

THE DELORO ANOROGENIC IGNEOUS COMPLEX, MADOC, ONTARIO. I. GEOCHEMISTRY AND FELDSPAR MINERALOGY OF THE FELSIC PLUTONIC ROCKS

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ABSTRACT

The Late Proterozoic anorogenic Deloro igneous complex, Madoc, Ontario, contains the association hypersolvus syenite, peralkaline hypersolvus granite, and granophyric granite. The sequence shows a progressive increase in Si, K, Cs, Rb, Ta, Hf and Zr, and an overall decrease in Mg, Ca, Sr, Ba, Eu, Sc and Co. Hypersolvus granites exhibit an increase in *REE* over syenites, but the granophyric granites, more evolved, are poorer in *REE*. Low microcline of average composition 96% Or coexists with pure low albite, indicating a final temperature of equilibration below 300°C. The suite was produced by epizonal fractionation of crystals from a mafic syenitic or gabbroic liquid emplaced in the Grenville crust during an episode of extension. Anatectic reactions may have contributed to the formation of the granophyric granite. The feldspars recrystallized hydrothermally during episodes of reheating approximately 150 and 800 Ma after emplacement. These static low-temperature events account for the conversion of the K-feldspar to low microcline, the apparent lack of grid-tinned domains, and the partial resetting of the Rb-Sr and K-Ar systems.

Keywords: Deloro igneous complex, anorogenic magmatism, syenite, hypersolvus granite, granophyric granite, feldspar mineralogy, ion exchange, reheating, Grenville Province, Ontario.

SOMMAIRE

Le complexe igné anorogénique de Deloro (Madoc, Ontario), d'âge Protérozoïque tardif, contient l'association syénite hypersolvus, granite hypersolvus hyperalkalin, et granite à texture granophyrique. La séquence montre une augmentation progressive en Si, K, Cs, Rb, Hf et Zr, et une diminution en Mg, Ca, Sr, Ba, Eu, Sc et Co. Les granites hypersolvus sont enrichis en terres rares par rapport aux syénites, mais le granite granophyrique, plus évolué, en est appauvri. Le microcline ordonné, de composition moyenne Or₉₆, coexiste avec une albite pure ordonnée, ce qui indique une température d'équilibration finale inférieure à 300°C. La suite résulterait de la cristallisation fractionnée à faible profondeur d'un magma-parent mafique, syénitique ou gabbroïque, mis en place dans la croûte grenvillienne lors d'un épisode d'extension. Des réactions anatectiques pourraient avoir contribué à la formation du granite granophyrique. Les feldspaths ont pu recrystalliser en présence d'une phase fluide lors de légers réchauffements survenus environ 150 et 800 Ma après la mise en place. Ces événements statiques, à basse température, expliquent la mise en ordre finale du feldspath potassique, l'absence de

maillage quadrillé évident dans le microcline, et la ré-équilibration partielle des systèmes Rb-Sr et K-Ar.

Mots-clés: complexe igné de Deloro, magmatisme anorogénique, syénite, granite hypersolvus, granite granophyrique, minéralogie des feldspaths, échange d'ions, réchauffements, province du Grenville, Ontario.

INTRODUCTION

In his classic investigation of the petrogenesis of felsic plutonic rocks, O.F. Tuttle (1952, Tuttle & Bowen 1958) chose a sample of granite from the Deloro complex (referred to as Madoc granite) to illustrate the hypersolvus texture. Hypersolvus granites characteristically are anorogenic and crystallize in an epizonal environment (*e.g.*, Martin & Bonin 1976). The pristine state of the exsolution texture in the perthite grains, which led Tuttle to choose the Deloro granite as a type example, indicates that the complex cooled in a relatively static environment and that the texture has not been significantly modified since then. Yet the setting of this anorogenic pluton, in the Central Metasedimentary Belt of the Grenville Province (Wynne-Edwards 1972, Stockwell 1982, Fig. 20), is far from being one of tectonic quiescence!

The Deloro syenite - granite complex, which covers an area of about 35 km², is located 6 km northwest of Madoc, southeastern Ontario. The crescent-shaped body occurs in the so-called "Hastings metamorphic low", which is the only part of the Grenville Province in Ontario to contain greenschist-facies rocks (Lumbers 1967, Carmichael *et al.* 1978, Anovitz & Essene 1986). These metamorphic host-rocks consist of 1) the Grenville Supergroup, subdivided into Hermon (older) and Mayo Groups (Lumber 1967), and 2) the Flinton Group (Moore & Thompson 1980). Silver & Lumbers (1966) dated two samples of metarhyolite from the Bancroft - Madoc area; these were taken from the dominantly basaltic to andesitic Tudor Formation, at the base of the Hermon Group, and give an age of 1286 ± 15 Ma (U-Pb method using zircon; revised decay-constants). This is widely considered to be the age of the base of the Grenville Supergroup in southeastern Ontario. Gneissic basement rocks dated at 1334 ± 24 Ma are exposed in Chandos Township, 65 km to the north (Heaman *et al.* 1984), but are not found in the Madoc area.

Wilson (1940), Saha (1959) and Hewitt (1968) interpreted the intermediate and felsic volcanic rocks to the east of the Deloro complex to be "basement", *i.e.*, these were assigned to the Tudor Formation, Hermon Group. Bartlett *et al.* (1984) pointed out that the Deloro granite occupies a subcircular ring structure that encloses intermediate to felsic volcanic rocks distinctly less deformed than those of the Tudor Formation. Bartlett *et al.* also suggested that the emplacement of this high-level complex postdated the deposition of the Flinton Group, as the eastern boundary of the Deloro *appears* to truncate the Madoc syncline of post-Flinton age. Furthermore, in view of the apparent lack of deformation in the Deloro suite and the spatially associated volcanic rocks, and the penetrative deformation that affected the Flinton Group in the Madoc area, most investigators have considered the Deloro to be "post-tectonic", *i.e.*, emplaced *after* the two episodes of deformation and metamorphism that affected the Flinton Group (Moore & Thompson 1980, Easton 1986).

The definitive geochronological data, reviewed below to provide a framework with which to explain the mineralogical results, show that the consensus about the age of the Deloro is in error. This finding necessarily raises questions concerning the deposition and metamorphism of the Flinton Group, at least in the Madoc area; these questions will be examined briefly in the Discussion section, mainly to focus further investigations in the area.

The purpose of our geochemical and mineralogical investigation is threefold: 1) to provide information on the trace-element geochemistry of the Deloro syenite-granite suite, 2) to characterize the feldspar mineralogy of this type example of hypersolvus granite (Tuttle 1952), and 3) to provide a working hypothesis for the petrogenesis of the suite using geochemical and mineralogical indicators, evaluated in the light of the importance of open-system rock-fluid interaction, as revealed by the disturbances in the isotopic systems.

AGE OF THE DELORO PLUTON

There have been many efforts to date the Deloro pluton, in view of its importance in defining a tectonic setting. Silver & Lumbers (1966) reported on U-Pb geochronological studies using zircon from various plutons in the Bancroft - Madoc area. Two samples of zircon were taken from the coarse-grained hypersolvus granite facies of the Deloro pluton. Both were found to be discordant and consistent with an age greater than 1200 Ma (S.B. Lumbers, pers. comm., 1986). Revised U-decay constants indicate an age of 1226 ± 25 Ma (L. Heaman, pers. comm., 1987). Heaman *et al.* (1987) have confirmed that the Deloro pluton belongs to the oldest of the three epi-

sodes of igneous activity recognized in the Central Metasedimentary Belt. It was emplaced toward the end of the 50-Ma interval between 1290 and 1240 Ma. This new findings is confirmed by results on zircon obtained by the Geological Survey of Canada (1245 ± 3 Ma; O. van Breemen, pers. comm., 1987; sample of hypersolvus granite collected from first roadcut into granite along Highway 7, 7.2 km west of Madoc).

The suite of rocks covers an unusually broad range of Rb/Sr values, from 0.6 to 20 (Bell & Blenkinsop 1980). It should thus be amenable to radiometric dating by the Rb-Sr method. The early work (Wanless & Loveridge 1972), based on six whole-rock samples (one of aplite and five of granite), gave a relatively imprecise age of 1096 ± 48 Ma (Bell & Blenkinsop 1979) and an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7036 ± 0.0030 . Twenty-seven samples were analyzed by Bell & Blenkinsop (1979, 1980) in an attempt to obtain a more precise age. However, they too found pronounced scatter in their data.

In view of the high-precision results obtained on zircon, the scatter and the false age are now interpreted to reflect the extensive migration of fluid set in motion during or following the regional metamorphism that affected the Central Metasedimentary Belt. The Rb-Sr system of many plutons was reset by this event; where a pluton is only incipiently disturbed (*e.g.*, the Tallan Lake granodiorite, approximately 45 km northwest of Madoc), the Rb-Sr isochron agrees with the U-Pb (zircon) isochron away from obvious fractures, but gives a false age near fractures along which an aqueous fluid circulated and alkali metasomatism occurred (Heaman *et al.* 1986). The fact that the volume of rock predominated over that of the fluid during this episode of hydrothermal circulation suggests that the initial $^{87}\text{Sr}/^{86}\text{Sr}$ value calculated by Wanless & Loveridge (1972) is close to the original one for the Deloro suite.

If the disturbance had been thorough in the Deloro pluton, one could expect a precise Rb-Sr age. The imprecision in the "isochron" indicates that the system was inhomogeneously reset, as in the Tallan Lake example. But to complicate matters, there is evidence, among the twenty-seven samples analyzed by Bell & Blenkinsop (1979, 1980), for a still younger isochron, at 450 Ma (K. Bell, pers. comm., 1986). We consider this event to have been less extensive (*i.e.*, restricted to only some of the zones of earlier hydrothermal disturbance and metasomatism) and at a lower temperature than the earlier disturbance.

The existence of a mild Lower Paleozoic reheating in the area is supported by the $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronometry results of Lopez-Martinez & York (1983), who investigated the cooling history of the Cordova gabbro, 10 km west of the Deloro stock. They documented an age of 1143 ± 13 Ma on hornblende and 450 Ma using hydrothermally affected

plagioclase. Clark & Hanes (1985) documented the existence of the Ordovician event using the same approach on the Elzevir trondhjemitic batholith (Pride & Moore 1983), located 15 km north of the Deloro pluton and emplaced at approximately the same time (1240 Ma ago, determined by Rb-Sr method: Bell & Blenkinsop 1980).

Conventional K-Ar dating has been carried out on alkali amphibole from the Deloro complex. Macintyre *et al.* (1967) reported ages of 992 and 989 Ma (error $\pm 4\%$). Lopez-Martinez (1981) obtained an age of 1029 ± 3 Ma on the same material using the stepwise $^{40}\text{Ar}/^{39}\text{Ar}$ method. These results illustrate that the K-Ar system, like the Rb-Sr system, was reset by recrystallization of the rock-forming

minerals in the presence of a fluid phase otherwise equilibrated with the alkaline rocks.

PREVIOUS WORK AND FIELD RELATIONSHIPS

The pluton was first recognized by Wilson (1940), who later wrote about the occurrences of base-metal and silver mineralization in its aureole (Wilson 1965). Saha (1959) subdivided the complex into separate intrusive phases, and studied the mode of emplacement of the body. He considered the syenite to be a product of assimilation of gabbro by granitic magma (*sic*) during its forceful emplacement. Saha (1959) interpreted gabbro along the western border of the pluton (Fig. 1) to be the country rock. Bart-

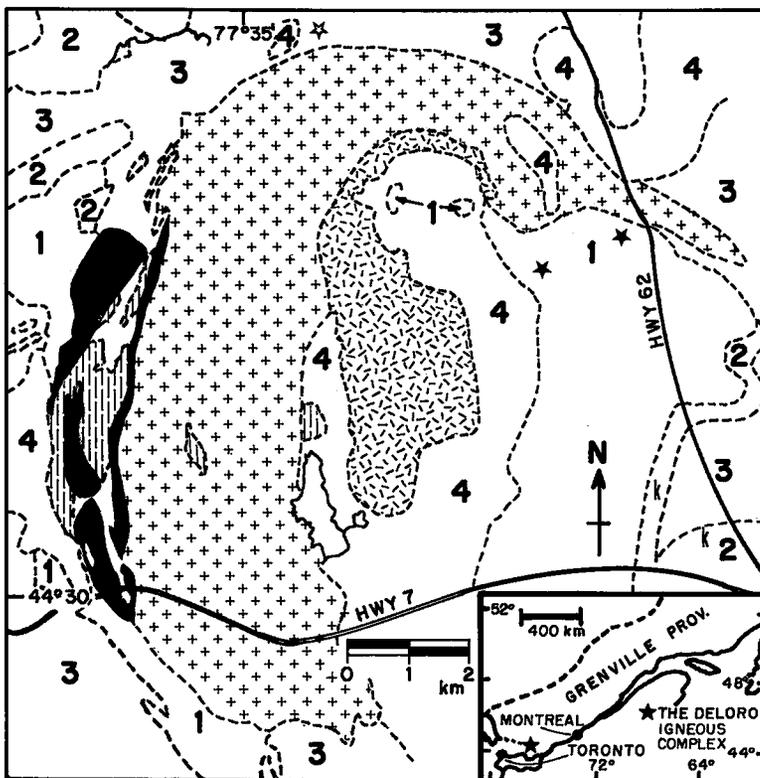


FIG. 1. Geological map of the Deloro pluton, southeastern Ontario, showing the distribution of the major intrusive phases and the country rocks. The map-units are modified from the map of Saha (1959): black unit: syenite; vertical dashes: gabbro; plus signs: peralkaline granite; central unit (patterned): granophyric granite. Numbered units: 1 metavolcanic rocks interpreted to belong to the Hermon Group (basement) by Wilson (1940), Saha (1959) and Hewitt (1968), but now considered likely to be related to the complex (Bartlett *et al.* 1984, this work), 2 metapelitic rocks, 3 marble, 4 Paleozoic cover. Kuehnbaum (1973) collected his samples of syenite and hypersolvus granite from roadcuts along Highway 7. The samples of rhyolite and of a mineralized vein are indicated by black and white stars, respectively. The approximate location of the kyanite occurrences (Thompson 1972) is shown by a "k".

lett *et al.* (1984) viewed the gabbroic rocks as part of the Deloro suite, a view consistent with what is found in numerous other anorogenic complexes the world over. Kuehnbaum (1973) analyzed representative specimens; he proposed that the hypersolvus granite, which is slightly alkaline, formed at a pressure close to 1 kilobar. He recognized that late albitization had affected some feldspar bulk-compositions, and that not all the riebeckitic amphibole (Abdel-Rahman 1982) is magmatic. Wu & MacRae (1986) have recently reported on the geochemistry of this syenite - granite complex, but the raw data on which they based their petrogenetic model (see below) have not been published.

The rocks of the Deloro suite are massive, and lack a deformation fabric. Both syenite and granite contain inclusions of gabbro, diabase, and volcanic rocks (Saha 1959). Dykes of peralkaline granite cross-cut the syenite (Abdel-Rahman 1982); there is a gradational eastward increase in the quartz content of the syenite. The peralkaline granite is injected by thin veins and irregular bodies of granophyric granite, considered the youngest intrusive phase, and possibly to have arisen by devitrification of glass (Kuehnbaum 1973). The granophyric granite is in sharp contact with the peralkaline granite and exhibits a very fine-grained texture that coarsens away from the contact.

The Deloro complex is partly concealed by Ordovician limestone of the Black River Formation (Fig. 1). Fault-related calcite - fluorite - barite - galena veins cut the Ordovician rocks and the underlying

Grenville marbles and granite (Melanson & Robinson 1982) and are expressions of the mild disturbance in the area in Lower Paleozoic time.

THE APPROACH USED

The present study is based on geochemical and mineralogical data reported for selected samples of the quartz-bearing syenite, peralkaline granite and granophyric granite. Most samples are taken from Kuehnbaum's thesis collection. He analyzed representative specimens for the major elements using the X-ray-fluorescence technique. Kuehnbaum also determined the concentration of Fe^{2+} by titration, and sodium by atomic absorption. The first author used the X-ray-fluorescence technique for Zr, Sr, Y, U and Th, and neutron-activation analysis for the rare earths, Na, Ba, Rb, Cs, Cr, Sc, Co, Hf and Ta (technique of Barnes & Gorton 1984). A precision of better than 5% was found for most elements determined by INAA.

The samples were irradiated at the Slowpoke-2 nuclear reactor at the University of Toronto. They were counted 7 and 35 days after irradiation. Concentrations of trace elements were calculated by comparing the area of the peaks in samples to those of a laboratory standard (UTB1) after correction of the peak areas for interference, differences in sample weight, and time elapsed since irradiation (Abdel-Rahman 1982). Chondrite values used in the normalization of the absolute concentrations are those of the Leedy chondrite (Masuda *et al.* 1973) divided by 1.2 (*cf.* Taylor & Gorton 1977).

The feldspars present in the same specimens and selected additional samples were characterized by X-ray diffraction. A powder-diffraction pattern was recorded using a Guinier-Hägg focusing camera, synthetic spinel standard, $a = 8.0833 \text{ \AA}$ at room temperature and $\text{CuK}\alpha_1$ radiation. The peak positions were measured, corrected, indexed and input into the cell-parameter refinement program of Appleman & Evans (1973). The results are relevant to the dominant feldspar structures in a small (approximately 1 mm^3), single grain of perthite; where the rock is aphanitic, 1 mm^3 of pulverized whole rock is used for the analysis. Among the additional samples examined are two samples of aphanitic felsic volcanic rocks from inside the outer ring (Fig. 1) and the pink feldspar that accompanies arsenopyrite - gold mineralization in a dyke near the northwestern edge of the pluton.

PETROGRAPHY

The syenite is a medium- to coarse-grained rock that consists mainly of perthite, clots of calcic amphibole (ferro-actinolite to hastingsite) and interstitial quartz (less than 10% by volume). The feldspar

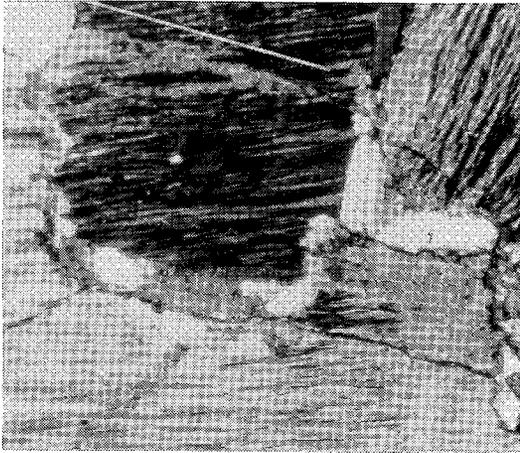


FIG. 2. Characteristic texture of a hypersolvus granite from Deloro in which the grains of turbid microcline perthite are lined by a film of post-exsolution albite. Zone of Na-for-K exchange occurs along a fissure located above (and parallel to) the white line. Width of field of view: 5 mm.

grains are mesoperthitic and subhedral. The K-feldspar is turbid, and shows no sign of cross-hatched domains. Aenigmatite is a rare accessory in the clots of mafic minerals. The hypersolvus syenite grades into peralkaline hypersolvus granite eastward.

The peralkaline granite consists of quartz (locally showing undulatory extinction), mesoperthite and alkali amphibole, with accessory annite, ilmenite, zircon, fluorite, calcite, hematite, chlorite, pyrite and titanite. The K-feldspar is pink and turbid (Fig. 2; Tuttle & Bowen 1958, Plate 2), and shows simple twins according to the Baveno and Carlsbad laws. There generally is no sign of cross-hatched domains typical of microcline formed by inversion from orthoclase. Tuttle (1952) noted the presence of perthite but did not specify whether or not the K-feldspar host consists of microcline; both Saha (1959) and Hewitt (1968) mentioned the presence of microcline in passing, but did not mention how this phase was identified. Alkali amphibole forms ragged, poikilitic grains; it seems to have crystallized late, possibly even after exsolution in the alkali feldspar in part.

In some specimens of syenite and granite, all the albite in the rock is within the perthite grains (*cf.* Tuttle & Bowen 1958, Plate 2). Saha (1959) pointed out that there is a gradation between such rocks, in which the perthite grains lack completely a rim of albite, and rocks in which there is a thin (<1 mm) rim of late albite along the edge of perthite grains (Fig. 2).

The granophyric granite is a pink leucocratic rock composed of radiating, spherulitic intergrowths of quartz and turbid perthite, and accessory muscovite, biotite, magnetite, pyrite, fluorite and zircon. The K-feldspar shows no cross-hatched domains.

Two samples of rhyolite also were examined. One (4-1) is pink and massive, and represents aphyric devitrified obsidian. The other (4-4) is ignimbritic, with flattened fragments of pumice appearing as pinkish lenticular masses. The mineralized vein is lined with pink grains of coarse, untwinned feldspar; arsenopyrite crystallized late, in the centre of the vein.

GEOCHEMISTRY OF THE DELORO SUITE

Major elements

The twelve analyzed samples define roughly linear trends in variation diagrams (Fig. 3) as a function of differentiation index (Thornton & Tuttle 1960), which ranges between 68 and 95. Calcium, Fe and Mg decrease gradually with differentiation index, whereas K shows a steady increase. Aluminum and sodium concentrations vary only slightly with D.I. The bulk compositions are plotted in three triangular diagrams, Qtz - Ab - Or (Fig. 4A), An - Ab -

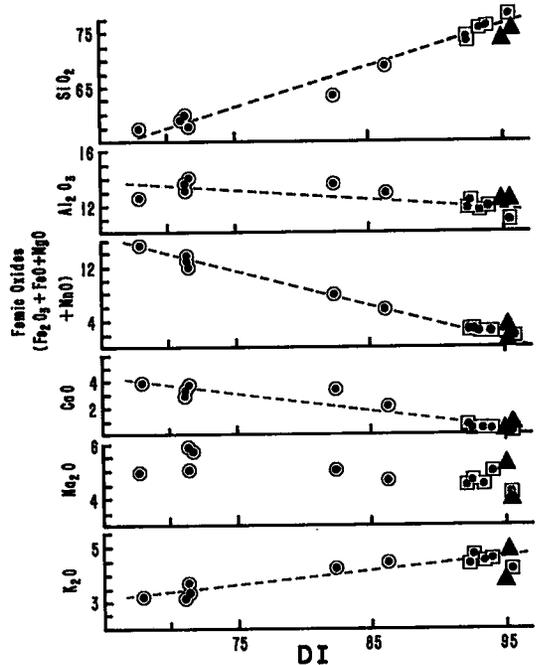


FIG. 3. Variation of the major elements, expressed as oxides (wt.%) as a function of differentiation index (Thornton & Tuttle 1960). The following symbols are used in all the other figures. Circles: syenites; squares: peralkaline granites; triangles: granophyric granite. Straight lines have been drawn where the variation is regular.

Or (Fig. 4B) and a part of the plot $\text{SiO}_2 - \text{Al}_2\text{O}_3 - (\text{Na}_2\text{O} + \text{K}_2\text{O})$ (Fig. 4C). Kuehnbaum (1973) presented the data using similar diagrams in his thesis.

In Figure 4A, only seven of the twelve bulk-compositions follow the trend expected of magmatic evolution of a syenitic parental melt on the Ab-Or join toward the H_2O -saturated minimum at a confining pressure of 1 kilobar. The five other points appear to be shifted to the left, toward the Ab - Qtz sideline. The five sodic bulk-compositions range in D.I. from 71 to 95; there does not seem to be any link between D.I. and extent of displacement from the expected magmatic trend, so that projection of the bulk compositions onto the D.I. = 100 plane is not considered responsible for the shift.

We attribute the displacement in primary bulk-compositions toward the Ab - Qtz sideline mainly to a postmagmatic ion-exchange reaction that affected the feldspar assemblage of some samples of granite and syenite after exsolution had occurred in the feldspar grains. Some perthite grains in the affected rocks are now almost monomineralic (*i.e.*,

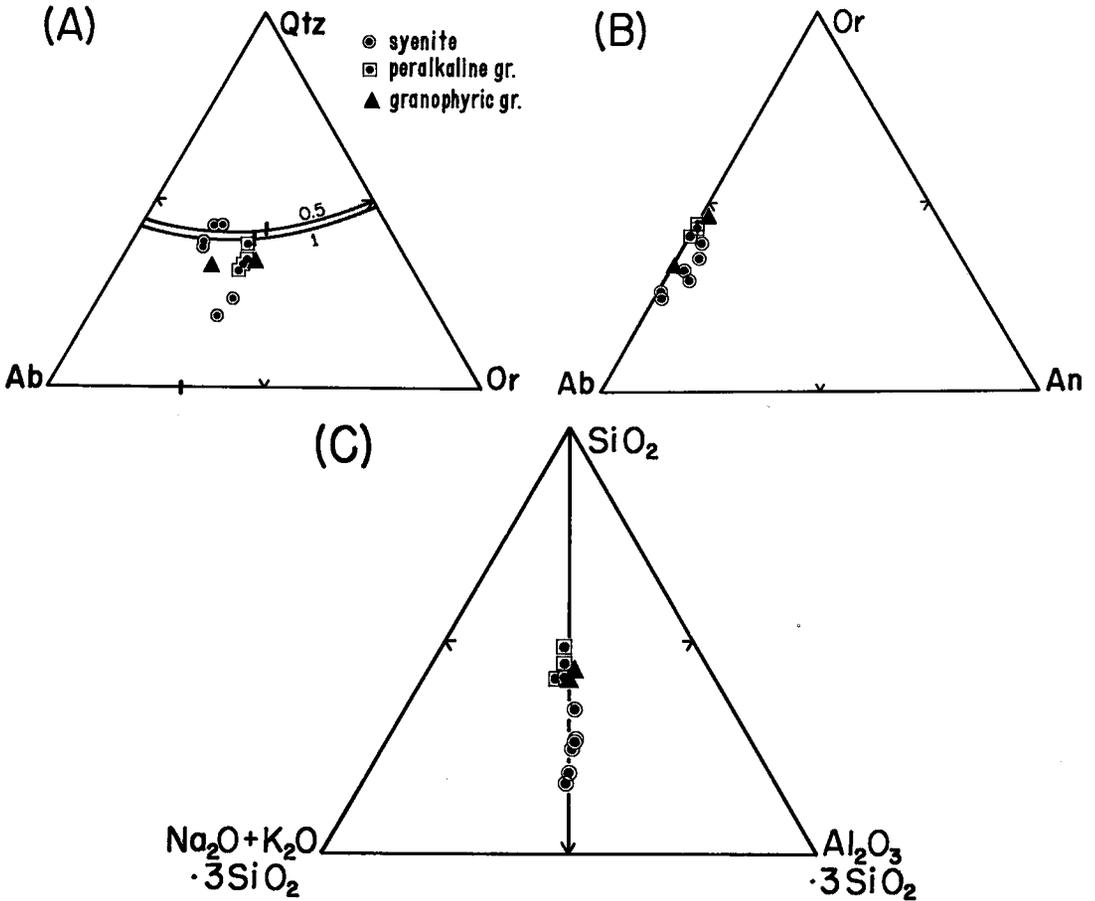


FIG. 4. Plots of the whole-rock compositions (Table 1) in terms of normative quartz, albite and orthoclase (A), normative Or, Ab and An (B), and $(\text{Na}_2\text{O} + \text{K}_2\text{O}) \cdot 3\text{SiO}_2 - \text{Al}_2\text{O}_3 \cdot 3\text{SiO}_2 - \text{SiO}_2$ (C). In A, the cotectic curves are shown for 0.5 and 1 kbar, as well as the location of the pseudobinary and pseudoternary minima (Tuttle & Bowen 1958). In C, the intersection of the vertical line ($\text{Na} + \text{K} = \text{Al}$) with the base line is the location of the feldspars KAlSi_3O_8 and $\text{NaAlSi}_3\text{O}_8$.

albitized), the K-feldspar being relegated to small, irregular domains away from the grain margin and fissures.

The expected increase in normative An with increasing Ca content of the bulk rock is not apparent in this suite (Fig. 4B). The maximum An content is 3.5%, in sample 148, which contains 3.2 wt. % CaO. In other words, the most calcic bulk-compositions, all syenitic rocks, contain a low-calcium feldspar assemblage that does not reflect the progressive enrichment in Ca in this unit. Figure 4B also illustrates the significant displacement of some bulk compositions toward the Ab corner.

Figure 4C groups sodium and potassium contents as the hypothetical end-member $(\text{Na}_2\text{O} + \text{K}_2\text{O}) \cdot 3\text{SiO}_2$; the corresponding end-member that accom-

modates aluminum is $\text{Al}_2\text{O}_3 \cdot 3\text{SiO}_2$. The remaining SiO_2 is shown as the third component. The figure illustrates clearly the peralkalinity of some samples and the metaluminous composition of one sample of granophytic granite and of four syenitic bulk-compositions. The slight excess of aluminum in these compositions does not seem entirely explained by the small proportion of the An component, as the two compositions poorest in SiO_2 and relatively rich in calcium (142, 154) show no such excess in aluminum.

The intersection of the vertical line, along which $(\text{Na} + \text{K})$ is equal to Al , with the base-line gives the position of the feldspars $\text{NaAlSi}_3\text{O}_8$ and KAlSi_3O_8 . The diagram shows well the progressive evolution of the suite, from rocks (and, presumably, magmas) of syenitic composition emplaced along the western

rim of the pluton to more silic compositions in the interior. The departure of the rocks from the line $(Na + K) = Al$ is relatively minor either way. The process of feldspar fractionation, which usually is proposed to explain the progression from syenitic liquid to granitic liquid, cannot explain the scattering of data points on both sides of the line $(Na + K) = Al$.

Trace elements

The trace-element distribution in rocks of the Deloro complex is interpreted to reflect *magmatic* processes of differentiation and a *postmagmatic* overprint during the cooling of the complex, and later, as a result of at least two distinct episodes of reheating in the presence of water. The concentration of some trace elements (Table 1) is illustrated in variation diagrams, as a function of differentiation index.

Rubidium (Fig. 5) increases progressively with differentiation index, and follows the trend defined by potassium. However, there is some scatter, some rocks being depleted at the low-D.I. as well as the high-D.I. end of the diagram. At the low-D.I. end, the Rb-depleted samples are two of the four K-depleted (Na-enriched) specimens of syenite (Fig. 4A); the sample of granophyric granite that is depleted in K is also depleted in Rb. The same pattern should apply to the distribution of cesium, which is even more incompatible and highly mobile. The most evolved rocks contain less cesium (0.3 ppm) than some of the less evolved ones (Table 1). Most

of the cesium may have been lost from the granophyric granite at the postmagmatic stage, in view of the fineness of its grain size.

Barium decreases progressively with D.I., from over 800 to 300 ppm (Table 1). This progressive decrease is characteristic of a fractionating sequence, but the unusually low amount in the sodium-enriched granophyric granite (P8-140) suggests that some barium may have left with potassium during the post-magmatic exchange of alkalis. Strontium varies from 110 ppm in the mafic syenites to less than 20 ppm in the peralkaline and granophyric granites (Fig. 5). The mobility of Rb and Sr accounts for the erroneous age inferred for these rocks by Wanless & Loveridge (1972).

Cobalt and scandium normally follow Mg and Ca, and are concentrated in the more mafic rocks (Fig. 5). They show a gradual decrease with increasing D.I. On the basis of these two compatible elements, the granophyric granite seems clearly to be part of the same evolutionary sequence as the peralkaline granite.

The distribution of zirconium is complicated because its behavior depends strongly on the alkalinity of the system. Even among specimens of peralkaline granite of comparable D.I., however, there is great variability (between 1120 and 250 ppm Zr: Table 1). Not all the Zr is present as zircon in the peralkaline granite. That portion that may be tied up in alkali zirconium silicates and the mafic minerals may have been subject to late-stage redistribution. Both specimens of granophyric granite contain close to 300 ppm Zr; presumably this is entirely accom-

TABLE 1. CHEMICAL COMPOSITION OF SYENITIC AND GRANITIC SPECIMENS FROM THE DELORO PLUTON

		141	142	147	148	149	154	114	117	118	121	139	140
SiO_2	wt. %	57.41	57.93	68.93	63.60	58.91	58.38	77.74	75.49	76.09	74.11	75.54	74.19
TiO_2		1.08	1.01	0.37	0.58	1.07	1.08	0.04	0.10	0.07	0.16	0.07	0.11
Al_2O_3		12.57	13.59	13.23	13.95	12.94	13.44	11.05	11.64	11.88	11.99	12.53	12.49
Fe_2O_3		5.29	3.72	1.77	3.89	4.12	3.50	0.08	0.49	0.31	0.46	0.39	1.96
FeO		8.59	7.49	3.52	3.08	7.79	8.19	1.55	1.96	1.64	1.90	0.58	1.01
MnO		0.47	0.22	0.13	0.15	0.31	0.24	0.03	0.07	0.06	0.06	0.03	0.02
MgO		0.90	1.22	0.07	0.42	1.12	1.19	0.03	0.24	0.18	0.05	0.07	0.12
CaO		3.79	3.55	1.95	3.20	3.04	3.09	0.38	0.40	0.39	0.56	0.64	0.40
Na_2O		4.97	6.05	4.66	4.99	5.00	5.99	4.18	4.45	5.06	4.62	3.98	5.19
		4.99	6.09	4.33	4.39	4.67	5.57	4.09	4.67	4.66	4.27	3.65	5.30
K_2O		3.23	3.55	4.44	4.13	3.68	3.21	4.24	4.49	4.57	4.42	4.89	3.52
Rb	ppm	37	25	66	44	55	34	26	82	118	94	124	55
Sr		113	103	30	72	60	110	3	16	15	12	19	22
Ba		827	659	415	689	792	893	533	778	636	521	460	301
Cs		0.6	0.3	0.4	0.5	0.4	0.4	0.5	0.3	0.5	0.4	0.4	0.3
Sc		7	7	0.5	4	6	8	0.7	2	0.7	6	1	2
Co		6	4	2	3	4	4	2	1	1	4	1	2
Zr		505	292	741	712	546	407	250	1121	686	574	290	329
Hf		11	8	19	19	15	11	29	29	30	15	10	11
Ta		1	0.8	2	3	2	1	4	3	6	2	2	2
Y		93	77	124	142	119	98	100	220	331	159	106	98
U		0.7	1	0.6	0.2	0.1	0.2	2	2	5	3	2	3
Th		0.5	0.8	6	6	4	2	12	19	25	15	18	15

Data on major elements are taken from the thesis of Kuehnbaum (1973); his sample numbers are prefixed by P8-. Concentrations of Sr, Zr, Y, U, and Th were determined using X-ray-Fluorescence (XRF); concentrations of Na, Rb, Ba, Cs, Sc, Co, Hf and Ta were determined by instrumental neutron-activation analysis (INAA). Details of the procedure are provided in the text and in Abdel-Rahman (1982). Samples 141, 142, 147, 148, 149 and 154 are syenites, 114, 117, 118 and 121 are peralkaline granites, and 139 and 140 are granophyric granites. Two values of Na_2O are listed; the first was obtained by XRF analysis, the second, by INAA. The first value was used in Figures 3 and 4, and in the calculation of differentiation index.

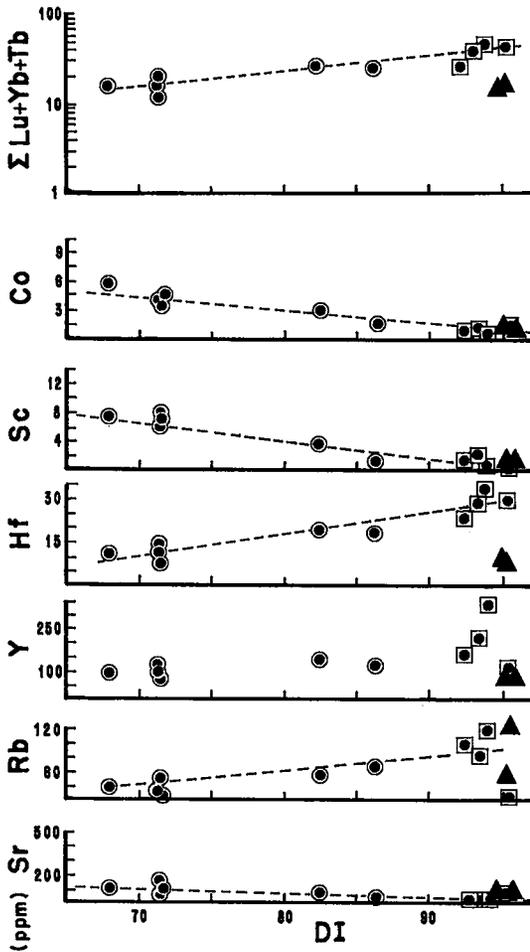


FIG. 5. Variation of trace elements as a function of differentiation index. Straight lines have been drawn where the variation is regular.

modated in accessory zircon, as their bulk composition is not alkaline.

Although hafnium is expected to show a similar pattern because of its striking geochemical coherence with zirconium, such is not the case (Fig. 5). The concentration of hafnium increases progressively with D.I., from mafic syenite to peralkaline granite. The two samples of granophyric granite are depleted in hafnium (10 ppm). The yttrium content increases with increasing D.I., but there is some scatter among the peralkaline granites, as for Zr, and the granophyric granite is depleted (100 ppm; Fig. 5), as for Hf.

Uranium and thorium both increase with D.I. The samples of peralkaline and granophyric granites contain very similar amounts of uranium and thorium (Table 1). These two elements behave highly incompatibly, and presumably remain in the melt phase until forced into the crystals. Thorium increases more regularly than uranium.

The Deloro suite is relatively enriched in rare-earth elements (Table 2), as is typical of anorogenic suites the world over (Bowden *et al.* 1979, Collins *et al.* 1982). The sum of the rare earths ranges from 180 to 295 ppm in the syenites and from 560 to 820 ppm in the peralkaline granites; the two samples of granophyric granite contain only 215 and 290 ppm. The chondrite-normalized plots (Fig. 6) show that the syenites have a relatively unfractionated, almost flat pattern.

The patterns for the five samples of peralkaline granite (Fig. 6) are parallel and slightly light-rare-earth enriched compared to those of the syenites. The negative Eu anomaly is striking in these rocks, but it cannot be attributed to the fractionation of plagioclase, as normally proposed, because plagioclase is absent as a discrete primary mineral in the Deloro syenites. The negative Eu anomaly may reflect the progressive concentration of all the rare earths except europium, removed preferentially *via*

TABLE 2. CONCENTRATIONS OF RARE-EARTH ELEMENTS IN WHOLE-ROCK SAMPLES FROM THE DELORO PLUTON

	141	142	147	148	149	154	114	117	118	121	144	139	140
La ppm	37.1	30.3	45.9	37.7	43.5	41.5	109.8	155.3	150.5	97.3	118.8	62.3	41.7
Ce	97.1	74.9	125.7	103.1	116.9	100.9	255.1	386.9	338.6	186.5	295.4	140.8	96.7
Nd	61.4	46.7	75.1	67.2	78.0	62.4	123.9	196.1	147.4	97.5	160.3	56.8	46.7
Sm	16.7	12.2	20.4	17.9	17.9	16.4	29.4	43.3	34.7	22.0	39.7	14.7	11.8
Eu	4.13	2.92	1.89	2.82	3.49	3.38	1.76	2.48	2.04	1.52	3.07	1.03	1.11
Tb	2.77	1.87	3.02	3.22	2.75	2.44	5.62	6.66	6.45	3.71	6.91	2.46	2.88
Ho	3.40	3.59	6.68	5.12	4.94	4.63	9.91	9.05	10.1	8.13	13.1	4.31	3.54
Yb	11.8	9.30	20.0	21.2	14.9	12.3	31.7	26.9	36.6	20.2	38.6	12.7	12.7
Lu	1.91	1.52	3.33	3.20	2.32	1.89	4.48	3.84	4.94	2.95	5.30	0.17	1.89
Ce/Yb	8.3	8.1	6.3	4.9	7.8	8.2	8.1	14.4	9.3	9.2	7.6	11.1	7.6
Eu/Yb	0.32	0.32	0.09	0.12	0.20	0.29	0.05	0.08	0.05	0.06	0.08	0.07	0.06
ΣLu+Yb+Tb	16.5	12.7	26.4	27.6	20.0	16.6	41.8	37.4	48.0	26.9	50.9	15.4	17.5
ΣREE	232.9	179.6	295.4	256.4	279.8	241.2	561.8	821.6	721.3	431.7	668.1	290.9	215.5

Concentrations of rare-earth elements determined by neutron-activation analysis (see text for the details). Sample numbers should be prefixed by P8-; the samples are from the collection of Kuehnbach (1973). Samples 141, 142, 147, 148, 149 and 154 are syenite, 114, 117, 118, 121 and 144 are peralkaline granite, and 139 and 140 are granophyric granite.

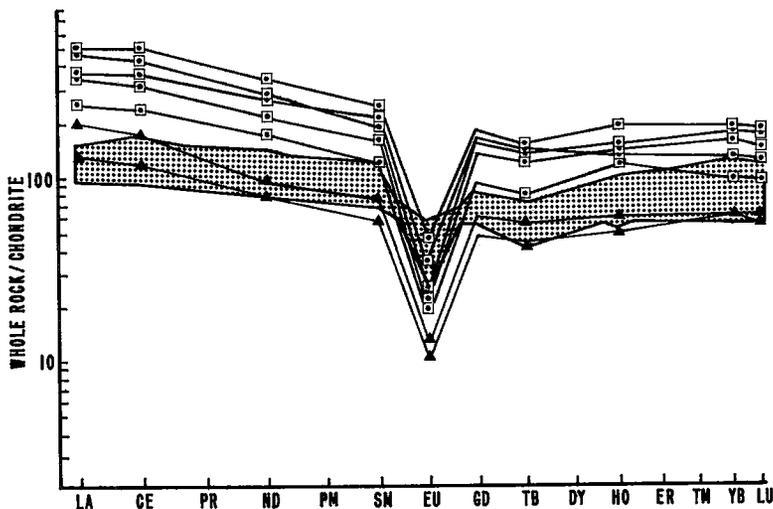


FIG. 6. Chondrite-normalized plot showing an envelope of six rare-earth patterns for syenites superimposed on data for five samples of peralkaline granite and two of granophyric granite. Raw data are reported in Table 2.

the fractional crystallization of sanidine. The trivalent rare-earths reside in the accessory phases, whereas europium is much more strongly partitioned in the feldspar as Eu^{2+} .

The granophyric granites (Fig. 6) are somewhat parallel in their profile to the peralkaline granites, but are displaced toward lower concentrations of each element. The magnitude of the europium anomaly is more pronounced than that for the peralkaline granites. The total concentration of the rare earths in the granophyre falls in the range of the least evolved syenites (Figs. 5, 6), in spite of the more evolved nature of this late batch of granitic magma (as indicated by the major elements).

The smooth variation in the concentration of Ca, Sr, Sc, Co, Mg + Fe + Mn in the sequence syenite - peralkaline granite - granophyric granite strongly suggests that all samples are interrelated by a process of fractionation. The depletion of rare earths, Hf and Y in the granophyre could be due to 1) the early fractionation of a rare-earth-bearing accessory phase on the liquidus (*cf.* Payette & Martin 1986), 2) the loss, during the emplacement of this subvolcanic plug, of a primary volatile phase in which these incompatible elements had concentrated, or 3) subsolidus readjustments involving an oxidizing fluid phase that preferentially interacted with the granophyric granite and that may have destabilized a primary REE-bearing accessory phase. Much more work would be required to account for the behavior of these elements quantitatively.

FELDSPAR MINERALOGY OF THE DELORO SUITE

The cell dimensions of the potassium- and sodium-rich feldspars in the eighteen samples examined are listed in Table 3, which is available at nominal cost from The Depository of Unpublished Data, CISTI, National Research Council of Canada, Ottawa, Ontario K1A 0S2. Tables 4 and 5 show the inferred composition and degree of Al-Si order of the potassium-rich and sodium-rich feldspars, respectively.

TABLE 4. COMPOSITION AND DEGREE OF Al-Si ORDER OF THE K-FELDSPAR IN ROCKS OF THE DELORO PLUTON

	rock type	Al^{IV}	$\epsilon_{10} + \epsilon_{1m}$	$\epsilon_{10} - \epsilon_{1m}$	ϵ_{10}	Δ
P8-114	peralkaline granite	0.980	0.993	1.009	1.00	0.99
P8-117	peralkaline granite	0.945	0.971	1.012	0.99	1.02
P8-118	peralkaline granite	0.966	0.997	1.004	1.00	0.98
P8-121	peralkaline granite	0.950	1.001	0.977	0.99	0.97
P8-137	granophyric granite	0.981	0.984	0.992	0.99	0.96
P8-138	granophyric granite	0.956	0.973	1.003	0.99	1.00
P8-139	granophyric granite	1.004	0.990	1.000	1.00	0.99
P8-140	granophyric granite	0.928	0.968	0.954	0.96	0.95
P8-141	syenite	0.946	0.988	0.989	0.99	0.94
P8-142	syenite	0.955	1.010	0.989	1.00	0.99
P8-144	peralkaline granite	0.956	0.968	0.955	0.96	0.96
P8-147	syenite	0.976	1.007	0.996	1.00	0.99
P8-148	syenite	0.951	0.997	1.019	1.01	1.03
P8-149	syenite	0.960	0.997	0.975	0.99	0.99
P8-154	syenite	0.955	0.937	0.890	0.91	0.92
4-1	devitrified obsidian	0.989	1.040	1.042	1.04	0.99

Composition is calculated from cell volume using the equation of Krohl & Ribbe (1983). Degree of Al-Si order, expressed as ϵ_{10} , is calculated using the expressions of Blasi (1977). Error in Al^{IV} (expressed as a mole fraction) and ϵ_{10} is estimated to be ± 0.015 . Obliviquity $\Delta = 12.5(\epsilon_{131} - \epsilon_{131})$. The sample numbers prefixed by P8 are taken from the collection of Kuehnbauer (1973).

TABLE 5. COMPOSITION AND DEGREE OF Al-Si ORDER OF THE ALBITE IN ROCKS OF THE DELORO PLUTON

rock type	$\bar{X}Or$	An	$\epsilon_1O+\epsilon_{1m}$	$\epsilon_1O-\epsilon_{1m}$	ϵ_1O	131	
P8-114	peralkaline granite	0.011	0	1.026	1.000	1.01	1.069
P8-117*	peralkaline granite	0	0	0.996	1.019	1.01	1.089
P8-118*	peralkaline granite	0	0	0.980	1.008	0.99	1.081
P8-121	peralkaline granite	0	0	0.994	1.000	1.00	1.096
P8-137*	granophyric granite	0.001	0	1.015	1.003	1.01	1.096
P8-138	granophyric granite	0.001	0	1.004	0.998	1.00	1.085
P8-139	granophyric granite	0.014	0	0.983	0.995	0.99	1.095
P8-140	granophyric granite	0.002	0	0.991	0.991	0.99	1.082
P8-141*	syenite	0	1	1.025	1.009	1.02	1.157
P8-142*	syenite	0.001	0	1.019	1.008	1.01	1.084
P8-144*	peralkaline granite	0	1	1.033	0.997	1.02	1.133
P8-147	syenite	0.011	0	0.998	1.002	1.00	1.072
P8-148*	syenite	0.009	1	1.002	0.991	1.00	1.106
P8-149	syenite	0.002	1	1.019	0.988	1.00	1.118
P8-154	syenite	0.010	2	1.016	0.961	0.99	1.149
4-4	devitrified obsidian	0	1	0.988	0.985	0.99	1.123
Ars	mineralized vein	0.001	1	0.997	0.985	0.99	1.117

Composition is calculated from cell volume using the equation of Kroll & Ribbe (1983). Degree of Al-Si order, expressed as ϵ_1O , is calculated using the expressions of Blasi (1977). Error in $\bar{X}Or$ (expressed as a mole fraction) is estimated to be ± 0.015 . An content is estimated from the $\epsilon^* - \epsilon^*$ plot (Fig. 8). The sum $\epsilon_1O + \epsilon_{1m}$ is supposed to have a maximum value of 1. Values exceeding 1 probably reflect the presence of a small amount of the An component or of slight disorder that persists in the structure (or both). For this reason, the qualitative estimate of degree of Al-Si order derived from Figure 8 is considered more informative than the value of ϵ_1O normally quoted. * Evidence of slight disorder (Fig. 8). 131: $2\theta_{131} - 2\theta_{131}$, in degrees, for $CuK\alpha_1$ radiation.

All specimens examined except the two samples of rhyolite and the vein material contain two feldspars. The proportion of the K-feldspar to albite is not constant, but varies as a function of the late-stage exchange of K by Na and of the deposition of secondary albite along grain margins. Albite and K-feldspar are present in subequal proportions in the undisturbed mesoperthite. The sample of aphyric devitrified obsidian contains albite + quartz (no trace of K-feldspar), as does the arsenopyrite-bearing vein. The devitrified flattened pumice fragments (specimen 4-1) contain the association of K-feldspar + quartz (no trace of albite).

Microcline

The K-feldspar in the Deloro suite is low microcline (Figs. 7, 8). In most cases, the value of t_1O , the proportion of aluminum occupying the T_1O position, is 0.99 or 1.00. The data points lie close to the low microcline corner, but are not tightly clustered, owing to minor variations in composition and degree of Al-Si order. Three samples contain microcline that departs significantly from fully ordered microcline in degree of order; the most disordered microcline has, on average, 91% of its aluminum in the T_1O position (Table 4). One of the samples of granophyric granite has a significantly more sodic microcline (93% Or) than all the other samples (average 96%). The coexistence of Or₉₆ and pure albite (see below) indicates a temperature of final equilibration below 300°C in the presence of an aqueous phase. In spite of this low temperature of equilibration, the microcline failed to recrystallize thoroughly in the time available in its field of stability (maximum 400°C). This would be consis-

tent with a rapid cooling of the epizonal complex, and only mild annealing later. Submicroscopic albite- and pericline-twinned domains are inferred to be present in the microcline because it inverted from a monoclinic primary feldspar. A very fine scale of intergrowth of the twin domains, which would reflect the limited degree of recrystallization, precludes their direct observation by optical microscopy.

The microcline in the devitrified pumiceous material in the ignimbritic rhyolite has a t_1O value of 1.04. This anomalous value (the maximum is 1.0) is attributed to the presence of a large cation (*e.g.*, rubidium) in the structure; this causes an expansion of the unit cell, and a position in Figures 7 and 8 clearly beyond the low microcline corner. As this rock underwent complete K-for-Na exchange (*i.e.*, no trace of albite is left), an increase could be expected in the concentration of rubidium, whose geochemical coherence with potassium is well established.

Albite

Compared to microcline, the unit-cell refinement of albite in these rocks is invariably based on a greater number of indexed lines in the powder pattern. This is because the albite is more homogeneous than the microcline, both structurally and compositionally; as a result, the standard errors on the unit-cell constants are smaller for albite. The albite contains very little calcium (Fig. 9); the maximum seems to be An₂ (specimen P8-154). Many of the specimens depart somewhat from complete Al-Si order. The findings of Martin (1984) suggest that this slight disorder reflects the albitization of a more calcic albite (or oligoclase). The composition of the original sodic plagioclase lamellae in the perthite has been adjusted to An₀ or An₁ during the subsolidus re-equilibration. The original plagioclase may have been An₅ or An₆, as predicted from the calculation of the normative constituents (Fig. 4B). The X-ray-diffraction technique provides information on the *dominant* structure present; if the volume of "new" albite produced as a result of ion exchange and hydrothermal deposition is subordinate to the volume of "old" albite that resulted from the albitization of An₆, its presence would not be detected in the powder pattern.

We contend that the devitrified obsidian that contains the assemblage An₁ + quartz represents a product of the ion-exchange reaction driven to completion. During devitrification of the obsidian, or possibly after, the potassium (as well as rubidium, presumably) was removed efficiently *via* an intergranular pore-fluid, and sodium was added to the feldspar. This type of exchange reaction is common in ignimbritic rocks, and is inferred to have occurred in a higher-temperature regime than would be the

case for the complementary K-for-Na reaction (*e.g.*, Martin & Bowden 1981).

The mineralized vein sampled northwest of the Deloro complex (Wilson 1965, Sangster & Bourne 1982) contains albite but no microcline. The same fluids that deposited hydrothermal albite in the syenite and granite at a relatively high subsolidus temperature may have transported Ag, Au and the base metals outward, into the fractured host-rocks. More work is needed to confirm that fluids saturated in albite are responsible for ore transport at Deloro.

Discussion of the feldspar mineralogy

The mesoperthitic texture that characterizes the hypersolvus granite at Deloro was formed as a result of exsolution of albite_{ss} from primary, single-phase alkali feldspar (sanidine solid-solution, of composition close to Or₆₀Ab₄₀). The temperature of exsolution was approximately 625°C (*e.g.*, Martin 1974). Subsequent cooling allowed a coarsening of the exsolution texture, and thus local mobility of Na and K. In some plutonic samples, sodium was added and potassium was removed at this stage, and the exsolution texture became modified. This sodium metasomatism is partly responsible for the shift of some bulk compositions toward the Ab + Qtz sideline in Figure 4A. The inversion to microcline may have occurred at approximately 400°C, thus after the exsolution, during the continued cooling of the epizonal complex. However, results of analogous studies of degree of Al-Si order attained in K-feldspar in hypersolvus granites and syenites of other SiO₂-saturated anorogenic complexes of comparable size (*e.g.*, Martin & Bowden 1981, Lalonde & Martin 1983) suggest that at Deloro, the cooling was probably too rapid to permit such a major reconstructive transformation to low microcline to be completed. Structurally intermediate microcline + low albite, with residues of orthoclase, may have been the assemblage present in the perthite grains 1.2 billion years ago. The successful conversion to low microcline occurred as a result of the later, low-temperature hydrothermal events, primarily the event that partly reset the Rb-Sr system, in the interval 1070–1040 Ma (Heaman *et al.* 1987) possibly with further local ordering during the Ordovician event recorded in the Elzevir batholith 15 km to the north (Clark & Hanes 1985) and the Cordova gabbro 10 km to the west (Lopez-Martinez & York 1983). The relatively low temperature of these events, as well as the lack of associated deformation, can account for the local persistence of slight disorder and the absence of coarsely twinned domains in the microcline. The time available would have been ample for compositional equilibration between the microcline and the albite at this low temperature (estimated to be approximately 200°C according to the thermochronometric findings quoted above).

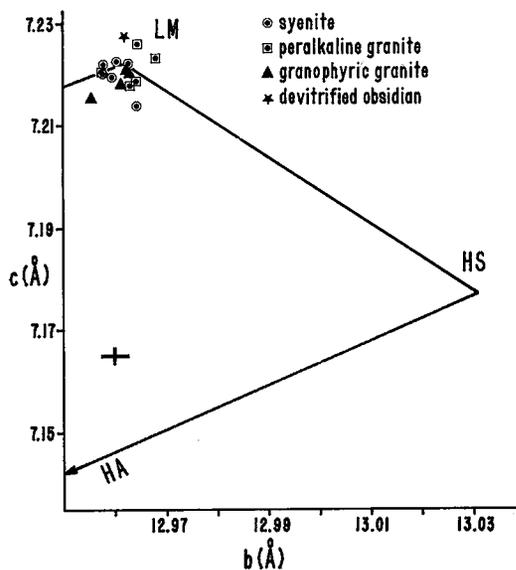


FIG. 7. A portion of the *b* - *c* quadrilateral showing the distribution of the microcline data-points. LM low microcline, HS high sanidine, HA high albite. The error bars in *b* and *c* represent an average standard error for all the samples plotted. The standards errors are provided by the program of Appleman & Evans (1973). Raw data are reported in Table 3.

DISCUSSION

Tectonic setting

The occurrence of the Deloro anorogenic complex in the southern part of the Central Metasedimentary Belt of the Grenville Province is unusual, because of indications of coeval orogenic magmatism close by. As more high-precision U-Pb ages and bulk-composition data become available for the intrusive rocks of this belt, it is clear that the first cycle of igneous activity, which culminated at 1240 Ma (Heaman *et al.* 1987), involved the intrusion of mantle-derived mafic magmas. In some cases, such magma rose quickly into the upper crust, in a state of distension, as there are no associated differentiates (*e.g.*, in the Cordova gabbro). In others, like at Deloro, the mafic magma ponded near the surface and differentiated, to give the observed suite of felsic differentiates. The low initial ⁸⁷Sr/⁸⁶Sr value determined for these felsic rocks, ±0.7036, is consistent with this proposal. The Deloro reservoir probably was sheet-like in form, as the syenite + granite body consists of a slab (maximum thickness 0.5 km) that thins southward under the Paleozoic cover (Real &

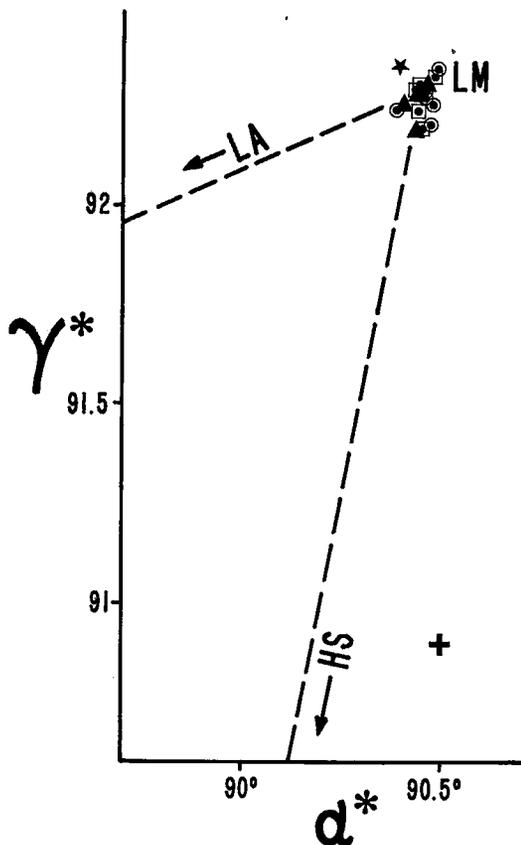


FIG. 8. A portion of the α^* - γ^* plot showing the location of the microcline data-points with respect to the LM corner. Note that the datum for the devitrified obsidian (star) lies distinctly outside the quadrilateral, as in Figure 7. The error bars in α^* and γ^* represent an average standard error for all the samples plotted. The standard errors are provided by the program of Appelman & Evans (1973).

Thomas 1987) and that is concealed at the surface by volcanic units which we consider genetically related (Abdel-Rahman & Martin, in prep.). At the same time and in the same part of the belt as these rift-related complexes, however, magmas of apparent calc-alkaline affinity also were being intruded. Could the calc-alkaline signature of plutons such as the Elzevir (Pride & Moore 1983) be an artifact of the generation of intermediate magmas by melting of the basement by the primitive mafic magmas that rose into the distended crust, followed by their hybridization? The juxtaposition in time and space of the two magmatic lineages is anomalous, and requires an explanation.

Magmatic processes

The geochemical data provided here are consistent with trends produced by fractional crystallization. The parallel chondrite-normalized REE patterns indicate a close genetic link between syenite and peralkaline granite. The evolution of the peralkaline granite was probably controlled in part by the early crystallization of calcic amphibole from syenite melts (e.g., Abdel-Rahman 1987). More work is required to document the exact nature of the parental mafic magma that was emplaced in the upper crust and to identify the assemblage of liquidus minerals that fractionated from the system to give the low-Ca differentiates. In this respect, gabbroic material associated with syenite in the western part of the complex should be re-examined, and its affinity to the Cordova gabbro evaluated.

A comparison of the Deloro suite with magmatic associations found in the classic anorogenic complexes suggests that 1) gabbro, syenite, hypersolvus granite and (in part, at least) granophyric granite are all comagmatic, and 2) the parental magma is basic, and not of crustal derivation. We do not agree with the inferences of Wu & MacRae (1986), derived by REE modeling, that the granitic melt is anatectic, formed by nonmodal partial melting of a silicic granulite. In their model, the gabbro in the area is a cumulate formed by the fractional crystallization (70 to 80%) of a low-K tholeiite, the residual melt being syenitic. The link between hypersolvus syenite and hypersolvus granite is not explored in their abstract.

The clustering of mafic and accessory phases and the lack of significant buildup of the An component in the plagioclase of relatively mafic syenites possibly reflect the crystallization of such rocks from an *emulsion* of conjugate Fe-dioritic and syenitic melts that are related by a phenomenon of immiscibility, as are found in jotunite - mangerite pairs in anorthositic complexes (Philpotts 1981). To propose an association of the Deloro suite with anorthosite is not far-fetched, as the same association is found in the more deeply dissected anorogenic complexes of Niger (Bowden *et al.* in press).

Anatectic reactions in the wall rocks may have led to the production of a highly evolved, leucogranitic fraction that became mixed in with the differentiate; alternatively, the geochemical distinctions recorded in the granophyric granite may be due entirely to the early fractionation of an accessory phase like britholite that appeared on the liquidus (Payette & Martin 1986) or to a postmagmatic hydrothermal overprint. In other areas, granophyric granites are notoriously disturbed geochemically and mineralogically (e.g., Taylor 1968). As granophyric rocks cool, they become very permeable owing to the

large surface-area that is a consequence of the fineness of the intergrowth; hence, they may be as susceptible to chemical exchange as volcanic rocks.

Postmagmatic overprints

The preservation of the granophyric texture in the central unit and of the hypersolvus texture in the syenites and granites implies that the degree of deformation since the time of exsolution has been negligible. The Deloro rocks are texturally very much like younger hypersolvus syenites and granites emplaced in crustal segments known to have been tectonically quiet at and since the time of emplacement. The minor effects of recrystallization that do occur in the Deloro rocks (*e.g.*, slightly strained quartz, Fe-rich phyllosilicates developed at the expense of amphibole, recrystallization effects in feldspar and amphibole: Davidson 1979) are recognized also in those younger complexes. The deposition of hydrothermal albite from a fluid medium that was saturated with respect to $\text{NaAlSi}_3\text{O}_8$ is believed to occur during cooling of the rocks in response to 1) decreasing temperature, and 2) shrinkage of the medium to coarse grains owing to thermal contraction, exsolution, Al-Si ordering, and Na-for-K ion exchange. It is likely that the "new" albite would grow in optical continuity with the exsolution lamellae in the mesoperthite, which project to the edge of the grains. The deposition of the rim albite thus seems to postdate exsolution.

At Deloro, all gradations exist in degree of subsolidus modification, from rocks devoid of secondary albite and of Na-for-K ion exchange to rocks where the ion-exchange process has gone to completion. The variability in extent of the geochemical and mineralogical modifications discussed in this paper, and specifically those involving Na, K, Rb and Cs (and, by implication, ^{87}Sr), undoubtedly are responsible for the scatter in the plot of $^{87}\text{Sr}/^{86}\text{Sr}$ versus Rb/Sr. Open-system behavior involving Rb and radiogenic Sr occurred at least three times, once during the cooling of the complex, during the 1070–1040 Ma regional "soaking", then again during the mild regional reheating in the Ordovician.

The main episode of regional reheating that affected the area may be a consequence of the intrusion of primitive mafic magma into the Grenville crust in a state of distension following the major episode of deformation at about 1100 Ma. Intrusive bodies also could be responsible for the Ordovician event. The zones of Ordovician mineralization share the orientation of the Ottawa – Bonnechère graben (Sangster & Bourne 1982); hydrothermal solutions set in circulation by the cooling rift-related bodies could account for the lead removed from rocks of the Grenville Supergroup (Fletcher & Farquhar 1982).

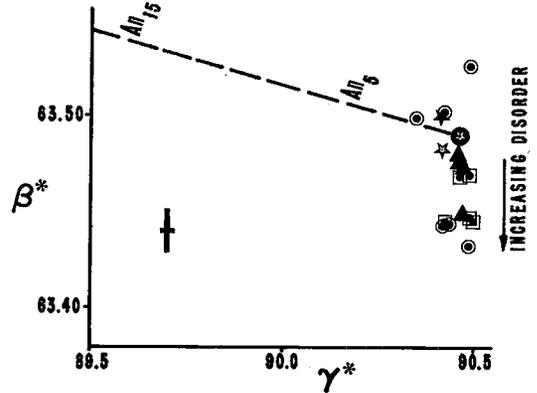


FIG. 9. A portion of the β^* - γ^* plot showing the location of the albite data-points with respect to end-member ordered albite (encircled star). The dashed line marks the locus of ordered structures in the range An_0 to An_{15} . A decrease in the degree of Al-Si order causes a decrease in the value of β^* . The error bars in β^* and γ^* represent an average standard error for all the samples plotted. The standard errors are provided by the program of Appleman & Evans (1973).

Relationship with the Flinton Group

The Deloro is not only undeformed, but considerably older than the rocks of the Flinton Group; yet these metasedimentary rocks show at least two episodes of deformation (Moore & Thompson 1980) and regionally developed metamorphic isograds (Carmichael *et al.* 1978). In the Madoc area, Moore & Thompson (1980) reported the occurrence of poikiloblasts of chloritoid, biotite, garnet, margarite and, at two localities (Fig. 1; Thompson 1972), kyanite (Madoc Fm.). Anovitz & Essene (1986) used the occurrence of kyanite and geothermometry on calcite-dolomite pairs from the overlying Stewart Formation to postulate that the area around Madoc had been buried to a depth of 13–16 km. There is no textural or mineralogical record of deep burial in the near-surface plutonic rocks and their volcanic cover; also, to expect an amount of uplift that brings back to the surface from such depths rocks formed at the surface is considered unrealistic.

The easiest way to reconcile the data is to propose that 1) the major episode of deformation that affected coeval plutonic bodies in the northern part of the Central Metasedimentary Belt soon after their emplacement (Heaman *et al.* 1987) had no effect on the Deloro body, perhaps because of its very near-surface character, perhaps because the intensity of that orogeny waned significantly southward, and 2) the contact with rocks of the Flinton Group in the Madoc area is tectonic. Another possibility is that the rocks assigned to the Flinton Group in the Madoc

area, their burial, recrystallization and later uplift, all *predate* the emplacement of the Deloro complex. Careful remapping of the southern and eastern contacts of the Deloro with the adjacent metasedimentary units will be required to solve the dilemma.

Deloro: a Late Proterozoic caldera?

The rocks exposed at the present level of erosion may provide an incomplete sampling, along an oblique section, of the root zone of a Late Proterozoic caldera (syenite and gabbro in the west, volcanic cover to the east). The sequence of intrusive events during the period of activity of the Deloro caldera complex probably will be found to parallel the classic eruptive sequence illustrated in much younger complexes (Smith & Bailey 1968). Particularly relevant will be detailed investigations of the earliest products of eruption from the Deloro magma chamber, now perhaps represented by the ignimbritic and massive rhyolites on the eastern side of the complex.

ACKNOWLEDGEMENTS

The first author thanks Professors John Gittins and John C. Rucklidge, of the University of Toronto, for introducing him to the problem and for supervising his geochemical investigations. Research costs for this study were covered by NSERC operating grants to John C. Rucklidge and to the second author. We acknowledge a fruitful exchange of ideas with Mark Dingman. Drs. Keith Bell, John A. Hanes and Otto van Breemen shared their unpublished geochronological findings. We thank Richard Yates for technical assistance in the preparation of this manuscript. Drs. Richard N. Abbott, Jr., Sandra M. Barr, John A. Hanes and Walter E. Trzcienski, Jr. critically read an earlier version of this manuscript; we thank them sincerely.

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Received March 13, 1986, revised manuscript accepted July 14, 1986.