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Amphiboles from the igneous complex at Sorel Point, Jersey, C.I. - Reflectors of acid-basic magma interaction

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The igneous complex at Sorel Point, Jersey, Channel Islands comprises plutonic rocks encompassing a broad compositional spectrum from olivine-gabbro to aplogranite. Field relationships suggest that certain of the diorites were produced by interaction between co-existing gabbroic and granitic (s.1.) magmas. The interaction is reflected in textural and chemical features of amphiboles, which are the predominant mafic minerals. Amphibole textures range from coarse-grained, strongly-zoned, sub-ophitic crystals with clinopyroxene cores to fine-grained, subhedral homogeneous crystals. Chemical composition of amphiboles throughout the basic and intermediate rocks range from kaersutite to actinolite. Within individual zoned crystals the compositional range from core to rim may be equally broad. The chemical features of amphiboles may allow monitoring of fluctuating chemical, and possible physical, conditions within interacting magmas.

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Introduction

Amphiboles occur in a wide variety of igneous and metamorphic rocks and cover a large compositional range (Deer *et al.* 1966). Because of the variety of cation substitutions possible, amphiboles have been referred to as "chemical waste baskets" or "sponges". Amphibole compositions can be controlled by several physical or chemical conditions such as P, T, fO_2 and fH_2O as well as bulk (liquid) composition (Robinson *et al.* 1982; Gilbert *et al.* 1982). This sensitivity to prevailing conditions means that amphiboles are valuable petrological tools. Unfortunately, the number of substitutions possible, and the variety of controlling factors, means that the number of variables is almost always greater than one. This makes the task of deciphering the encrypted clues a difficult one.

Locality and geological setting

Jersey and the other Channel Islands form part of the North Armorican Massif, the rocks of which record subduction-related magmatism and tectonism associated with the Cadomian orogeny (Bishop and Bisson 1989; D'Lemos *et al.* 1990; Brown *et al.* 1990). Sorel Point (Fig. 1) is situated on the north coast of the island close to the eastern edge of the North Western Granite Complex (NWGC). This is an annular body comprising an inner biotite microgranite, a porphyritic granodiorite and an outer coarse granite (Bland 1985). Exposed on the eastern flank of the NWGC is a body of pink aplogranite which is associated with basic and intermediate rocks in the area around Sorel Point. The rocks of Sorel Point form part of a Cadomian plutonic complex and range in composition from olivine gabbro through diorite, granodiorite and granite to aplogranite (Wells and Wooldridge 1931; Bishop 1963; Bland 1985; Salmon 1987). Field relationships indicate that several groups of intimately associated rock types were present as co-existing magmas (Salmon 1987). These contemporaneous groups are separated by a series of sharply defined temporal boundaries at which field evidence indicates contacts between solid rock and magma.

Rocks from two distinct groups will be described and referred to as the North Eastern Group (NEG) and the Western Group (WG) (Fig. 1). In the NEG the body of aplogranite underlies dioritic and gabbroic rocks along a contact which is essentially planar and dips south at approximately 45°. A body of granodiorite forms a screen up to 3m wide between the aplogranite and the diorite (Fig. 2). Direct contacts between aplogranite and diorite are rare. Against the felsic rocks the diorite has fine grained margins which are interpreted as chilled. Small flame-like structures of granodiorite pierce the fine grained diorite. The fine grained margins pass after a few centimetres into medium grained diorite which after approximately 400mm passes gradationally into transitional diorite. After several metres this transitional facies then passes gradationally into hornblende gabbro above which are layered hornblende gabbros which dip south at 45°. It is almost impossible to pinpoint exactly the point of transition between these various facies. Contacts between the aplogranite and granodiorite are gradational over one or two millimetres. Aplogranite enclaves within granodiorite are generally sub-rounded. The field relationships indicate that the aplogranite, granodiorite and diorite were all present contemporaneously as magmas.

Layered gabbros occupy part of the NW coast of the headland and are truncated at their southern end by a small body of granodiorite which is part of the WG (Figs 1 and 3). Sharp, angular contacts indicate that the layered gabbros were in a solid state when the granodiorite magma was emplaced. To the south the granodiorite is in contact with diorite which has fine grained margins and

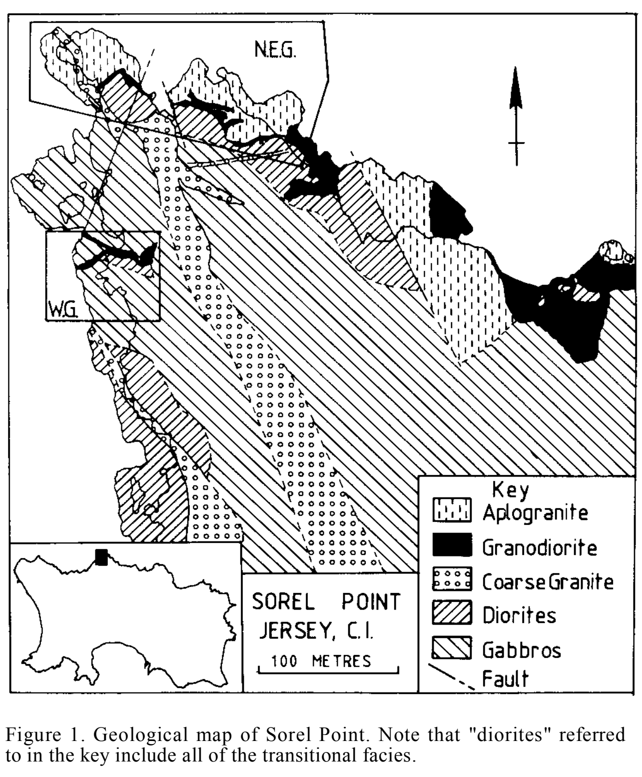

Figure 1. Geological map of Sorel Point. Note that "diorites" referred to in the key include all of the transitional facies.

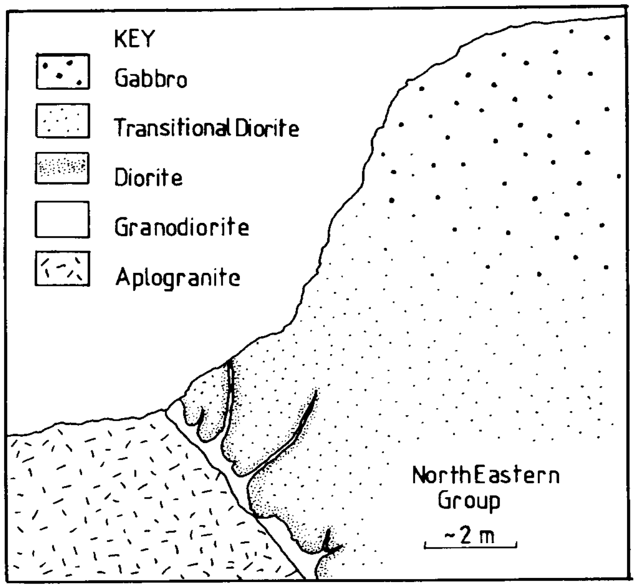

Figure 2. Schematic section showing relationships within the NEG. (scale is approximate).

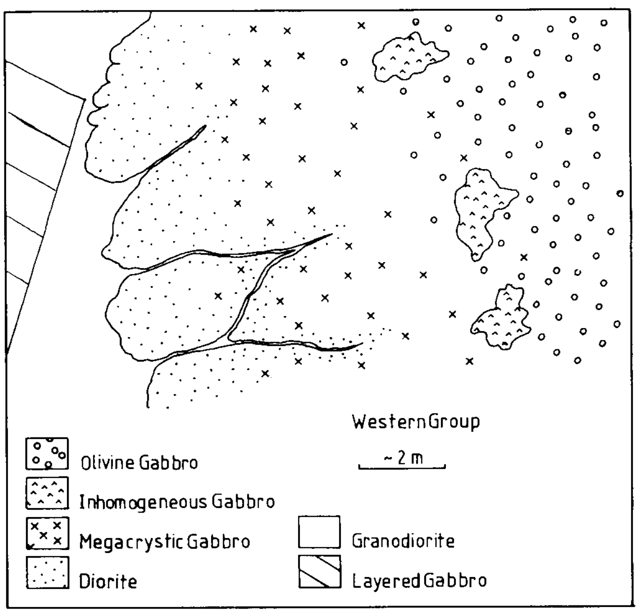

Figure 3. Schematic section showing relationships within the WG. (scale is approximate).

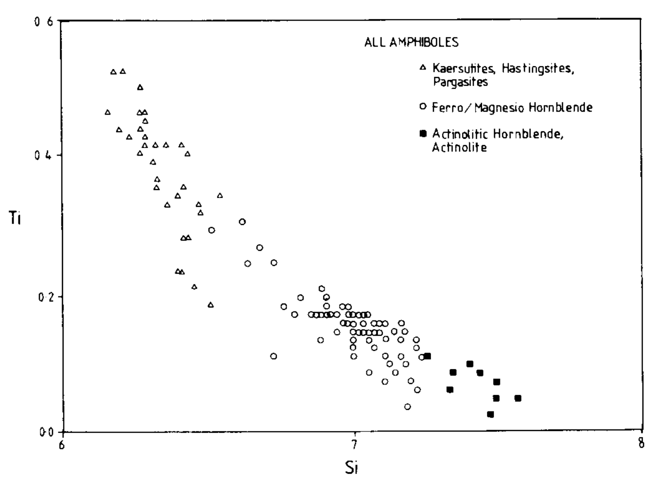

Figure 4. Ti *v*. Si for all amphiboles of the complex.

contact relationships which indicate a magma-magma relationship. Narrow veins of granodiorite extend, often for several metres, into the mafic rocks to the south. The diorites become medium grained over a distance of a few centimetres and then pass gradationally over two or three metres into megacrystic gabbro containing poikilitic amphibole crystals up to 5mm across. The megacrystic gabbro passes gradationally over several metres into olivine gabbro which occupies a large part of the western side of the headland. Occurring discontinuously between the megacrystic and olivine gabbros are inhomogeneous gabbros which contain irregular patches of coarse grained material. In the remainder of this paper the megacrystic and inhomogeneous gabbros, together with the transitional diorite of NEG will, when writing in general terms, be referred to collectively as "transitional rocks".

Petrography of the mafic rocks

North Eastern Group (NEG)

The fine grained margins of the diorite contain subhedral unzoned green amphibole in an intergranular texture with lath shaped oligoclase (occasionally with andesine cores). Some plagioclase crystals have acicular and/or skeletal textures indicative of rapid undercooling. Within a few centimetres of the granodiorite contact the grain size gradually increases, although texture and mineralogy remain broadly the same.

In the transitional diorite plagioclase cores are andesine, occasionally labradorite. Amphiboles are often subhedral, though mostly interstitial to plagioclase, and are zoned from red-brown cores to brown and green outer zones. The good crystal shape of successive zones indicates that they grew from a liquid. Fringes of blue-green amphibole are often present, though these are not so regular in outline.

The transitional diorite passes gradationally into hornblende gabbro in which plagioclase cores are labradorite, with outer zones of oligoclase. Amphiboles display the same style and colour of zonation as in the transitional diorite but are typically sub-ophitic and commonly have cores of clinopyroxene. The pyroxeneamphibole interface is irregular in outline, often consertal, in contrast to the straight-edged outlines of amphibole zones.

Throughout the transitional diorite and hornblende gabbro, sericitisation of plagioclase, chloritisation of biotite and amphibole and the presence of minerals such as sphene, epidote and actinolite are evidence of deuteric hydrothermal alteration.

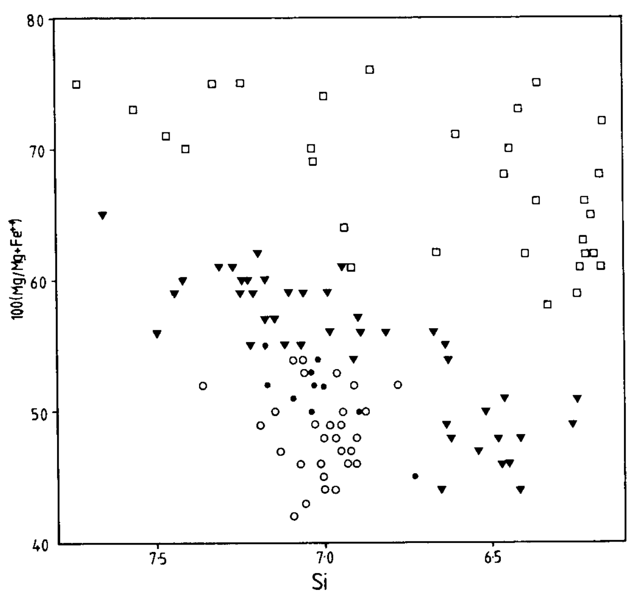

Figure 5. Mg/Mg+Fe^{2} *v*. Si for amphiboles of the NEG. Key: ● Diorite, fine grained margins; ○ Diorite, medium grained; ▼ Transitional Diorite; □ Gabbro

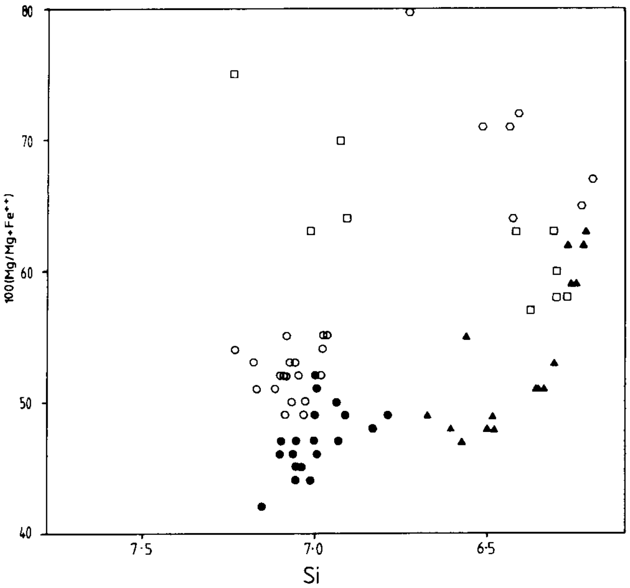

Figure 6. $Mg/Mg+Fe^2$ *v*. Si for amphiboles of the WG. Key: ● Diorite, fine grained margins; ○ Diorite, medium grained; ▲ Megacrystic Gabbro; □ Inhomogeneous Gabbro; o Olivine Gabbro.

Western Group (WG)

The fine grained diorite contains green unzoned amphibole in an intergranular texture with lath-shaped oligoclase. The medium grained diorite is broadly similar in both texture and mineralogy. With increasing distance from the granodiorite contact, irregularly shaped brown cores begin to occur in the amphiboles.

The distinctive amphibole megacrysts within the megacrystic gabbro are red-brown in colour, poikilitic and enclose laths of labradorite which are smaller than those in the surrounding groundmass. Narrow rims of zoned brown and green amphibole are similar in colour to zoned amphiboles in the groundmass. Clinopyroxene cores are uncommon.

The inhomogeneous gabbro comprises anhedral or subhedral zoned amphiboles in an intergranular texture with tabular or lath-shaped labradorite. In the coarse patches the mineralogy is the same but amphiboles are commonly subhedral to euhedral and occasionally elongate or acicular in habit. Clinopyroxene cores are fairly common in amphiboles.

The olivine gabbro is made up of tabular lath-shaped labradorite exhibiting a subophitic texture with clinopyroxene and amphibole. The pyroxenes are salite/augite. Sub-rounded olivine grains are present throughout the rock. Clinopyroxene makes up a higher proportion of the rock than in the other gabbroic facies, with amphibole typically being confined to intercumulus mantles. The amphiboles are zoned from red-brown cores to brown and green outer zones. The zones within amphiboles are straight, often with a well developed crystal shape, in contrast to the clinopyroxene-amphibole interface with is irregular or consertal. Plagioclase crystals which are wholly or partially enclosed are always within the amphibole portion of the crystal, suggesting that clinopyroxene may have been an early cumulus phase along with olivine and plagioclase.

Whole rock chemistry

Field and petrographic evidence suggests that the diorite and the "transitional rocks" were produced from initially homogeneous gabbroic magmas by interactions with incoming granitic magmas. In order to investigate this possibility samples were collected at various distances from granodiorite contacts. The compositions of rock types from each area were divided by their respective average gabbro composition. The results were plotted on graphs (not figured) in which the horizontal scale is distance from the granodiorite contact and the vertical scale indicates relative enrichment (> 1.0) or depletion (< 1.0). The chemical trends on these diagrams are summarised below.

North Eastern Group

SiO_2, Na_2O and K_2O all have values >1.0 and increase towards the granodiorite contact, YO having the largest proportional increase. Al_2O_3, MgO and CaO all have values <1.0 and decrease towards the granodiorite contact. TiO_2, FeO(T) and MnO (all mostly > 1.0) and P_2O_5 (mostly <1.0) show little variation towards the granodiorite contact.

Western Group

Chemical trends are very similar to those of the NEG with the following exceptions; P_2O_5 are all >1.0 and increase towards the granodiorite contact; TiO_2, FeO(T) and MnO all have highest values in the megacrystic and inhomogeneous gabbros.

Amphibole chemistry

Amphiboles throughout the mafic rocks as a whole display a wide range of compositions, as exemplified on the Ti *v*. Si diagram (Fig. 4). The amphiboles range from Ti-rich hastingsite and pargasite, occasionally kaersutite, through magnesio-and-ferro-hornblende to actinolitic hornblende and actinolite (Leake 1978; Rock and Leake 1984). The unzoned amphiboles within diorites account for a large proportion of the hornblende group. Individual zoned amphiboles in transitional and gabbroic rocks may encompass the full range of compositions from Ti-rich/Si-poor cores to Ti-poor/ Si-rich rims.

$100(Mg/Mg+Fe^2)$ *v*. Si for the amphiboles from NEG and WG are plotted in Figs 5 and 6. In both cases the amphiboles from diorites exhibit a restricted compositional range whilst those from gabbros exhibit a larger range representing core to rim zonation. This zonation has been produced by in-situ fractionation, the shape of the zones, as described above, indicating growth from a liquid. Amphiboles from transitional diorite, and from the megacrystic and inhomogeneous gabbros, plot between these two. The analyses from the megacrystic gabbro of WG fall into two distinct groups. Compositions of megacryst cores are similar to the core compositions from other gabbros, while the outer zones of megacrysts are

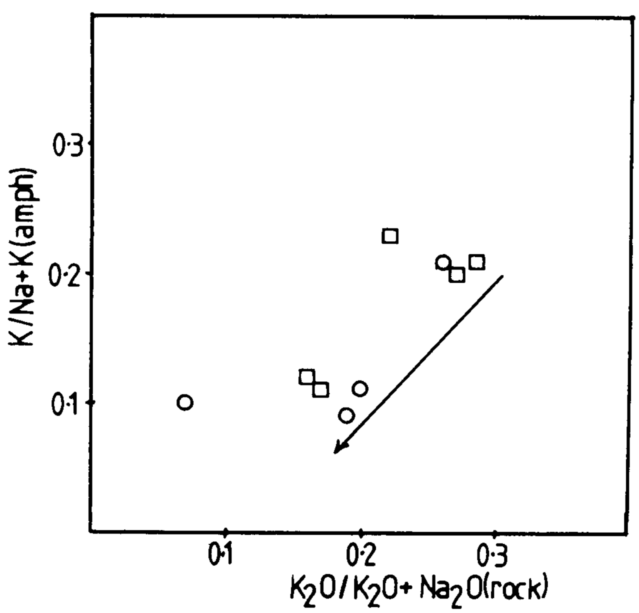

Figure 7. K_2O/K_2O+Na_2O(rock) v. K/Na+K(amph). Key: 0 NEG; 0 WG; Arrow indicates approximate direction away from granodiorite contact.

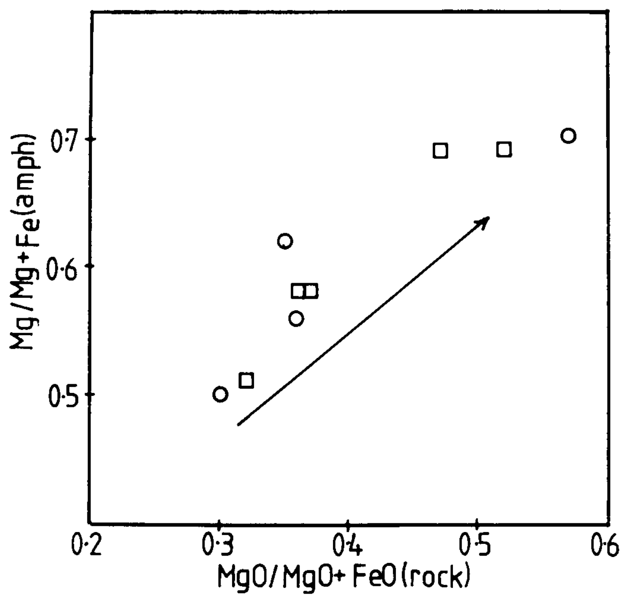

Figure 8. MgO/MgO+FeO(rock) *v*. Mg/Mg+Fe(amph). Symbols as for Fig. 7.

similar in composition to the groundmass amphiboles. The most noteworthy feature of these diagrams is that for any given Si value, the Mg/Fe ratio increases with distance away form the contact with granodiorite.

K/Na+K ratios for amphiboles from NEG and WG have an opposite relationship to that of the Mg/Fe ratio. For any given Si value the K/Na+K value decreases with distance from the contact with granodiorite.

Al^{vi} in amphiboles shows little variation in compositional range throughout all of the rocks. There are variations in Ti(amph) with increasing distance from the granodiorite, but the patterns of the changes are not as systematic as those seen in K/Na+K or Mg/Fe.

Discussion

Bulk compositions of the mafic rocks vary with distance from granodiorite. The fact that those oxides which increase towards this contact, SiO_2, Na_2O and K_2O, are those which would be expected to be present, along with H_2O, in late stage granitic fluids lends support to the hypothesis that magmatic interactions produced the dioritic and transitional compositions. These interactions took the form of magmatic and/or diffusional infiltration of material from granodiorite magma into initially homogeneous gabbroic magma. Amphibole compositions and textures also vary with distance from the granodiorite and the fact that the changes in amphibole composition coincide with those of the rocks suggest that the two are related and that the amphiboles are sensitive indicators of inter-magmatic processes.

Certain cation ratios in amphiboles are primarily controlled by bulk liquid composition, K/Na+K being one of them (Gilbert *et al. 1982).* This is borne out by the fact that K/Na+K increases towards the granodiorite, reflecting the greater mobility of K and the relative variation in K_2O and Na_2O in the bulk rocks (Fig. *7).*

Other substitutions in amphiboles are controlled by physical conditions such as temperature, pressure and oxygen fugacity, as well as liquid composition. The Mg/Fe ratio tends to increase with increasing temperature and fO_2 , but is little affected by changes in pressure (Gilbert *et al. 19825.* The variation in Mg/Fe(amph) reflects the relative changes in MgO(rock) and FeO(rock) towards the granodiorite contact, MgO decreasing and FeO remaining fairly constant, and is thus directly proportional to the MgO/FeO ratio of the magma (Fig. *8).*

Alvi in amphiboles is largely controlled by changes in pressure (Hammarstrom and Zen *1986)* with temperature having only a small effect. The dependence primarily on pressure may explain why there is little change in AI"' throughout the amphiboles. Other contributory factors are the low mobility of Al in silicate melts, and the fact that a large proportion of Al will be taken up in early formed plagioclase. Ti substitution into amphiboles is controlled by temperature as well as liquid composition (Helz *1973;* Otten *1984).* However, the variations in Ti(amph) with distance from granodiorite are generally inconclusive.

Some of the substitutions in amphiboles, which vary in a systematic way with distance from the granodiorite, can be controlled to some extent by temperature. The dependence on T (and fO_2), at constant bulk composition, suggests a possible explanation for the increase in Mg/Fe away from the granodiorite. If the intrusion of granodiorite set up a temperature gradient within the gabbroic magma, with T increasing away from the contact, the amphibole composition may be expected to vary accordingly. A "bulk zonation" in Mg/Fe ratio would thus be set up in the amphiboles. The problem with this hypothesis lies in the relatively short period of time over which it is thought such temperature gradients can survive.

Infiltration of granitic fluids probably took place in two ways. Diffusional infiltration is controlled by chemical gradients and is enhanced by the presence of liquid and high temperature. Even so diffusion rates are very slow and this process could only affect limited volumes of magma. Magmatic infiltration, in which fluid is physically introduced, has the capacity to affect much larger volumes and produce compositional gradients which would be relatively long lived. Such long lived compositional gradients will have a greater opportunity to affect amphibole composition. The presence of infiltrated fluids may prolong any induced temperature gradients.

Conclusions

The rocks exposed at Sorel Point demonstrate that interactions between gabbroic and granitic (s.1.) magmas have brought about changes in chemical composition within initially homogeneous gabbroic magmas. Compositional gradients thus created in the gabbroic magmas are reflected in amphibole compositions. This is exemplified by the increase in K/Na+K(amph), and the decrease in Mg/Fe(amph), towards the granodiorite contact.

It is possible that the imposition of a temperature gradient in the gabbroic magmas, produced by intrusion of granitic magmas and sustained by magmatic infiltration, may have contributed towards the variations in amphibole composition, especially that in Mg/Fe. However, the evidence in support of such a process is inconclusive.

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