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A three-component composite dyke and its associated intrusion, Pointe du Criard, Québec, Canada

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ABSTRACT: A three-metre-wide composite dyke made up of approximately equal quantities of diabase (at the rim), leucogabbro, and syenite, feeds a sill at least 50 m thick that is 98 % syenite. The intrusion was initiated by a diabase dyke and this conduit was then exploited by a leucogabbro, and finally a syenite. All components were probably derived from different magma chambers. Initiation of intrusions by dykes of low-viscosity magma, such as diabase, may be important elsewhere, especially for the case of acidic magmas which may otherwise be restrained by their viscosity.

1 INTRODUCTION

Evidence of mixing (homogeneous product) and mingling (heterogeneous product) of magmas is widespread in many intrusive and extrusive rocks (Blake et al. 1965; Walker & Skelhorn 1966; Yoder 1973). One example is the occurrence of composite dykes, which are particularly well-exposed in the Sept Iles layered mafic intrusion, Quebec (Higgins & Doig 1981). Most of these dykes are small and can be traced in the field into separate mafic and acidic dykes. However, there is one major composite sill, the Pointe du Criard intrusion, that is at least 50 metres thick and may be as much as 10 by 15 km in extent. It cross-cuts the main phase of the intrusion, but is unlikely to post-date it significantly. This paper is a description of the Pointe du Criard intrusion and a discussion of the possible link between its composite structure and emplacement mechanism.

2 THE SEPT ILES INTRUSION

The Sept Iles intrusion is situated on the north shore of the Gulf of St. Lawrence, about 800 km north-east of Montreal, Canada (Figure 1). It is a large, layered mafic intrusion, intruded post-tectonically into the Grenville province of the Canadian shield about 540 Ma ago (Higgins & Doig 1981, 1986). It was probably formed in response to rifting related to the opening of the Iapetus ocean. The intrusion is about 80 km in diameter with a maximum thickness of about 8 km (Feininger 1986). Most of the intrusion is concealed beneath the waters of the Gulf of St. Lawrence, but the uppermost part of the intrusion outcrops on the islands of the Sept Iles archipelago and the Pointe Noire peninsula. A deeper level is exposed on the mainland around the Baie des Sept Iles.

Geophysical evidence suggests that at least three kilometres of ultramafic rocks are present below the present level of exposure (Feininger 1986). The lowest unit currently exposed is the layered series which comprises layered gabbros, pyroxenites and Fe-Ti oxide rocks and is about 3 km thick. These rocks pass gradationally into a transitional series of anorthosites and leucogabbros one to two kilometres thick. These rocks are in turn overlain by the upper series of monzonites, syenites and granites. The roof of the intrusion is not exposed, and it is possible that it was capped by contemporaneous volcanic rocks (T. Feininger pers. comm.). The Pointe du Criard intrusion described here post-dates the transitional and upper series of the Sept Iles intrusion and appears to be contemporaneous with a late phase of gabbroic magmatism. All the intrusive rocks of the Sept Iles intrusion, including those of the Pointe du Criard intrusion, are now thought to have formed during a single magmatic episode.

3 THE POINTE DU CRIARD INTRUSION

The Pointe du Criard intrusion comprises both a keel dyke and a sill. The dyke section of the intrusion is exposed only at Pointe du Criard on the eastern tip of Ile du Corossol (Figures 1 & 2). It is about 3 metres wide and was intruded into rocks of the transitional and upper series of the Sept Iles intrusion.

The edges of the dyke are made up of diabase (Figure 3), which is chilled against the host rock.

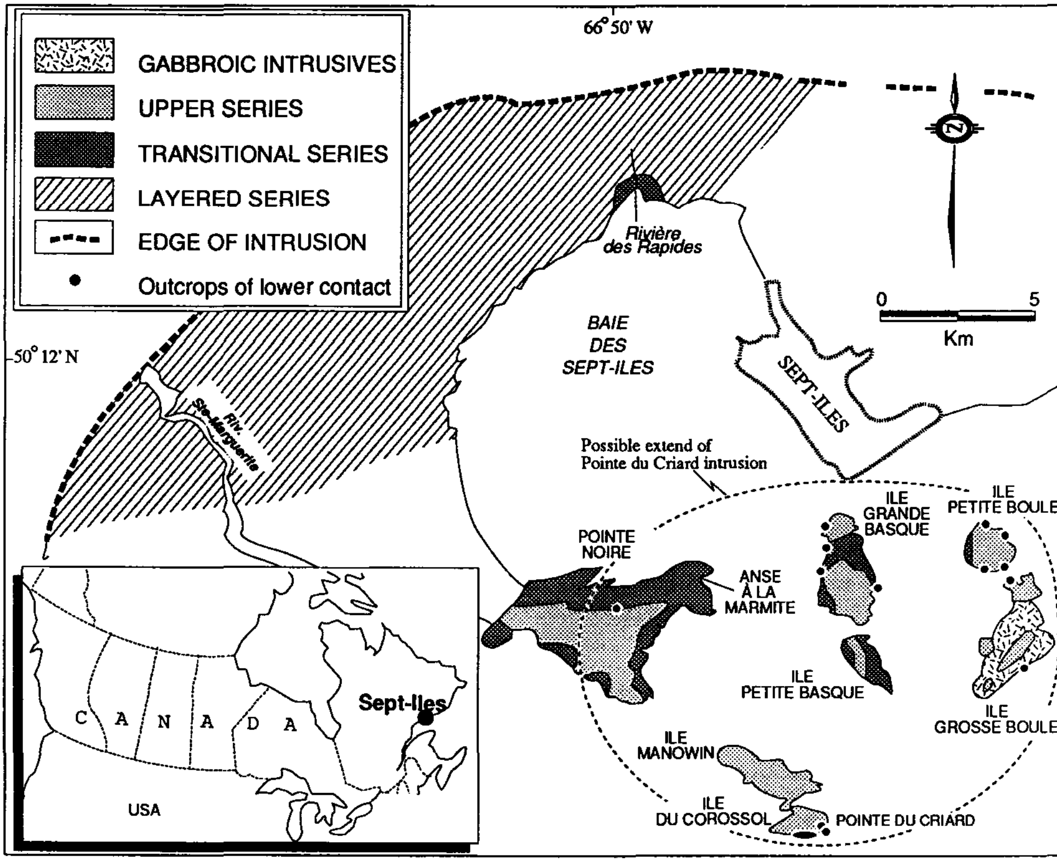

Fig.1: Geological map of the Sept Iles intrusion, Quebec, Canada. The Pointe du Criard intrusion outcrops on the eastern tip of Ile du Corossol. Small circles indicate the location of other outcrops. The late gabbroic intrusives so common on Ile Grosse Boule are widespread elsewhere as diabase sills and dykes. They probably represent the same magmatic phase as the Pointe du Criard intrusion.

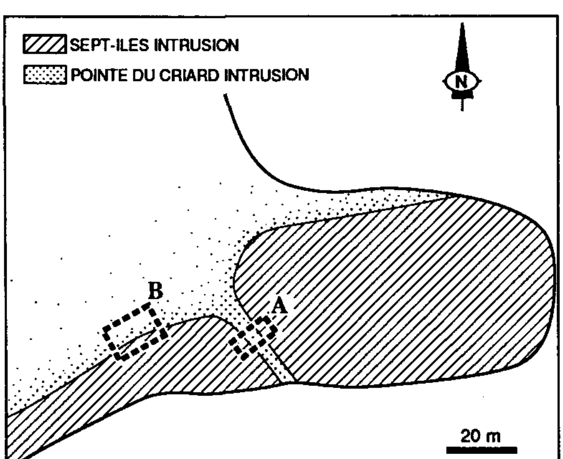

Fig.2: Sketch map of Pointe du Criard on Ile du Corossol. The Pointe du Criard intrusion is hosted by monzonite and anorthosite to the east, and syenite to the west. Area A is shown in more detail in Figure 3 and area B is shown in Figure 4.

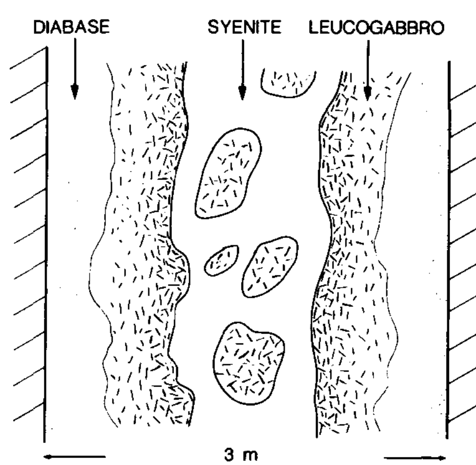

Fig.3: Schematic, generalised field relationships in the dyke, Pointe du Criard intrusion.

Plagioclase laths (mode = 50%, An_{45}-An_{50}) are typically about 0.3 mm long. Opaque minerals (10%) crystallised next and were followed by augite (30%). Minor late biotite is associated with the pyroxene and opaque minerals. Passing inwards in the dyke, the grain size of the plagioclase increases to about 1 mm, and plagioclase megacrysts (to 10 mm) become more common. These megacrysts (An_{55}-An_{60}) are rounded and commonly broken and have a zoned rim that follows their present outline. These features suggest that they are xenocrysts, probably derived from the leucogabbro. Weathered surfaces are mottled, which suggests that the diabase is slightly heterogeneous.

The transition from the diabase to the leucogabbro is gradual over 2 - 5 cm. The leucogabbro comprises up to 80 % plagioclase crystals (An_{55}-An_{60}), up to 1 cm long and is again slightly heterogeneous. Other minerals include augite and opaques. These field relationships indicate that the diabase and leucogabbro were two separate magmas that mingled together.

The leucogabbro passes transitionally into the syenite over a sinuous zone about 1-2 cm wide, with no evidence of chilling of either magma. This form of contact suggests that both magmas were liquid at the same time and at approximately the same temperature. If this was so then the syenite must have been superheated.

The syenite is homogeneous and comprises 75% equigranular perthitic feldspars crystals up to 1 cm long, that comprise approximately equal quantities of sodic and calcic phases. These crystals are overgrown by micrographic intergrowths of quartz and orthoclase (15%). Interstitial phases include amphibole (5%) which ranges in composition from hornblende to riebeckite, opaque minerals (5%) and zircon. This rock is on the border between syenite and quartz-syenite.

The syenite contains rounded enclaves of leucogabbro up to 30 cm long, most of which are similar in composition to the leucogabbro described above. However, some of these enclaves contain megacrysts of perthitic feldspar similar to those in the syenite, and these were probably formed by the mixing of the leucogabbro and syenite magmas.

The dyke described above can be traced at Pointe du Criard into an associated sill at least 50 metres thick (Figures 2 & 4). The sill is partly hosted by a syenite that is very similar in the field to the syenite of the sill, hence the basal contact zone appears at first glance to be a highly asymmetrical mafic sill with a zone of enclaves on the upper side.

The basal contact of the sill is extremely complex. It generally commences with diabase that is chilled against the country rock, as in the dyke. However, at some points this has been eroded away by the leucogabbro which is chilled against the host rock. At one point there is a thin layer of fine-grained syenite between the diabase and the country rock, but it is possibly a later intrusion. Leucogabbro overlies the diabase and locally has an upper zone of plagioclase crystals aligned parallel to the contact with the syenite. This contact is sinuous and transitional over a few centimetres. All these rock types are mineralogically similar to those in the dyke.

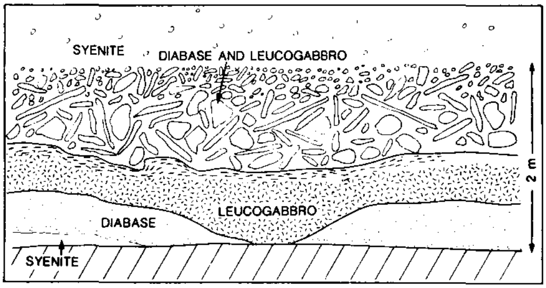

Fig.4: Schematic, generalised of the field relationships at the base of the sill, Pointe du Criard intrusion. The host Sept Iles intrusion is shown at the base.

The lower 1 - 2 metres of the syenite contains about 40 to 50% mafic enclaves. Although rounded enclaves of leucogabbro similar to those seen in the dyke are present, the dominant type of enclave, diabase, is one not present as enclaves in the dyke. The diabase enclaves are commonly elongated with typical thicknesses of 10 - 20 cm and lengths up to 2 metres. Such shapes may form by mixing of syenitic and mafic magmas in a conduit, and subsequent magmatic deformation of the mixture during flow. The leucogabbro enclaves may have been too viscous, or too rapidly chilled for this process to have occurred.

The contacts of the diabase enclaves with their host are commonly sinuous on a scale of a few centimetres (Figure 5). The enclaves are normally size-sorted (smallest at the top). Above the zone of enclaves the syenite is homogeneous, except for occasional mafic enclaves up to 10 cm long. Although the upper contact of the sill is not exposed at Pointe du Criard it must be at least 50 metres thick.

The core of the diabase enclaves is very fine-grained with plagioclase (An_{25}) laths to 0.1 mm (mode = 50%). Biotite and green amphibole are abundant, together with minor quantities of opaque minerals. Between this core and the host syenite there may be a more leucocratic zone with sharp edges, typically from zero to 20 mm thick. This zone is mostly comprised of orthoclase (50%, 0.1 mm), green amphibole (40%) and opaque minerals. Sphene (1%) is occasionally rimmed by rutile. Perthitic feldspar xenocrysts up to 10 mm long are also abundant, and were derived from the host syenite. Some enclaves are comprised entirely of this mixed-magma material. They tend to be more

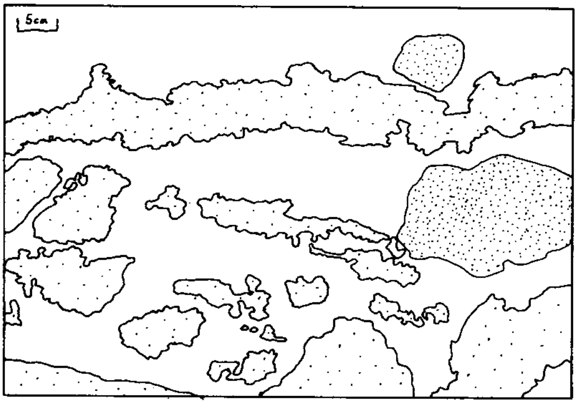

Fig.5: Tracing of a photograph of enclaves in a matrix of syenite at the base of the sill. Diabase enclaves are indicated by the less dense pattern. Enclaves of leucogabbro and mixed magmas are shown in the denser pattern. The top of the sill is towards the top of the photograph.

rounded than than the less contaminated enclaves.

Contact zones very similar to that at Pointe du Criard have been observed elsewhere on the islands and the Pointe Noire peninsula (Figure 1). These zones are generally approximately horizontal and occur at about the same structural and topographic level. The width of the components of these contacts vary greatly: At some locations the diabase may be up to 10 metres thick and the leucogabbro 50 metres thick. Similarly, the basal zone rich in enclaves may also be up to 10 metres thick. On Ile Petite Boule both the diabase and zone rich in enclaves are absent, and only the leucogabbro separates the two syenites. On the northern part of Ile Grande Basque the contact sequence is repeated twice, and the main part of the sill comprises an intermingling of monzonite and syenite magmas. Elsewhere in the intrusion monzonite and syenite are closely related, possibly by differentiation (Higgins & Doig 1980).

The roof of the intrusion was identified tentatively at only one location. It was very similar to the lower contact except that it lacked the zone rich in enclaves. If all these fragments represent the same intrusion then it must have extended over an area of at least 10 by 15 km and have had a volume of at least 8 km^3.

A keel dyke such as that seen at Pointe du Criard may represent either a feeder for the sill or a spur developed downwards from the sill. If the latter were true then exactly the same enclave population would be expected in the dyke and the sill. Since this is not so, the dyke must represent a feeder to the system. The current width of the dyke, three metres, may not have been its width when active, and the dyke may be wider near to the principal conduit. A modern analogue may be the Inyo volcanic chain, California, where the feeder dyke is at least five times wider beneath the lava domes than between the domes (Eichelberger et al. 1985).

The role of feldspar accumulation or fractionation in the various components of the intrusion was determined by the analysis of the rare-earth elements (Figure 6). The diabase and leucogabbro components do not have significant Eu anomalies (except for one sample which probably contains a component of syenitic magma) indicating that little feldspar has been fractionated from these magmas. Other diabase dykes in the Sept Iles intrusion also lack significant Eu anomalies, reinforcing the similarity between these dykes and the diabase of the Pointe du Criard intrusion seen in the field. The two syenite samples have strong negative Eu anomalies that indicate significant feldspar fractionation.

4 ORIGIN OF COMPOSITE INTRUSIONS

Composite intrusions are widespread and many theories have been advanced for their origins. These include liquid immiscibility and sequential partial melting (see review by Yoder 1973) but recently models based on discontinuously stratified magma chambers have become very popular (e. g. Blake & Campbell 1986). It will be discussed here if these models can be applied to the Pointe du Criard intrusion or if a model based on the interaction of separate magma chambers is more suitable (e. g. Higgins 1988).

Blake & Campbell (1986) have attempted to model the behavior of magmas extracted from a discontinuously stratified magma chamber. They have shown that the order of emplacement in the conduit above the magma chamber is not necessarily the same as the original order in the

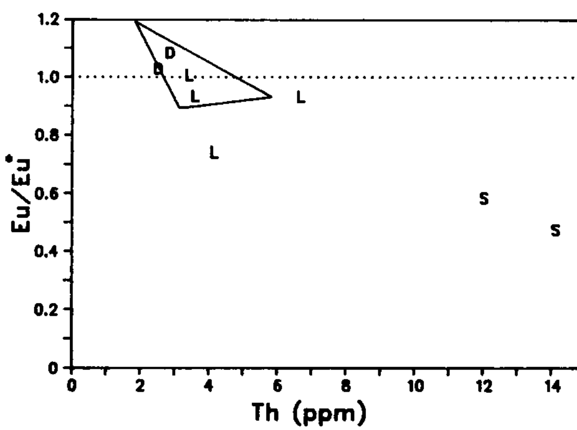

Fig.6: Europium anomaly (Eu/Eu*) vs Th for various components of the Pointe du Criard intrusion. D = Diabase, L = Leucogabbro, S = Syenite. The triangle denotes the range in composition of late diabase dykes in the Sept Iles intrusion.

magma chamber: low viscosity liquids tend to overtake high viscosity liquids and line the upper parts of the conduit. However, these experiments were based on newtonian liquids and it is not clear if it applies to non-newtonian liquids such as most magmas.

If the single, stratified chamber model is applied to the Pointe du Criard intrusion then this magma chamber must have had plagioclase cumulates at the floor (which became the leucogabbro), a centre of aphyric gabbro (the diabase) and an upper zone of syenite. Extraction of magmas from the roof into a conduit would have first tapped the syenite. When the non-crystallised magma at the centre of the chamber was drawn up then it would have overtaken the syenite and lined the conduit. Finally the plagioclase crystal mush at the base of the intrusion would have been drawn up and overtaken the syenite. Finally the syenite would have followed the other magmas and filled out the intrusion. Other, more complicated schemes can also be envisaged.

Crystal fractionation does produce plagioclase cumulates at the base of magma chambers and it has been proposed that fractionated, acidic liquids may flow up the walls of the chamber in a counter-current to accumulate beneath the roof (McBirney 1984). Finally the core of the magma chamber could remain free of crystals.

There are several deficiencies in this model:

1) the diabase does not have a significant Eu anomaly, as would be expected for a magma that has differentiated sufficiently to produce syenite. In fact the diabase chemically and petrologically resembles the abundant late gabbroic dykes and sills of the intrusion (Figures 1 & 5).

2) The leucogabbro is not a plagioclase cumulate, but a gabbro that has had time to develop large crystals. The more calcic compositions of the plagioclase crystals in the leucogabbro rule out an origin for this rock by differentiation of the diabase.

3) The presence of monzonite in the part of the sill exposed on Ile Grande Basque implies the existence of another magma. Even if this magma is closely related to the syenite, then it would necessitiate further complexity in the magma chamber.

The Pointe du Criard intrusion may also be modelled using separate magma chambers for each component: In this case the initial magma was a diabase, which opened up a conduit from a lower magma chamber to the upper part of the intrusion, where it initiated both the dyke and sill parts of the intrusion. Transfer of magma changed the stress field around the dyke and sill and opened up new fissures. These fissures then intersected a magma chamber containing the leucogabbro, which was drawn into the dyke by the pressure gradient. This step further changed the stress field around the dyke, and may have produced more fissures. Finally the fissures radiating from the dyke intersected chambers containing the syenite and monzonite magmas. These rose up the dyke to form the bulk of the final intrusion. Mingling of both the diabase and leucogabbro magmas produced the enclaves in the syenite.

This model has several advantages over the single chamber model:

1) There is no need to postulate a complex magma chamber in which three or four different magmas were simultaneously mobile.

2) It is easier to integrate the production of this intrusion into the overall evolution of the Sept Iles intrusion. The diabase strongly resembles the diabases and gabbros of the late phase. The leucogabbro is similar to the 'anorthosites' (mostly leucogabbros) of the transitional series and the syenite and monzonite are similar to those in the upper series of the Sept Iles intrusion. These magmas may have been derived from parts of the intrusion that solidified more slowly.

3) The model accords with the field evidence for the origin of the smaller composite dykes in the Sept Iles intrusion. For both models mixing and mingling occur in the conduit itself.

If the multiple magma-chamber model is correct then the role of the diabase may be viewed as that of an agent that aids the transport of other the magmas towards the surface. This process may be important in the case of acidic magmas, which might otherwise be restrained from movement by their viscosity. In this case the low-viscosity diabase can open up much longer dykes than the more acidic rocks (Spence & Turner 1985) and the acidic rocks can flow much more readily in the open, preheated conduit. Some individual dykes in a swarm may intersect partially molten regions or magma chambers and initiate transport towards the surface. The widespread occurrence of mafic and mixed-magma enclaves in acidic rocks (Didier 1973; Vernon 1983,1984) suggests the possibility that some may be composite intrusions initiated by mafic magmas.

5 CONCLUSIONS

Several conclusion can be drawn from this intrusion:

1) The composition of a feeder dyke need have little in common with that of the intrusion that it feeds. Similarly a single, well-defined intrusion can have extremely variable composition.

2) The simplest model for the formation of this intrusion involves the participation of several magma chambers. In this model transport of magma deformed the surrounding region and established connections with adjacent magma sources that then utilised the conduit.

3) The bulk of the syenite in the sill does not

display any evidence of its composite origin, except in the presence of mafic enclaves.

4) The initial conduit was opened up by a low-viscosity magma (diabase) which was followed by progressively more viscous magmas. It is possible that this emplacement mechanism may be important for some acidic intrusions.

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