.

Characteristic features were recognized for deposits from different eruptive phases. Samples from phreatomagnastic deposits show the following features:

- glass alteration;
- presence of secondary minerals on the external surfaces or inside the cavities;
- coatings;
- presence of aggregate formed by juvenile and lithic particles.

Other features, indicated by many authors as resulting from magma–water interaction, can arise from different mechanisms and cannot discriminate between phreatomagmatic and magmatic nature of deposits.

The conclusions from SEM observations are in perfect agreement with the results of granulometric and component analysis on the same eruptive sequences.

Introduction

Scanning electron microscopy (SEM) analysis of pyroclastic fragments is widely used in volcanological studies, particularly in the field of eruptive phenomena connected with magma–water interaction.