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Composite layering in the Isle au Haut Igneous Complex, Maine: evidence for periodic invasion of a mafic magma into an evolving magma reservoir

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ABSTRACT

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The Paleozoic Isle au Haut Igneous Complex, Maine, is a composite layered sequence of alternating gabbroic and dioritic units situated between two granitic bodies. Field and textural relationships for a layered sequence of ten alternating gabbroic and dioritic units show that they were liquid or largely liquid contemporaneously. The bases of the gabbros are chilled against the underlying diorite, from which cylindrical pipes of a component of the diorite intrude vertically into the gabbro. Immediately below the chilled gabbro contacts, pillow-like lobate structures, also chilled, have become detached and sunk into the diorite for a half meter or less. These pillows are compositionally identical to the chilled margins of the overlying gabbro and preserve their liquid composition.

Chemistry of the gabbros indicates that they are similar to within-plate tholeiites and that they are uniform in average composition throughout the stratigraphic succession. The dioritic units, on the other hand, change progressively from mafic quartz diorite to quartz monzodiorite with stratigraphic height. A comparison of their respective densities indicates a gravitationally unstable situation if both the gabbroic and dioritic units were simultaneously liquid. However, a gravitationally stable situation would exist if the diorite were in fact the cumulate floor of a more felsic magma reservoir. Thus, we contend that the composite-layered sequence represents the successive invasion, or replenishment, of an evolving dioritic chamber by a compositionally uniform gabbroic magma that intruded sill-like between the cumulate floor of the chamber and the overlying melt.

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; Wager 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 Druitt, 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-

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gree. 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 km^2) (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 km^2) 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-

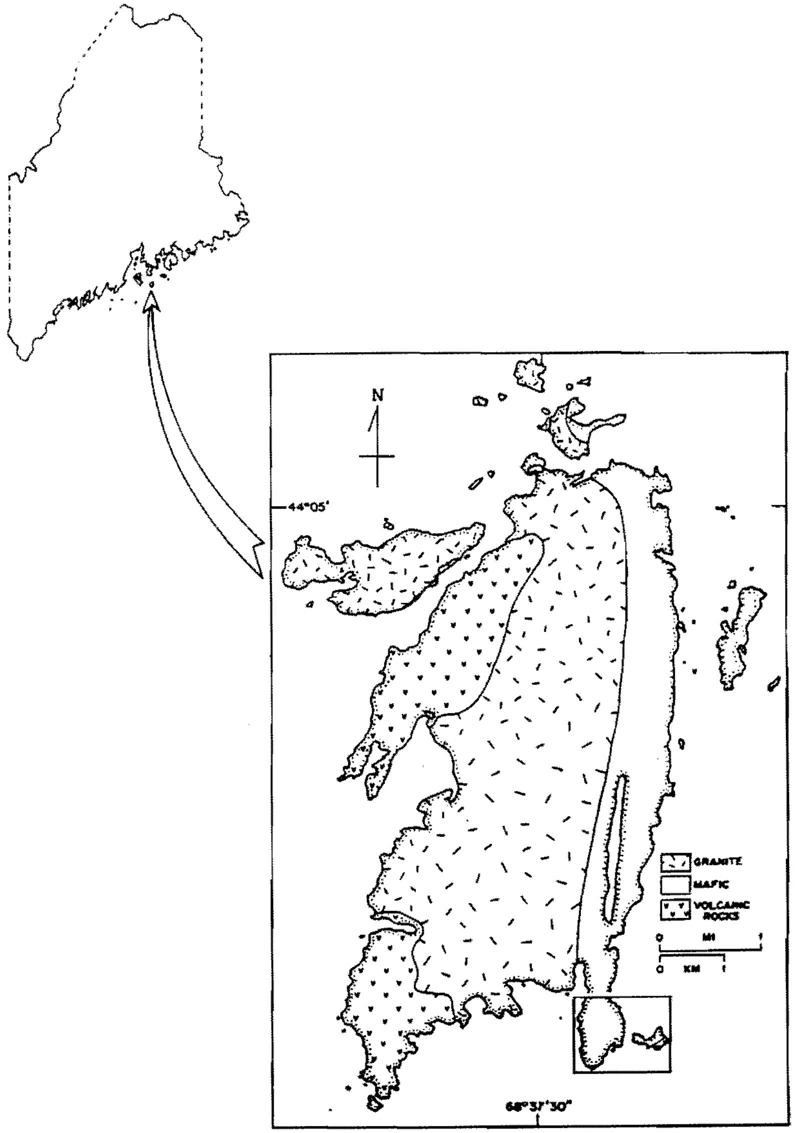

Fig. 1. Location and generalized geologic map of the lithologic units which comprise the Isle au Haut Igneous Compl
taken from Smith et al. (1907) and Luce (1962). Box shows area of our concentrated research.

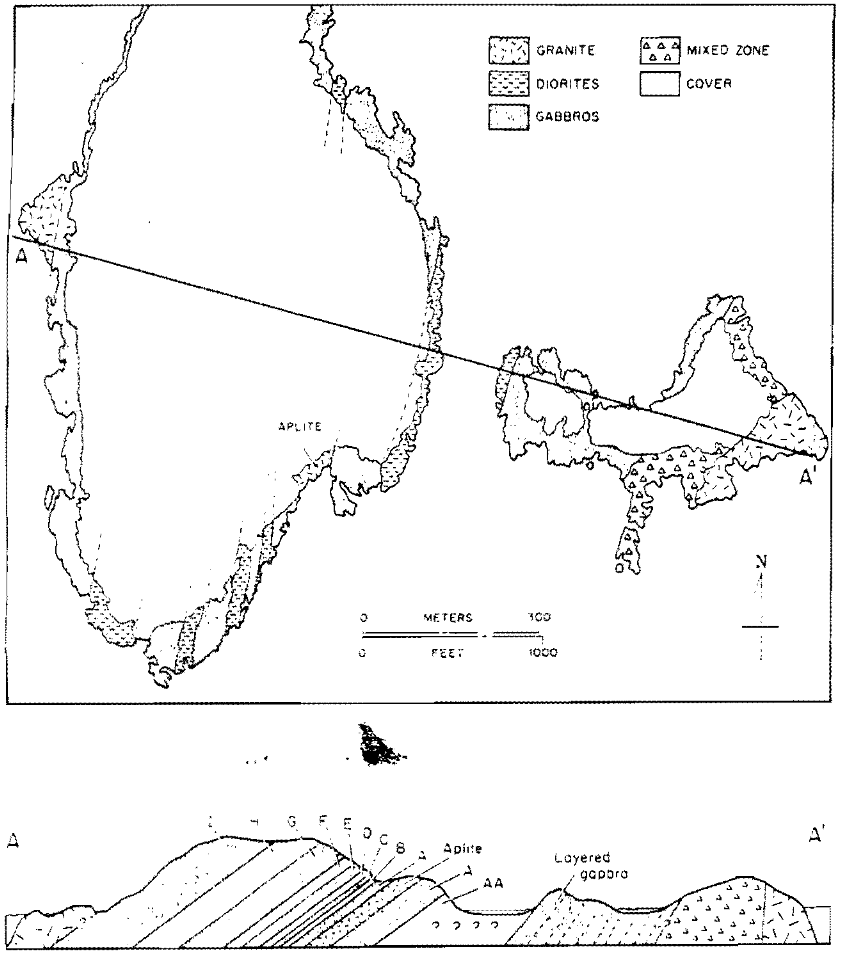

Fig. 2. Geologic map and cross section (vertical exaggeration 4x) of the composite layering of Gabbro-Diorite units and Granites exposed on Eastern Head peninsula and Eastern Ear island.

liminary ages mentioned earlier. However, because of the large uncertainty in ages (±17 Ma) it is not inconceivable that this granite could also be contemporaneous with the mafic rocks, possibly down faulted to its present position. Most of the mafic rocks exposed on Eastern Head peninsula (the southern end of the island) are gabbro, locally interlayered with diorite and quartz monzodiorite (Figs. 2 and 3). Regional structural events have tilted these layers to a post-magmatic attitude of N10°E; 35°W which has exposed an almost complete and continuous cross section of ten layers within the mafic complex (Fig. 4).

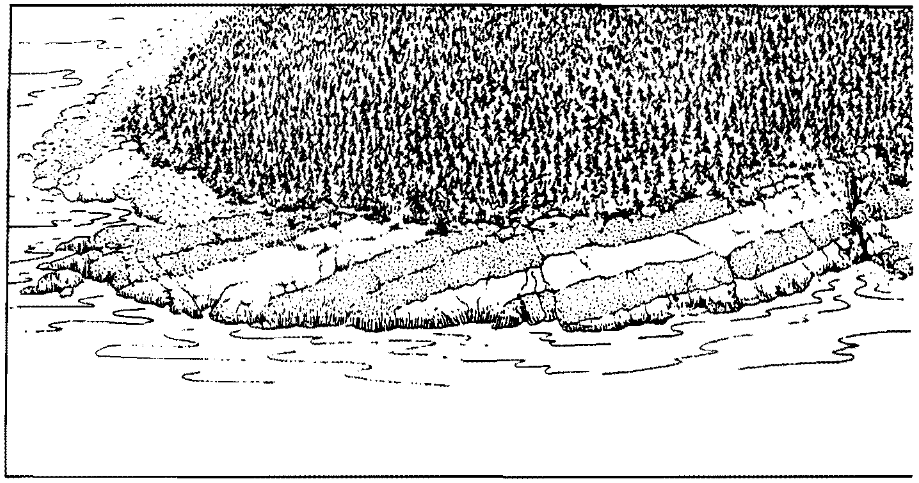

Fig. 3. Sketch of aerial photograph shows alternating sequence of layers exposed along the southern shoreline of Easte Head.

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 i Table 1 and are plotted according to the IUG classification scheme of Streckeisen (1973) i Figure 5. We have systematically collected an analyzed in detail the five gabbroic and fiv dioritic layers across the exposed sequenc along the southern coast. Major- and trace-el ment concentrations were obtained by XR (Norrish and Chappell, 1967; Norrish an

TABLE I

Modal analysis of a representative sample from each layer (1500 counts, 1/3 mm interval)

Sample	AA2	A1	B3	C3	D1	E4	F4	G4	H6	I1	F10 (Pipe)
Plagioclase	62.8	51.8	48.4	44.0	51.5	50.2	56.7	42.4	48.4	37.8	-
Alkali feldspar	-	2.1	3.7	-	6.5	-	11.2	-	16.6	-	85.2
Quartz	4.3	0.2	3.4	-	4.9	-	9.4	0.2	8.4	-	0.2
Amphibole	18.7	38.3	18.7	33.0	21.2	19.4	12.3	17.1	17.1	54.2	1.6
Cpx	-	-	5.0	-	0.6	1.2	-	4.3	-	0.6	-
Biotite	5.2	1.4	8.0	5.6	4.1	7.3	1.1	5.1	3.0	-	-
Chlorite	1.9	1.0	4.7	13.9	2.9	20.0	3.2	27.1	0.2	2.2	10.0
Apatite	1.8	0.6	0.9	0.4	0.8	-	1.0	0.2	1.5	0.4	0.8
Sphene	-	-	0.3	-	0.4	-	-	0.1	0.1	-	1.8
Zircon	-	-	0.2	-	0.5	0.1	-	0.1	-	0.2	-
Oxides	4.6	4.2	6.2	2.8	6.1	1.6	4.8	3.0	4.4	4.0	0.4
Rutile	0.3	-	-	-	-	-	-	-	-	-	-

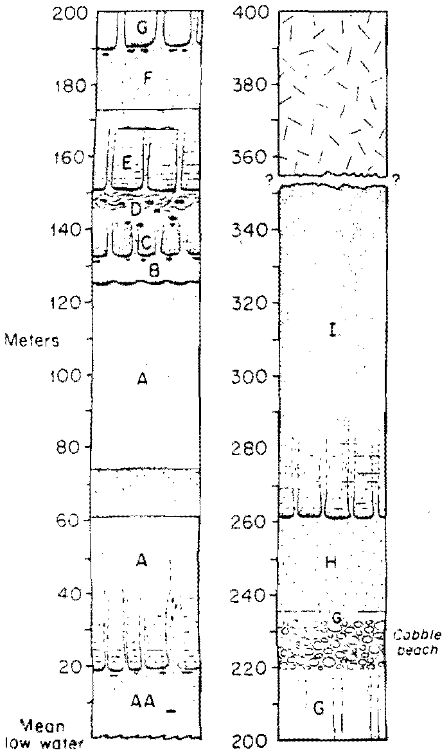

Fig. 4. Schematic stratigraphic column across the southern coast of Eastern Head showing the exposed relationships of Gabbroic (dark stipples) and Dioritic (light stipples) layers and their thicknesses. An aplite sill at 60 m and the Isle au Haut Granite at 358 m are shown by fine and coarse hash marks, respectively. All contacts are clearly exposed except where indicated.

Hutton, 1969; Rhodes, 1988). The average composition of each layer is listed in Table 2.

Gabbros

Rocks from the gabbroic units show little modal variation throughout the stratigraphic succession. All five layers are hornblende gabbros from the lowest layer through the uppermost layer (Fig. 5). They range between 40 and 50 modal percent plagioclase which is zoned from An_{62} cores to An_{35} 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 pargasitic 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 to intersertal 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 (Irvine, 1982). A few of the units show fine rhythmic layering.

Compositionally, the gabbroic units are tholeiitic and show limited chemical variations (Table 2). They resemble within-plate tholeiites according to the classifications of Pearce and Cann (1973) and Meschede (1986) and are restricted to the normal subalkaline series of Peccerillo and Taylor (1976) as shown in Figure 6. Plotted on an AMF diagram (Fig. 7), the gabbros are largely consis-

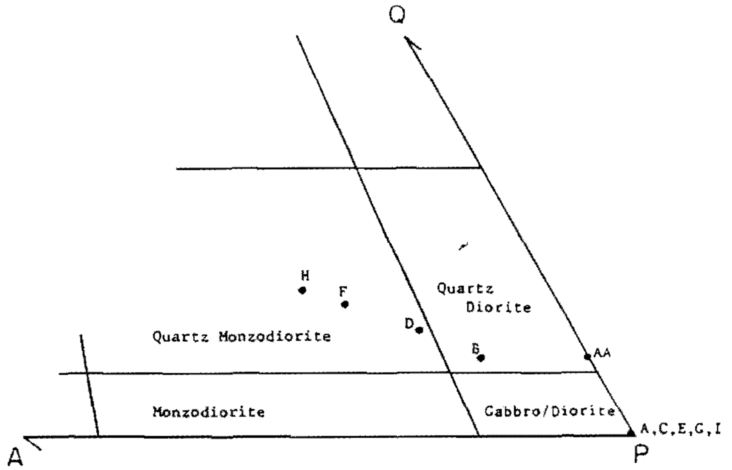

Fig. 5. IUGS classification of igneous rocks (after Streckeisen, 1973) and the average modal analysis for each lay $Q+A+P=100$.

tent 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, or 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 subophitic.

Plagioclase makes up 44 to 63 modal percent of the dioritic units and is zoned normally from An_{30} cores to An_{6} rims. The grains are n nearly as corroded as those from the gabbrc nor do core to rim variations appear as abrup

Alkali feldspar is intersertal and also prese as a very late-stage rim to plagioclase, but on in layers B and above. With increasing stra graphic height, alkali feldspar becomes mo abundant as a cumulus phase. Late-stage, i tersertal anhedral quartz increases in amou with stratigraphic height, though not as dr matically as does the alkali feldspar.

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

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

At Eastern Head, the dioritic units show n

TABLE 2

Average major and trace element compositions for each layer

Layer: Unit:	AA Quartz diorite	A Gabbro	B Quartz diorite	C Gabbro	D Quartz m dior.	E Gabbro	F Quartz m dior.	G Gabbro	H Quartz m dior.	I Gabbro	F Pipe average
Major elements (wt.%)											
SiO_2	54.52	51.09	55.35	49.57	53.62	50.71	59.38	49.38	59.76	50.25	64.03
TiO_2	2.22	1.26	1.79	1.95	2.23	1.74	1.49	1.91	1.56	1.65	1.15
Al_2O_3	17.07	17.04	15.26	16.14	15.38	16.56	15.93	16.05	15.74	16.40	15.96
$Fe_2O_3^*$	9.89	9.58	10.64	11.96	11.52	10.91	8.49	11.67	8.12	10.70	4.66
MnO	0.20	0.19	0.20	0.20	0.19	0.19	0.13	0.21	0.14	0.18	0.07
MgO	2.72	7.14	3.64	6.77	4.05	6.45	1.90	7.08	2.19	6.89	1.64
CaO	6.47	9.61	6.73	9.10	7.19	8.72	4.47	9.35	4.44	9.82	3.46
Na_2O	5.03	3.11	4.64	3.20	4.13	3.43	5.69	3.30	4.89	3.05	8.38
K_2O	1.06	0.76	1.40	0.94	1.47	1.04	1.95	0.87	2.55	0.86	0.20
P_2O_5	0.60	0.14	0.33	0.33	0.31	0.30	0.41	0.31	0.33	0.29	0.26
Total	99.77	99.92	99.96	100.14	100.08	100.05	99.85	100.12	99.73	100.11	99.79
Trace elements (ppm)											
Ba	271	110	378	165	310	159	385	156	543	125	58
Sr	438	243	257	273	264	275	210	240	189	252	142
Zr	179	102	411	161	319	172	490	196	603	142	974
Nb	18	6	17	8	13	8	17	7	18	6	20
V	57	172	167	230	236	206	67	223	122	207	40
Cr	-	180	55	161	47	144	5	167	10	179	2
Ni	10	98	20	68	23	69	9	88	13	85	12
Zn	83	83	115	95	86	76	53	188	54	96	42
Ce	77	29	68	37	55	41	82	31	74	59	74
La	34	12	24	13	21	14	34	11	31	9	29

$Fe_2O_3^*$ = Total iron as Fe_2O_3.
M dior. = monzodiorite.

obvious foliation, but are generally massive. This massive texture is in stark contrast to the diorite which makes up the northern two-thirds of the island. Away from the composite layering on Eastern Head, the diorite shows strong plagioclase foliation. Xenoliths are rare; however, two dioritic units (AA and G) each contain an isolated and heavily resorbed chilled gabbroic xenolith of a hybrid composition.

Chemically, the dioritic layers show an evolving calc-alkaline trend (Fig. 7). In accordance with the change from quartz diorite proper to quartz monzodiorite, the dioritic layers show increasing abundances of incompatible elements and decreasing abundances of compatible elements with stratigraphic height (Fig. 8). There are also strong variations within each unit which are sympathetic to the overall stratigraphic trend. That is, changes in composition within each unit mimics the overall variations throughout the stratigraphic succession.

The pipes differ from their associated diorites in composition and texture. Most are pegmatitic, consisting almost entirely of albite with interstitial concentrations of secondary actinolite and chlorite (Table 1). Some pipes terminate a few meters into the overlying gabbro. The terminus of these pipes contain concentrations of 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., K_2O and Ba, Table 2). Unfortunately, a more detailed quantitative analysis of the pipes suffers the inherent problems associated with sampling very coarse-grained and pegmatitic bodies.

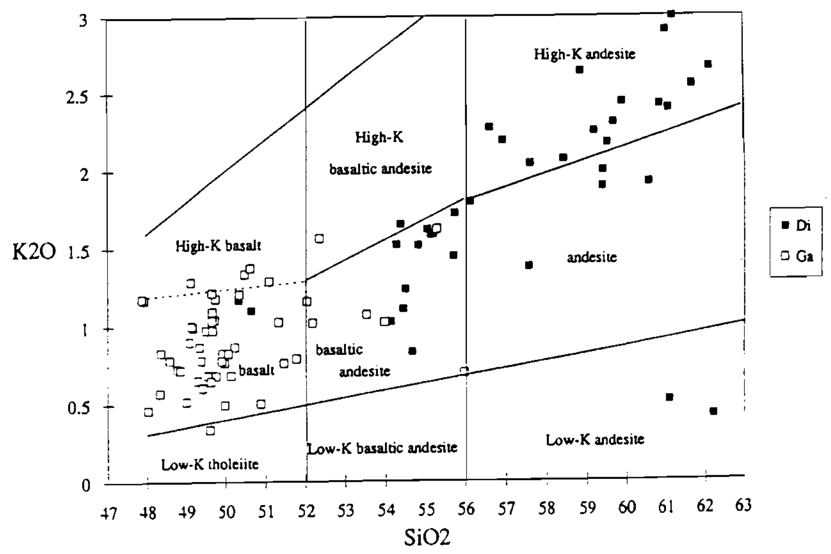

Fig.6. Composition of the gabbros and dioritic units on the K_2O and SiO_2 diagram; boundaries of arc tholeiite, cal alkaline, and high-K calc-alkaline series of Peccerillo and Taylor (1976).

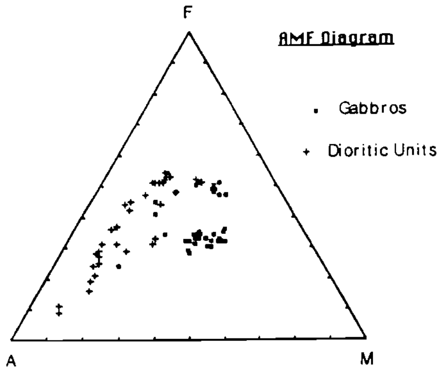

Fig. 7. AMF diagram (Na_2O+K_2O–MgO–FeO*) of the gabbroic and dioritic units.

Relationship of the layered gabbro–diorite units

Gabbros overlying dioritic units

The southernmost exposures on Isle au Ha reveal an alternating layered sequence of fi diorites *sensu lato* and five gabbros (units A/ I) dipping to the west (Fig. 8). The gabbrc units range in thickness from 7 to 106 m. . their bases, they have very fine-grained co tacts, approximately 4–5 cm thick, which a pear to have chilled against the underlyi: dioritic units. Immediately above this chill rind, the grain size progressively coarsens ov 5 m to a coarse gabbro with 6 mm plagiocla laths and 11 mm equant hornblende crysta Local concentrations of coarse plagioclase-ri pegmatitic crystals occur as irregular, ra domly scattered patches throughout the unit

At the interface of the gabbro and the unde lying diorite units are lobate. cuspate stru

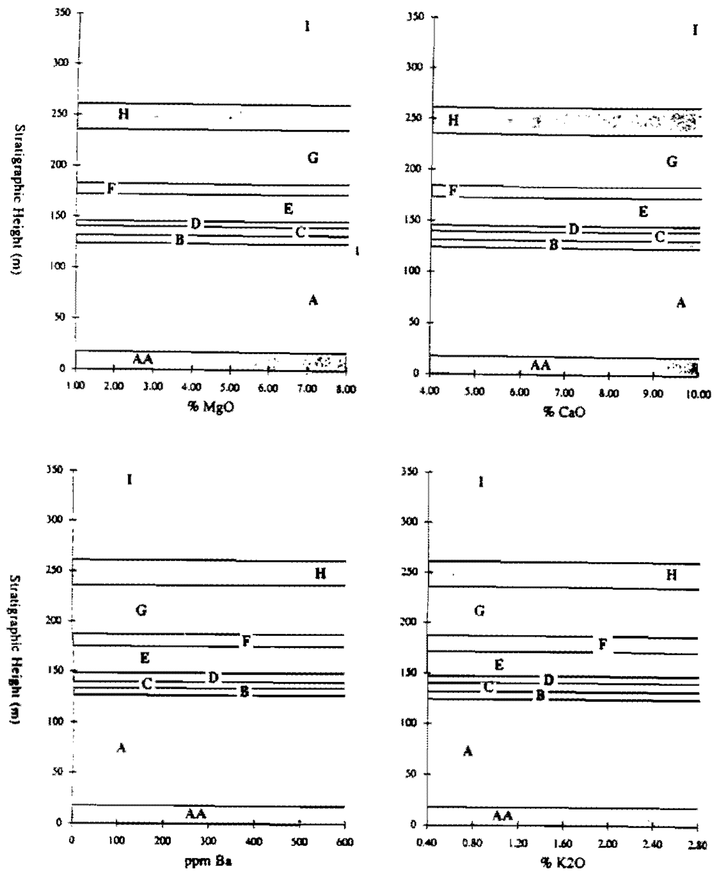

Fig. 8. Letters represent average incompatible and compatible element compositions (wt.%) versus stratigraphic height for samples in the alternating layered series. Average composition ignore obvious effects of hybridization at some boundaries. Gabbros are layers *A, C, E, G* and *I*; dioritic layers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

tures (Fig. 9) which can best be described as "load cast structures" (Pettijohn et al., 1972, p. 24; Reineck and Singh, 1980, p. 84). Others have found it useful to adopt this sedimentological term for similar igneous structures (Wiebe, 1974a; Thy and Wilson, 1980; Parsons and Becker, 1987). Within the dioritic units, immediately below the chilled contacts, are randomly spaced, globular, mafic "pillow-like" structures ranging in size from a few centimeters up to a meter in diameter. Similar features have been described as "load ball structures" (Parsons and Becker, 1987); however, due to their chilled texture, we prefer to use "pillow" to convey both a structural and petrogenetic connotation. Although commonly found less than half a meter from the contact, many "pillows" are completely detached from

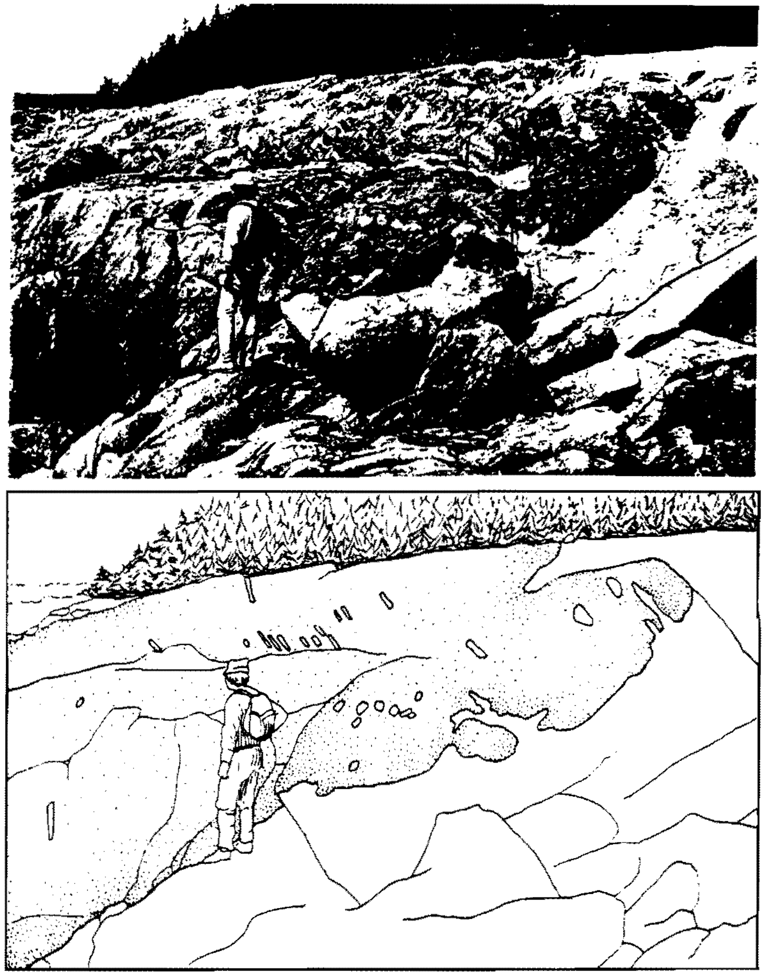

Fig. 9. Photograph and sketch of the contact between gabbro I overlying quartz monzodiorite H. Contact shows cusp "load cast" structures and pipes intruding into the gabbro.

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 chilli against the dioritic units, and for sinking largely molten "pillows" into the underlyi diorite.

At the same interfaces, fingers or pipes o part of the dioritic unit penetrate upwards in the gabbro unit for several meters (Fig. 9

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 relationship 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.

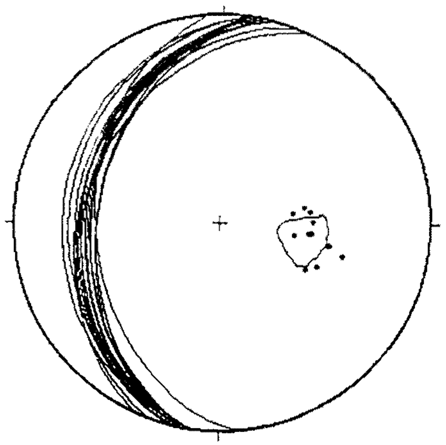

Fig. 10. Equal-area, lower-hemisphere projection of the plunge of a representative 12 pipes against 24 attitudes of the composite layers contacts (outline is of the pole of the planes).

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; Butcher 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 displacive 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 co-

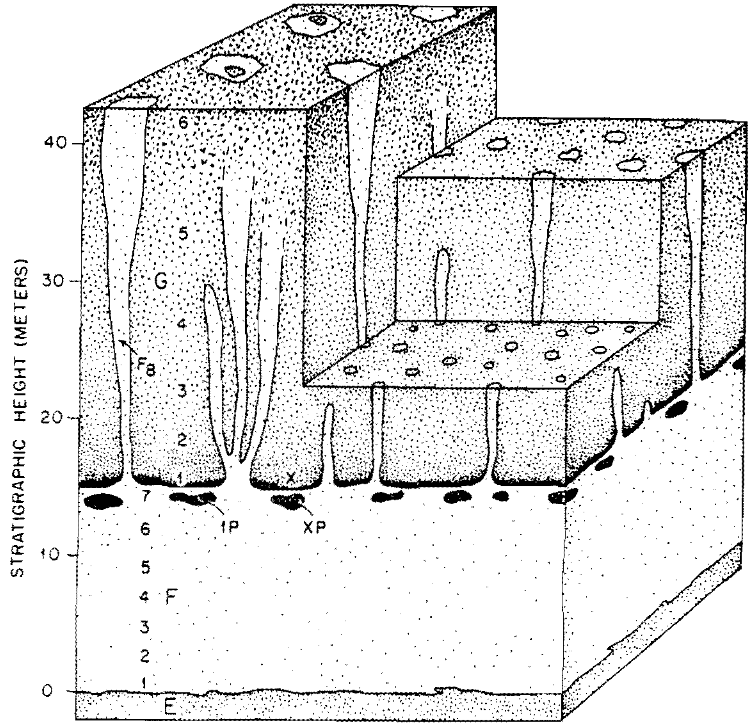

Fig. 11. Block diagram showing schematic contact relationships between gabbros *E* and *G* and quartz monzodiorit This relationship is consistent for all contacts with the exceptions of diorite B overlying gabbro A and diorite D o gabbro C (which shows complex mixing and intermingling, as shown in Fig. 4). Sample location indicated by number

existing, 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 fartl than half a meter or so.

Similar relationships of composite layeri has been described on both Guernsey and J sey in the Channel Islands by Elwell et (1960, 1962). These features are most markably exposed in the Bordeux Dior Complex (northern Guernsey) and the l ered diorites and gabbros at le Nez (southea ern Jersey). They include chilled bases of ma units overlying more felsic units, which sh cuspate margins, and the presence of pipes i truding the overlying mafic units. The layer diorites in the Channel Islands, however, d fer from Isle au Haut in that many layers gra 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. Elwell 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 metasomatism 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 as 1000°C, though this estimate may be somewhat high. The densities of the gabbro and quartz monzodiorite magmas, calculated using the method of Bottinga and Weill (1970),

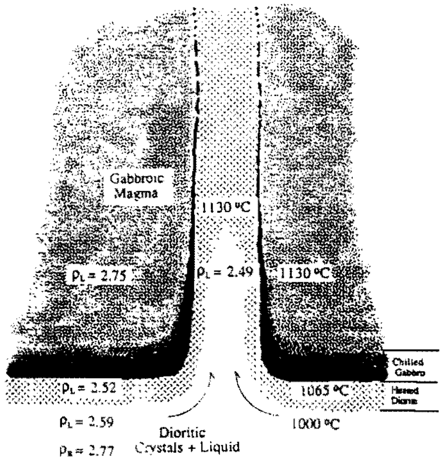

Fig. 12. Estimated temperatures and densities of the gabbro G, quartz monzodiorite F, and pipe calculated from their respective compositions as liquids, ρ_L, or as solid rock, ρ_R, in the case of a dioritic cumulate floor. Densities calculated using the method of Bottinga and Weill (1970).

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 crystal–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 crystal–liquid 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 s vive; both layers should completely overtu Furthermore, repeating this inherently stable process many times, as the alternat succession of dioritic and gabbroic layers quire, simply stretches credulity. The appar paradox of a less dense dioritic liquid bene a denser gabbroic liquid can be resolved if underlying dioritic layer represents cumulat largely solidified, forming the floor of evolving dioritic, or perhaps more silic magma body (Fig. 12). As this body cools crystallizes, it is invaded by a pulse of gabbr magma that intrudes, sill-like, between denser crystal mush of the cumulate floor the overlying less dense magma (Fig. 1 Wiebe (1974a, b) describes a similar exam from Cape Breton Island, of a floored dior pluton invaded by successive pulses of g broic magma. The pipes represent the resid interstitial fluid within the cumulate cry mush, which collects beneath the gabbro owing to compaction and deformation of cumulate floor. This residual fluid, heated the gabbro, and now gravitationally unsta will penetrate the overlying gabbroic liquic form the pipes. This must occur before gabbro can solidify to form an impenetra cap. The fact that the pipes are preserved plies that the gabbroic magma was not vig ously convecting following emplacement, some fluid dynamic models would prec (e.g., Huppert and Sparks, 1980; Hupper al., 1982; Campbell and Turner, 1986), that a quiescent crystallization history is m likely (Marsh, 1989).

The overlying dioritic chamber would be perheated by the invasion of the gabbroic It would vigorously convect, and would crystallize further until the ponded gab cooled and largely solidified. We envisage t this new floor to the evolving chamber wo form the substratum onto which the dior magma would continue to crystallize, there forming a new floor of crystal mush. Repea

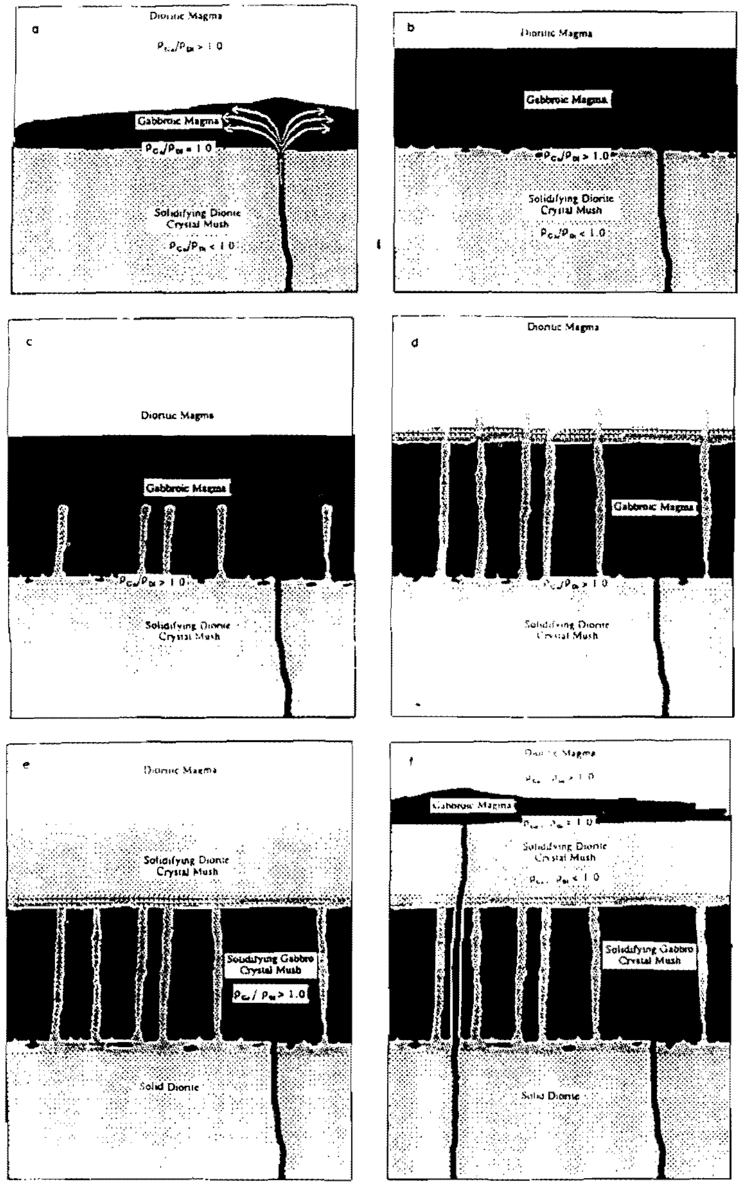

Fig. 13. Model shows the sequence (a–f) of emplacement for two of the gabbroic magmas invading the evolving dioritic chamber, development of "load cast" structures, and formation of pipes which breach the top of the gabbroic magma.

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 H).

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 sills, 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 reser-

voir. It is possible that the Isle au Haut gran could represent the upper part of such a magi body, that has been down faulted into its cu rent position juxtaposed with the lower, la ered mafic part of the pluton.

(b) Our second hypothesis is essentially open-system assimilation-fractional crystal zation process (e.g., McBirney, 1980; D Paolo, 1981; Watson, 1982; Grove et al., 198 1988). The initial composition of the magr in the pluton may well have been gabbro probably related to the magma that continu to invade and periodically replenish the magr reservoir. Assimilation of crustal material the magma cooled, crystallized, and was fu ther replenished, could lead to progressi changes in the composition of the magma, a: to zoning of the magma body (McBirne 1980). The progressive change with stra graphic height from layered gabbro, throu diorite, to quartz monzodiorite cumulates the floor of the magma chamber would ther fore be a reflection of this continuing proce Melting of crust by the invading basal magma might result in pulses of contempo neous granitic melts invading the magma bo to produce a hybrid magma, thereby accel ating the differentiation process. The gran exposed to the east is possibly contempo neous with the layered gabbro and diorites a could be an example of this type of compone

Conclusion

We believe that the composite mafic lay ing exposed on Isle au Haut is the plutor equivalent of a periodically replenished, or i vaded evolving magma reservoir. Movi down the succession of layers provides "sna shots" of its magmatic development that c be explored geochemically and petrological Our own investigations in the Coastal Mai Magmatic Province and field excursions to t Channel Islands lead us to believe that th process should in fact be quite common provinces which show a bimodal association silicic and mafic magmas. Moreover, a review of the literature persuades us that, although largely unrecognized as such, there may be numerous examples of the effects of periodic 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).

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

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ABSTRACT

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

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

In each stratigraphic sequence the single samples were examined and their shape, type of vesiculation, and state of glas (edge modification by abrasion, alteration, presence of aggregates, secondary minerals and coatings) were analyzed an described.

Characteristic features were recognized for deposits from different eruptive phases. Samples from phreatomagmati 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 juvenile clasts from the phreatomagmatic phases of these eruptions of Vesuvius always show primary vesiculation this observation supports the presence of fragmented magma at the time when interaction occurred.

The conclusions from SEM observations are in perfect agreement with the results of granulometric and componen 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.

An exhaustive review of hydrovolcanism can be found in Sheridan and Wohletz (1983), and we will refer to their definitions in the foll ing; particularly, we will use "hydromagr tism" as a general term for an explosive p cess involving the contact between magma a external water, while "phreatomagmatism' always referring to events where the exter water have a surely phreatic origin.

The criteria for recognizing deposits belo ing to hydromagmatic phases by scanning el tron microscopy are illustrated in numer papers (Walker and Croasdale, 1972; Heik

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