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COEXISTING ACID AND BASIC MAGMAS OF THE ELIZABETH CASTLE IGNEOUS COMPLEX, JERSEY, CHANNEL ISLANDS

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At Elizabeth Castle, Jersey, plutonic igneous rocks are observed in intimate relationships. A variety of dioritic rocks has been invaded by the Fort Regent Granophyre. These diorites are mainly medium-grained and equigranular, though porphyritic varieties are present. Diorite frequently occurs as irregularly shaped enclaves within the Fort Regent granophyre, which elsewhere intrudes the diorite as sub-horizontal sheets. Contacts between the diorite and granophyre are usually crenulate, with the diorite often displaying fine-grained margins. These contact relationships indicate that the rocks were initially present as co-existing magmas, with the hotter basic magma having chilled against the cooler acidic magma, the process known as magma-mingling. Later incursions of granophyre have locally disrupted the mingled rocks, producing planar contacts. A further granitic variant occurs intermittently along contacts between the granophyre and diorite. It is suggested that this is a hybrid resulting from interactions between the dioritic and granitic magmas. All of these rocks are cross-cut by intrusions of Red Granite which are in turn cross-cut by members of the Jersey Main Dyke Swarm.

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INTRODUCTION

Jersey is the largest of the Channel Islands, situated in the Gulf of St Malo just off northern Brittany, France. The rocks form part of the North Armorican Massif and were produced during the Cadomian orogeny, which spanned the period 700-425 Ma (Figure 1). The oldest rocks on Jersey belong to the Jersey Shale Formation which comprises a series of Brioverian sediments deposited between 660 and 540 Ma (Guerrot and Peucat, 1990). This formation is succeeded by a series of calc-alkaline volcanic rocks known as the Jersey Volcanic Group. Three plutonic igneous complexes, the North-West, South-West and South-East Granite Complexes, intrude these sedimentary and volcanic rocks. The North-West and South-West Granite Complexes are predominantly granites, while the South-East Granite Complex contains a large proportion of gabbro and diorite (Bishop and Key, 1983; Key, 1977, 1985, 1987; Topley and Brown, 1984).

Elizabeth Castle is situated in St Aubins Bay and forms part of the western edge of the South-East Granite Complex. The rocks are very well exposed on the outcrops and reefs surrounding the castle itself.

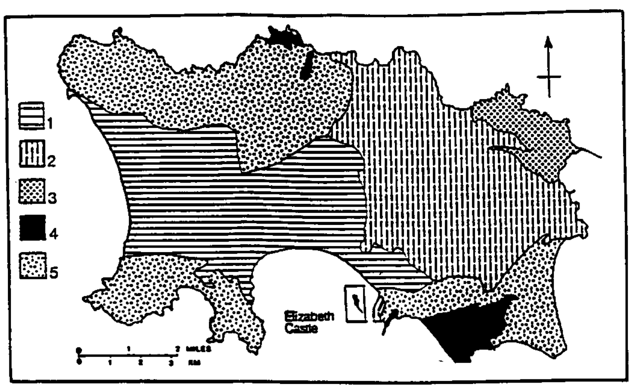

Figure 1. Simplified geological map of Jersey showing the major units: 1, Jersey Shale Formation; 2, Jersey volcanics; 3, Rozel Conglomerate; 4, Gabbros and diorites; 5, Granites.

The area comprises two major rock types, namely granophyre and diorite (Figure 2). These are intimately intermingled and display a variety of contact relationships. A further lithology occurs intermittently between these two. The purpose of this paper is to describe the lithologies and field relationships found around Elizabeth Castle and to present our preliminary thoughts as to the processes that led to their formation. These investigations are part of an ongoing research project which is currently investigating the physical and chemical interactions involved. The end results of this project will enhance knowledge of the geology of Jersey and, in a wider context, will contribute towards a greater understanding of physical and chemical processes within multi-magma complexes.

Igneous rocks of contrasting composition are often found in intimate relationships in both plutonic and volcanic environments. Characteristic features in plutonic rocks include crenulate or irregular contacts, fine-grained margins in the basic rock, enclaves of the basic rocks within the acid rock and extensive veining of the basic rock by the acid rock. The production of these relationships has previously been attributed to a number of processes including recrystallization (Reynolds, 1946) and metasomatic reaction (Chapman, 1962; Bishop and Key, 1983). It is now recognised that they are the result of magma-mingling (e.g. Walker and Skelhorn, 1966; Salmon, 1987; Seaman and Ramsey, 1992). Some confusion exists in published literature concerning the use of the terms magma-mixing and magma-mingling (e.g. Gamble, 1979; Furman and Spera, 1985). Magma-mingling is the process whereby two or more magmas, often of contrasting composition, come together and survive as discrete entities with stable interfaces between them. The process is distinct from that of magma-mixing, in which two magmas are physically blended to produce an intermediate hybrid (e.g. Bowen, 1928; Vogel *et al.,* 1984). Following magma-mingling, chemical exchange may still take place between the coexisting magmas. Crenulate margins indicate that the two rocks originated as coexisting magmas (magma-mingling). Straight or planar contacts indicate that one of the magmas was substantially crystallized or solid before coming into contact with the other.

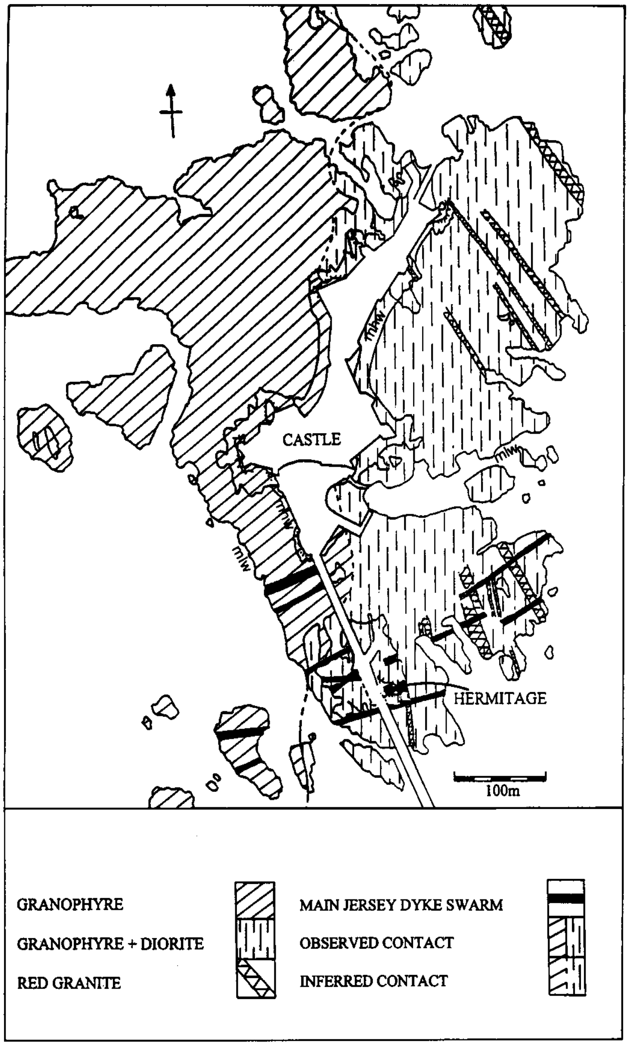

Figure 2. Simplified geological map of Elizabeth Castle.

THE GEOLOGY OF THE AREA AROUND ELIZABETH CASTLE

The reefs surrounding Elizabeth Castle measure approximately 850 by 950 metres. The majority of the work for this project was undertaken on the eastern reefs where both diorite and granophyre are present. All of the rocks are very well exposed at low tide. At high tide only the Hermitage section is readily accessible. The relatively fresh state of the rocks exposed around the Hermitage is due to the fact that the area was quarried in the late nineteenth century. Therefore this locality was used for many of the detailed observations.

The area was examined by Wells and Wooldridge (1931) who were the first to describe the contact relationship between the granophyre and diorite. The locality was also referred to by Bishop (1963) in his investigation of "dark margins". Since this date no detailed studies of the area have been published. Bishop and Key (1983) suggested that some of the diorites of south-east Jersey originated by the metasomatic alteration of gabbros, rather than crystallizing directly from a dioritic magma. However, this assertion was disputed by Topley and Brown (1984) who concluded that field and other evidence supports a primary igneous origin for the diorites.

ROCK TYPES AND FIELD RELATIONSHIPS

The predominant rock type in the area around Elizabeth Castle is a medium to coarse-grained pink granophyre. The western reefs are composed of granophyre alone, but to the east the granophyre is intimately associated with diorite. The contact between these mappable units strikes approximately north-south through the centre of the study area (Figure 2). In places the diorite and granophyre are present as a sheeted complex, elsewhere the diorite is present as enclaves within the granophyre. A rather larger mass of similar rock occurs a kilometre or so to the east, where it forms a prominent topographic feature next to St Helier harbour. On the BGS map (Bishop *et al.,* 1982) the two rock masses are mapped as the same lithology under the name of the Fort Regent Granophyre.

The granophyre is composed of c. 25% quartz, c. 45% plagioclase, c. 25% alkali feldspar and c. 5% biotite. It is porphyritic, with the groundmass having a grain-size of c. 2 mm. Quartz is usually anhedral. Plagioclase, which is often sericitized, is present as equant or tabular phenocrysts up to 5 mm in size. These are mostly subhedral, with albite twins, and are frequently zoned. The phenocrysts are randomly orientated within the rock, displaying no alignment due to flow or other processes. Alkali feldspar is subhedral, often sericitized and occasionally displays rapakivi texture. Alkali feldspar is also graphically intergrown with quartz to produce the granophyric texture which is a distinctive feature of this rock type. The granophyric texture nucleates around pre-existing plagioclase and alkali feldspar crystals. Biotite is often partially altered to chlorite. Minerals present in minor amounts include epidote, chlorite, apatite and magnetite.

Four main varieties of diorite have been recognised. These are defined here as medium-grained diorite, porphyritic diorite, monzodiorite and coarse diorite. The variability within the dioritic rocks, which has not previously been reported, is a function of texture and modal composition. All are dark grey or grey-green and predominantly comprise hornblende and plagioclase in various proportions. The hornblendes are anhedral and most have been partially altered to chlorite. Plagioclase is extensively altered to sericite and epidote. The minor amounts of alkali feldspar present have also been replaced by sericite. This alteration is so pervasive that in some thin sections only the alteration products are visible. The medium-grained diorite, which has an average grain size of 1 mm, is the most abundant, with the groundmass of the three other varieties of diorite being similar to this. The porphyritic diorite contains c. 5% tabular white plagioclase phenocrysts up to 2 mm long, giving the rock a white speckled appearance in hand specimen. The monzodiorite contains a higher proportion of alkali feldspar (c.20%) than the other three, while the coarse diorite contains abundant (c.35%) subhedral to euhedral phenocrysts of greenish plagioclase up to 10 mm long. Most of the diorites contain numerous acicular apatite crystals.

Sub-horizontal layering in the diorites is well-displayed in outcrops c. 17 m west of the Hermitage (Figure 2). The layering is defined in terms of textural variation, colour index and the presence or otherwise of feldspar phenocrysts. Layers of relatively densely-porphyritic coarse diorite with good cumulate textures are present. These layers are c. 40 cm thick with gradational upper and lower margins.

The layered diorite is intercalated with sub-horizontal sheets of granophyre, producing the sheeted complex (Figures 3a and 3c). In the vicinity of the Hermitage the sheets dip c. 12° WNW. Below the eastern walls of the castle, sheets dip c. 8° ENE. It is a distinctive feature of the complex that the granophyre sheets are almost parallel to the layering within the diorites. All of the granophyre sheets have (often highly) irregular, crenulate contacts with the adjacent diorites (Figures 3a and 3b). The thickness of sheets varies from c. 3 cm to c. 50 cm. Most sheets have irregular upper and lower interfaces (Figure 3a). The degree of irregularity of the interface appears to be related to the thickness of the sheet, so that sheets of only a few centimetres thickness have crenulations on the millimetre scale. Some sheets have much more planar (or undulose) interfaces, with crenulations on the millimetre scale. Near the top of the sheeted complex just to the west of the Hermitage, is a granophyre sheet with a distinctly planar base (again with mm-scale crenulations) and

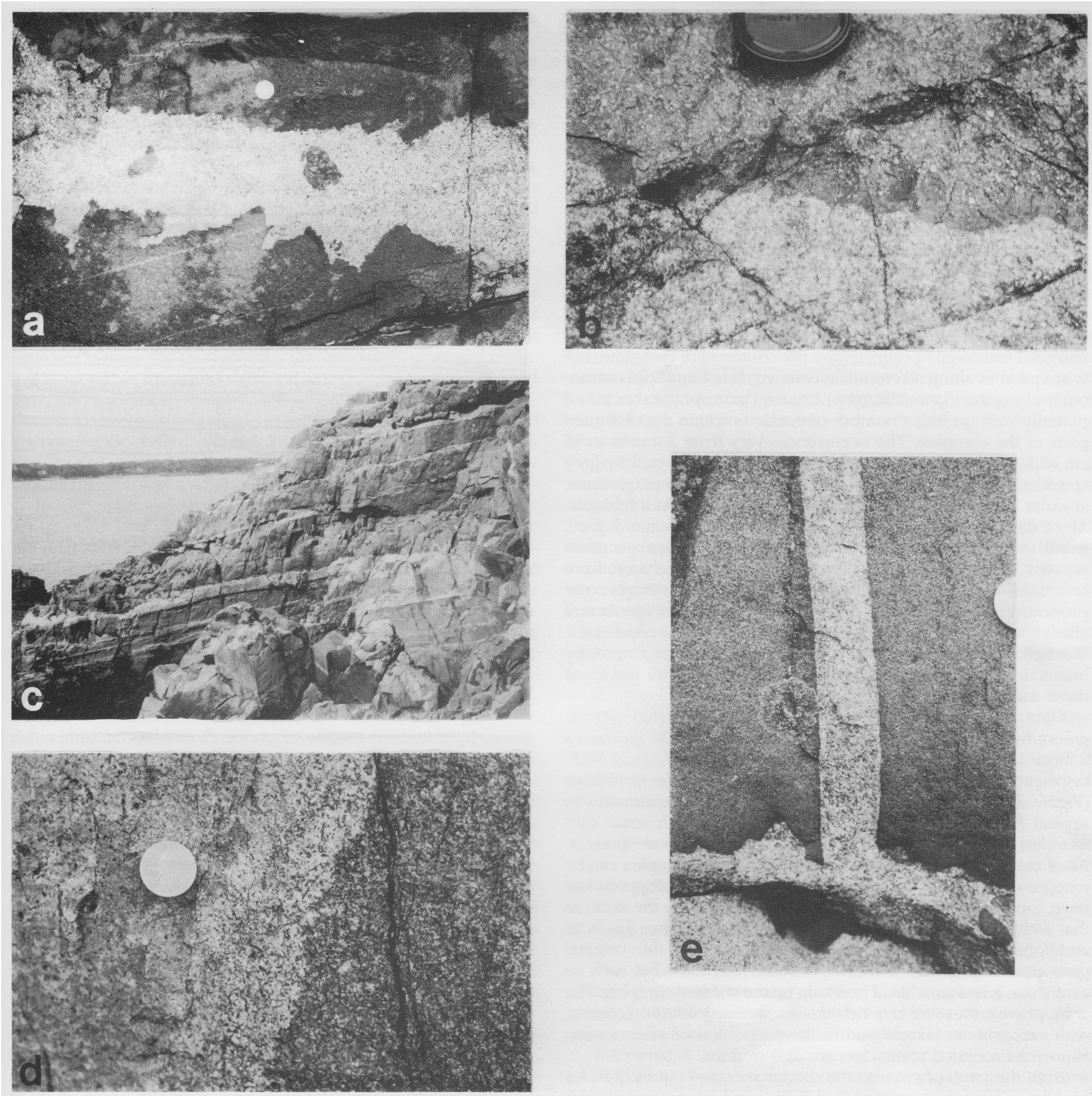

Figure 3. Field relationships within the Elizabeth Castle complex: (a) typical sharp, crenulate contacts between diorite and a granophyre sheet; (b) contact between porphyritic diorite and granophyre, showing the chilled margin; (c) granophyre sheets within layered diorite next to the Hermitage; (d) a marginal hybrid zone (centre) between granophyre (left) and diorite; (e) straight-sided sheet of granophyre cross-cutting a crenulate, chilled margin in diorite.

a highly irregular top. The diorite has fine-grained margins, which vary in width from less than a millimetre to c. 6 cm (Figure 3b), against the granophyre sheets. In thin-section, some fine-grained margins display elongate plagioclase crystals in an open spherulitic texture.

The sub-horizontal sheets are interconnected by occasional sub-vertical sheets, which cross-cut the porphyritic layers within the diorites. Sub-vertical sheets occur in two orientations, approximately normal to each other. Irregular veins and apophyses also rise from sub-horizontal sheets into the overlying diorite. The net effect of this pattern of intrusion is a series of large, flat-lying masses of diorite surrounded by granophyre (Figure 4). In places, the diorite has been partially disrupted, resulting in the presence of smaller sub-angular enclaves in the granophyre. Small (a few cm or so) sub-rounded enclaves of diorite also occur within the granophyre, as well as rounded mafic clots which are less than 1 cm across. Intruding the sheeted complex to the west of the Hermitage is a sub-vertical dyke which is up to 1.5 m wide and oriented approximately N-S. Although filled with granophyre which is very similar to that within the sub-horizontal sheets, the dyke appears to slightly post-date the sheets. This dyke connects with the main western mass of granophyre.

Occasionally, granophyre cross-cuts fine-grained margins forming straight-sided offshoots in the diorite (Figure 3e). The granophyre in these veins is the same as the surrounding granophyre, i.e. that which produced the crenulate and fine-grained margins. It is clear that the granophyre magma was still mobile (or had become remobilised) at a time when the diorite had become either solid or substantially crystallized.

In some apophyses, granophyre grades upwards into a fine-grained diorite which is much paler in colour than the surrounding diorite. The texture of this pale-grey diorite is relatively inhomogeneous, with felsic patches, pink alkali feldspar, which is often concentrated along the margins, and small pods of pegmatitic quartz and alkali feldspar, some of which are miarolitic. Contacts between this material and the surrounding diorite are sharp. A few sub-horizontal sheets, generally only a few cm thick, are filled with similar, though even finer-grained, pale-grey diorite. In at least one occurrence, the pale-grey material is crosscut at its upper end by the next granophyre sheet up in the series. In the apophyses in particular, it appears that the pale-grey diorite is a product of interaction between the granophyre and the diorite, possibly by means of infiltration.

A minor, but none-the-less important, lithology occurs intermittently between the diorite and granophyre (Figure 3d). This marginal facies only occurs where the contacts are crenulate, but is not present along all crenulate contacts. It is found discontinuously along the top and bottom of several granophyre sheets and partially surrounding a number of enclaves within the disrupted parts of the complex. The occurrences vary from 2 mm to c. 15 cm wide. The rock is fine to medium-grained with a creamy-grey speckled appearance, comprising subhedral tabular plagioclase, acicular amphibole, anhedral quartz with minor alkali feldspar. All of the feldspars and amphiboles are altered to some degree. Small (< 0.5 cm) rounded dioritic enclaves or clots are often present. In most occurrences, there is a gradational change from one side to the other. Moving away from the diorite, the proportion of amphibole decreases, the proportion of quartz and alkali feldspar increases and the extent of sericitization decreases. We believe this minor lithology to be a hybrid produced by interaction between the diorite and granophyre. The nature of these interactions is currently under investigation.

Over large areas of the eastern reefs, the sheeted diorite-granophyre complex has been disrupted, dispersing the diorites as a host of enclaves within the granophyre. The effect is well-displayed on the rock walls immediately beneath the Hermitage (Figure 2). The enclaves range in size from a few centimetres to several metres and are mostly sub-angular, although some sub-rounded enclaves with undulose or crenulate margins are present. All of the diorite types present within the sheeted complex can be recognised, and more besides. The disruption and dispersal has been carried out by granophyre which appears to be the same as that within the sheeted complex. It is not clear whether this is an additional intrusion of granophyre, or whether the original granophyre has, by some means, become remobilised to such an extent that it was capable of breaking up the sheeted complex. The granophyre in these enclave-rich areas is often very inhomogeneous, with variations in texture and in the proportion of phenocrysts. Numerous rounded mafic clots are also present.

Both the granophyre and the diorite are cross-cut by a series of dykes of medium-grained Red Granite which range in width from two to eight metres. Contacts between the Red Granite and surrounding rocks are sharp and planar. Xenoliths are present within the Red Granite, these being predominantly diorite or coexisting diorite and granophyre. The relationships indicate that the diorite and granophyre were solid when the Red Granite was emplaced. Cross-cutting all of the aforementioned rocks are members of the Jersey Main Dyke Swarm (Lees, 1986) which in turn are cross-cut by aplite sheets.

DISCUSSION

The contact relationships between the granophyre and the diorite indicate that they were originally present as coexisting magmas. The relationships typical of such associations (referred to as magma-mingling) are well-documented and widely accepted. The fine-grained margins which are present in the diorites next to irregular interfaces are here interpreted as chilled margins. However, other processes have been proposed for the formation of fine-grained margins; e.g. metamorphism (Richey, 1937), fusion by recrystallization (Reynolds, 1951) and recrystallization in response to the migration of fluids (Bishop, 1963). Fine-grained margins should therefore be interpreted with a degree of caution, taking into consideration associated phenomena. The interpretation as chilled margins in the Elizabeth Castle rocks is strengthened by the presence in some of open-spherulitic textures, which are attributed to rapid cooling (e.g. Shelley, 1993) due to considerable thermal contrast between the two magmas.

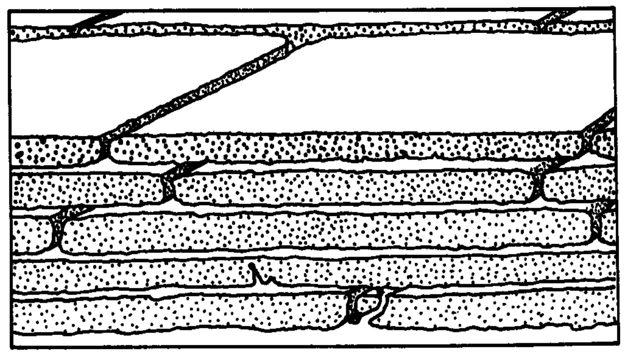

Figure 4. Schematic 3-D representation of flat-lying masses of diorite (stippled) surrounded by granophyre. Diorite masses are 1 to 2 m thick.

Straight-sided offshoots filled with granophyre cutting across chilled-margins may be explained in terms of the higher temperature of the dioritic magma in comparison to the granophyre magma. When the two come together, the dioritic magma will be cooled by the granophyre, as evidenced by the chilled-margins. The granophyre, on the other hand, will be heated by the dioritic magma and so become increasingly fluid. The result is that the granophyre remains mobile when the diorite has become either substantially crystallized or solid. Any disturbance may then result in the diorite fracturing, allowing the still mobile granophyre to infill the fractures.

Two lithologies occur at Elizabeth Castle on a minor scale. One is the intermittent marginal facies with acicular amphiboles, the other is the fine-grained, pale-grey material that fills certain apophyses and thin sheets. Both of these are envisaged as hybrids, produced by interaction between the dioritic and granitic magmas. One possible explanation is that these hybrids were produced by simple magma-mixing between the two main rock types. However, the presence of viscosity contrasts and chilled margins would probably prevent this taking place. Two other processes, fluid migration and chemical diffusion, have been proposed to account for the exchange of elements between magmas (Yoder, 1973; Watson and Jurewicz, 1984; Platevoet and Bonin, 1991). In the case of the pale-grey diorite, evidence such as felsic patches, alkali feldspar and pegmatitic pods suggest infiltration, probably by residual fluids from the granophyre, as the most likely explanation. A similar interpretation has been placed on some granitic veins intruding gabbro in the Pleasant Bay intrusion (Wiebe, 1993). In the case of the intermittent marginal facies, the likeliest explanation is that diffusional exchange took place between the coexisting magmas. Diffusional exchange can be driven by chemical contrasts between adjoining magmas, which is certainly the case at Elizabeth Castle. However, because of the slow rates at which diffusion takes place (e.g. Hoffman, 1980; Baker, 1990), even in the presence of water (Baker, 1991), it has the ability to affect only small volumes. This limitation does not present too great a problem at Elizabeth Castle, where the relative volume of the proposed hybrid is small.

Of particular interest at Elizabeth Castle is the presence of sub-parallel sheets of granophyre in the diorite, forming the sheeted complex (Figure 3c). There are (at least) three possible ways in which this relationship could be produced. These are:

1. Non-forceful introduction of the granophyre magma into a magma chamber filled with diorite magma, in the form of sheets, as seen;

2. Forceful introduction of the granophyre magma into a magma chamber filled with diorite magma, disrupting the diorite magma into pillows which then settle with granophyre magma between them;

3. Periodic introduction of diorite magma into a magma chamber filled with granophyre magma, the diorite magma settling as pillow-like masses with granophyre between them.

We interpret the relationships at Elizabeth Castle as indicating (for reasons set out below) that granophyre magma was intruded into diorite magma. The style of intrusion was initially sluggish and non-forceful, producing the granophyre sheets and interconnections. The viscosity contrast between the two magmas may have been instrumental in maintaining the physical integrity of sheets during this stage of intrusion. Following the formation of the sheeted complex, it was then disrupted and dispersed as enclaves within the granophyre. The sub-angular nature of the enclaves within the granophyre indicate that most of the sheeted complex was solid or substantially crystallized when this occurred. The presence of some irregularly-shaped or sub-rounded enclaves with chilled margins suggests either that certain portions of the sheeted complex were still magmatic, or that further diorite magma was available close-by.

In magma-mingled complexes, the acid magma commonly sends veins into the basic magma. However, these tend to be irregular in form, or produce a net-vein pattern on the metre or sub-metre scale. Such occurrences are present at other localities in the Channel Islands and elsewhere. At Beaucette Marina, within the Bordeaux Diorite Complex of northern Guernsey, leucocratic material invades mafic rocks which are in the form of alternating mesodiorite and meladiorite layers. Within the mesodiorites, the leucocratic material forms thin sub-horizontal sheets which are interconnected vertically to form a net-vein pattern (Elwell *et al*, 1962). The vertical interconnections are much more closely spaced than at Elizabeth Castle. However, it is significant that the sheets are sub-parallel to the layering in the diorites. In the meladiorites the leucocratic material forms a series of straight, uniformly inclined cylindrical pipes (Elwell *et al*., 1960). As it appears likely that the leucocratic material in both pipes and net-veins is the same (Topley *et al*., 1990), it has the appearance of moving upwards through the series of dioritic layers, interacting differently with each. This type of behaviour, and its resultant intrusion patterns, suggests fairly passive intrusion such as in option 1 above. Elwell *et al*. (1962) believed that the physical state of the diorite was such that it was able to propagate fractures parallel to the plane of the layering, even though crystallization was not very far advanced. A similar explanation may be tenable for the sheeted complex at Elizabeth Castle.

At Sorel Point, Jersey, granodiorite invades mafic rocks as sheets, veins and cylindrical pipes (Salmon, 1987, 1992, 1996). The sheets are not so extensive as those at Elizabeth Castle, nor do they occur as a series of sub-parallel sheets. Net-veining has occurred in places, producing pillows with domed tops and tapered bases. Enclaves of the mafic rocks occur throughout the granodiorites, often in the form of enclave swarms. The field evidence suggests that at Sorel Point granodiorite emplacement was rather more forceful and disruptive than at Beaucette Marina, more in the style of option 2 above.

Wiebe (1980) describes magma-mingling in the Na in anorthositic complex, Labrador. In the Zoar contact zone this takes the form of diorite pillows in a granitic matrix. In the Tigalak layered intrusion similar relationships occur, with the "planar structure" produced by lensoid pillows being parallel to layering within the diorite. In both instances Wiebe (ibid.) suggests that intrusion of granite magma into the basic magma has disrupted it with consequent settling of diorite pillows. This again appears to be similar to option 2 above.

In the Pleasant Bay layered gabbro-diorite intrusion, Coastal Maine, USA, there are "...hundreds of macrorythmic units consisting of basally chilled gabbro that grades upward to diorite or highly evolved leucocratic silicic cumulates." Wiebe (1993). At the top of each of these units is the base of the overlying unit. The bases are irregular, crenulate and "convex-downward". Pipes, veins and dykes of the underlying dioritic material project upward into the overlying gabbro. Elsewhere within the complex are pillows or lenses of gabbro with complete chilled margins within a leucocratic matrix. Modal layering and lamination of tabular plagioclase (together with modal and chemical compositions) indicate that the leucocratic rocks are cumulates. Wiebe (ibid.) has interpreted each of the macrorythmic units as a new injection of basaltic magma into a silicic magma chamber. This is the same as option 3 above.

This interpretation is significant because, having visited the Channel Islands, Wiebe (1993) has suggested that many of the mingled complexes there can be interpreted using this model. It has also been suggested by others (e.g. R.S. D'Lemos, 1996, pers. comm.) that this explanation may apply to the Elizabeth Castle rocks. Certain of the relationships at Elizabeth Castle do seem to bear this out, in particular the regular, sub-parallel and extensive nature of the granophyre sheets. However, whilst it is too early in the current research project to be absolutely certain, we feel that Wiebe's interpretation may be untenable on the following grounds:

1. The granophyre sheets and veins at Elizabeth Castle do not display cumulate textures (i.e. there is no modal layering or alignment of phenocrysts).

2. Sheets and interconnections at Elizabeth Castle cross-cut distinct modal layering in the diorite. If the diorite bodies represent individual intrusions, it seems unlikely that modal layering could have been produced in the short time before interconnections were formed.

3. Next to the Hermitage, a granophyre sheet can be seen cross-cutting a pale-grey hybrid-filled apophyse which originates from the sheet below.

4. A sub-vertical, granophyre-filled dyke post-dates other granophyre sheets, providing further evidence of granophyre intruding diorite.

5. Disruption of the sheeted complex may have been the result of further intrusion of granophyre magma, reinforcing the idea of granite magma invading basic magma.

Both the physical and chemical interactions in the Elizabeth Castle complex are currently under investigation and the results will be published in due course.

CONCLUSIONS

The rocks of the Elizabeth Castle complex predominantly comprise granophyre and diorite. They display a variety of contact relationships, all of which have been interpreted elsewhere as resulting from magma-mingling. These are:

i) Extensive veining of diorite by granophyre;

ii) Contacts between the diorite and granophyre are sharp and undulose or crenulate;

iii) The diorites have fine-grained margins, which are interpreted as chilled margins;

iv) Dioritic enclaves within the granophyre are usually rounded or irregular in shape, with chilled margins;

v) Straight-sided veins cross-cut chilled margins, yet are filled with the surrounding granophyre, i.e. that which produced the chilled margins.

These relationships are interpreted in terms of the following sequence of events:

i) The formation of a layered intrusion of diorite in which four main types of diorite may be identified;

ii) Intrusion into the layered diorite magma of interconnected sheets of granitic magma which crystallized to form the granophyre;

iii) In places, residual fluids from the granophyre infiltrated from the tops of apohyses into the diorite magma, producing the pale-grey hybrid diorite;

iv) Diffusional exchange between the granophyre and diorite produced the marginal hybrid facies;

v) The sheeted complex was disrupted, either by further intrusions

intrusions of granophyre or remobilisation of the original granophyre, resulting in dispersal of the diorites as enclaves within the granophyre.

vi) When all were solid, a series of Red Granite dykes was emplaced, followed by dykes of the Jersey Main Dyke Swarm.

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