CHAPTER 15

EARLY TO MIDDLE MESOPROTEROZOIC (M_1 1460–1350 Ma)

The units considered in this chapter have been given the same time designation (M_1) as those in Chapter 14, but differ in that: i) they have no spatial links with the Pinware terrane, ii) they appear to be younger (within the context of available geochronological data), and iii) they represent a contrasting tectonic setting. The best-known and most widespread unit is the Michael gabbro. Two other mafic units, both undated, are 'parked' here for want of better time alternative. They are: i) a linear mafic body within the Labradorian Cartwright intrusive suite, and ii) mafic dykes that intruded the Upper Paradise River intrusive suite. Finally, the dated Mokami Hill granitoid intrusion also belongs to this time period.

Representative stained slabs are given in Appendix 2, Slab 15.1 (Michael gabbro), 15.2 (linear mafic body in Cartwright intrusive suite), and 15.3 (Upper Paradise River mafic dykes).

15.1 MICHAEL GABBRO (M_1d)

15.1.1 SUMMARY OF INVESTIGATIONS

Various mafic intrusions, including some now known to be Michael gabbro, were identified in coastal areas during the earliest stages of geological investigations in eastern Labrador (*e.g.*, by Daly, Kranck and Christie; *cf.* Chapter 2). The first systematic mapping (1:250 000 scale) of the mafic intrusive rocks that included Michael gabbro was carried out by Stevenson (1970) east of longitude 60°W and by Williams (1970) west of longitude 60°W. Based on the dykes' metamorphic state, Stevenson recognized that more than one age of mafic intrusive rocks was present in the area. He considered some intrusions to be pre-Grenvillian and some to be late Grenvillian. The term 'Michael gabbro' was introduced by Fahrig and Larochelle (1972), who conducted paleomagnetic sampling of the gabbro concurrently with Stevenson's mapping.

Remapping at 1:100 000 scale of various areas that include Michael gabbro was carried out by Bailey (1979), Bailey *et al.* (1979), Gower (1981, 1986), Gower *et al.* (1981, 1882a, b), and, west of the area addressed here, by Ryan (1984). Brief field and petrographic descriptions are included in these reports. Coronitic assemblages in the Michael gabbro and their implications with respect to the metamorphism of the region have been evaluated by Emslie (1983), Gower (1986) and Gower and Erdmer (1988). On the coast, in the Smokey area, the Michael gabbro was mapped by Owen (1985) as part of a detailed study straddling the boundary between the Makkovik and Grenville provinces. He provides petrographic descriptions, whole-rock and mineral geochemical data and an assessment of the coronitic textures. Tulk (1996) investigated coronitic gabbroic rocks in the Rigolet area, in a study that included the boundary between the Groswater Bay and Lake Melville terranes. A geochemically oriented study, involving comparison of the Michael gabbro with other Mesoproterozoic mafic intrusive suites in Labrador, was carried out by Gower *et al.* (1990a), and a geochemical–isotopic–petrogenetic study carried out by Emslie *et al.* (1997). A paleomagnetic investigation, more detailed than that of Fahrig and Larochelle (1972), was completed by Park and Gower (1996). The Michael gabbro has also been the subject of K–Ar geochronological investigations by Grasty *et al.* (1969), Wanless *et al.* (1972, 1973) and Hunt and Roddick (1987); of Rb–Sr studies by Fahrig and Loveridge (1981), Brooks (1982a, b) and Emslie *et al.* (1997); of Sm–Nd studies by Emslie *et al.* (1997) and Devereaux (2011); and of U–Pb studies by Schärer *et al.* (1986), Corrigan *et al.* (2000) and Rogers (2017).

15.1.2 RECOGNITION OF MICHAEL GABBRO

Although the impressive list of investigations given above would lead one to think that the identity and character of Michael gabbro is well established, such is not the case. The heart of the problem is that the Michael gabbro occurs in the same region as mafic rocks having an earlier emplacement age of *ca.* 1650 Ma. The first of the *ca.* 1650 Ma mafic intrusions to be dated was the Adlavik Intrusive Suite in the Makkovik Province and equivalent rocks in both the Makkovik and northern Grenville provinces have come to be known as Adlavik Intrusive Suite correlatives (Chapter 11). There was no awareness during either 1:250 000-scale or 1:100 000-scale mapping projects that this dichotomy existed, hence no discrimination was attempted between the two groups in the field. Criteria to distinguish between them began to be developed in 1982 during sampling (by R.F. Emslie, J. Park and the author) of the Michael gabbro for lithogeochemical and paleomagnetic purposes. Unfortunately, apart from Gower's subsequent mapping in the Double Mer

White Hills area in 1983, most of the areas in which Michael gabbro occurs had already been mapped at 1:100 000 scale. In his final report for the Double Mer White Hills area, although Gower (1986) acknowledged the existence of the two suites he did not attempt to discriminate them on his accompanying map, pleading difficulty in deciding to which suite any particular rock should be assigned.

As not all outcrops of mafic rock were sampled during the various mapping projects and still fewer investigated petrographically or geochemically, later attempts to assign, retroactively, the mafic rocks to their respective suites have also been problematic. Where isotopic, whole-rock geochemical and petrographic data are available, it has proved possible to achieve a high level of confidence regarding the rock-unit identity of many outcrops. Where such information is not available, acute uncertainties remain, and are embodied in the unit designator string in the database. The unit designator for the Adlavik Intrusive Suite correlatives is P_{3C}rg (locally P_{3C}am or P_{3C}ln for other associated rock types) and that for the Michael gabbro is M_1d. In the author's database, the unit designator strings include P_{3C}rg, P_{3C}rg/M_1d, M_1d/P_{3C}rg and M_1d, depending on the level of confidence regarding the unit to which the rock belongs. Note that outcrops also exist where both units are present (designated as P_{3C}rg;M_1d). The remainder of the section on Michael gabbro addresses only those rocks to which the designator M_1d has been specifically applied.

The presently understood distribution of the Michael gabbro is shown in Figure 15.1. This is based on the 1:100 000 maps of Gower (2010a), which draw on all types of currently available data to achieve a best-available assessment of mafic rock affiliation. For areas outside the maps of Gower (2010a), additional outcrops of Michael gabbro are included from Ryan (1984; west of longitude 60°30'W) and Bailey (1979; west of 59°30' W and north of 54°30'N).

The Michael gabbro usually forms low to prominent hills rising above the surrounding, poorly exposed, lowlands. During mapping, the whole hill was generally taken as the extent of the gabbro at that locality. In the northwest, the hills form near-continuous, east-northeast-trending ridges (Plate 15.1A). Where interruptions in ridge continuity occur, the ridges are commonly offset, suggesting cross-faulting. Farther south, the hills become smaller and are more isolated, and have less well-defined orientations, although typically they tend to be elongated close to the regional structural trend in that area. In keeping with the well-established profound metamorphic gradient progressing south (Emslie, 1983; Gower and Erdmer, 1988), increasing outcrop isolation is interpreted as due to progressively increasing dismemberment during Grenvillian orogenesis of originally continuous gabbroic sheets. Sufficient contacts are exposed, especially on the coast (Plates 10.2A–D, 10.4C and 15.1B, C), to show that the sheets were intruded discor-

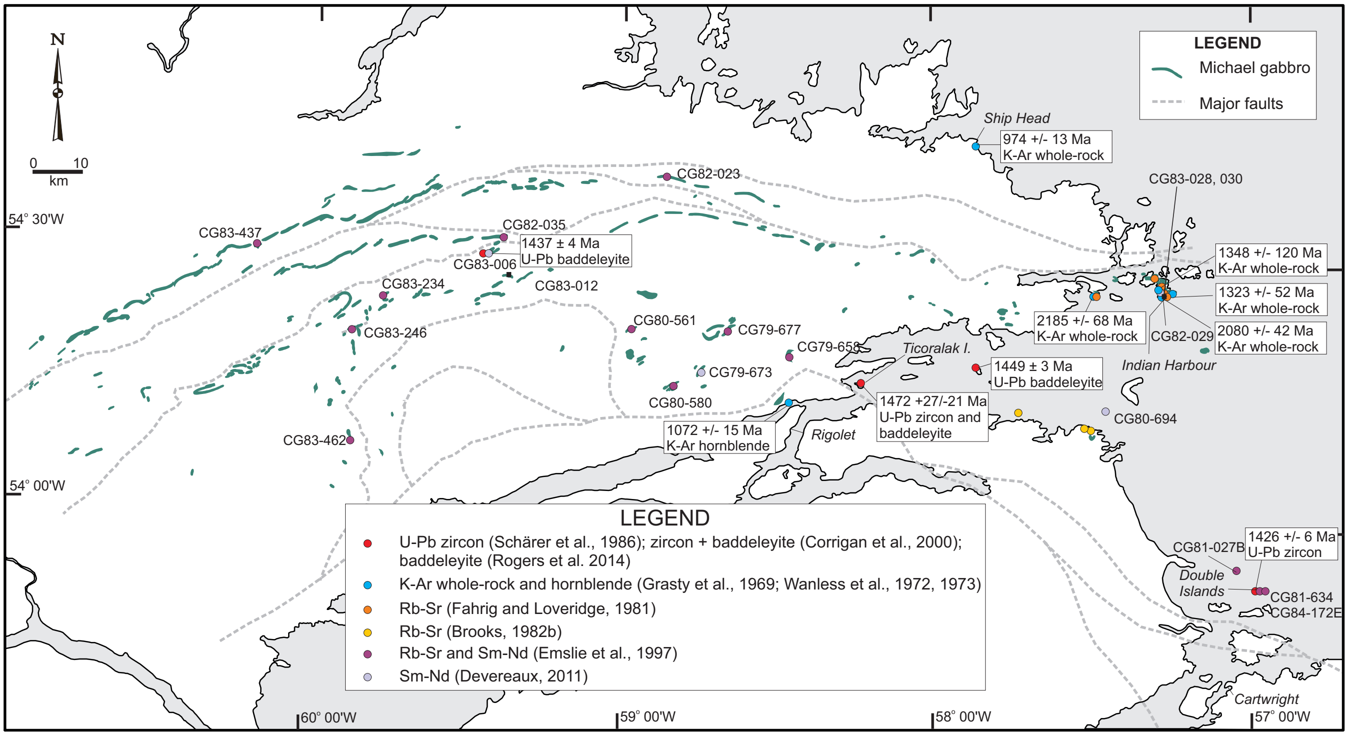


Figure 15.1. *Distribution of Michael gabbro. Geochronological results also shown; U–Pb and Sm–Nd sample sites labelled.*

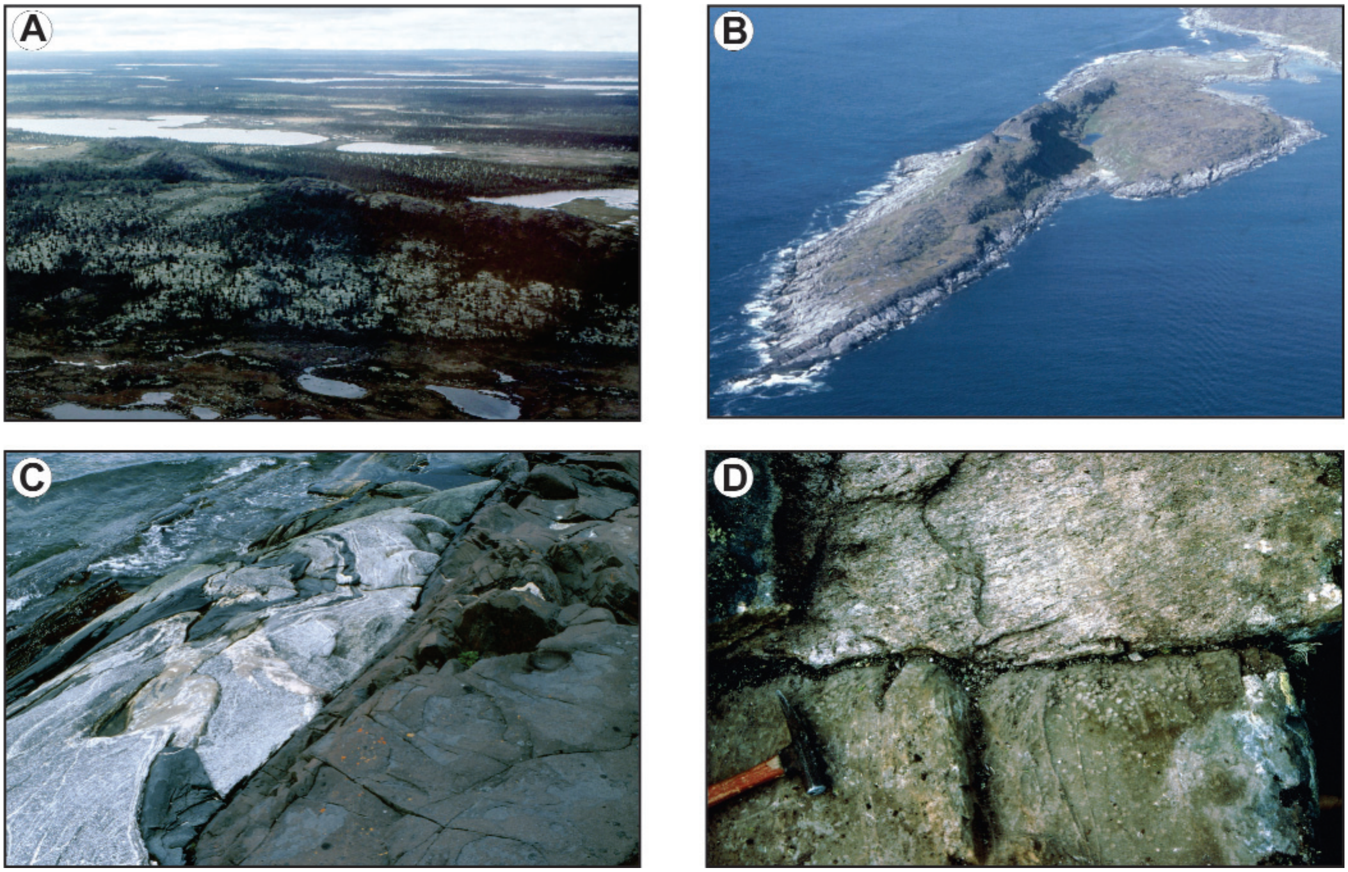


Plate 15.1. *Michael gabbro and Upper Paradise River mafic dyke. (UPRIS – Upper Paradise River intrusive suite). A. Inland outcrops of Michael gabbro forming hills (foreground right to middle distance left) (CG83-012), B. Coastal outcrop of Michael gabbro (dark band; foreground left to middle distance centre) (CG82-030).* See *also Plates 10.2A, B and 10.4C, C. Michael gabbro (right) intruding quartzofeldspathic gneiss hosting metamorphosed mafic dyke remnants (CG82-028), D. Upper Paradise River mafic dyke (lower half) discordantly intruding UPRIS granite dated to be 1501 ± 9 Ma (CG91-072).*

dantly into pre-existing gneissic rocks. The discordance means that, by definition, the sheets must be termed dykes, although, because of subsequent deformation, the original attitude of the dykes is commonly far from certain. The original thickness of the dykes is also rather uncertain, but over 100-m thick was probably common.

Identifying Michael gabbro in outcrop is challenging because of textural and metamorphic variations. 'Typical' Michael gabbro is brown-, purplish- or black-weathering, massive, homogeneous, and shows subophitic texture. A diffuse, almost imperceptible, layering is evident in places. The brown, purplish and black colours can be correlated, at least partially, with primary igneous olivine, primary igneous titaniferous clinopyroxene, and metamorphic amphibole, respectively. Although characteristically massive and homogeneous, the gabbros may be foliated close to their margins, which are also locales where retrogression to amphibole-bearing assemblages is typically found. Despite being mostly medium to coarse grained, very fine-grained variants occur in narrow dykes, and 1- to 10-cm-thick chilled margins are aphanitic. Small plagioclase phenocrysts occur rarely and microphenocrysts of olivine are even less common; they are typically found in the finer grained intrusions. In places, the gabbros are transacted by fractures or shear zones and intruded sporadically by pegmatite, microgranite or quartz veins. Development of retrogressive amphibole and/or garnet-bearing assemblages adjacent to fractures is fairly common (this garnet is distinct from coronal garnet).

15.1.3 GEOCHRONOLOGY

The long-standing accepted age for the Michael gabbro is 1426 ± 6 Ma obtained by Schärer *et al.* (1986; *see* later in this section), but several earlier dating attempts had been made. The first was by Grasty *et al.* (1969; sample L1A) who reported a K–Ar whole-rock date of 2080 ± 42 Ma (2076 Ma recalculated) from Indian Harbour for an olivine gabbro now accepted as part of the Michael gabbro suite (the longitude co-ordinate reported in the original paper is incorrect). A similar K–Ar whole-rock result of 2185 ± 68 Ma (2179 Ma recalculated) was obtained by Wanless *et al.* (1973; sample GSC72-140) for a gabbro 14 km west of Grasty *et al.*'s locality. No interpretation is offered for the 2185 Ma date, but, for the 2080 Ma date, Grasty *et al.* suggested excess argon to be the cause. Two other K–Ar whole-rock ages were obtained in the Indian Harbour area, within *ca.* 2 km of Grasty *et al.*'s locality. These were 1340 ± 120 Ma (Wanless *et al.*, 1972; sample GSC70-142; 1348 Ma recalculated) and 1315 ± 52 Ma (Wanless *et al.*, 1973; sample GSC72-150, average of two determinations; 1323 Ma recalculated), both of which are broadly consistent with the currently accepted age. The only remaining K–Ar date pertinent to the Michael gabbro was reported by Hunt and Roddick (1987; sample GSC87-3), and is a hornblende age of 1072 ± 15 Ma from within the Lake Melville terrane in the Rigolet area. The date is consistent with the time of Grenvillian metamorphism in that area. In their report, Hunt and Roddick list five results under their heading 'Mineral K–Ar Ages in the Michael gabbro', but the other four localities have been excluded here as probably not part of the Michael gabbro. Clarification is also needed regarding Fahrig and Larochelle's (1972) inclusion of Grasty *et al.*'s sample L56 from near Ship Head in their tabulation of then available age data for the Michael gabbro. The sample yielded a K–Ar whole-rock age of 974 ± 13 Ma (985 Ma recalculated). The author has not investigated this site, but suspects it is not Michael gabbro as: i) the age is abnormally young for a Michael gabbro in an area not affected by Grenvillian metamorphism and, ii) being in the Makkovik Province, the location is very anomalous compared to other Michael gabbro occurrences. Possibly, the intrusion is an Aillik dyke correlative.

The first formally published Rb–Sr geochronological study of the Michael gabbro is that of Fahrig and Loveridge (1981), who, using samples from the Indian Harbour, reported an errorchron of 1461 ± 96 Ma, I_{Sr} = 0.7033. This result was based on 5 samples from a chilled margin, coarse-grained centre, and three felsic veinlets within the gabbro that were believed to be very late-stage crystallization products of it. Note that the data were originally obtained by R. Wanless, analyzing samples collected by W. Fahrig, and were previously mentioned by Wanless *et al.* (1973) and Fahrig and Larochelle (1972). Wanless *et al.* gave the date as 1390 ± 81 Ma ($\lambda = 1.47 \times 10^{-11}$ yr^{-1}; *cf.* sample GSC72-150) and Fahrig and Larochelle (1972) gave it as 1488 ± 107 Ma ($\lambda = 1.39 \times 10^{-11}$ yr^{-1}). Owen (1985) expressed reservations regarding the date, arguing that the veinlets, being enriched in Si and alkalis, and depleted in Fe, Mg and Ca, could contain extraneous material derived from the host rocks into which the gabbro was emplaced.

Another attempt to date the Michael gabbro by the Rb–Sr method was made by Brooks (1982b) using some of the author's samples. Although the result obtained (1383 ± 56 Ma, I_{Sr} = 0.70165) overlaps with Fahrig and Loveridge's (1972) result, little credence should be given to it. It was based on 3 samples, none of which may belong to the Michael gabbro suite. Similarly, an alternative date of 1346 ± 117 Ma, I_{Sr} = 0.70195 involving additional samples that was given by Brooks (1982a) must be rejected as the regression involved at least two groups of rocks that are unrelated. The currently most thorough evaluation of the Michael gabbro using Rb–Sr data is that of Emslie *et al.* (1997). This study involved reported Rb–Sr and Sm–Nd isotopic data for 13 samples that had been carefully screened and accredited as being Michael gabbro using petrographic, whole-rock, major- and trace-element (including rare-earth elements) data. The Rb–Sr isotopic data scattered in a linear array about an age of 1175 ± 130 Ma. Emslie *et al.* commented that this is much younger than the 1426 Ma U–Pb zircon age and likely significantly disturbed by Grenvillian effects. Note that, although the 1175 Ma Rb–Sr date is somewhat similar to the 1250 Ma U–Pb age of the Mealy dykes (*see* later), any thoughts of correlation can be dismissed as the εNd isotopic signatures of the two suites are very different.

Emslie *et al.* (1997) reported a Sm–Nd isochron age of 1512 ± 520 Ma utilizing the same data set as that for the Rb–Sr age result. They noted that the array was highly scattered, but that the nominal date was broadly consistent with the 1426 Ma U–Pb zircon age. Including the data of Devereaux (2011) modifies the age result to 1534 ± 400 Ma.

The 1426 ± 6 Ma U–Pb age, already mentioned in the introductory paragraph, is based on three near-concordant zircon fractions, with the lower intercept of the chord anchored by titanite (978 ± 4 Ma) from the adjacent gneiss (Schärer *et al.*, 1986). The sample (CG84-172E) comes from (west) Double Islands, 20.6 km north-northeast of Cartwright, a locality where field relationships with associated rocks are superbly and unequivocally displayed (Plate 10.2A). The gabbro clearly discordantly truncates pegmatite (dated to be 1499 +8/–7 Ma) that is hosted in quartz diorite (dated to be 1654 ± 5 Ma; both ages from Schärer *et al.*, 1986). The Michael gabbro at the locality is boudinaged (Plate 10.2D) and intruded by undated pegmatite. Both boudinage and pegmatite emplacement are presumed to be related to Grenvillian orogenesis.

From Ticoralak Island, Corrigan *et al.* (2000), on the basis of 3 fractions of clear zircon, 2 fractions of polycrystalline zircon and 3 baddeleyite analyses, obtained an age of 1472 +27/–21 Ma, with a lower intercept of 1010 ± 10 Ma, the latter essentially defined by the two polycrystalline zircon fractions. Explanations offered for the difference in age with respect to the result of Schärer *et al.* (1986) were that the 1426 Ma age represents either a younger dyke-emplacement event, or the rock experienced an early Grenvillian Pb-loss event. Gower and Krogh (2002) challenged the validity of the result of Corrigan *et al.* as providing an age of emplacement of Michael gabbro on two grounds, namely: i) the regression excluded some analyses, and, more importantly, ii) the whole-rock data of Tulk (1996) for the same sample shows high Al_2O_3, CaO and Na_2O and anomalously low Fe_2O_3t, MgO, and MnO, even compared to those Michael gabbro samples enriched in plagioclase and depleted in ferromagnesian minerals.

Results from Rogers (2017) have established that the Michael gabbro was emplaced over at least a 25-million-year time span, based on two additional precise age determinations, using four baddeleyite fractions from each sample. The ages obtained are 1449 ± 3 Ma (sample FA71-04) and 1437 ± 4 Ma (sample CG03-006).

15.1.4 MINERAL ASSEMBLAGES

The approach adopted here to addressing mineral assemblages in Michael gabbro is in terms of the earlier alluded-to metamorphic gradient increasing from north to south. Use is made of the zonal scheme of Gower and Erdmer (1988) who, in the Double Mer–Lake Melville region, established three major metamorphic subdivisions (Zones 1, 2 and 3) that were applicable to all the pre-Grenvillian rocks present. In Zone 1, six subdivisions were distinguished (1a to 1f; equivalent to 1.1 to 1.6 of Gower, 1986) within Michael gabbro, and a few occurrences of Michael gabbro identified in Zone 2 (Figure 15.2).

> *Zone 1A* is characterized by Michael gabbro in its least metamorphosed state, having a near-pristine igneous assemblage consisting mainly of olivine, colourless to mauve clinopyroxene with minute exsolved opaque inclusions, and well-twinned, very pale-brown plagioclase showing straight grain boundaries. Large primary, red-brown biotite flakes, typically mantling a primary opaque oxide, and apatite are other phases. Hypersthene, amphibole, sulphide and interstitial K-feldspar are additional minor and sporadic igneous phases. Very narrow, less than 0.005 mm wide, double coronas between olivine and plagioclase, consisting of an inner corona of colourless, radial, prismatic orthopyroxene and an outer corona of clinopyroxene, or pale-green pargasitic amphibole and very fine spinel, make their appearance in Zone 1a, increasing in width progressing southward. Rare secondary, retrograde minerals are chlorite, epidote and carbonate.
>
> *Zone 1b* shows double (and, locally, multiple) orthopyroxene–amphibole coronas between olivine and plagioclase becoming wider, southward reaching up to 0.5 mm and easily seen in outcrop. There is no sharp boundary between Zones 1a and 1b. Olivine is more altered to secondary Fe oxides than father north, and orthopyroxene–opaque mineral symplectites start to develop. Partial amphibole coronas also exist between plagioclase and opaque oxides + biotite. Progressing south, plagioclase takes on a slightly brownish appearance due to dusty spinel inclusions, and its grain boundaries start to become wavy, due to recrystallization. The coronal reaction between olivine and plagioclase (Gower and Erdmer, 1988, and sources therein) can be written as:
>
> $$\textit{Plagioclase (2Ab + 4An) + 12 Olivine + Magnetite + } 2H_2O = \textit{12 Hypersthene + 2 Ferriparagsite + 1 Hercynite}$$

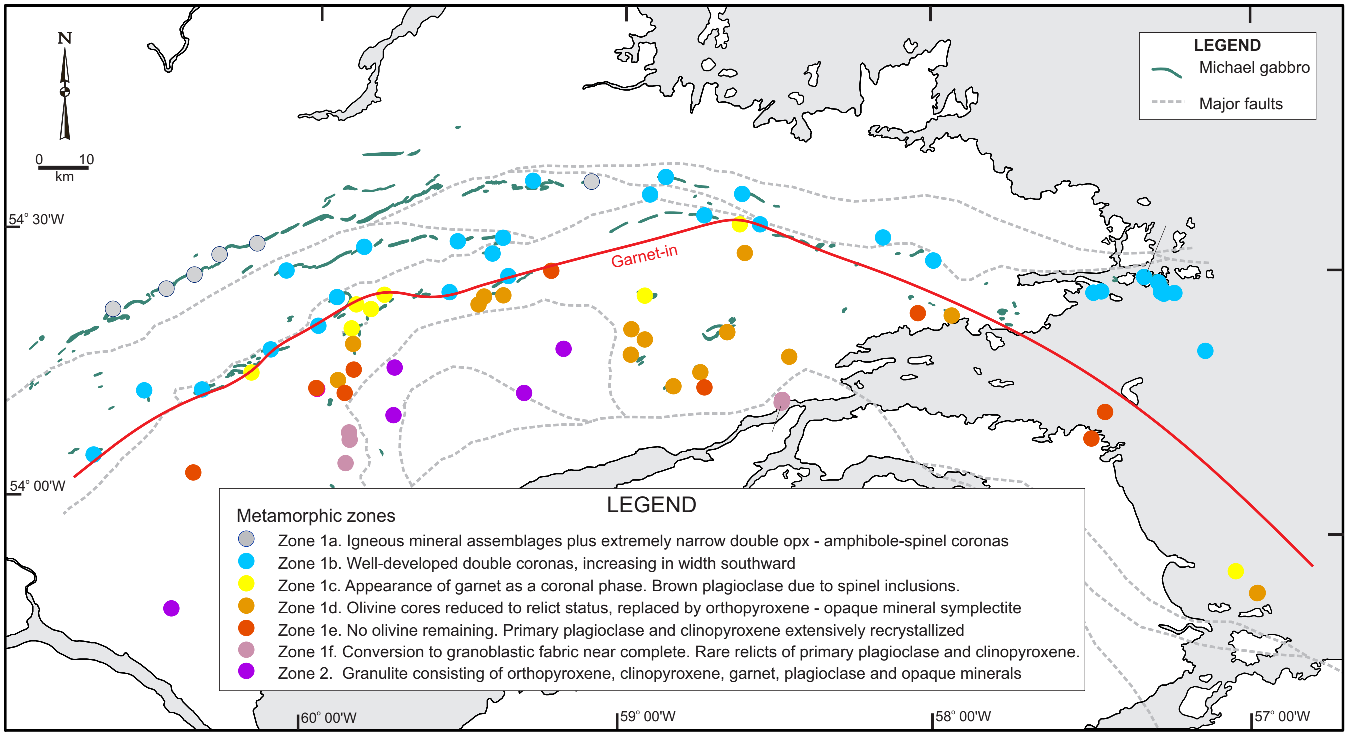


Figure 15.2. *Metamorphic zones defined on the basis of mineral assemblages in Michael gabbro.*

(Under anhydrous conditions, clinopyroxene is a product instead of amphibole + spinel).

Zone 1c is marked by the appearance of garnet as an outer coronal phase between the olivine-related double orthopyroxene–amphibole coronas and plagioclase, first developing as small isolated grains, then coalescing into discontinuous necklaces. Garnet also forms as a coronal mineral associated with biotite and amphibole marginal to primary opaque oxide (locally slightly earlier than where associated with olivine coronas). Much olivine has been replaced by coronal minerals in the upper part of Zone 1c. Primary plagioclase is characteristically brown due to abundant spinel inclusions, but, marginal to coronas, it is colourless (due to consumption of spinel). Grain boundaries in plagioclase are typically wavy-recrystallized. Primary clinopyroxene has larger opaque inclusions and may be mantled by narrow zones of amphibole. Biotite is present as both primary red-brown flakes and recrystallized orange-brown aggregates. The garnet-forming reaction suggested by Gower and Erdmer (1988, and sources therein) is

Plagioclase + Hypersthene + Amphibole + Spinel = Garnet
+ Clinopyroxene + more Na-rich Plagioclase

Zone 1d has only relict olivine remaining, most having been replaced by an orthopyroxene–opaque mineral symplectite or incorporated into multiple hypersthene–clinopyroxene–amphibole–spinel–garnet coronas. Much primary plagioclase remains. It is brown where spinel inclusions are present, but colourless where corundum platelets have formed. Clinopyroxene persists as relict primary grains mantled by amphibole and garnet coronas. Much clinopyroxene has been recrystallized to aggregates. Amphibole and garnet form coronas around opaque minerals. Garnet-forming reactions were suggested by Gower and Erdmer (1988, and sources therein) to be:

Coronal to Clinopyroxene:

Plagioclase + Clinopyroxene = Garnet
+ Secondary Clinopyroxene

Coronal to opaque oxides:

Plagioclase + Magnetite + Quartz = Garnet
+ Na-rich Plagioclase + O_2

By *Zone 1e* no olivine remains, although its former existence is still evident from orthopyroxene–opaque oxide symplectites. Primary plagioclase is present as a relict mineral, having been extensively modified by recrystallization. Remnant brown patches with coarse spinel are present, but clear plagioclase with abundant corundum is prevalent. Clinopyroxene is extensively recrystallized and garnet coronas are separated from clinopyroxene by clear plagioclase moats. Biotite occurs as recrystallized aggregates in association with coronal garnet around opaque oxides.

In *Zone 1f* conversion to a granoblastic fabric is near complete. Not only is olivine absent, but indication of its former presence is vague. Similarly, primary plagioclase is only present as rare, colourless relict grains with corundum platelets; most is recrystallized to polygonal aggregates without corundum. Clinopyroxene forms rare relict primary grains, but has been mostly recrystallized to polygonal aggregates. Orthopyroxene, biotite and opaque oxides are only found as polygonal aggregates.

Zone 2 is characterized by granoblastic, pleochroic orthopyroxene, and recrystallized polygonal plagioclase and clinopyroxene (although some rare relict primary grains of both tenaciously remain). Biotite occurs are coarsely recrystallized aggregates around recrystallized aggregates of opaque oxides.

Thin section descriptions are available for the following samples (* Thin section loaned and never returned, *see* Appendix 1.8).

Zone 1a: CG83-426, CG83-437*, CG83-504, CG83-513*, CG83-532*, BR76-507 (from A.B. Ryan's collection).

Zone 1b: CG79-591B (chilled margin), CG79-591C*, CG79-400B, CG79-599.1, CG79-599.2, CG80-707, CG82-020*, CG82-023*, CG82-025, CG82-028 (chilled margin), CG82-029A* (chilled margin), CG82-029B*, CG82-030 (chilled margin; Photomicrograph 15.1a), CG82-031A* (chilled margin), CG82-031B*, CG82-034B, CG82-035*, CG82-036*, CG83-006, CG83-013, CG83-115, CG83-229 (retrograded), CG83-237, CG83-427, CG83-429 (retrograded), CG83-519, CG83-545, CG83-566, CG83-582*, CG83-587, EC82-7 (from Emslie, 1983), BR78-111 (from A.B. Ryan's collection), V-436 (retrograded), V-505, V-554, V-740 (V- series from J.V. Owen's collection).

Zone 1c: CG79-402, CG80-559A, CG81-627B*, CG83-234*, CG83-239 (retrograded), CG83-240 (retrograded), CG83-246*, CG83-578*.

Zone 1d: CG79-411B, CG79-633, CG79-658*, CG79-673, CG79-677.1*, CG79-677.2, CG80-561B*, CG80-562, CG80-574*, CG80-580*, CG81-634, CG83-017A, CG83-020, CG83-021, CG83-250A, CG83-280, CG84-172E (note: CG81-634 and CG84-172E are same locality).

Zone 1e: CG79-637B, CG80-582, CG80-615, CG80-694C, CG83-008 (retrograded), CG83-261, CG83-288*, CG83-609*, SGJ68-301 (from I. Stevenson's collection).

Zone 1f: CG80-035A, CG80-035B, CG88-046, CG83-283, CG83-405, CG83-462*, CG83-469C.

Zone 2: CG83-027, CG83-085, CG83-264, CG83-314.

15.1.5 MINERAL CHEMISTRY

Mineral analyses for the Michael gabbro have been reported by Emslie (1983), Owen (1985) and Gower (1986). In addition, mineral analyses from mafic rocks in the Rigolet area have been reported by Tulk (1996), but, to this author, it is uncertain that the rocks are part of the Michael gabbro suite. Emslie (1983) provided geochemical data for mafic minerals from three samples (EC82-7, EC82-8 and EC82-30), tabulating analyses for primary olivine, clinopyroxene, and biotite, and for metamorphic orthopyroxene, clinopyroxene, amphibole and garnet. It is clear from his accompanying text and figures that many other analyses were obtained, including primary orthopyroxene and plagioclase, and metamorphic orthopyroxene, clinopyroxene, amphibole, garnet and plagioclase. Owen's (1985) mineral data are for four samples of Michael gabbro (V436, V505-2, V554-1, V740), approached from the perspective of analyses of core primary olivine or ilmenite and their various coronal phases, including orthopyroxene, amphibole, biotite and garnet. Gower's (1986) analyses were from three samples (CG83-237, CG83-246, CG83-437) and targeted mostly primary igneous phases (olivine, orthopyroxene, clinopyroxene, biotite, ilmenite, and plagioclase), but included a few analyses for coronal orthopyroxene, amphibole and garnet.

As noted by Emslie (1983), primary olivine in Michael gabbro shows a substantial range in composition (Mg/Mg + Fe ranges from 0.418 to 0.677). The two olivine analyses reported by Owen (1985) are distinctly Fe-rich (Mg/Mg + Fe = 0.42). Emslie's (*op. cit.*) Figure 17.3 plots one primary olivine having an equally low Mg/Mg + Fe value (0.41), but the sample's numerical data and location are not reported. Some of Emslie's samples are from the same area as those of Owen (Indian Harbour). If Emslie's low Mg/Mg + Fe sample is one of them, this might provoke questions as to whether the Indian Harbour mafic intrusions belong to the Michael gabbro suite. Emslie's Figure 17.4 depicts data for two primary orthopyroxene samples (no numerical data given) and Gower (1986) included data for one primary orthopyroxene (Mg/Mg + Fe = 0.650). In particular, high Al_2O_3 (2.31%) distinguishes it clearly from coronal orthopyroxene, which has Al_2O_3 values between 0.35 and 1.18%. Primary clinopyroxene is noted by Emslie (1983) to be low-Ca augite (as is that of Gower, 1986). Biotite (TiO_2 rich) and an opaque mineral (ilmenite) are the other primary phases. Emslie (1983) also reported analyses for recrystallized clinopyroxene, which is more Ca-rich and aluminous than primary clinopyroxene, and coronal amphibole, which is also very aluminous.

15.1.6 WHOLE-ROCK CHEMISTRY

The author's geochemical database includes whole-rock geochemical data for 61 samples of Michael gabbro, of which 21 samples have rare-earth element (REE) data. Earlier, Gower *et al.* (1990a) reported averaged whole-rock major-element data for 70 samples of Michael gabbro, trace-element data for 69 samples and REE data for 25 samples. Their average included the 61 analyses in the current database, plus major-element data for 9 samples that are no longer deemed to be Michael gabbro (8 samples for trace-elements and 4 samples for REEs). The exclusions are based on refined discrimination between Michael and Adlavik-type mafic rocks.

Emslie *et al.* (1997) tabulated whole-rock geochemical data for 13 samples of Michael gabbro. These results are drawn from the author's database, except of some trace elements (Ba, Cr, Ga, Nb, Rb, Sr, V, Y, Zr) that were re-analyzed prior to publication and updated values included. Comparison between the author's database and Emslie *et al.*'s data for the re-analyzed trace elements shows good correlation for Sr, V, Y and Zr; mediocre correlation for Ba, Cr and Rb; and poor correlation for Ga and Nb. The data of Emslie *et al.* are recommended, but, of course, only apply to the 13-sample subset. In the case of Nb in the author's database, at the time analysis was carried out, many samples were below detection limit for the method used. Given the author's suspect Nb values, they have not been used for petrotectonic analysis purposes. Devereaux (2011) re-analyzed 4 samples of Michael gabbro (along with 11 samples of Adlavik-type gabbro – *see* earlier), for major and trace elements, including REEs. For the 9 trace elements listed above, quality of element correlation is similar to that for Emslie *et al.* (1997).

The basic geochemical features of the Michael gabbro are well established. Both Gower *et al.* (1990a) and Emslie *et al.* (1997) noted that the Michael gabbro is similar to other continental diabase suites. They characterized the gabbros as tholeiitic, transitional between subalkaline and alkaline – as indicated in the alkalis–FeOt–MgO and alkalis–SiO_2 plots of Irvine and Baragar (1971), for example. These are shown in Figure. 15.3A, B, using the author's 61-sample database. Emslie *et al.* (1997) interpreted Labradorian subcontinental mantle lithosphere as the most plausible controlling influence on the composition of the Michael gabbro parent magmas.

A key new contribution developed by Rogers (2017) is that distinct geochemical subgroups exist within the Michael gabbro. The distinction is clearly evident in a plot of Zr *vs.* P_2O_5 (Figure 15.3C), which can, most readily, be used to define the two subgroups. The author was aware of this geochemical separation, but all credit should be assigned to C. Rogers, who independently recognized the distinction, and has made a thorough attempt to understand it. Red and blue symbols identify the high-P and low-P groups, respectively (open symbols from the author's database; filled symbols are those samples re-analyzed by Emslie *et al.*, and Devereaux). The grouping is not confined to these two elements.

The extended-element plot (Figure 15.3D) uses only the superior-analyzed samples of Emslie *et al.* and Devereaux. It provides an update of a similar diagram included by Emslie *et al.* (1997), which, apart from illustrating the fractionation range in the Michael gabbro, also showed a prominent positive Ba and a negative Nb anomaly, explained by Emslie *et al.* as due to contamination by components of arc-related crust. Positive Sr and Eu anomalies are evident in the least fractionated samples *vs.* negative anomalies in the most fractionated samples – the fractionation being strongly influenced by plagioclase. Note that the low-P subgroup samples tend to be the more fractionated and are characterized, in particular, by high Th and U.

In Figure 15.4, several standard petrotectonic discrimination plots illustrate the already well-established conclusion that the Michael gabbro has a within-plate character. More pertinent to the present discussion is that the diagrams

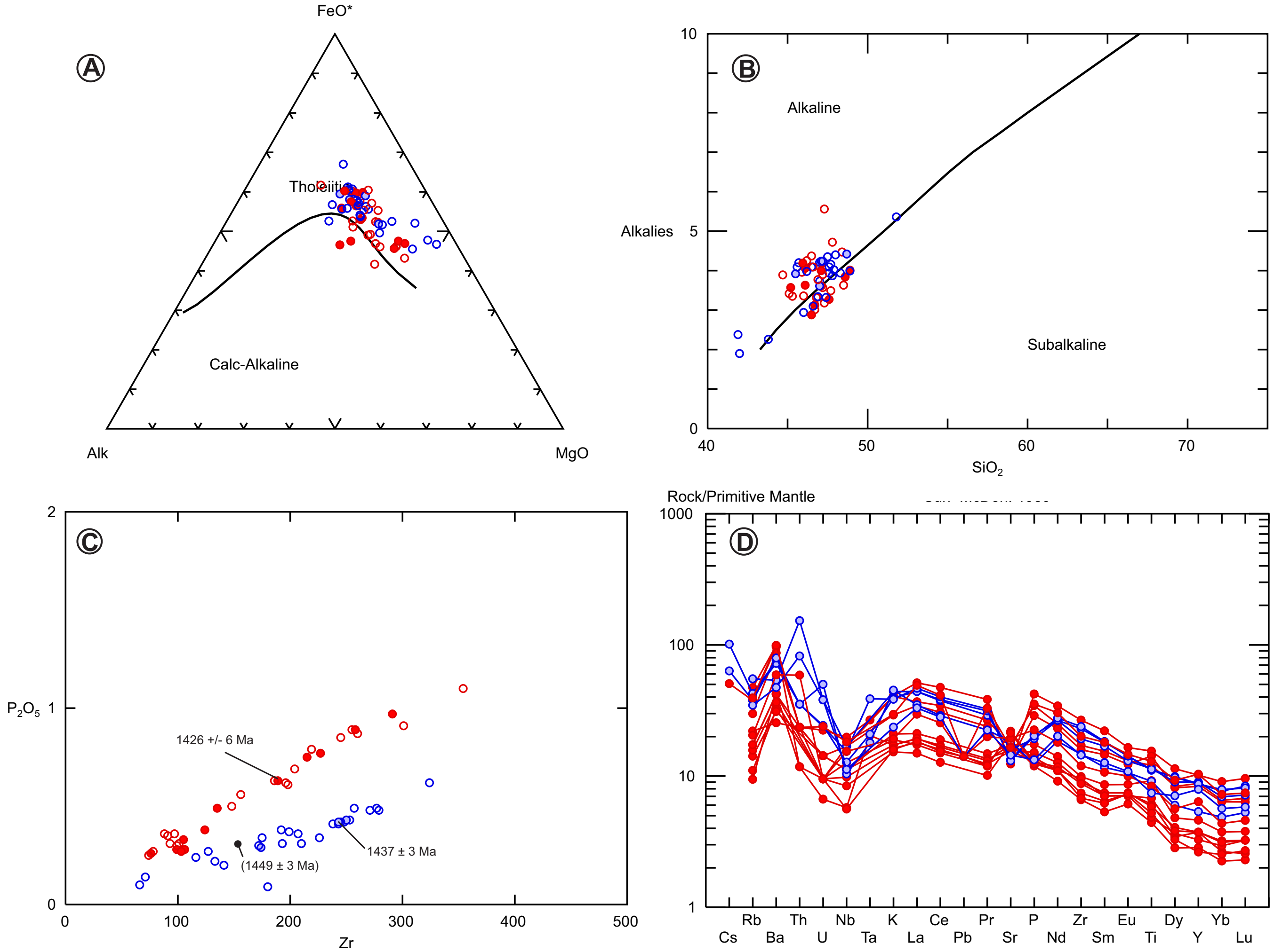


Figure 15.3. *Michael gabbro major- and trace-element geochemical variation diagrams. Red circles – high P_2O_5 group; blue circles – low-P_2O_5 group. Open circles are from the author's database; filled circles are samples re-analyzed by R.F. Emslie and N. Devereaux (and for which Sm–Nd isotopic data are also available).*

also demonstrate the high-P and low-P subgroups, albeit with some overlap between them. In particular, the low-P group has higher Zr/Ti, lower Ti/Y and higher V/Ti.

The identification of the two subgroups begs further interpretation of the Michael gabbro. As Emslie *et al.*'s 13-sample data set included only 2 samples belonging to the low-P group, their conclusions remain largely applicable to the high-P group. The most obvious explanation for the geochemical grouping is that it represents two separate magmatic pluses. Rogers (2017) observe that the two samples, for which they reported 1449 and 1437 Ma ages belong to the low P_2O_5 group, whereas the sample yielding the 1426 Ma age belongs to the high P_2O_5 group. The author does not have geochemical data for the 1449 Ma sample, but the other two are identified on Figure 15.3C.

Geographically, the two subgroups occur in alternating, well-defined linear east–west belts (from north to south; low-P, high-P, low-P, high-P, especially in the western part of the region; Figure 15.5). One interpretation is that they could indicate the presence of Grenvillian interleaved thrust slices. If so, no correlation with currently proposed structural elements is especially evident, implying that interpretational revisions are likely required.

15.2 LINEAR MAFIC BODY IN CARTWRIGHT INTRUSIVE SUITE (on map as $P_{3C}rg$)

A 40-km-long linear sheet-like mafic intrusion within the Cartwright intrusive suite was mapped by Gower *et al.* (1982b) (Figure 12.5). On 1:100 000-scale maps it is includ-

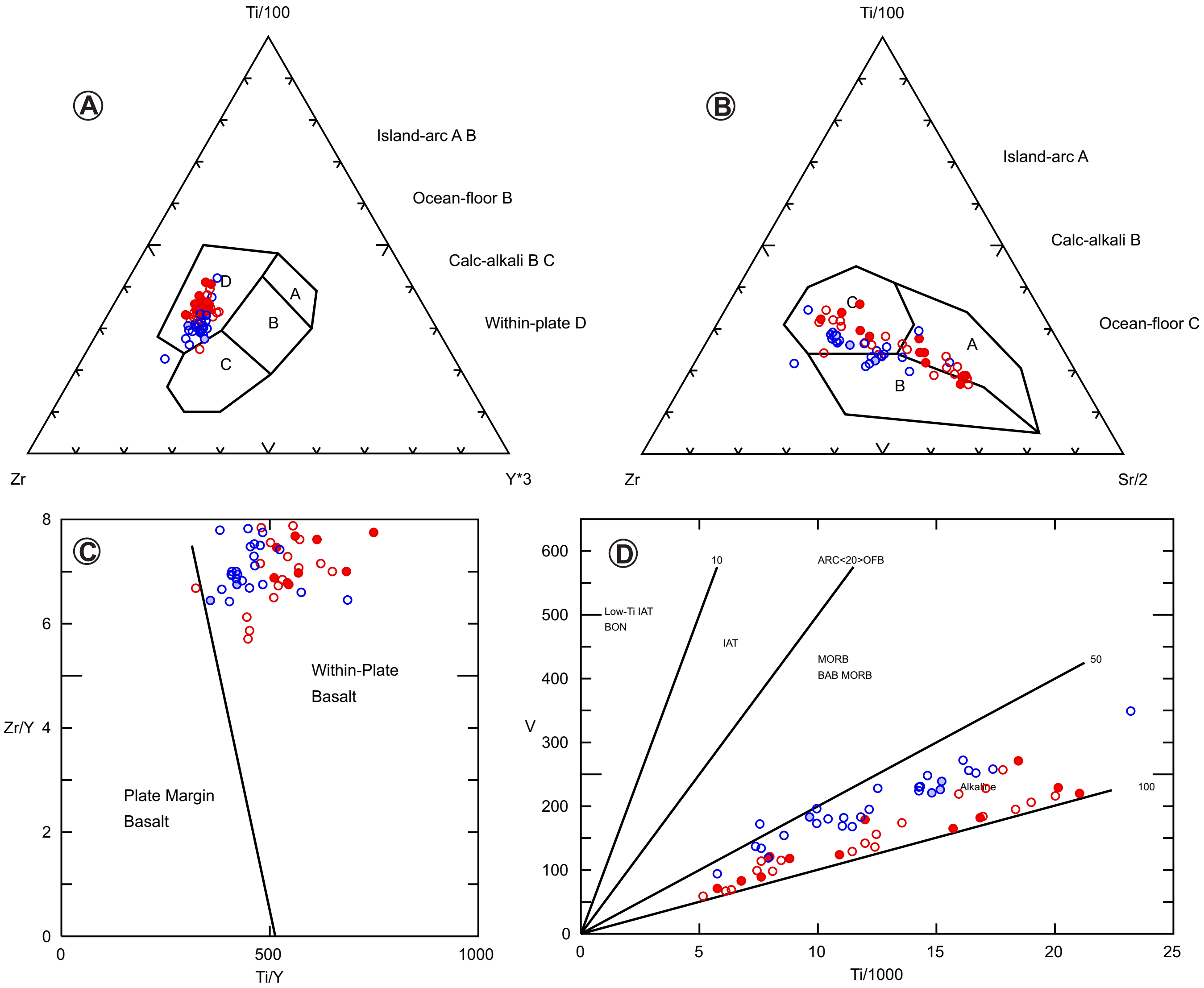


Figure 15.4. *Michael gabbro trace-element petrotectonic discrimination diagrams.*

ed with Unit P$_{3C}$rg. This is likely incorrect, as more detailed petrographic study indicates that these rocks are quite distinct. They have not been dated, but their inclusion here carries the tacit implication that they might be similar in age to the Michael gabbro. The only age constraints are that the Cartwright intrusive suite host rocks have been dated to be 1645 +7/–5 Ma and the mafic intrusion is metamorphosed (*i.e.*, at least Grenvillian). For what it's worth, stained slabs show close similarity in appearance to the 1248 Ma Lourdes-du-Blanc-Sablan gabbronorite.

The body has an overall east-southeast trend and is guesstimated to be about 300 m thick. It consists of a series of discontinuous elongate segments, each several kilometres long (Figure 12.5). The various segments can be confidently correlated because of the unit's distinctive nature. These include: i) lack of a foliation, apart from one exception (*see* below), ii) a well preserved, generally coarse grained, ophitic texture, iii) olivine mantled by very narrow double coronas, iv) common, late-crystallizing K-feldspar (best seen in stained slab), v) abnormally heavy samples (for gabbro), partly due to an unusually high opaque-mineral content, vi) large euhedral apatite crystals, and vii) obvious (in thin section) euhedral zircon. The 'foliation-present' exception is sample VO81-214, which superbly displays a mylonitic fabric in both stained slab and thin section. The localized deformation can be easily explained, as the sample was collected from a locality adjacent to a major strike-slip fault (presumed Grenvillian) that has resulted in a displacement of 1.5 km between the ends of two segments of the gabbro.

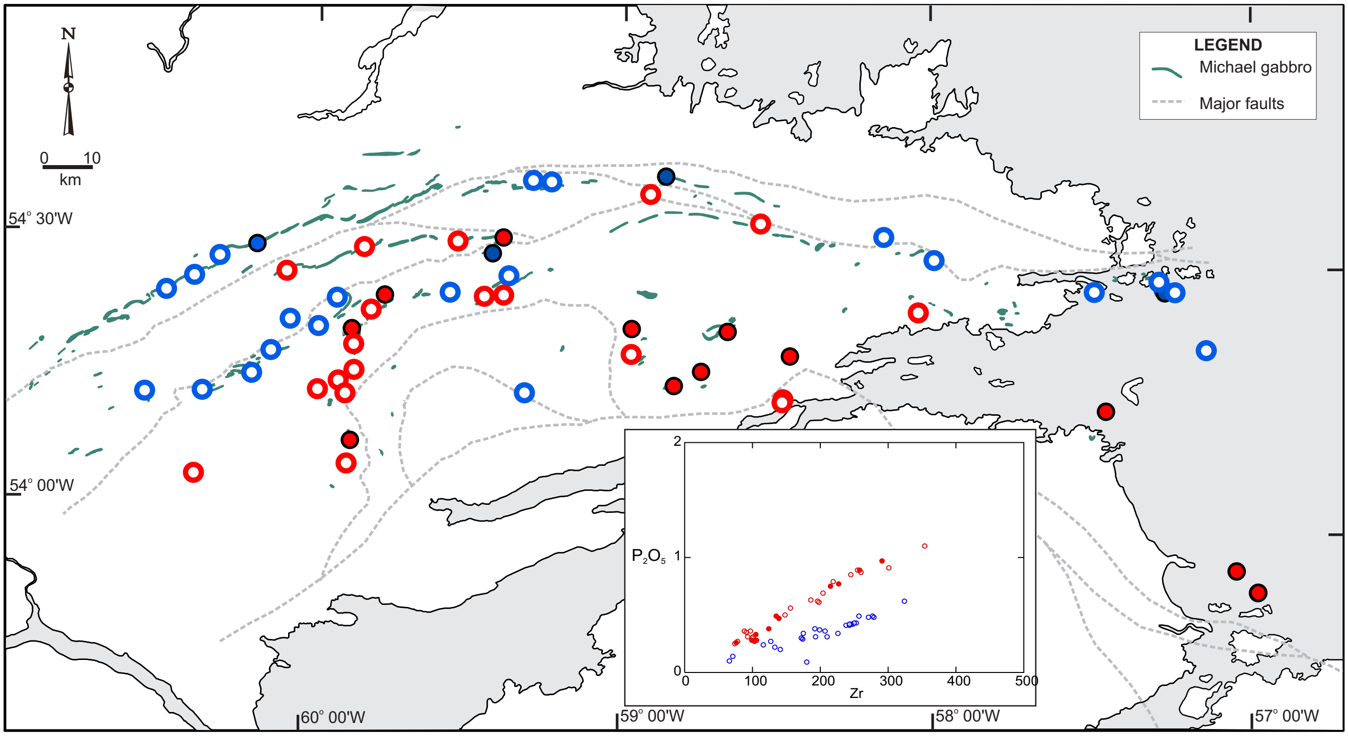


Figure 15.5. *Michael gabbro showing distribution of high* P_2O_5 *(red circles) and low-*P_2O_5 *(blue circles) groups. Filled circles are sites for which Sm–Nd isotopic data are also available).*

At locality MC77-057, the full width of the gabbro is exposed. Both north and south contacts are sharp and chilled against granitoid gneiss. This outcrop is shown on the map of Cherry (1978b) and included in his Unit 6 (which is now known to embrace gabbroic rocks ranging in age from 1640 to 615 Ma). The site has been visited by the author (CG81-031).

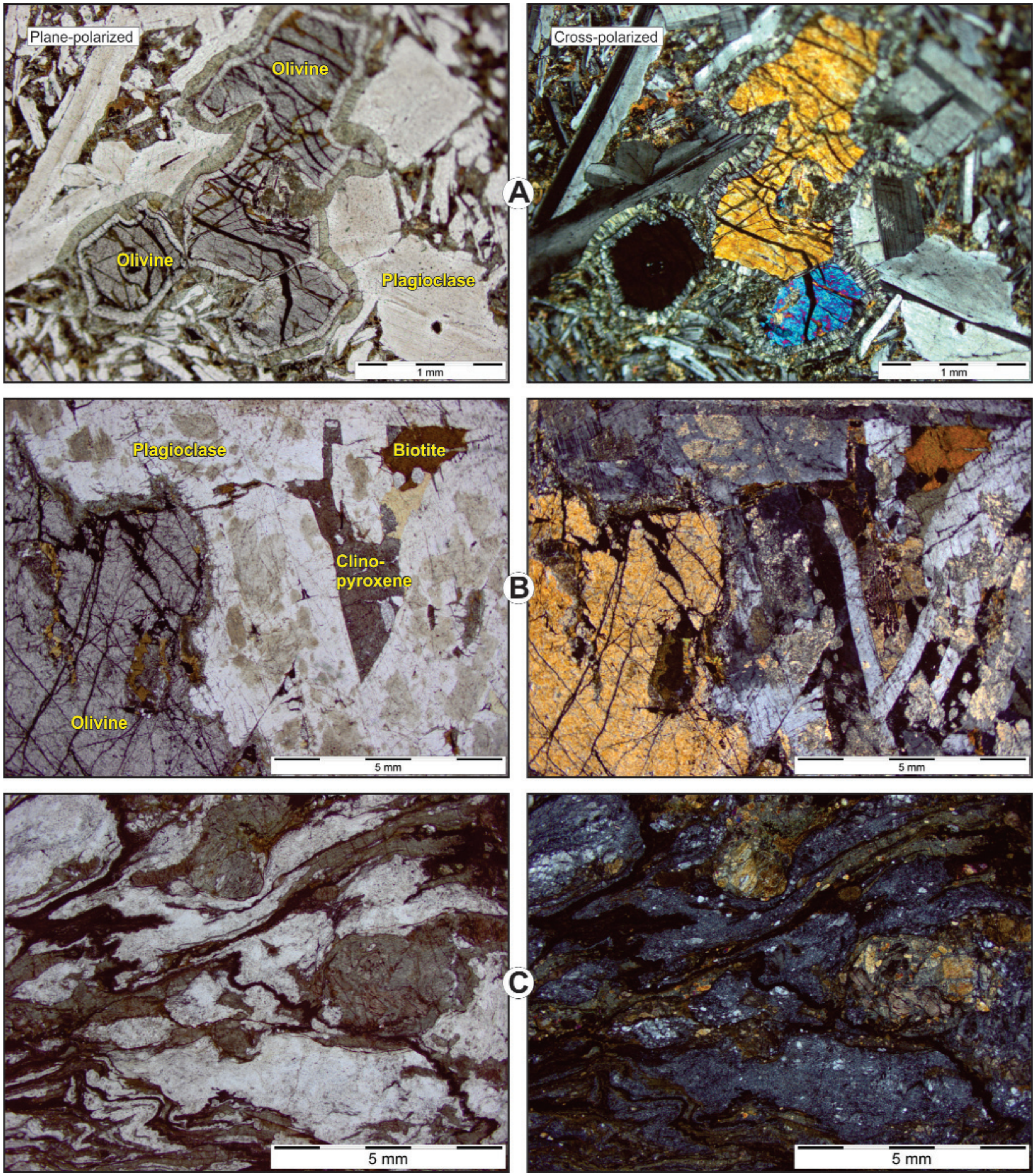
Five samples were examined in thin section (Photomicrograph 15.1B), of which two are coarse grained (CG81-426, MC77-057B), one is medium grained (VO81-441), one is the fine-grained chilled margin to MC77-057B (CG81-031), and one is mylonitic (VO81-214). The coarse- and medium-grained samples have an essentially pristine igneous mineral assemblage consisting of, i) subhedral, unaltered, well-twinned plagioclase that, in part, shows a primary cumulate alignment, ii) large crystals of late-crystallizing, interstitial K-feldspar, iii) relict olivine, typically extensively altered to secondary Fe oxides and serpentine, and showing very narrow coronas (inner – orthopyroxene; outer – pale-green amphibole, iv) mauve-brown clinopyroxene that shows complex, intricate primary growth patterns in detail, v) weakly to moderately pleochroic orthopyroxene, vi) foxy red-brown biotite, characteristically mantling an opaque oxide, vii) primary opaque oxide grains, viii) large, euhedral apatite, ix) fairly large, euhedral zircon associated with biotite, and x) hercynite intergrown with the primary opaque oxide. The fine-grained chilled margin is partially recrystallized and has a mostly metamorphic mineral assemblage, apart from microphenocrysts of euhedral plagioclase. The former presence of olivine microphenocrysts can be discerned from ovoid granular clusters of secondary opaque oxides enveloped in pale-green amphibole aggregates. The matrix of the rock consists of partially recrystallized plagioclase (skeletal form evident in places), and completely recrystallized pale-green amphibole, red-brown biotite, yellow-orange serpentine and opaque minerals.

The mylonite contains broken, bent and otherwise deformed porphyroclasts of pyroxene and plagioclase within a variable grain-size granular matrix in which fragments of most of the above-mentioned primary minerals can be identified. In addition, seams of very fine-grained, granular garnet mark the interfaces between plagioclase and mafic/opaque grains. The mineral assemblage indicates a modest metamorphic overprint, and the brittle–ductile mylonitic deformation implies moderate burial (Photomicrograph 15.1C).

15.3 UPPER PARADISE RIVER MAFIC DYKES (M_1d/M_2d)

This section addresses mafic rocks mapped within the Upper Paradise River suite, plus one occurrence east of the suite (Figure 15.6). It needs to be stated at the outset that this is a very poorly understood group of rocks. They have been given an M_1d/M_2d designation on the author's 1:100 000-scale maps, but even this latitude may not be sufficiently encompassing. Most of the outcrops were found during mapping by van Nostrand *et al.* (1992) and a brief description was provided by van Nostrand (1992).

The locality for which the most information is available (and possibly a signpost for the others) is CG91-072, where a mafic dyke intrudes alkali-feldspar granite (Plate 15.1D). The granite has a Pinwarian U–Pb zircon crystallization age



Photomicrograph 15.1. *Examples of Early to Middle Mesoproterozoic (1460–1350 Ma) units. A. Double coronas (inner orthopyroxene; outer amphibole + spinel) between olivine and plagioclase phenocrysts in fine-grained Michael gabbro (CG82-030), B. Linear mafic body in Cartwright intrusive suite; typical texture (CG81-426), C. Deformed equivalent of Linear mafic body in Cartwright intrusive suite (VO81-214).*

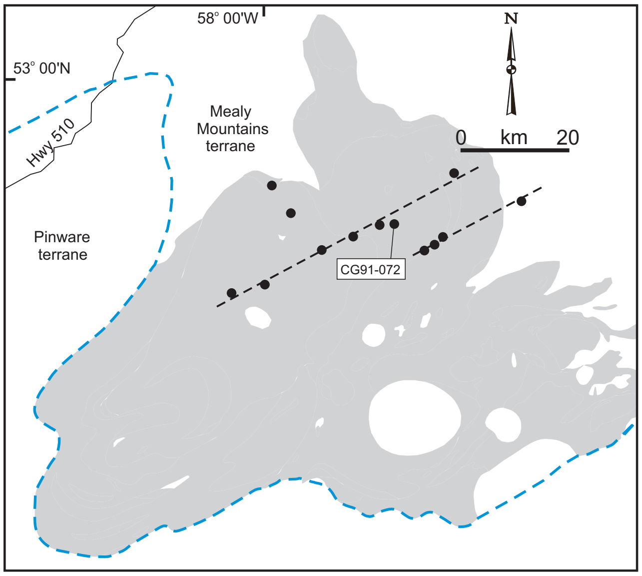


Figure 15.6. *Upper Paradise River mafic dyke(?) localities (black circles) and suggested dyke trend (dashed lines). For geographic reference, grey background represents Upper Paradise River intrusive suite and Kyfanan Lake layered mafic intrusion.*

of 1501 ± 9 Ma (Wasteneys *et al.*, 1997), the sample having been collected at this locality. The mafic dyke–host rock contact is well exposed and clearly shows that the dyke discordantly intrudes the alkali-feldspar granite. The dyke has a 252/77°N trend and its width is at least 10 m (the other contact is not exposed). Wasteneys *et al.* sampled and processed a sample of the dyke for U–Pb age analysis, but no dateable material was recovered.

The mafic dyke is dark-grey-weathering, aphanitic to medium grained, homogeneous and unfoliated.

In thin section (CG91-072B), plagioclase is relict igneous, has elongate habit and has a dusty appearance due to opaque inclusions. The rock does not contain olivine, but has relict igneous orthopyroxene (slightly pleochroic) and clinopyroxene, both of which are mostly polygonal and metamorphic, although some relict igneous material remains. Clinopyroxene contains abundant opaque inclusions. It also contains red-brown biotite and an opaque oxide. Garnet, partly coronal around pyroxene, is common and is responsible for the spotty appearance in outcrop of the rock close to its margin.

Despite all other mafic rocks mapped within the Upper Paradise River intrusion having been assigned an M_1d/M_2d designation, only one of them can be demonstrated to be a dyke, as contacts with their host rocks are not exposed elsewhere. The exception is at data station VN91-400 in the northwest part of the Upper Paradise River intrusion, where the mafic rock discordantly intrudes foliated monzonite and has a chilled contact against it. The strongest justification for considering the mafic rocks to be dykes is that seven of the outcrops collectively define an east-northeast trend, which is the same as the known dyke orientation at CG91-072, and three (four, if an occurrence outside the Upper Paradise River intrusion is included) of the remaining seven occurrences define a parallel trend.

Two thin sections are available from the seven aligned outcrops (CG99-015, VN91-214). Like CG91-072, thin section CG99-015 contains plagioclase, both clinopyroxene and orthopyroxene, red-brown biotite and an opaque mineral, but, in contrast, it also contains common amphibole and lacks garnet. Sample VN91-214 lacks clinopyroxene, contains abundant garnet, and has been more extensively recrystallized. Two thin sections from the parallel trend (CG91-078, VN91-217) are also distinct from each other and from CG91-072. Sample CG91-078 is a coarse-grained, biotite-bearing amphibolite. Sample VN91-217 retains some vestiges of its igneous parentage in relict, subhedral plagioclase and opaque-dusted clinopyroxene, but also contains metamorphic biotite, amphibole and garnet. The remaining thin section (CG91-067B) is a clinopyroxene-bearing amphibolite.

What can one conclude from these rocks, if, indeed, they even form a coherent group? The most solid conclusion is that one occurrence, at least, is a dyke (CG91-072B). It must be younger than *ca.* 1501 Ma, and (because it is metamorphosed) must be pre-Grenvillian. The others could be either dykes or enclaves of older mafic rocks. If the apparent east-northeast trend has any significance, then the argument could be advanced that these rocks are correlative with the 1250 Ma Mealy dykes (Section 16.3). Features supporting such an inference are: i) they have the same trend as the Mealy dykes, and ii) the whole-rock composition of the only sample analyzed (CG91-072) consistently plots within the cluster for the Mealy dykes. On the other hand, these rocks differ in that they lack olivine, have igneous orthopyroxene as an essential phase, have mostly metamorphic fabrics, and contain garnet. Unless one invokes a substantial metamorphic gradient (for which there is no evidence), then it would seem unlikely that they are Mealy dyke correlatives.

15.4 MOKAMI HILL GRANITOID INTRUSION (M_1gr/M_1yq)

The Mokami Hill intrusion is situated in the Groswater Bay terrane 57 km north-northeast of Goose Bay and 5 km north of the mouth of the Sebaskachu River (Figure 15.7). It forms a prominent, steep-sided hill, rising abruptly from the surrounding lowlands (which are 50 m above sea level) to a height of 486 m. The hill is a local tourist attraction and can be reached by a trail from the shore of Sebaskachu Bay. Mokami Hill was first distinguished as a separate unit from the surrounding lowland granitoid gneisses by Stevenson (1967a), who described the rocks as monzonite, quartz monzonite and granite and grouped them as part of an 'Anorthosite Series'. It is included in the map of Erdmer (1984) who subdivided the Mokami Hill intrusion into two

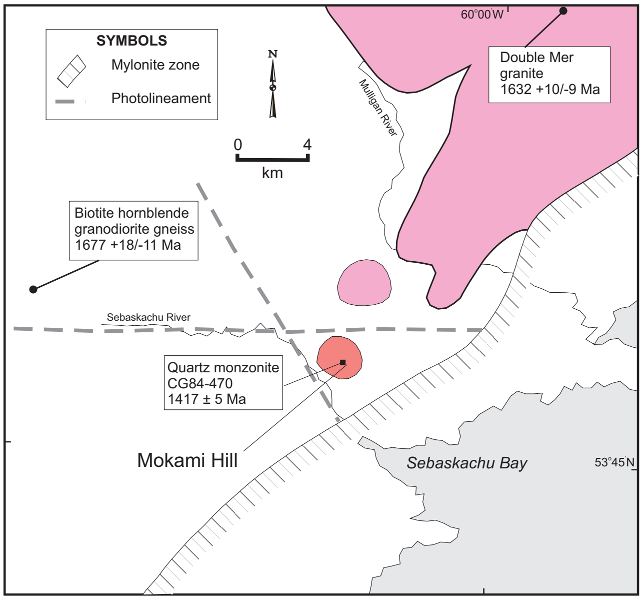


Figure 15.7. *Mokami Hill granitoid intrusion location.* See *text for reference to other features also shown.*

units, namely: i) massive to well-foliated hornblende granite to quartz monzonite, and ii) massive, coarse-grained, brown biotite monzodiorite. Topographic lineaments suggest that the hill may owe its existence to a triangular network of enveloping faults. Biotite hornblende granodiorite gneiss from the lowlands has yielded an age of 1677 +18/–11 Ma (Schärer *et al.*, 1986).

The author first visited Mokami Hill in 1984 and collected a sample (CG84-470) for U–Pb dating (Gower and Kamo, 1997, from whom most of the material in this section has been drawn). The sample was from an outcrop of massive, weakly to moderately recrystallized, coarse-grained quartz monzonite.

> In thin section, the Mokami Hill quartz monzonite is seen to comprise quartz; perthitic alkali feldspar showing coarse flame texture; minor, well-twinned sodic plagioclase; orthopyroxene extensively altered to bastite; pale-green clinopyroxene containing exsolved opaque mineral inclusions; and dark-green amphibole. Accessory minerals are large zoned allanite, an opaque mineral, common zircon (thin rims), apatite, and minor orange-brown phyllosilicate, which is probably a Fe-rich biotite. The mineral characteristics and assemblage are typical of AMCG suites.

A whole-rock geochemical analysis is not available for the dated sample, but Erdmer (1984) reported petrographic and whole-rock geochemical data for two samples (MW82-031, MW82-032) from the body. The geochemical data are tabulated and discussed by Gower and Kamo (1997). The two analyzed rocks are chemically individually distinct and it remains uncertain which (if either) is representative of the dated sample.

During the geochronological investigation, a homogeneous population of generally large, pale-brown, equant to elongate prismatic zircon grains was recovered. Two single- and two multigrain-zircon fractions were analyzed. Three of the fractions are collinear and give a near-concordant upper intercept age of 1417 ± 5 Ma. The fourth data point has a slightly older ^{207}Pb/^{206}Pb age of 1422 ± 2 Ma and was interpreted by Gower and Kamo (1997) as having a small inherited component.

The Mokami Hill quartz monzonite is the only known granitoid intrusion of its age in eastern Labrador. Erdmer (1984) grouped the Mokami Hill intrusion with an unnamed 3-km wide granitoid body 5 km to the north-northeast and, farther northeast, the 20-km-wide Double Mer granite. The 3-km-wide body and Double Mer granite are petrographically and compositionally similar (*cf.* thin sections and/or whole-rock geochemical analyses PE82-098A, PE82-098B, PE82-099, PE82-108), but distinct from the Mokami Hill intrusion. The Double Mer granite was dated by Schärer *et al.* (1986) to be 1632 +10/–9 Ma confirming that the two units are unrelated. Also predating the Mokami Hill intrusion, but closer in age to it, is Pinwarian granitoid intrusive activity between 1520 and 1460 Ma. The Pinwarian activity largely occurred much farther south, in the Pinware terrane, and is compositionally distinct, so there is no direct linkage between the two. The Mokami Hill quartz monzonite is separated from later known granitoid intrusive activity in eastern Labrador by a large time gap, as the next granitoid intrusive activity known was emplacement of the Upper North River pluton at 1296 +13/–12 Ma.

The unit closest in age to the Mokami Hill quartz monzonite is the Michael gabbro, which also occurs in the Groswater Bay terrane. Its youngest age analytically overlaps at 1426 ± 6 Ma. Given their spatial proximity, the Michael gabbro and the Mokami Hill quartz monzonite may belong to a single bimodal mafic–felsic intrusive event, although there are no other obvious lithological candidates in eastern Labrador that might be correlative with the Mokami Hill body. Gower and Krogh (2002) noted that the nominal lower intercept of 770 Ma is somewhat younger than a more typical Grenvillian Pb-loss age of about 1000 Ma, so a different treatment of the data could produce a marginally older age that would be closer to the of the *ca.* 1450 Ma early Elsonian AMCG suites north of the Grenville front, in keeping with the model advocated by Gower and Krogh (2002) for early Elsonian magmatic activity in eastern Labrador that envisaged shallow subduction and an over-ridden spreading centre.