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A new interpretation of the structure of the Sept Iles Intrusive suite, Canada

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Abstract

The layered mafic intrusion at Sept Iles, Canada, is one of the largest intrusions in the world. A new interpretation of its structure is proposed, based on a review of its geology and a comparison with the Skaergaard intrusion, Greenland. Several different magmatic components are recognized; hence the name Sept Iles Intrusive suite (SIIS) is proposed. Emplacement of the suite may have been preceded by eruption of flood basalts. The first magmas of the suite rose in the crust to accumulate beneath the density filter afforded by the basalts. The largest component is the Sept Iles Mafic intrusion (SIMI). The Lower series of the SIMI is dominated by leucotroctolites and leucogabbros. Above it lie the Layered series, which is largely comprised of gabbro and troctolite. Both these units are unchanged from earlier interpretations. The anorthosites (s.l.), gabbros and monzogabbros, formerly called the Transitional series, are now considered to be the Upper Border series, developed by floatation of plagioclase. Common autoliths in the Layered series are parts of the hydrothermally altered Upper Border series from towards the interior of the intrusion, which have foundered and settled through the magma. The contamination of the magma that accompanied this event oxidised iron in the magma and led to the precipitation of magnetite around the periphery of the intrusion. The subsequent depletion of Fe^{3+} and/or increase in SiO_2, CaO and P_2O_5 may have induced apatite saturation and accumulation to form two layers rich in apatite, near the base and at top of the Layered series. Granitic magma was developed by fractional crystallisation and was emplaced along the roof of the chamber, where it acquired large quantities of xenoliths. These were probably derived from the flood basalts, their evolved members and fragments of mafic dykes chilled by the granitic magma. Accumulations of monzonite pillows in this unit testify to another magmatic event and a floor to the granitic magma chamber, indicating lateral transport of magma. Chemically distinct syenites in the upper part of the intrusion are part of the Point du Criade intrusion, a large, late composite sill. Diabase and leucogabbro components show a close link with the SIMI and all the acidic magmas may have originally formed by differentiation of the main magma in cupolas towards the centre of the intrusion. A series of late gabbro intrusions that cut the SIMI may represent a rejuvenation of magmatism. The Border zone is a mass of fine-grained rocks that occurs along the border of the SIMI: it may be another magmatic component, or just the lateral border series of the SIMI.

Keywords: Layered mafic intrusion; Plagioclase floatation; Fe–Ti oxides; Apatite; Anorthosite; Skaergaard

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1. Introduction

The shape and internal structure of major layered mafic intrusions are generally poorly known, not just through lack of research, but because they have commonly been deformed, dissected and partly buried deeper by later events (Cawthorn, 1996). Both the Stillwater intrusion, USA, and the Bushveld intrusion, South Africa, are such fragments of larger intrusions. It is only in the smaller intrusions that we may see all, or most, of the components: the roof, walls, floor and core. The best-known small mafic intrusion is the Skaergaard intrusion, Greenland (Wager and Brown, 1968). This young intrusion has never been deeply buried and is very well exposed in an area of considerable relief. Hence, all parts of the intrusion have been examined intensely by petrologists during the last 70 years. Although the Skaergaard and Sept Iles intrusions differ greatly in size, they share many characteristics. In this paper I use the clearly exposed structure of the Skaergaard intrusion to clarify many aspects of the structure of the Sept Iles intrusion.

The Sept Iles intrusion is recognised now as one of the largest layered mafic intrusions in the world (Higgins and Doig, 1986; Loncarevic et al., 1990), however, this was not always so. The early descriptions of the geology of the Sept Iles area emphasized the presence of the anorthosite and, indeed, the 'Sept Iles anorthosite complex' was considered to be a type example of an undeformed Proterozoic massif-type anorthosite complex (Wynne-Edwards, 1972). The intrusion was first mapped in detail by T. Ahmedali in the 1960s and although his data were never published, it showed that the intrusion was much more complex than previously thought. He distinguished a series of layered gabbros, overlain by anorthosite and finally syenite and granite (Fig. 1). He also defined a series of late gabbros, which crop out principally on the eastern islands. This broad division was confirmed by the unpublished mapping of T. Feininger (Geological Survey of Canada) in 1985–1990.

Dating of parts of the intrusion by the Rb–Sr method (Higgins and Doig, 1977, 1981) showed that the intrusion was much younger than the ~1000 million year old surrounding Grenville province, with an age of about 540 million years old. Their most precise ages were based on isochrons from the granite and syenite. The ages were also confirmed by measurements on granitic and syenitic granophyre 'pods' in the anorthosites. The age of the intrusion, and its location, connected it with the St Lawrence rift system and the opening of the Iapetus Ocean (Kumarapeli and Saull, 1966).

Interest in the intrusion and the need for greater precision prompted redating of the intrusion by the U–Pb zircon method (Higgins and van Breemen, 1998). Zircon extracted from a granophyric pod in the layered gabbros, a unit not dated previously, gave an age of 564 ± 4 Ma. The difference between the U–Pb and Rb–Sr ages is not surprising, considering the errors associated with earlier dates. On the basis of this date, and the ages of other igneous rocks and uplift, Higgins and van Breemen (1998) proposed that the Sept Iles intrusion was associated with an important mantle plume (Sept Iles Mantle Plume).

The size of the Sept Iles intrusion is clearly indicated by gravity measurements. The gravity anomaly is about 80 km in diameter and has a maximum Bouguer anomaly of 80 mGal, making it the largest in eastern North America (Loncarevic et al., 1990). Detailed measurements of the density of surface samples suggested that the intrusion must have a hidden zone to account for the gravity anomaly (Loncarevic et al., 1990). However, more detailed measurements from sub-surface samples indicated a higher density, and hence removed the necessity for a hidden zone (Dion et al., 1998).

An important magnetic anomaly overlies the body. It comprises a narrow magnetic high that lies about 1 km in from the border of the intrusion and a series of three arcuate 1 km wide anomalies that lie in the northwest part of the intrusion (Fig. 1). The latter are associated with magnetite-rich layers at the surface (Cimon, 1998).

The size of the intrusion and its composition suggested that it might host nickel and platinum group deposits. To this end, two holes 2 and 2.5 km deep were drilled into the layered gabbros on the mainland. Metallic deposits were not found, but instead two important layers rich in apatite were intersected (Cimon, 1998). As a result, Cimon (1998) remapped the mainland part of the intrusion and made a detailed study of the mineral and rock chemistry of the whole intrusion, with extra detail on the apatite deposit itself.

Kirschvink et al. (1997) have proposed that changes in the distribution of mass with the earth may have forced the axis of rotation to migrate with reference to the lithosphere, a process named inertial interchange true polar wander. This is expressed as a common polar wander curve for all the continents, and rapid movements of continents through an angle of 90°. Palaeomagnetic data from Sept Iles (Tanczyk et al., 1987) have been used to both support and reject ideas on inertial interchange true polar wander. This is because of the several ages and palaeomagnetic poles available. This prompted the remeasurement of the palaeomagnetism of the intrusion by Kirschvink (in progress). However, even this further study has confirmed that several different poles are present with an angular difference of at least 70°, raising the possibility that the Sept Iles intrusion may contain several components of different ages. Clearly, it is time to reassess data on the Sept Iles intrusion and propose a new structure.

2. Existing interpretation of the structure of the Sept Iles intrusion

There is no definitive published description of the intrusion, but the earlier work is best summarised in Cimon (1998). The following description follows the interpretation generally accepted by most workers (Figs. 1 and 2).

The *Lower series* is only seen in one of the drill holes (Figs. 1 and 2) and possibly near the edge of the

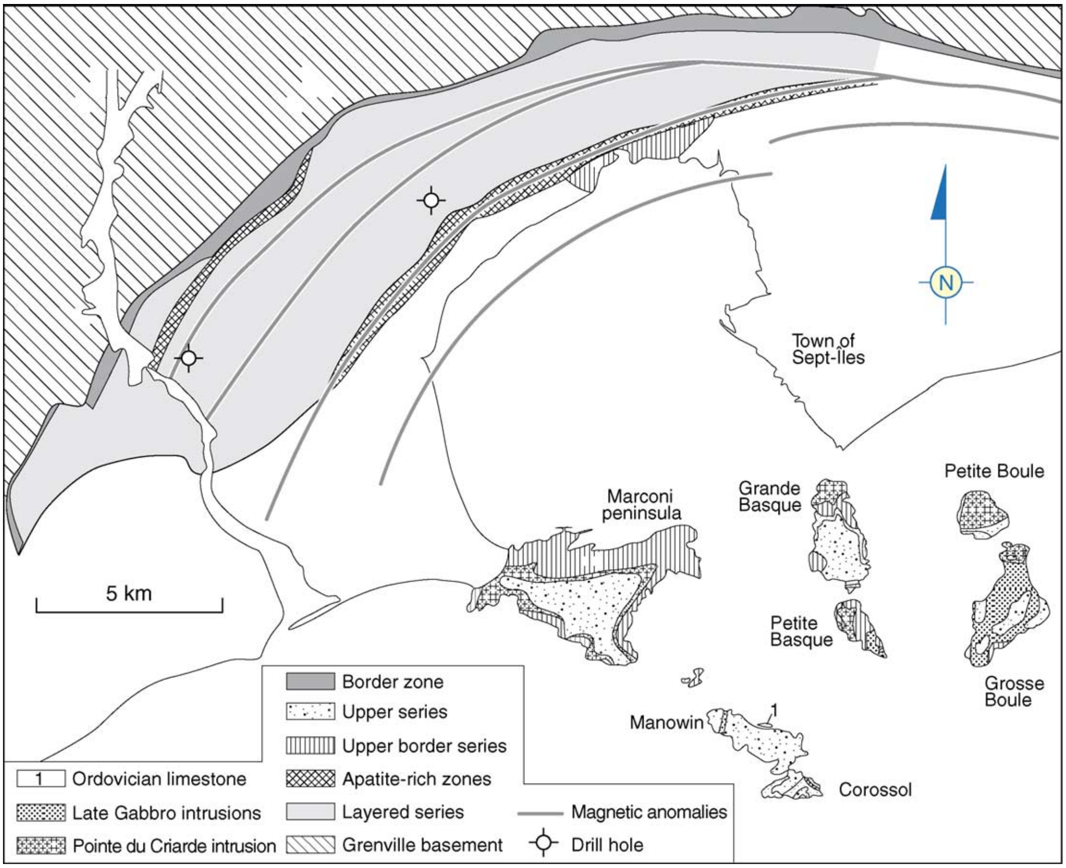

Fig. 1. Geological map of the Sept Iles region. The geology of the mainland and location of the magnetic anomalies are after Cimon (1998). The geology of the islands is from Higgins and Doig (1981) and Higgins (1990), which was based on the unpublished maps of T. Ahmedali (Department of Geology, McGill University).

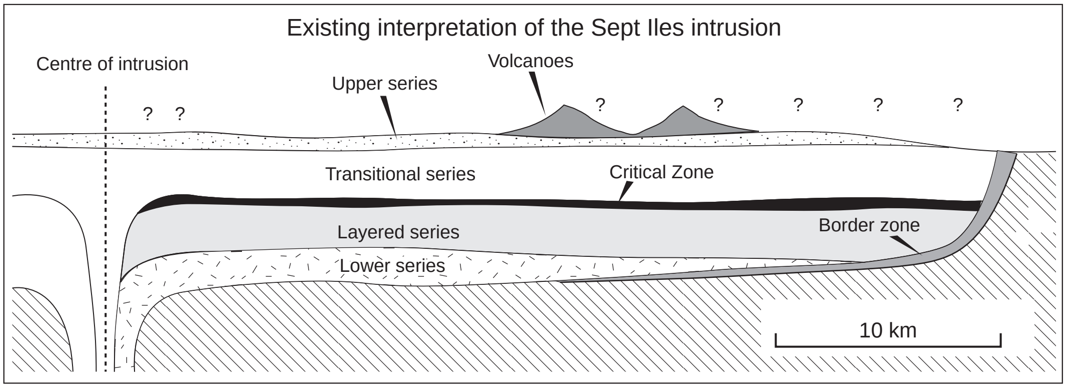

Fig. 2. Former interpretation of the structure of the Sept Iles intrusion, after Cimon (1998).

intrusion. It has a minimum thickness of 650 m and is dominated by leucotroctolite and leucogabbro. Plagioclase is the only cumulus phase, with poikilitic olivine and clinopyroxene. Olivine commonly has coronas of orthopyroxene, clinopyroxene and hornblende.

The lowest level of the intrusion that is currently well exposed, is the *Layered series*, which is 2.8 km thick. This unit is only exposed on the mainland and has been divided into five zones by Cimon (1998). It is dominated by layered gabbros and troctolite, with five metric-scale layers of magnetitite. Apatite-rich layers, each about 150 m thick, occur near the base and in uppermost part of this series. The upper layer was termed the *Critical zone* by Cimon (1998), and is dominated by nelsonite (magnetite–ilmenite–apatite rock). The rocks of this series typically dip at about 15–30° towards the centre of the intrusion (Cimon, 1998).

Certain levels of the Layered series contain up to 20 vol.% blocks of altered anorthosite and other plagioclase-rich rocks, up to 10 m long. These blocks are completely undeformed, coarse-grained and generally massive. The plagioclase is commonly white, as opposed to the black plagioclase that is seen elsewhere in the intrusion. All minerals have been partly altered to low-temperature hydrothermal minerals, such as epidote, chlorite, biotite, hornblende, sericite and carbonate.

These rocks pass upward abruptly into the *Transitional series* (later I will rename this series the Upper Border series; Fig. 1). This comprises anorthosites (sensu lato, more strictly leucogabbros, leuconorites, leucotroctolites and anorthosites), gabbros and monzogabbros (Higgins and Doig, 1981, 1986). The anorthosites are best exposed on the islands of the Sept Iles archipelago and the Marconi peninsula, but there are also outcrops on the mainland around the mouth of the Rapides river. A significant proportion of the anorthosite is well foliated (Fig. 3; Higgins, 1991). Blocks of more and less plagioclase-rich material are locally present, and some blocks contain smaller blocks. These blocks do not resemble the autoliths in the Layered series because they contain

Fig. 3. Thin section of laminated anorthosite from the Upper Border series in cross polarised light.

black plagioclase and are completely unaltered. Parts of the anorthosite, both foliated and massive, are permeated by syenitic to granitic granophyre (Fig. 4). This is commonly interstitial to plagioclase, but may accumulate in pods and dykes. The adjacent plagioclase is strongly zoned to albite. Such pods were used for dating purposes (Higgins and Doig, 1981). Cimon (1998) considered that the Transitional series represented a second cycle of magmatism, with a return to less evolved mineral compositions from the Layered series.

The Transitional series is in turn overlain by syenites and granites of the *Upper series*. There are no xenoliths of Grenville age rocks (older than 1000 Ma) in the intrusion, except within a few metres of the contact, and no strontium isotopic evidence of crustal contributions to the syenites and granites of the Upper series (Higgins and Doig, 1981). Chemical analysis confirms the petrology that the rocks of this series are bimodal (Higgins and Doig, 1986). Parts of the granite in the Upper series are loaded with up to 50 vol.% fine-grained enclaves. Loncarevic et al. (1990) proposed that they represent fragments of consanguineous mafic and felsic volcanic rocks from the upper parts of the body.

The *Border zone* forms an envelope of variable thickness around the exposed edge of the intrusion (Cimon, 1998). Geophysical data are not sufficient to determine if it continues under the sea. The Border zone is composed of massive olivine gabbro, commonly with significant amounts of hornblende and biotite. Mineral and whole rock compositions suggested to Cimon (1998) that this rock crystallised from a more evolved magma than the Layered series and he proposed that this unit was emplaced after the main intrusion. A series of *Late Gabbro* dykes and sills was emplaced throughout the intrusion on the islands, but are most common on Grosse Boule Island. They are not seen on the mainland.

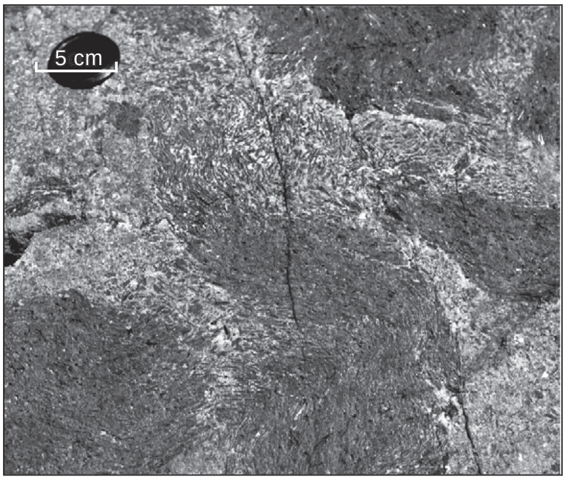

Fig. 4. Syenite invading laminated anorthosite in the Upper Border series. The pale syenite has disaggregated a laminated and previously folded anorthosite. The anorthosite cannot have been completely solid at this time.

3. Problems with the existing interpretation of the structure and further observations

3.1. Anorthositic blocks in the Layered series

The anorthositic blocks found in the Layered series are sufficiently abundant that their presence must be explained. Cimon (1998) proposed that these blocks foundered from the roofs of deeper magma chambers and were transported upwards. There is a mechanical problem with transporting these blocks up from the mid-crust: they are not pure anorthosite and, therefore, were probably slightly denser than the magma. It is difficult to envisage how such large blocks could be transported, except by rapid magma flow. In addition, the blocks commonly show the development of minerals such as chlorite and epidote, which are not present in the Layered series, nor stable in the mid-crust.

A simpler explanation is offered by a comparison with the Skaergaard intrusion (Wager and Brown, 1968). There, similar blocks are considered to be autoliths: that is, fragments of the roof that foundered into the chamber and were transported by the circulating magma across the top of the chamber and down to the floor, where they accumulated. A similar explanation is possible at Sept Iles. The alteration products seen in the blocks suggest that they formed at very shallow levels: hydrothermal circulation undoubtedly occurred in the roof of the intrusion during solidification. The blocks are generally massive in contrast to the anorthositic rocks currently exposed, which may be laminated. This suggests that they came from a slightly different part of the intrusion—perhaps further towards the centre of the intrusion, where lateral magmatic currents were less strong (see discussion of the laminated anorthosite below). It is certainly likely that the roof of an intrusion such as this would not be stable for the entire period of solidification, especially as the intrusion was likely intersected by a fault belonging to the Saint Lawrence Rift system (Kumarapeli, 1993). However, some calderas have roofs comparable in size to that of the Sept Iles intrusion.

3.2. Apatite-rich rocks

Cimon (1998) proposed that the apatite-rich rocks occur at the top of a magmatic cycle, just before the influx of new, less evolved, magma that formed the Transitional Series. However, it is not clear why apatite should crystallise in such abundance under these circumstances. It cannot be related to the influx of new magma as this will be hotter and with a lower phosphorous content. Hence, phosphorus would remain in solution and any apatite should dissolve. In addition, this does not explain why a similar, though less rich, apatite-bearing layer should occur near the base of the Layered series.

In other mafic intrusions, such as the Bushveld and Kiglapait intrusions, apatite-rich rocks are developed at the top of the intrusion (Cawthorn, 1996); in the Skaergaard intrusion the apatite-rich rocks of the 'sandwich horizon' are the last of the exposed magmas to crystallise, although some apatite occurs earlier (Wager and Brown, 1968). This accords with the fractional crystallisation of feldspars and mafic minerals, which will increase the phosphorous content of the magma to high levels. Such an interpretation would indicate that the critical zone of the Layered series is not at a magmatic discontinuity produced by the influx of new magma, but is instead one of the last exposed parts of the intrusion to crystallise. The composition of plagioclase bears this out: it is less anorthite-rich than in the overlying rocks (Cimon, 1998). The lower apatite-rich zone may represent an earlier period of apatite saturate that was diluted by influx of less evolved magma.

3.3. Magnetite-rich layers

One of the most striking aspects of the geomagnetic field of the intrusion is a series of three arcuate 1 km wide anomalies that lie in the northwest part of the intrusion, further into the intrusion from a similar anomaly that overlies the Border zone. The outer two anomalies can be correlated with four layers rich in magnetite that have been observed both in the field and in drill core (Cimon, 1998). These magnetite-rich layers occur in the Layered series, particularly near the top of the gabbro–troctolite zone and the base of the cyclic zone of Cimon (1998). One of the magnetic anomalies occurs southeast of the outcrop of the Critical zone, partly beneath the bay of Sept Iles (Fig. 1). Cimon (1998) considered that the Critical zone marked the transition between two magmatic cycles. Hence, this anomaly must be produced by a magnetite-rich layer within the transition series, his second magmatic cycle. However, no such layers have been observed in the Transitional series, and anyway this unit is not generally well layered. It is more logical to ascribe the innermost anomaly to another magnetitite layer in the Layered series.

The shape of the magnetitites, as revealed by their magnetic anomalies, may also be significant (Fig. 1). They are widely spaced in the NW part of the intrusion, but converge to the east and south. This may reflect a shallowly dipping contact in this area as the magnetite-rich rocks are only a few metres thick, but the anomalies are 1 km wide. The convergence of the anomalies to the east suggests a steepening of the layers. This makes sense if the edge of the intrusion is the Saint Lawrence graben fault, which runs east–west along the north shore.

3.4. Transitional (Upper Border) series

The rocks of the Transitional series are very different from the Layered series. Cimon (1998) has noted that mineral compositions tend to be richer in CaO and MgO, but the series is very heterogeneous. The most plagioclase-rich parts have the largest crystals and the greatest textural heterogeneity, and greatly resemble Proterozoic anorthosite, except for their lack of deformation. It is difficult to see why injection of a new, less evolved magma, as Cimon (1998) proposed, should produce such coarse-grained rocks dominated by plagioclase. An additional problem is presented by the widespread occurrence of granophyre in the anorthosite. This does not seem to fit with the notion of a less evolved, hotter magma.

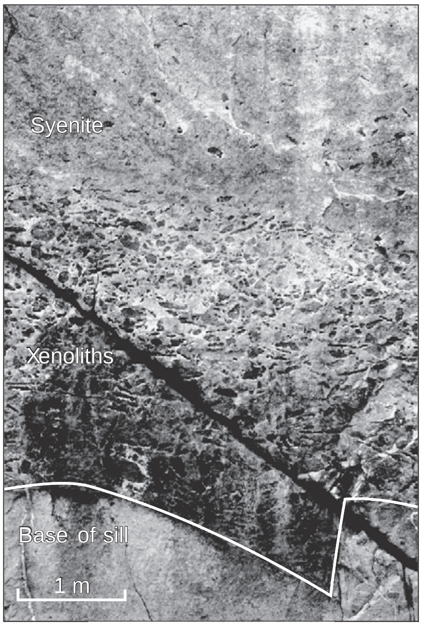

Fig. 5. Base of the Pointe du Criade intrusion, northern part of Grosse Boule. The host rock here is granite. The lower part of the sill is loaded with diabase and leucogabbro xenoliths. A few xenoliths are still present in the upper part of the photograph.

Better candidates for a later, higher MgO magma are fine-grained troctolite dykes a few centimetres to metres in thickness that were emplaced into the upper parts of the Layered series.

3.5. Upper series and Pointe du Criade intrusion

The Upper series comprises a variety of different acidic rocks. Mapping and chemical analysis indicated an initial division into syenite and granite (Higgins and Doig, 1981, 1986), but further study has indicated more complexity. I showed that the syenite is part of a separate magmatic component: the Pointe du Criade intrusion (PdC; Higgins, 1990). This sill has three magmatic components and was emplaced into anorthosite and other rocks of the main part of the intrusion. The sill was initially opened by diabase magma, which is preserved as a chilled margin 0.1–3 m thick against the host rocks, on both the upper and lower surfaces of the sill. The next magma to exploit this conduit was leucogabbro, similar in many ways to the anorthosite of the main part of the intrusion. It is commonly a few meters thick, but may reach 30 m in places. The contact between the diabase and leucogabbro is commonly gradational. The final magma was syenite. It occupies the central 30 to 50 m of the sill. In most areas the lower part of the syenite is charged with enclaves of diabase and leucogabbro. This contact is very distinctive and easy to recognise in the field (Fig. 5). The extreme aspect ratios of some enclaves (up to 5 by 300 cm) suggest that they formed by mixing of mafic and syenite magmas in an environment of strong simple shear. The most likely place for this is in the conduit.

The PdC intrusion crops out on all the islands and the Marconi peninsula (Fig. 1). Recent reexamination of parts of the intrusion has revealed other contacts of this sill, making it even more extensive and equating it with the syenite in the map of Higgins and Doig (1981). Hence, it is a volumetrically important magmatic component. Chemical analysis of the chilled diabase margin of the PdC sill shows that it is very similar to late gabbro dykes that are so common on the islands (Hounsell, 2003).

The granites exposed on the summits of the Marconi peninsula, Grande Basque and Manowin islands do not have compositions that extend to those of the syenites of the PdC intrusion, but are petrographically distinct. Loncarevic et al. (1990) pointed out that the granites contain abundant felsic and mafic porphyritic inclusions and proposed that these enclaves were formerly volcanic rocks (Fig. 6). They concluded that the Sept Iles intrusion originated as a lava lake and had no roof.

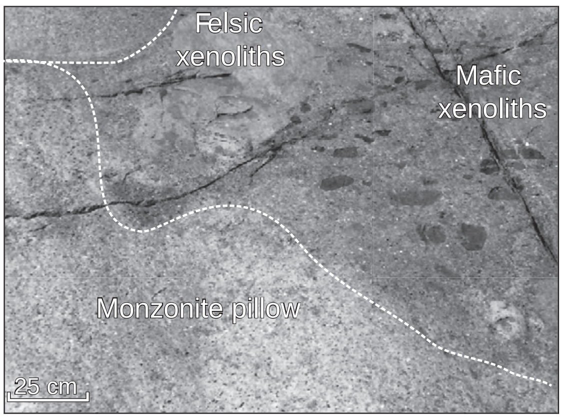

Fig. 6. Pillows of xenolith-free monzonite emplaced into xenolith-rich granite. Both felsic and mafic xenoliths are present.

Detailed field observations indicate a more complex history. The granites consist of two components: 'pillows' of xenolith-free monzonite, up to 5 m long, which are contained in a second xenolith-rich, granitic phase. A vertical section on the south side of Corossol shows the relationships between the two phases (Fig. 7). At the base, the pillows are more abundant and the xenolith-bearing phase is only present as narrow wisps. At the top, the xenolith-rich phase dominates, with just the occasional pillow of the xenolith-free phase. These field relationships indicate that the xenolith-rich magma formed first. The xenolith-free magma was emplaced into the magma chamber before the first magma had solidified. The abundance of the pillows at the base of the outcrop and their scarcity at the top suggest that they have descended and accumulated against some barrier. The simplest explanation is that the granitic chamber had a floor. Similar pillows are recorded from other intrusions, but unusually with more contrasting magmas (Wiebe, 1996).

Loncarevic et al. (1990) considered that the xenoliths were fragments of contemporary volcanic rocks—a kind of scum that floated on the surface of the lava lake. However, it seems more reasonable to assume that they were parts of the flood basalt volcanic series that pre-dated emplacement of the SIIS or perhaps fragments of dykes emplaced into and chilled by the granitic magma. In that way the presence of a huge, open lava lake is avoided. Nevertheless, the large size of the intrusion and the presence of the St Lawrence graben faults probably meant that the roof was not a single rigid block. Hence, magma may have leaked out along faults to the surface.

4. Proposed emplacement and crystallisation model for the Sept Iles Intrusive suite

4.1. The Sept Iles Intrusive suite

It is now clear that there are a number of different intrusions that were formerly grouped together as the Sept Iles intrusion. Therefore, I propose that this group of intrusions be named the Sept Iles Intrusive suite (SIIS). It comprises all post-Grenville (less than 1000 Ma) intrusive rocks in the Sept Iles region: the Sept Iles Mafic intrusion (SIMI), possibly the Sept Iles Border intrusion, the Pointe du Criade intrusion and the Sept Iles Late Gabbro intrusions (Fig. 8; Table 1).

- The SIMI is precisely dated at 564 ± 4 Ma (Higgins and van Breemen, 1998).
- The Sept Iles Border intrusion, if it exists as Cimon (1998) proposed, and is not just the lateral border series of the SIMI, must be younger than the SIMI, but it is not clear by how much. It is indicated as the Border zone on the figures.
- The Pointe du Criade intrusion cuts the SIMI and hence must be younger. The Rb/Sr dates of Higgins and Doig (1981) are in fact largely from this intrusion, but their precision is not very good. It does not cut the Sept Iles Border intrusion and hence their relative age cannot be determined.
- The Sept Iles Late Gabbro intrusions must be younger than the SIMI, but their age relationships with the other components are not clear. Further geochronological and palaeomagnetic measurements, now under way, should clarify the chronology.

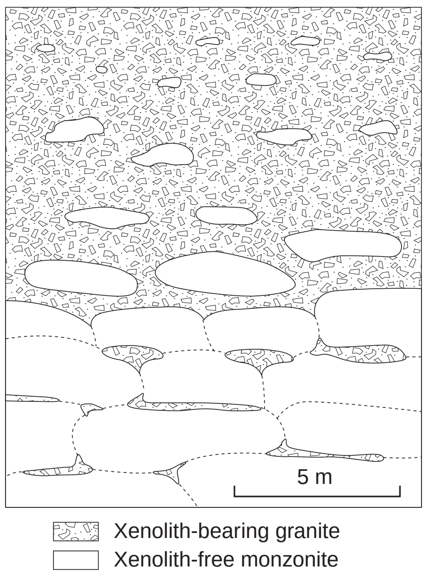

Fig. 7. Schematic view of the granitic rocks on the southern part of Corossol. Pillows of xenolith-free monzonite are abundant at the base. They are outlined by wisps of xenolith-bearing granite. Further up xenolith-bearing granite is the dominant rock, with just a few pillows of monzonite.

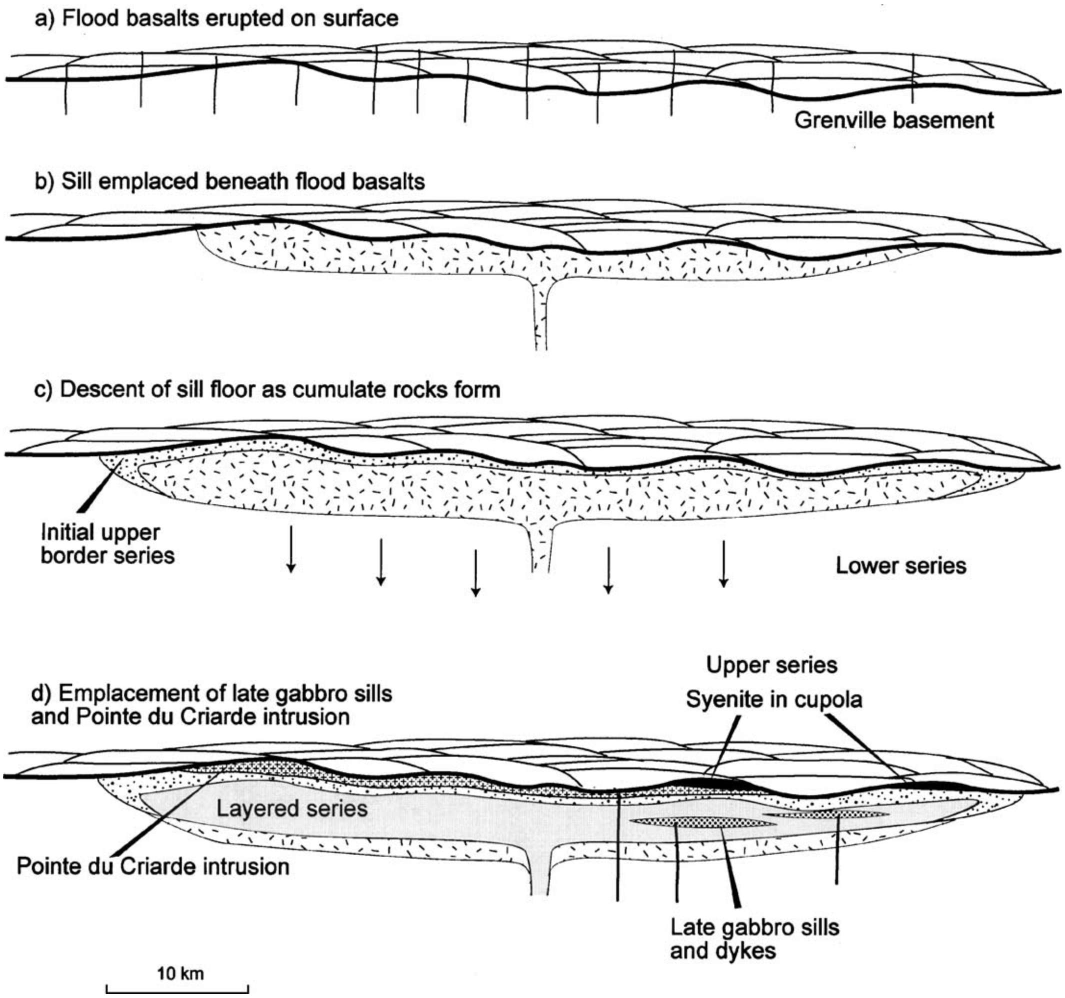

Fig. 8. New interpretation of the Sept Iles Intrusive suite, as proposed in this paper. This figure is schematic and not all components are to scale.

4.2. Emplacement of the SIIS

The absence of Grenville age xenoliths in the rocks of the SIIS is particularly striking—they are only seen in the Border zone very close to the contact. Loncarevic et al. (1990) suggested that the intrusion had no roof and was just topped by contemporaneous felsic volcanics, now preserved as fine-grained felsic xenoliths in some of the acidic rocks. However, the felsic rocks are thought to be late differentiates, hence, this interpretation does not address the problem of the initial emplacement of mafic magma—a lava-lake 80 km in diameter does not seem feasible.

Continental rifting can produce great expanses of flood basalts (Basaltic Volcanism Study Project, 1981). These sections can be particularly thick if the rift was initiated by a mantle plume, as suggested for the SIIS (Higgins and van Breemen, 1998). Flood basalts similar in age to the SIIS are seen to the southwest as the Tibbit Hill volcanics and possibly elsewhere in the Appalachians (Fig. 8a; Higgins and van Breemen, 1998). If such flood basalts were present to the north of Sept Iles, then they must have been completely eroded. This is entirely possible, as a number of geologic units originally covering the shield are now only known from meteorite impact craters or diatremes, although flood basalts have not been

Table 1
The Sept Iles Intrusive suite (SIIS)

Intrusive component	Magmatic units	Significant lithologies
Sept Iles Late Gabbro intrusions	Widespread dykes and sills	Gabbro/diabase
Pointe du Criade intrusion	Large composite sill (Includes part of former Upper series)	Syenite, leucogabbro, diabase
Sept Iles Border intrusion	Intrusion along the border of the SIMI. May be just the lateral border series of the SIMI.	Gabbro
Sept Iles Mafic intrusion (SIMI)	Lower series, Layered series, Upper Border series (former Transitional series), Upper series	Gabbro, anorthosite, magnetite-rich rocks, apatite-rich rocks, granite

recognised. If flood basalts were present to the south and east then they may still be present underneath the Gulf of St Lawrence. Unfortunately, such basalts are not easy to recognise by geophysical means. Their physical parameters would closely resemble those of the intrusive suite itself. In addition, there are no recent high-quality seismic reflection studies of this region.

If such flood basalts existed then further mafic magmas rising through Grenville crust, which has an intermediate composition, would have tended to pond beneath denser basalts. The initial intrusion was in the form of a sill, not necessarily with the same dimensions as the final intrusion (Fig. 8b). Subsidence of the floor of the sill could then have expanded and thickened the sill into the final intrusion. This process could have been more or less continuous, without the need for a deep magma chamber at any time.

A number of other significant mafic intrusions are thought to have been emplaced by a similar mechanism to that proposed here for Sept Iles. Cheney and Twist (1991) have proposed that the Bushveld intrusion was emplaced as a large sill along an unconformity beneath extensive, slightly older volcanic rocks and sediments. They also point out that the Duluth complex (USA) and Muskox intrusions (Canada) also share the same environment, as well as the smaller Skaergaard and Kap Edvard Holm intrusions (Greenland).

4.3. Formation of the Lower and Layered series

Although it is clear that most layered mafic intrusions have solidified dominantly from the base upwards, the importance of in situ crystallisation versus crystal settling is still not clear. Much of the Lower and Layered series is layered. In many of these layers the base is well defined and rich in denser minerals, whereas the top is rich in plagioclase. Such a texture is certainly permissive of crystal settling. However, Scoates (2000), and many others, have pointed out that plagioclase is almost neutrally buoyant or even less dense than most mafic magmas (see Upper series below). Hence, plagioclase cannot have descended as a series of independent crystals. This has lead to suggestions that plagioclase and mafic minerals grew in situ in the boundary layer at the base of the magma chamber.

In situ growth is certainly attractive as it avoids all problems with floatation of plagioclase, however, another mechanism must then be sought for the production of the layering. There is no shortage of possibilities (Naslund and McBirney, 1996), but little evidence for their action. Another possibility is that the plagioclase and mafic minerals descend as a two-phase flow—that is a package of liquid and crystals that is denser that the surrounding magma (Morse, 1986). At the base of the chamber the mafic minerals descend to the floor. The density of plagioclase may be so close to that of the magma and the crystals sufficiently small, that the crystals were restrained by the yield strength of the magma and the proximity of denser minerals. Note that large blocks with the same density difference may be able to float or sink as the overall buoyant force is large enough to overcome the yield strength of the magma and neighbouring crystals. The floor of the magma chamber may have descended as the cumulate rocks formed (Fig. 8c). Hence, the magma chamber may never have been more that a few 100 m to 1 km thick.

4.4. Upper Border series

Cooling of the intrusion through the roof led to crystallisation of the magma. The abundance of plagioclase in the Upper Border series indicates that it was a significant phase during much of the solidification of the intrusion. Although much discussed in the past it now seems clear that plagioclase floats in most gabbroic magmas (Scoates, 2000). The density difference between plagioclase and magma is less than that of mafic minerals and magma, hence the floatation cumulates would have remained loosely packed. Mafic minerals that crystallised between the plagioclase would have had a chance to escape by sinking out of the upper boundary layer, at least in the early stages of solidification.

There are two principal facies of the anorthosite of the Upper Border series: massive and foliated (Higgins, 1991). The massive anorthosite is generally medium to coarse-grained with relatively equant crystals. The autoliths found in the Layered series resemble the massive anorthosite. This facies must have crystallised in a quiescent environment, without significant magma currents, or it would have developed a foliation (Higgins, 1991). Such an environment may be more common towards the centre of the intrusion, where a lower cooling rate may have produced weaker or more chaotic convection currents (Figs. 8c,d and 9). Their coarse-grained nature suggests that accumulation of crystals was relatively slow, allowing for growth to occur.

The laminated anorthosite must have formed in a region of simple shear produced by strong and persistent convection currents (Higgins, 1991). Convection currents were probably complex, but may have been more intense and persistent towards the edges of the intrusion, where cooling was more intense. Such convection currents sheared the magma and wafted the crystals dominantly towards the edges of the intrusion. Such a dynamic environment of crystallisation will remove the depleted magma around each plagioclase crystal, yielding their flattened tabular form (Sunagawa, 1987; Higgins, 1991). At the upper outside edge of the intrusion the magma descended towards the floor of the intrusion, but plagioclase remained at the top of the intrusion because it is less dense than the magma.

The rocks of Upper Border series may be compared with those of similar intrusions. In the Skaergaard intrusion the Upper Border series contains both laminated and massive anorthosite texturally very similar to that seen at Sept Iles (author's observations and Naslund, 1984). Similarly, such well-laminated anorthosite is not seen in the rocks that formed on the sides and base of the intrusion. At Skaergaard evidence for floatation of plagioclase in the Upper Border series is strong. Similar well-laminated anorthosite also occurs in the Taguli ring complex, Air, Niger (Moreau et al., 1987) and the Hidra massif, Norway (Demaiffe and Hertogen, 1981). At Sept Iles and all in the other intrusions the plagioclase cumulates are commonly invaded and

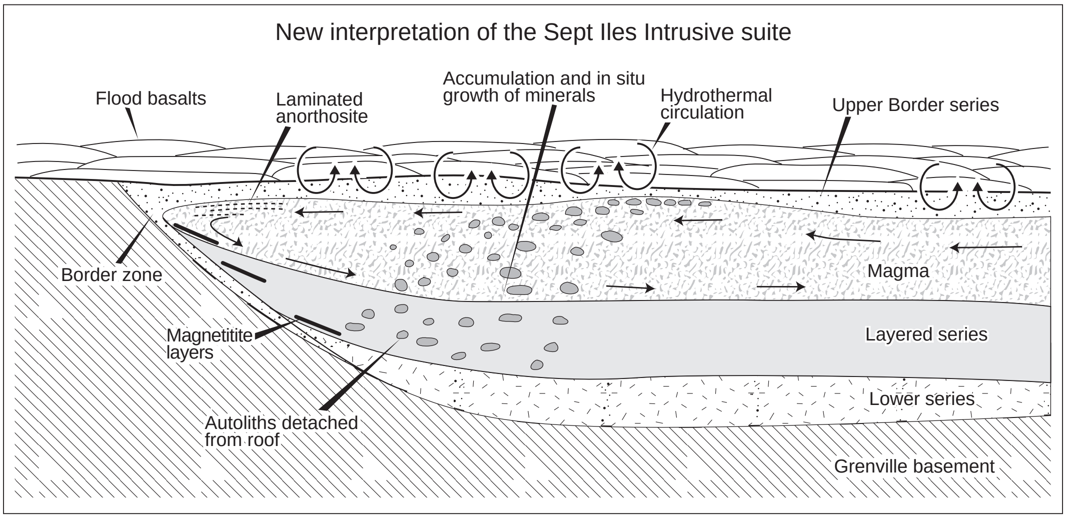

Fig. 9. Detail of the margin of the magma chamber during solidification (see text for details).

disaggregated by granophyric material. This can easily be explained if the plagioclase cumulates are at the top of the magma chamber. Low density granophyric magma formed by differentiation of the interstitial liquid or in the magma chamber would tend to rise into the Upper Border series and infiltrate between the loosely packed plagioclase crystals. Veins and dykes of granophyre may form at the later stages by fracture of the anorthosite during shrinkage or fracturing of the roof.

The solidified part of the Upper Border series was susceptible to fracturing as the pressure of the magma in the chamber varied, and possibly following movements of the Saint Lawrence rift fault that cuts the intrusion. Heat from the cooling magma chamber would have caused circulation of hydrothermal fluids, further cooling the rocks, as well as causing alteration of minerals in the solidified parts of the Upper Border series (Fig. 9). This fracturing may also have caused parts of the roof to founder into the magma chamber. Although plagioclase was able to float in the magma, the solidified material contained other denser minerals. Hence, larger blocks would have descended to the floor of the magma chamber, now seen as the autoliths in the Layered series. Smaller blocks may have dissolved in the magma before they could reach the floor. Melting was helped by water released from the solution of low temperature hydrothermal alteration minerals.

The foundering of the roof blocks must have occurred at the same time as the crystallisation of the Layered series and the accumulation of the Upper Border series. This contradiction may be resolved if a part of the roof of the magma chamber became so eroded by autolith formation that the solid exterior was exposed to the magma. This part may have been located along the St Lawrence rift fault, where movements during solidification of the magma chamber may have disrupted the roof.

4.5. Magnetite-rich layers

The magnetic anomalies in the interior of the SIMI are well defined and symmetric. If the magnetite layers responsible for these anomalies descended at a moderate slope with a constant amount of magnetite in each layer, then each anomaly would not terminate so abruptly towards the centre of the intrusion, but continue on with decreasing intensity (Fig. 9). Hence, the magnetite rich layers must be radially restricted to a zone about a kilometre wide. A model for their formation can be developed from observations of the Skaergaard intrusion. There, in the Middle series, magnetite-rich rocks occur as layers close to the contact with the border series. These layers are only about 20 m long and wedge out towards the centre of the intrusion (author's observations). The magnetite-rich rocks in the SIMI may have the same geometry, although they are clearly much more abundant. Such geometry would conform to the shape of the magnetic anomalies.

The spatial distribution of the magnetic anomalies may be explained by differences in the slope of the floor of the magma chamber at the time of their formation. In the west, the anomalies are clearly separated, suggesting a gentle slope to the layers. The Layered series has a slope of about 30° in this region, which may be that of the magnetitite layers also. To the east and north the magnetic anomalies converge, which may reflect a steeper slope of the magma chamber floor. These changes in slope may reflect the development of faults. The St Lawrence graben fault is east–west in this area, parallel to the northern part of the intrusion.

Magnetite accumulations in the Layered series near the border must have been deposited from circulating magmatic currents some of which swept along the roof and descended the walls of the chamber to the floor. If magnetite crystallised while the magma was near the roof an important fraction could have been swept along until the magma reached the edge of the intrusion. There, the downward movement of the magma would have reinforced descent of the crystals by gravity and the magnetite would have accumulated. But what caused more magnetite to precipitate during these periods? The presence of abundant autoliths shows that the roof of the intrusion was unstable. The autoliths are commonly altered; hence foundering of the roof and solution or dehydration of the autoliths, may have added significant amounts of water to the magma, increasing the fugacity of oxygen. Iron in the magma was then oxidised and if sufficient iron was present magnetite started to crystallise. Autoliths are not found in the magnetite-rich rocks, but this is perhaps not surprising, as the greater size of the autoliths would have enabled them to sink much faster than the smaller magnetite crystals, bypassing the magnetite deposits at the edge of the intrusion (Fig. 9). Therefore, the magnetite-rich horizons may have been produced by foundering of the roof, perhaps in response to faults movements associated with the Saint Lawrence rift system.

4.6. Apatite-rich rocks

The apatite-rich rocks must have been produced by saturation of the magma in apatite and accumulation of the mineral at the base of the magma chamber. Such a process may have been associated with the same roof foundering events that produced the magnetitites: It is known that phosphorous stabilises high Fe^{3+} in silicate multi-component solutions (Toplis et al., 1994). High Fe^{3+} is necessary for a liquid to crystallise a lot of magnetite, therefore, the silicate liquids from which the magnetite crystallised may have been also rich in phosphorous. If the inverse is also true, that is Fe^{3+} stabilises phosphorous in silicate solution, then reduction the Fe^{3+} content of the liquid by magnetite precipitation may provoke apatite saturation. This has not been proven, but another process may be equally effective: magnetite precipitation will increase SiO_2, CaO and P_2O_5 in the magma and this could also have produced apatite saturation. The significant difference in density between magnetite (5.2 g cm^{-3}) and apatite (3.2 g cm^{-3}) and the size of the crystals means that these two minerals may be separated by magmatic processes (Fig. 9).

If this model for the origin of the apatite-rich units is correct then other apatite-rich rocks may occur at stratigraphically higher levels, perhaps associated with the uppermost magnetitite layer, currently concealed beneath the shallow bay of Sept Iles and the sand-plains that connect the Marconi peninsula to the mainland.

4.7. Upper series and Pointe du Criade intrusion

The simplest interpretation of the field relationships of the acidic rocks at Sept Iles indicates two intrusive components: the Upper series and the Pointe du Criade intrusion. Both may be related as a large, thin, tabular body, such as the SIMI, will likely segment into separate cupolas or cells during the final stages of solidification.

The earliest component of the Upper series was a slightly peralkaline granitic magma, probably developed by fractional crystallisation of the gabbroic parent magma of the intrusion (Higgins and Doig, 1986). This magma was emplaced near the roof of the original magma chamber. This may have involved lateral transfer of magma, as intermediate compositions are not abundant in the exposed part of the suite. This magma stoped and engulfed fine-grained mafic and felsic rocks. The mafic rocks may have been from the flood basalt series. The felsic blocks may have been more evolved parts of the volcanic series, or possibly an earlier sub-volcanic intrusion of the same granitic magma. Before this magma solidified a new magma was injected into the chamber. This magma was somewhat less evolved, and denser than the earlier magma, and accumulated as a series of pillows on the floor of the chamber. This magma may have been derived from an adjacent 'cell' of the late, segmented magma chamber and been injected laterally. The whole package was solidified before the emplacement of the Pointe du Criade intrusion.

The Pointe du Criade intrusion is a three-component sill that crops out on the islands and the peninsula (Fig. 1). The first magma was a diabase, possibly part of the widespread 'Late Gabbro' sills and dykes (Figs. 8d and 9). It opened the whole sill, as is currently exposed. It was chilled against the Upper series granites of the SIMI, but these were not cold. The feeder dyke must have then intersected a semi-consolidated leucogabbro, which was partly mobilised into this system. The petrographic similarity of this part of the intrusion with the anorthosite of the SIMI Upper Border series suggests that this was derived from the inner, unconsolidated part of that unit—that is a loose floatation cumulate of plagioclase. Finally this magmatic system tapped a body of syenitic magma, possibly similar to the second magmatic component of the SIMI Upper series granites described above. Plagioclase floatation cumulates were also invaded by syenites elsewhere in the SIMI Upper Border series, so the association is not unique to this intrusion.

5. Conclusions

1. The igneous rocks at Sept Iles are best considered as a suite, rather than a single intrusion.
2. Igneous activity probably started with the eruption of flood basalts, in response to a mantle plume (Sept Iles mantle plume). These flood basalts have not been identified on the surface, but may be preserved beneath the St Lawrence, or in the Appalachians.
3. Further mafic magmas ponded at the unconformity between the Grenville basement and the flood basalts. As more magma accumulated, the magma chamber expanded laterally until it reached the present diameter of the intrusion, 80 km. Descent of the floor of the chamber matched magma input, so that the actual thickness of magma was never very great.
4. Crystals started to form in the upper part of the magma chamber. Plagioclase was lighter than the magma and accumulated to make the rocks of the Upper Border series. Convection currents moved the magma towards the rim of the intrusion. Here, simple shear lead to the lamination of the plagioclase crystals.
5. At the rim the magma descended, carrying with it any mafic minerals that had formed at that stage. At the base of the magma chamber mafic minerals accumulated. Further growth of all minerals, including plagioclase, occurred in situ, producing the Lower and Layered series.
6. Parts of the Upper Border series solidified by crystallisation of interstitial mafic minerals. Cooling may have been aided by hydrothermal circulation that also partly altered the rocks. These processes increased the density of the rocks of the Upper Border series, which became more dense that the magma. Blocks of this material foundered into the magma and settled to the floor as autoliths in the layered series.
7. Addition of altered material increased the oxygen fugacity of the magma and lead to crystallisation of magnetite. These crystals were swept along to the rim of the magma chamber by convection currents. Where the magma started to descend the walls, magnetite was precipitated as a band. This cycle appears to have happened at least three times.
8. The late magmas were already enriched in phosphorous by fractional crystallisation of plagioclase and mafic minerals. Decreases in Fe^{3+} or increases in SiO_2, CaO and P_2O_5 following magnetite crystallisation lead to saturation and crystallisation of large quantities of apatite. The strong density difference between magnetite and apatite may have been responsible for their separation. Two horizons are known, but a third may be associated with the highest magnetite layer, that lies beneath the bay of Sept Iles.
9. It is possible that anorthosites in other intrusions, such as those in Niger, may also represent the roof of the intrusion, formed by floatation of plagioclase.
10. There are a number of different acidic magmatic components of the suite, which may have been produced by fractional crystallisation. At this late stage the tabular magma body may have segmented into isolated cupolas, each of which had its own emplacement history.

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