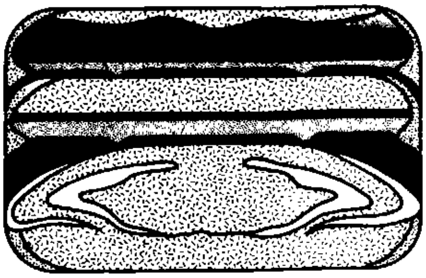

Anorthosite-Farsundite Complexes in the Southern Part of the Grenville Province

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Abstract
Three major anorthosite-farsundite complexes in the Grenville province underlie about 50 per cent of a northeasterly area, about 200 km long and 60 km wide, situated north of Montreal and lying parallel to the St-Lawrence River. The plutonic complexes are surrounded by a highly varied, layered assemblage of granulite-facies country rocks, some of which, at least, are of sedimentary origin ("Grenville Supergroup").

The plutonites were emplaced diapirically and came to rest near the interface of the pre-Grenville basement and Grenville metasediments. Diapiric rising, or lateral spreading of parts of the complexes induced large scale deformation in the country rock.

Granulite facies metamorphism took place before and during diapirism and lasted until about 1100 Ma ago. Retrograde metamorphism due to cooling at high pressure followed diapirism.

The emplacement of the crystallising plutonites is thought to be the fundamental cause of the evolution of this area in terms of deformation and metamorphism.

Résumé
Trois grand complexes anorthosito-farsunditiques occupent, dans le sud de la province de Grenville, environ la moitié d'une bande de 200 km de long par 60 km de large, parallèle au Saint-Laurent, et située au nord de Montréal.

Entre les complexes plutoniques se trouvent divers types de roches de facies granulite dont certaines sont manifestement d'origine sédimentaire ("Supergroupe de Grenville").

Les plutonites sont montées par diapirisme jusqu'à la limite entre le socle pre-Grenvillien et sa couverture métasédimentaire. La montée diapirique et localement l'étalement latéral de ces complexes ont causé des déformations majeures dans les roches encaissantes.

Le métamorphisme de faciès granulite a eu lieu avant et pendant le diapirisme et s'est arrêté il y a 1100 Ma. Un métamorphisme rétrograde correspondant à un refroidissement à haute pression a suivi le diapirisme.

L'emplacement de masses plutonites en voie de consolidation est considéré comme la cause fondamentale de l'évolution de cette région en termes de déformation et de métamorphisme.

Introduction

The southern, Canadian part of the Grenville province is underlain by metamorphic rocks which belong for the major part to the granulite facies and are intruded by several plutons of the anorthosite-farsundite suite (Fig. 1). The specific region of the Grenville province discussed here is a north easterly trending band of about 200 km long and 60 km wide.

The area is similar in many respects to the Adirondacks Highlands from which it is separated by the St-Lawrence Lowlands.

Plutonites occupy roughly half the area and occur in three major complexes: the Morin Complex, the Lac-Croche Complex, and the St-Didace Complex (Fig. 2).

Results of about 15 years of study in this area have been reported in a series of papers (Martignole, 1969 a and b, 1971, 1974 a and b; Schrijver 1968 a and b, 1973 a, b and c; Martignole and Schrijver 1968, 1970 a and b, 1971, 1972, 1973), a D.Sc. Thesis (Martignole, 1975), a monograph (Schrijver, 1975) and a number of M.Sc. and Ph.D. theses

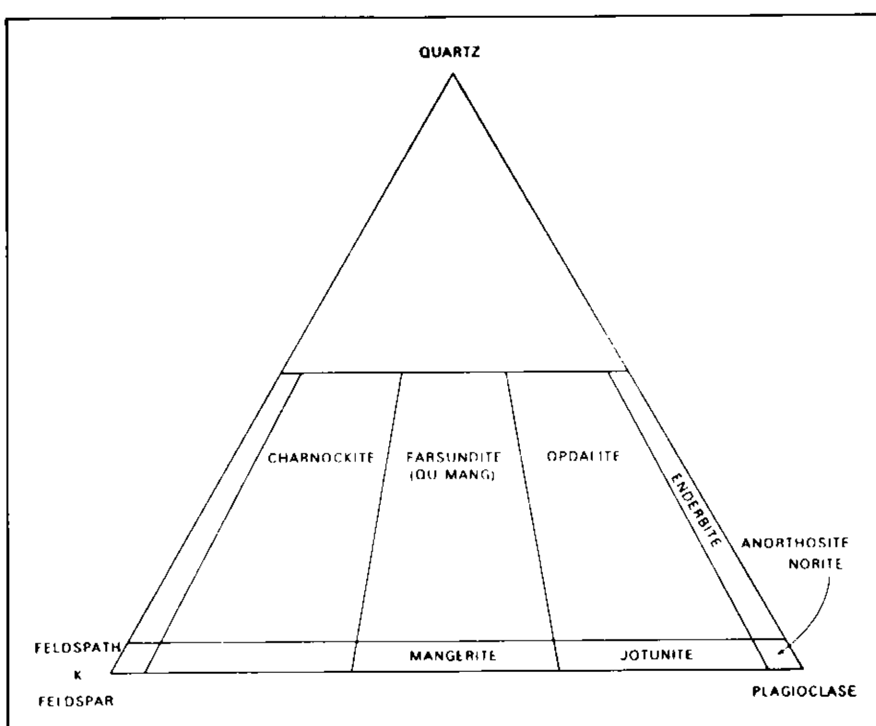

Figure 1
Rock nomenclature in the anorthosite-farsundite suite

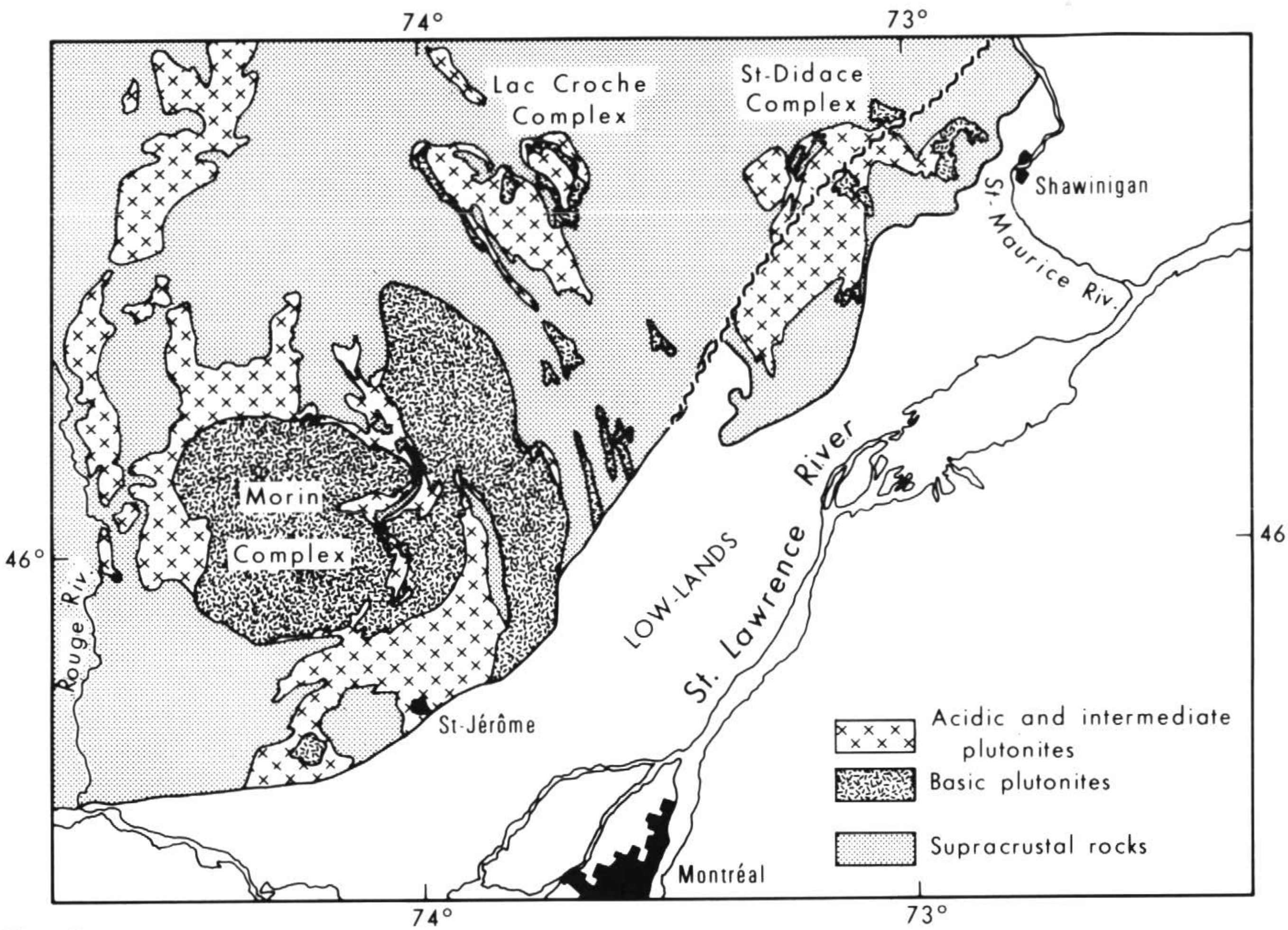

Figure 2
Plutonic complexes in the southern part of the Grenville province.

(Barondeau, 1974; Barraud, 1971, 1977; Bouillon, 1973; Ducrot, 1974; Goulet, 1971; Hocq, 1969; Nantel, 1977; Schimann-Cameron, 1971).

Besides the works quoted above, a recent contribution to knowledge of the petrology of the Morin anorthosite has been published by Emslie (1975), who also gives an inconclusive discussion of our preferred hypothesis of emplacement and deformation.

The aim of the present paper is to review the main results obtained and to reevaluate some of our working hypotheses in the light of recent petrologic and isotopic data.

Complexes

The Morin Complex is the largest of the plutonic complexes in the area. Its centre consists of an andesine-anorthosite dome, 40 km in diameter, flanked on its eastern side by an elongate lobe of gneissic anorthosite. The lobe has been interpreted as forming the core of a nappe of penninic style. A sill of troctolite is present (plagioclase-olivine gabbro) between the dome and lobe (Fig. 3).

Different modes of emplacement and deformation of dome and lobe are held responsible for the transition from relict-magmatic textures in the anorthosite of the dome to pervasively recrystallized, gneissic anorthosite in the lobe. There is no doubt, however, that both units shared a large part of their early - including magmatic - history.

An asymmetric negative Bouguer anomaly over the anorthosite body suggests that buoyancy of the dome was arrested before density equilibration with the surroundings took place, and that the lobe spread eastward as a nappe.

Ferrogabbro, jotunite, opdalite, and farsundite (see Fig. 1; "acid and intermediate plutonites" in Fig. 2) envelop the dome semi-concentrically, but are virtually absent around the lobe. Flow or depositional fabric, and occurrences of both, partially recrystallized anorthosite inclusions and primary andesine xenocrysts (similar to the plagioclase of the anorthosite) in the plutonites of the envelope show that the protolith(s) of these rocks was (were) largely liquid while the anorthosite was crystalline and partially recrystallized.

Chemical studies have failed to provide a unique hypothesis of the magmatic evolution of the Complex, the main problem being whether rocks as different as magnesian troctolite and ferrous, acidic farsundite could conceivably stem from a single magma. If this parental magma were basaltic, it would be difficult to account for the

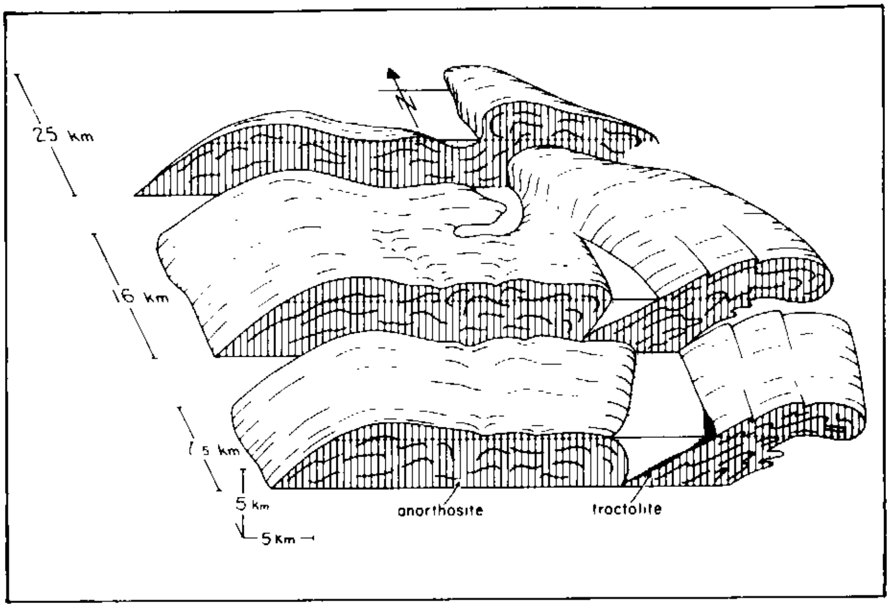

Figure 3
Schematic block diagram of Morin anorthosite mass. Dotted line indicates present level of exposure. Reprinted by permission of the Geological Society of Finland (Note this figure was first published by Martignole and Schrijver, 1970a, and has subsequently been reproduced elsewhere without proper attribution: Laurin et al., 1972, Séguin 1976)

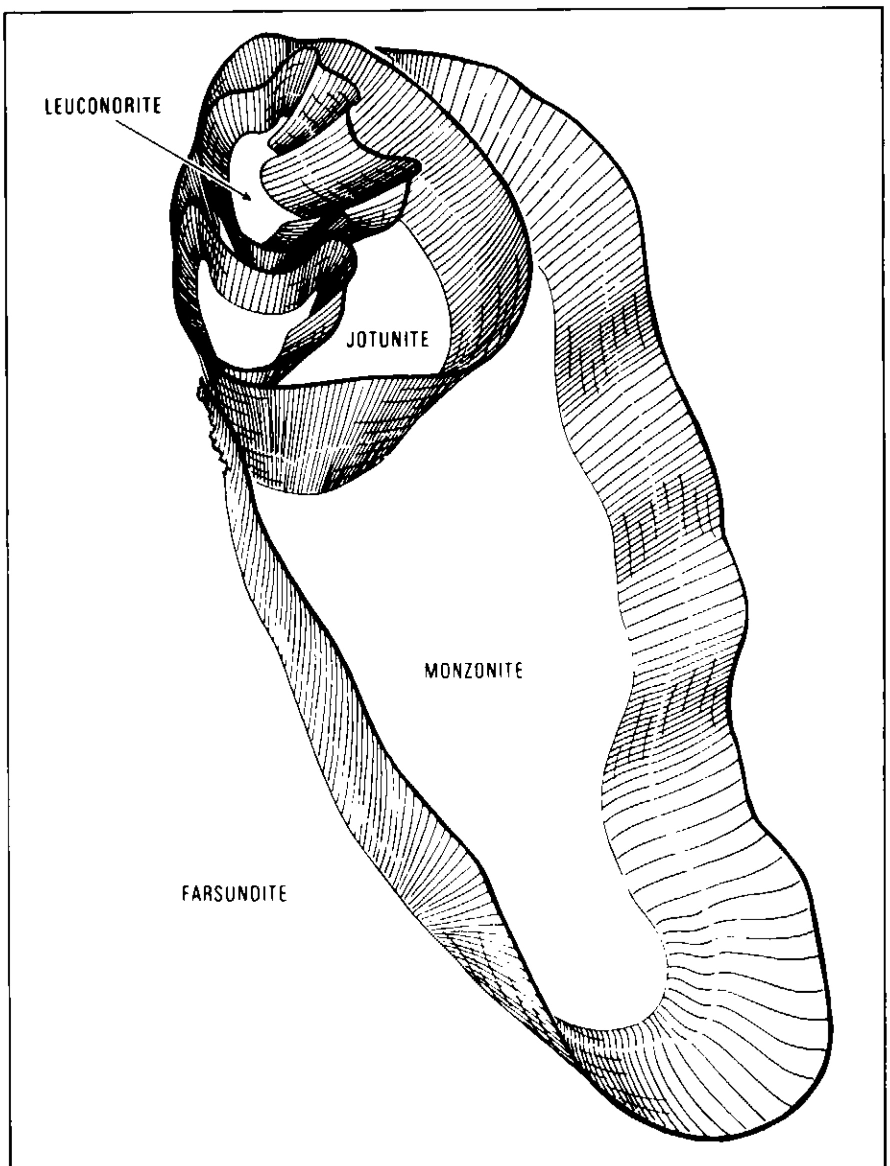

Figure 4
Possible form of central section of Lac-Croche. From Schrijver (1975) by permission of Geotektonische Forschungen.

volume of associated farsunditic (acidic) rocks in view of the strong iron enrichment observed in the intermediate rocks (Skaergaard type trend). Maintaining the hypothesis of a basaltic parent, the farsundite could represent either an anatectic aureole due to melting accompanying or preceding anorthosite intrusion, or a separate intrusion following the same path through the crust. If, on the other hand, the parental magma were intermediate in composition (dioritic, jotunitic) it could account for the proportions of anorthositic and acidic rocks, but then a separate intrusion of troctolite would have to be postulated.

As the present position of the various plutonic rock units is due, at least to some degree, to post-magmatic ascent during protracted consolidation and cooling of the complex, a study of chemical trends of differentiation is not straightforward (Martignole, 1974 a). Nevertheless, density measurements on rocks and density calculations from chemical analyses have shown that such features as layering in basic and intermediate rocks as well as the presence of plagioclase xenocrysts in acidic rocks can be interpreted as being due to magmatic processes of gravity accumulation and convection currents (Martignole, 1974 b). The relatively low viscosity that seems to be required in such processes is in conflict with the highly viscous intrusion that is deduced from field observations. One way out of this conflict is to propose a model in which the time of consolidation is long enough for gravity accumulation and convection currents to operate, even in a highly viscous magma.

Conceivably, this condition can only be attained in katazonal (deep metamorphic) environments where sufficient time would be available for repeated intrusion in the same complex, with possible hybridization and differential movement of magmatic masses, the viscosity of which would be at the upper limit of what is usually considered the liquid state (10^{12} - 10^{14} poises, Martignole, 1974 b).

Protracted cooling is corroborated by widespread retrograde mineral intergrowths (diablastites) in the plutonic rocks. In the troctolite, bytownite reacted with forsterite to form enstatite, diopside and spinel in corona textures. In opdalitic and farsunditic rocks of low $Mg/(Mg + Fe^{++})$ ratio ($<$ 0.45) plagioclase and orthopyroxene reacted to form garnet and quartz, with or without clinopyroxene. As these reactions have gentle positive slopes in P-T diagrams, they have been interpreted as due to cooling at high pressure rather than to prograde metamorphism (Martignole and Schrijver, 1970, 1971, 1973). According to experimental phase-studies on troctolites (e.g., Emslie, 1970 a), this cooling could have occurred at pressures of about nine kb.

The Lac-Croche Complex (Fig. 2), which is on the northeastern side of the Morin Complex is described in a monograph by Schrijver (1975) who shows that it represents the deformed root of a composite diapir consisting mainly of farsundite and monzonite, and subordinate leuconorite and jotunite. Contacts and foliation planes outline a composite basin centred on a downward pointing cone the axis of which is subvertical (Fig. 4). He concludes that "regional metamorphism of granulite facies took place during diapirism and outlasted it", and that "both metamorphism and diapirism outlasted regional deformation".

The St-Didace Complex (Fig. 2) in the eastern part of the area has not been described in terms of simple structural units. The most prominent lithology of the pluton is a coarse-grained granitic rock (adamellite) intruded by several masses of leuconorite. The form of the pluton is difficult to reconstruct because its northwestern boundary is along a major fault, and its southeastern boundary is covered by recent deposits.

The northern end however, appears to be a deformed noritic basin. This noritic mass rests conformably on south-dipping metasediments and is locally stratified. a chilled margin (calcic andesine, orthopyroxene and some orthoclase) a few metres thick, is overlain by a noritic zone (plagioclase An 47) which grades upward into a leuconoritic zone with two pyroxenes. The top layer of this mass is formed by pure labradorite anorthosite. Local occurrences of corundum, spinel and cordierite in the norite suggest that assimilation of pelitic material may have favoured the precipitation of plagioclase (Martignole, 1969 a).

The other noritic masses which intrude the adamellite in the central part of the St-Didace Complex are not stratiform.

Isotopic, total-rock, Rb-Sr data have been published for two of the three complexes by Barton and Doig (1972; 1974). All plutonites of the Lac-Croche Complex except the central, youngest, granite lie on a single, 13 point, isochron of 1124 ± 27 Ma. Interpreted by the authors as an age of crystallisation, it has been reinterpreted by Schrijver (1975) as an age of *recrystallisation* after final emplacement.

Acidic members of the St-Didace Complex lie on a single, 8 point isochron of 1163 ± 51 Ma which is not significantly different from the one obtained for the Lac-Croche Complex. Isotopic data are still missing for the Morin Complex.

Similarities in fabric, mineralogy, composition and age strongly suggest a genetic link between the plutonic complexes of the region. The characteristic differences in gross form - domical for the Morin Complex and conical for the Lac-Croche Complex - can be explained in a number of ways. The simplest would seem to be that they have been brought about during diapirism: the upper part of a relatively dense, anorthositic complex is exposed, whereas the lower part of a relatively light, and more ductile, farsunditic complex is exposed. In this explanation we do not have to assume either major, pre-emplacement synforms or antiforms, or regional, post-emplacement differential uplift. A question remains, however, as to why some complexes are essentially anorthositic and others farsunditic. Clearly, there is no reason to assume that the Lac-Croche Complex diapir has ever been associated - at, above or below its present level of exposure - with a major anorthositic facies. From the moment of its coalescence into a coherent, composite body and its effective diapiric ascent, it was essentially a farsunditic mass.

Figure 5 incorporates our present understanding of the gross geometrical relations in this terrane. As shown in this figure, we think it likely that *a regionally extensive layer of anorthosite and norite is present at depth, and that this layer took part in diapirism only locally and partially.*

Envelopes and Country Rock

The three major complexes have been emplaced in rocks of essentially supracrustal origin. They form two distinct sequences: a lower sequence, containing granulites, amphibolites and some migmatites, and an upper one which has the lithological characteristics of the Grenville Supergroup (marbles, metapelites, quartzites, etc ...). Although major changes in lithology and tectonic style frequently occur near the interface of the two sequences, no unambiguous features (conglomerate, unconformity) have been found to identify a basement and a cover. Also, the relationships between the two sequences change from east to west with increasing grade of metamorphism and deformation.

North of the St-Didace Complex, several thousands of metres of granulites and amphibolites, gently dipping to the south are conformably overlain by the Grenville Supergroup, with a migmatite zone straddling the boundary between the two sequences.

East of the Morin Complex, granulites and rocks of the Grenville Supergroup are involved in a set of recumbent folds which obscures stratigraphic relations. Nevertheless, a distinctive formation, about 50 metres thick, occurs along the anorthosite lobe. This formation consists of quartzite, quartzofeldspathic gneiss and pyroxene amphibolite. It is stratigraphically overlain by garnet-sillimanite gneisses and may represent the lowermost unit of the Grenville Supergroup. If this is correct, it is conceivable that the buoyant anorthosite has been arrested by a quartzitic layer at the interface of a basement and its metasedimentary cover (Emslie, 1970 b).

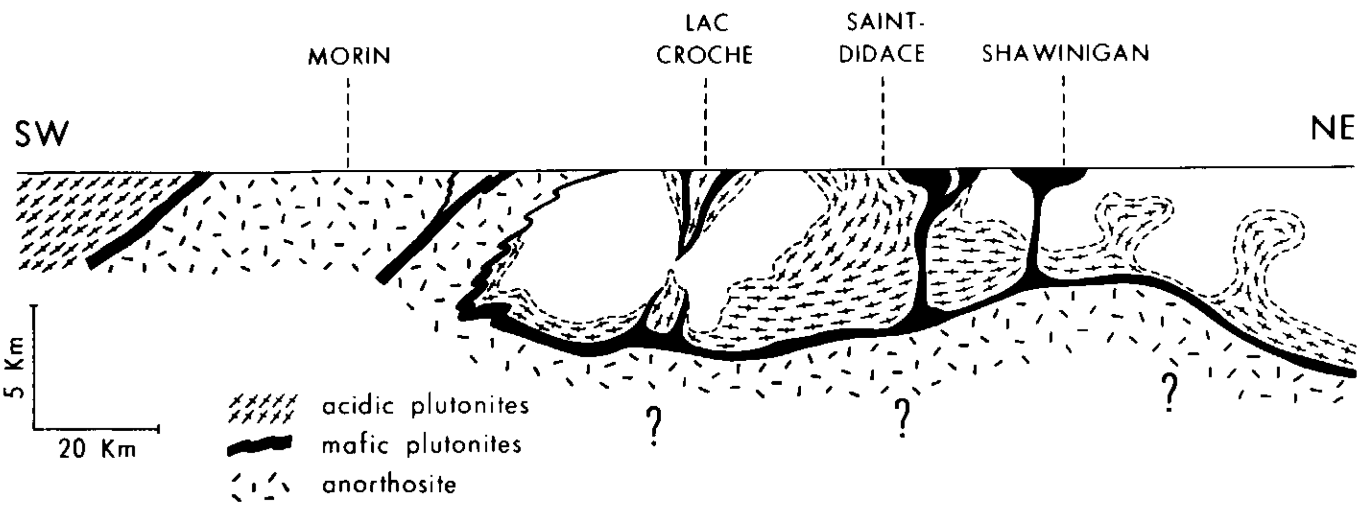

Figure 5
Hypothetical cross-section through plutonic complexes of the southern part of the Grenville province (from Martignole, 1975, modified).

South of the Morin Complex, large irregular semi-domical masses of granulite are separated by pinched synclines of metasediments including a large proportion of marble and metapelites. The granulites are strongly remobilised and are reminiscent of the well-known mantled gneiss domes of Finland. But here also, basal conglomerates have not been recognized and deformation is too intense to allow for a confident distinction of basement and cover (Barraud, 1977).

The hypothesis for the existence of a sialic pre-Grenville basement, for which geological evidence is weak and circumstantial at best, is reinforced, however, by radiometric dating of the supracrustal rocks. According to Barton and Doig (1973), the granulites underlying (or intercalated with?) the Grenville Supergroup have whole-rock Rb-Sr isochrons of 1576 ± 19 Ma to 1400 ± 58 Ma (lower Paleohelikian age). Therefore, the Grenville Supergroup, which was metamorphosed about 1094 ± 43 Ma ago, would have been deposited in upper Paleohelikian. This age would be in agreement with the 1310 Ma age found in metavolcanics associated with Grenville metasediments in Ontario (Silver and Lumbers, 1966).

Metamorphism

Metamorphism has reached the granulite facies in the entire region, but important differences in both pressure and temperature exist between the St-Didace area and the Morin area. Sillimanite is the ubiquitous aluminium silicate, but locally and rarely it is associated with andalusite, kyanite or orthopyroxene. South of the Shawinigan norite, a unique occurrence has been found of coexisting sillimanite, kyanite, and andalusite, suggesting that P-T conditions were not far from those of the aluminium silicate triple point. North of the Lac-Croche Complex, kyanite is locally associated with sillimanite, *but only in late- or post kinematic migmatites and thus indicates cooling at relatively high pressure*. South of the Morin Complex, sillimanite was formed together with orthopyroxene and quartz at the expense of cordierite and garnet. This reaction is thought to represent extreme conditions of metamorphism.

A similar regional variation in metamorphic grade is reflected by calc-silicates assemblages in the St-Didace and the Morin area. South of the Morin Complex, wollastonite is regionally developed, probably in equilibrium with a CO_2-bearing fluid phase (with the mole fraction of CO_2 in the fluid phase greater than 0.3), which implies extremely high temperature if fluid pressure was high. On the other hand, in the St-Didace area, wollastonite, coexisting with grossularite, is restricted to the contact of the norite (fluid phase with mole fraction of CO_2 less than 0.3; Martignole, in prep.).

The thermal climax of regional metamorphism coincided grossly with the emplacement of plutonites in both time and space. Along the contact of the Shawinigan norite, garnet broke down to a cordierite-orthopyroxene-spinel assemblage which is stable at temperatures of about 1000°C between five and six kb, under low oxygen fugacity. Around the Morin Complex, extremely high temperature is indicated by the development of wollastonite or orthopyroxene-sillimanite assemblages *which make it impossible to distinguish between regional and contact metamorphism*. At this climax, this composite, plutonic, metamorphism may have reached 900°C at pressures approaching nine kb.

Reaction features indicative of retrogression, well displayed by the plutonites (see above), are also abundant in metasediments where wollastonite is rimmed by quartz, or has broken down to grossularite and quartz where it was in contact with plagioclase or scapolite. Idocrase also developed in calc-silicate rocks when diopside, plagioclase and calcite reacted during decreasing temperature and increasing water activity (Martignole, 1975). Retrograde gradients drawn from retrograde reactions from both plutonites and metasediments are indicative of cooling at high pressure, under low but increasing activity of H_2O.

Tectonics

Regional tectonics cannot be described in terms of conventional concepts of regional trends or superimposed folding.

It appears that the location, physical properties and movements of the plutonic masses had a great if not dominant influence on the regional stress field, and thus have determined the style of regional deformation and the map-pattern at most scales of observation.

Most rocks show mineral lineations and foliation planes which, in metasediments, are about parallel to bedding planes. Minor folds are common, and their axes are parallel to the regional mineral lineation. Axial plane foliation occurs in the hinge zones of some minor fold.

East of the Morin Complex, the main axial trend follows the curving contact of the anorthosite mass and thus changes from SSE to S (See Fig. 2). Here supracrustal rocks are intensely folded into a set of recumbent folds (F_2) involving the anorthosite lobe as well. Fabric elements have the same geometrical characteristics in both the gneissic anorthosite and the supracrustal rocks. This is one of the reasons for attributing the generation of F_2 folds to eastward spreading of the anorthosite, after its diapiric ascent. These folds, however, do not represent the first episode of folding. South of the St-Didace Complex, SSE plunging folds (F_2) refold ancient E to NE trending structures (F_1), giving rise to crescent, hooked, and saddle patterns of superimposed folding. The Shawinigan norite is deformed by F_2 folding, but noritic dykes cutting older folds (F_1?) shows that this intrusion is probably younger than F_1.

F_2 folding in the St-Didace and Morin areas is contemporaneous with the climax of metamorphism, orthopyroxene in metabasites and sillimanite in metapelites are developed in L_2 lineation. In the Morin area, F_2 folds overprint most of the older structures, but relicts of deformed folds show that an F_1 set of folds may have been present and could be the equivalent of the incompletely overprinted F_1 set of folds visible south of the St-Didace Complex.

Late, minor, NE trending deformations locally disturb F_2 or L_2 structures.

Discussion

Recent studies in the southern part of the Grenville province have given rise to a debate on the relative timing of the main tectonic and petrological events.

Even if it is accepted that a sialic pre-Grenville basement exists, there are still uncertainties about the limits of this basement, even in regions where detailed maps are available. At the moment, the consensus of opinion is that plutonites of the anorthosite suite do not form part of this basement because they are locally intrusive into the Grenville Supergroup. As well, it is quite likely that Grenville sediments were metamorphosed under granulite facies conditions prior to anorthosite emplacement which also took place under high-grade conditions.

Turning now to the markers available to establish an absolute time-scale, the 1124 Ma age of the Lac-Croche Complex and the 1094 Ma age of the Grenville metasediments are not significantly different, they probably represent the time of closure of the isotopic system after the thermal climax of high-grade grenvillian metamorphism (Schrijver, 1975, p. 100). As the presence of older ages in the granulites (1576 and 1460 Ma) is in agreement with circumstantial geological evidence for the existence of a basement, a remaining problem in temporal relationships is therefore the one concerning emplacement of plutonites on one hand and their high-grade metamorphism on the other.

Taking the best known complex, the Lac-Croche Complex, it seems quite unlikely that a pre-existing crystalline plutonic suite, distinctly and markedly older than the thermal climax of metamorphism, was isotopically homogenized about 1100 Ma ago, for at least two reasons: 1) mineralogically similar granulites of the country rock were not homogenized as they form isochrons corresponding to about 1500 Ma, 2) within the complex there is no evidence of remobilization processes that could conceivably contribute to thorough homogenization, chemically or isotopically.

We see the evolution of this complex, as well as of the other two, as a continuous series of events, from magmatic crystallization through emplacement and to metamorphic recrystallization, uninterrupted by periodic freezing and subsequent remobilisation. Tracing this type of history isotopically, and trying to distinguish ages of crystallization from ages of recrystallization will demand more than the reconnaissance-type, whole-rock, Rb-Sr studies carried out to date. Radiometric data are needed on dykes, enclaves and mineral separates of samples from rock bodies whose place in the relative time-scale is well established.

Conclusions

From a study of field relations (contacts, dykes, enclaves), structure, petrography and published radiometric data of both plutonites and country rock it appears that:

1) Granulite-facies metamorphism, deformation, and emplacement of plutonites took place shortly before 1100 Ma ago. This was followed immediately by regional retrograde metamorphism of intermediate to high load pressure and very low but gradually increasing partial pressure of water.

2) The bulk of the plutonites in all complexes was emplaced in the solid state, i.e., diapirically, and came to rest near the interface of pre-Grenville basement and Grenville metasediments.

3) Locally diapirism and sparse igneous activity outlasted deformation, if we except gentle and minor NE trending refolds.

4) Prograde metamorphism of granulite facies took place before and during diapirism; it may locally have outlasted diapirism. The immediately following retrograde metamorphism outlasted diapirism.

Neither metamorphism nor deformation can clearly be separated into a "regional" and a "local" component. At the presently exposed level, emplacement of plutonites, deformation and metamorphism took place penecontemporaneously.
We prefer to see the emplacement of solidifying magmas and finally crystalline rocks, as the tangible and thus fundamental cause of the petrotectonic evolution in this area.

Acknowledgements

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