

U–Pb AGES FROM MAFIC ROCKS ASSOCIATED WITH ORTHOMAGMATIC Ni–Cu–Co SULPHIDE MINERALIZATION IN WEST-CENTRAL LABRADOR

A. Kerr and V. McNicoll¹

Mineral Deposits Section

¹Geological Survey of Canada, 601 Booth Street, Ottawa, ON, K1A 0E8

ABSTRACT

Most orthomagmatic Ni–Cu–Co sulphide mineralization in Labrador is associated with Mesoproterozoic plutonic suites. The best-known examples are at Voisey's Bay and Pants Lake, where host intrusions are dated between 1332 and 1313 Ma. Magmatic sulphide mineralization in western Labrador is associated with the Michikamau Intrusion, and sheet-like mafic intrusions assigned to the Shabogamo Gabbro. This article presents U–Pb zircon and baddeleyite data that constrain the ages of these intrusions and their contained syngenetic mineralization.

Mineralization in the Michikamau Intrusion was dated using a coarse-grained pegmatitic variant of the host leucotroctolite, adjacent to, and gradational with, a sulphide-bearing zone. Single-grain analyses of baddeleyite define an age of 1469 ± 1 Ma, indicating that this is the earliest Mesoproterozoic magmatic sulphide mineralization yet identified in Labrador. The result is consistent with a previous age determination inferred to represent associated contact metamorphism. In the Evening Lake area of the Gagnon terrane, sulphide mineralization was dated using a dioritic variant of the sheet-like gabbroic host intrusion, which gave a zircon age of 1448 ± 2 Ma. This confirms the assignment of the host rocks to the Shabogamo Gabbro, and is the first precise age from these rocks within the autochthonous foreland of the Grenville Province in Labrador. A closely similar zircon age of 1444 ± 4 Ma was previously obtained from gabbro of the sparsely mineralized Mount Fyne intrusion, emplaced within deeper level crystalline rocks of the Molson Lake terrane. The results confirm general correlation of mafic intrusive suites across the boundary between the Gagnon and Molson Lake terranes as high-level and deep-level representatives of a single magmatic suite.

Results confirm that magmatic sulphides are hosted by older Mesoproterozoic anorthositic and gabbroic suites as well as their younger counterparts. They also suggest that the Shabogamo Gabbro may have wider potential for magmatic sulphide mineralization. However, age is not the only determining factor that should be used in assessing the potential of individual intrusions. The apparent contrast in prospectivity between the Evening Lake and Mount Fyne intrusions suggests that local geological factors such as the presence of suitable sulphide-bearing country rocks may be an equally significant indicator of mineral potential.

INTRODUCTION

The 1994 Voisey's Bay discovery drew wide attention to the potential for Ni–Cu–Co ($\pm$ PGE) sulphide deposits in Labrador. The greatest exploration effort was directed toward the Nain Plutonic Suite (NPS), a complex assemblage of mafic, intermediate, anorthositic and granitic rocks emplaced between 1350 and 1290 Ma ago, within which a mafic intrusion hosts sulphide mineralization at Voisey's Bay. Orthomagmatic sulphide mineralization was known prior to 1994 in older (>1400 Ma) anorthositic and mafic rocks, notably of the Harp Lake and Michikamau intrusions

(Figure 1). Magmatic sulphide mineralization was also known in gabbroic intrusions within the Grenville Province near Fermont, Québec, where they were correlated with the *ca.* 1450 Ma Shabogamo Gabbro. Subsequently, magmatic sulphides were discovered in similar rocks in western Labrador, also assigned to the Shabogamo Gabbro.

The age of magmatic sulphide mineralization in the NPS is now well constrained. The age of the Voisey's Bay deposit was obtained using U–Pb baddeleyite and zircon data from the host troctolite intrusion, indicating crystallization at 1333 ± 1 Ma (Amelin *et al.*, 1999). Minor sulphide min-

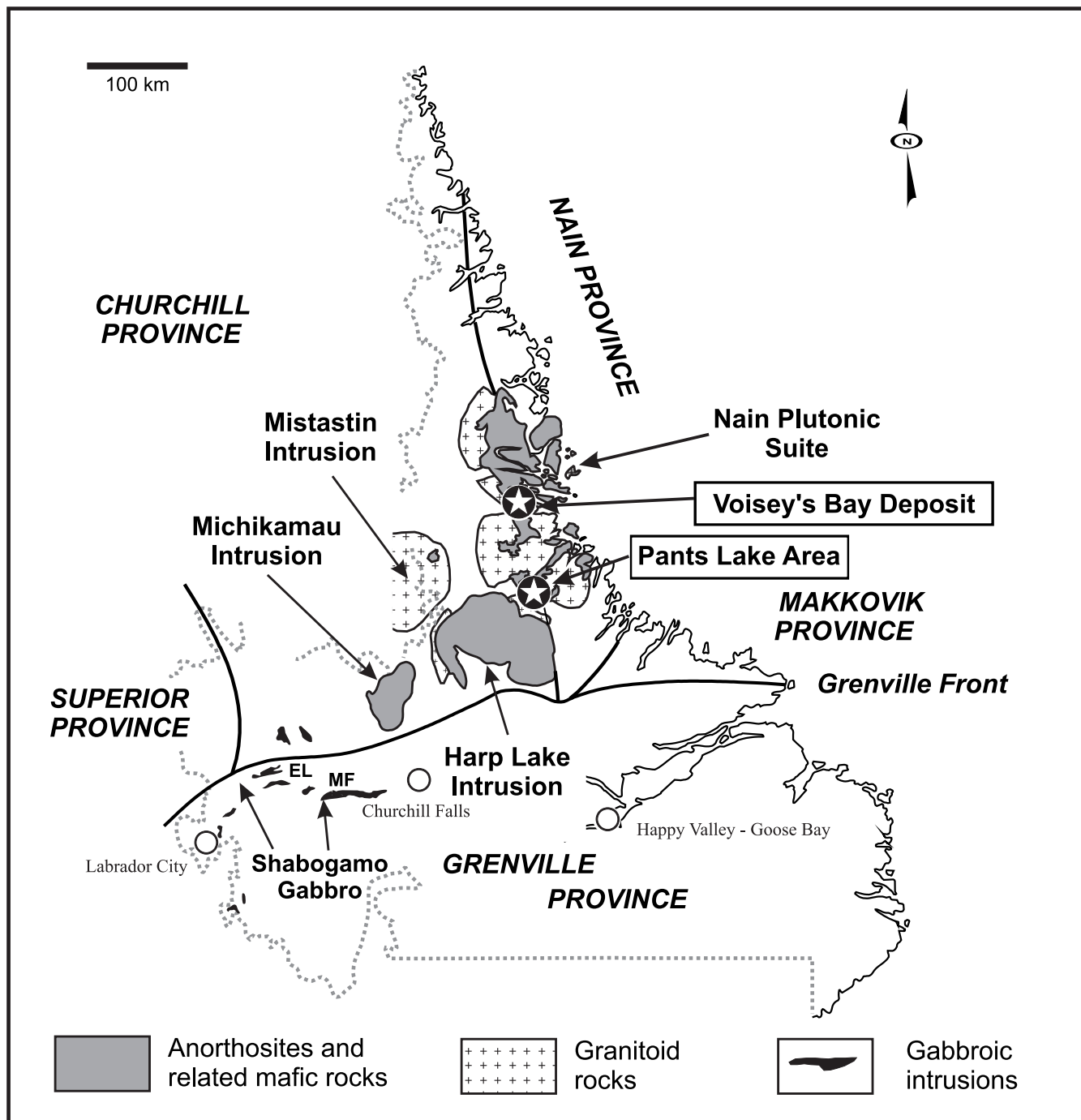


Figure 1. Location map, showing Precambrian structural provinces in Labrador, and major mafic-anorthositic intrusive complexes located north of the Grenville Front. Note that the scale permits only the larger constituent intrusions of the Shabogamo Gabbro to be shown. EL - Evening Lake intrusion, MF - Mount Fyne intrusion.

eralization also occurs in the adjacent Mushuau intrusion, which gave a younger U-Pb age of 1313 ± 1 Ma (Li *et al.*, 2001). Similar gabbroic and troctolitic rocks associated with widespread mineralization in the Pants Lake area gave U-Pb baddeleyite ages of 1338 ± 2 and 1322 ± 2 Ma. (G.R. Dunning and J.N. Connelly, reported by Smith, 2006). This

article presents new U-Pb geochronological data that establish the timing of older episodes of magmatic sulphide mineralization in Labrador, at *ca.* 1469 and 1448 Ma. These results are part of research work in western Labrador focused on the Michikamau Intrusion, the Shabogamo Gabbro, and the Ossok Mountain Intrusive Suite (Kerr, 1999;

Dyke *et al.*, 2004; Kerr, 2007), and also from earlier regional mapping of the Churchill Falls area (Nunn and Christopher, 1983; Wardle, 1985).

REGIONAL GEOLOGICAL AND METALLOGENIC FRAMEWORK

The area is located between Churchill Falls and Labrador City–Wabush in western Labrador (Figure 1), and is underlain by parts of three geological provinces, namely the Archean Superior Province (termed the Ashuanipi Complex in Labrador), the Paleoproterozoic Churchill Province, and the Paleoproterozoic to Mesoproterozoic Grenville Province. The latter is, in part, superimposed upon the older structural provinces, and many elements of the Superior and Churchill provinces can be identified within its northern fringe. However, the Grenville Province also includes large-scale allochthons transported from the south, which do not have a direct connection to this older foreland. The largest of these, in the study area, is the Lac Joseph Allochthon, east of Labrador City (Figure 1). The following summary is condensed from an earlier report by Kerr (2007) and focuses on the Churchill and Grenville provinces.

CHURCHILL PROVINCE

General Geology

The Churchill Province in western Labrador exhibits wide variations in rock types, metamorphic grade and structural style from west to east (Figure 2). The western portion consists of well-preserved sedimentary and volcanic rocks that represent shallow-water and deep-water sedimentary basins collectively termed the ‘Labrador Trough’, itself part of a wider orogenic belt known as the New Quebec Orogen (Hoffman, 1988). The thick sedimentary sequence is termed the Kaniapiskau Supergroup. The western part of the Labrador Trough is dominated by deep-water turbidites, shales and mafic volcanic rocks of broadly similar depositional age. The low-grade sedimentary rocks of the Labrador Trough are bounded to the east by mylonite zones that juxtapose them against high-grade gneisses and granitoid rocks (Figure 2). These include reworked Archean basement, Paleoproterozoic metasedimentary rocks, and granitoid plutonic suites. In the extreme east of the area, these rocks (and the Michikamau Intrusion; see below) are overlain unconformably by quartzites and conglomerates of the basal Seal Lake Group.

The sedimentary and volcanic rocks of the New Quebec Orogen, and the gneissic rocks to their west, were all affected by Paleoproterozoic deformation prior to *ca.* 1850 Ma. They are unconformably overlain by small outliers of the Sims Formation, consisting of arkose and quartzite. The age

of these sedimentary rocks is not well constrained, but they are intruded by the Shabogamo Gabbro, considered to be *ca.* 1450 Ma.

Plutonic Rocks

Paleoproterozoic rocks of the Churchill Province, and the Sims Formation, are intruded by sheet-like mafic intrusions that are assigned to the Shabogamo Gabbro, originally defined by Frarey and Duffell (1964). These are part of a wide belt of mafic intrusions along the northern margin of the Grenville Province, also including the Michael Gabbro in eastern Labrador (*e.g.*, Gower *et al.*, 1991). The Shabogamo Gabbro intrusions are dated within the Grenville Province at *ca.* 1450 Ma (*see below*), but have not been precisely dated within the Churchill Province. It has been suggested that some mafic intrusions within this region (and perhaps also within the northern section of the Grenville Province) could be older suites of *ca.* 1650 Ma, which are well-known in eastern Labrador (*e.g.*, Kerr *et al.*, 1992). There is some supporting evidence in the form of ‘anomalously’ old Ar–Ar ages that may be valid, rather than artifacts caused by excess Ar (Gower, 2003), and rocks of *ca.* 1650 Ma certainly exist east of the Smallwood Reservoir (Gower and Krogh, 2002). The central gneissic domain of the Churchill Province is intruded by a large mafic to anorthositic body known as the Michikamau Intrusion (Emslie, 1968; Figure 2). Prior to this study, direct age constraints were provided only by a *ca.* 1460 Ma U–Pb zircon age from an intermediate rock that cuts the mafic and anorthositic rocks (Krogh and Davis, 1973).

GRENVILLE PROVINCE

General Geology

The Grenville Province consists of three broad terranes. In the west and the north, the Gagnon terrane comprises largely autochthonous rocks that correlate with the Ashuanipi Complex and the Labrador Trough (Figure 2). The exact position of the northern limit of the Grenville Province (the Grenville Front) depends on its definition, which can either be structural or thermal (*see discussion by Gower, 2003*). In the Gagnon terrane, the stratigraphy of the Kaniapiskau Supergroup remains recognizable, but the intensity of Grenvillian (*ca.* 1000 Ma) metamorphism and deformation increases southward. The Gagnon terrane passes laterally into the Churchill Falls terrane to the west, which is dominated by *ca.* 1650 Ma plutonic and volcanic rocks. The Gagnon and Churchill Falls terranes are bounded to the south by the paraautochthonous Molson Lake terrane, which represents a much deeper crustal level. The Molson Lake terrane is dominated by granitoid gneisses derived from *ca.* 1650 Ma plutonic suites of the Trans-Labrador

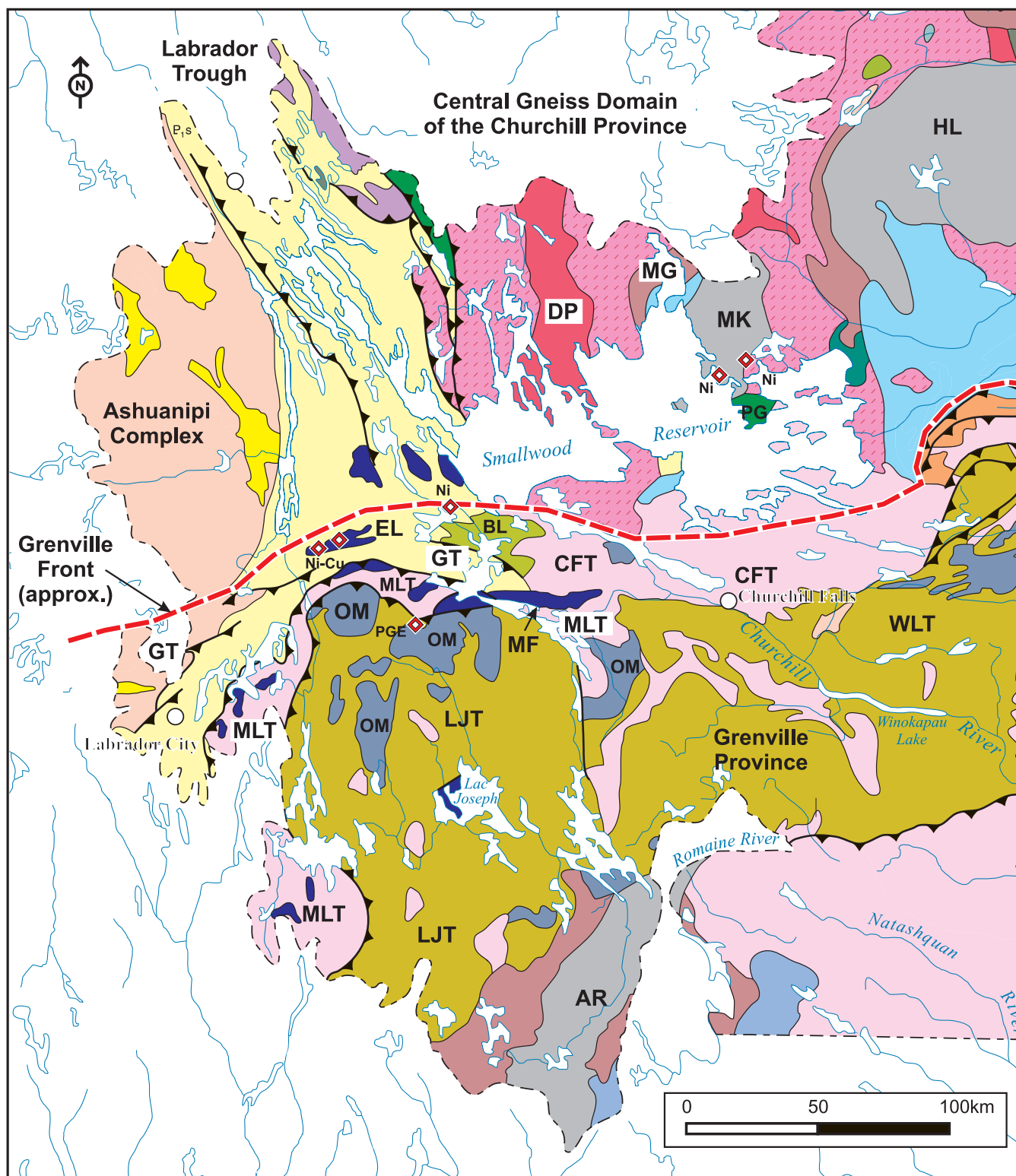


Figure 2. Simplified regional geology of west-central Labrador, showing the geological units discussed in the text, and locations of important magmatic sulphide mineralization.

LEGEND (Figure 2)**MESOPROTEROZOIC**

-  Terrestrial sedimentary rocks (Seal Lake Group)
-  Felsic volcanic rocks (Letitia Lake Group)
-  Mafic and intermediate intrusive rocks
-  Gabbroic intrusions (Shabogamo Gabbro)
-  Granitoid rocks
-  Anorthosite and related mafic rocks

PALEOPROTEROZOIC**Grenville Province**

-  Mafic and felsic volcanic rocks
-  Mafic intrusive rocks
-  Paragneiss
-  Granitoid gneiss

Central Churchill Province

-  Volcanic and sedimentary rocks
-  Granitoid rocks

Labrador Trough and adjacent areas

-  Mafic and ultramafic intrusive rocks
-  Mafic volcanic rocks
-  Mostly sedimentary rocks

ARCHEAN - PALEOPROTEROZOIC**Central Churchill Province**

-  Mafic metavolcanic rocks
-  Orthogneiss and paragneiss

ARCHEAN**Ashuanipi Complex (Superior Province)**

-  Paragneiss
-  Orthogneiss and migmatite

ABBREVIATIONS**Grenville Province Terranes**

GT - Gagnon Terrane
 CFT - Churchill Falls Terrane
 MLT - Molson Lake Terrane
 LJT - Lac Joseph Terrane
 WLT - Wilson Lake Terrane

Intrusive Complexes

HL - Harp Lake Intrusion
 MK - Michikamau Intrusion
 MG - Michikamats Granite
 AR - Atikonak River Intrusion
 EL - Evening Lake Intrusion
 MF - Mount Fyne Intrusion
 DP - De Pas Batholith
 OM - Ossok Mountain Intrusive Suite

Other Geological Units

BL - Blueberry Lake Group
 PG - Petscapiskau Group

◆ Magmatic sulphide zone
 (discussed in text)

batholith, associated with variably metamorphosed and coronitic mafic rocks, commonly assigned to the Shabogamo Gabbro (*see* below). The southernmost part of the Grenville Province depicted in Figure 2 forms part of the Lac Joseph terrane, which is entirely allochthonous. This is dominated by metasedimentary gneisses, intruded by *ca.* 1650–1630 Ma plutonic rocks, termed the Ossok Mountain Intrusive Suite (James, 1994).

Plutonic Rocks

The autochthonous rocks of the Gagnon and Churchill Falls terranes are intruded by numerous sheet-like mafic bodies assigned to the Shabogamo Gabbro. As in the adjoining regions of the Churchill Province, these are not dated precisely, but they intrude the Sims Formation south of the Grenville Front. As discussed previously in the context of the Churchill Province, the possibility of an older (*ca.* 1650 Ma) age cannot be excluded for some of these rocks. Mafic intrusive rocks in the Molson Lake terrane are generally coarser grained and more varied in texture than those in the Gagnon and Churchill Falls terranes, and display complex corona structures resulting from Grenvillian metamorphism. These rocks are grouped with the Shabogamo Gabbro, and have been dated imprecisely at *ca.* 1459 Ma (Connelly and Heaman, 1993) and *ca.* 1452 Ma (Connelly *et al.*, 1995; locations in Figure 2). The largest individual mafic body assigned to the Shabogamo Gabbro in the Molson Lake terrane is the Mount Fyne intrusion (Figure 2), which is discussed below.

GEOLOGY AND MINERALIZATION

This section summarizes the geology of intrusive rocks dated in this study, and also the associated magmatic sulphide mineralization. The Michikamau Intrusion hosts several discrete mineralized zones, within massive to layered mafic rocks. Rocks assigned to the Shabogamo Gabbro around Evening Lake host a disseminated sulphide zone, associated with the basal contact of a sheet-like mafic intrusion. Smaller sulphide showings occur in other intrusions within the surrounding area. The Mount Fyne intrusion also locally contains disseminated sulphides, but no extensive mineralized zones have yet been defined within it.

MICHIKAMAU INTRUSION

Geological Relationships

The Michikamau Intrusion was described in a classic study by Emslie (1965, 1968) and is believed to have a lopolithic shape, in which a lower funnel-shaped mafic layered sequence is capped by the anorthositic rocks (Figure 3). The country rocks to the intrusion are gneisses and granites

of the central domain of the Churchill Province, and also metavolcanic and metasedimentary rocks of the Paleoproterozoic Petscapiskau Group. Metasedimentary rocks in the latter are locally sulphide-bearing.

The Michikamau Intrusion has several major subdivisions (Figure 3). The marginal zone consists of a thin sequence of chilled mafic rocks and banded gabbro to norite, sandwiched between the country rocks and the main mass of the intrusion. The lower section of the intrusion (termed the layered sequence) contains four main units, which are dominated by troctolite, leucotroctolite, layered gabbro and anorthosite, in ascending stratigraphic order. These rocks are characterized by rhythmic modal layering, and other textures suggestive of cumulate processes. Ultramafic cumulates (melatroctolite and peridotite) occur near the base of this sequence (Dyke *et al.*, 2004). The layered series is overlain by the massive anorthosite zone, interpreted to be some 3 km thick, above which there is a thin gabbroic upper border zone. The youngest components are the transgressive group, comprising iron-rich intermediate rocks (diorites, monzonites, and syenites). Emslie (1968) suggested that the thick anorthositic sequence developed through plagioclase flotation from the basaltic magma, possibly prior to crystallization of the layered series. The transgressive group is believed to represent the residual magma from crystallization of the layered series, or related mafic intrusions at depth. The interpreted geometry of the intrusion (*after* Emslie, 1965) is indicated in Figure 3.

Magmatic Sulphide Mineralization

Fraser Lake Area

Sulphide mineralization in the intrusion was first discovered in the Fraser Lake area (Figure 3), where there is a large gossan zone near the outer contact of the intrusion (Nunn, 1982). The area was explored by Kennecott Canada and Noranda in the early 1990s, and tested by limited drilling (Thein and Rudd, 1992; Burgess, 1993). Disseminated pyrrhotite and chalcopyrite were intersected in massive to layered plutonic rocks, with rare thin semimassive sulphide zones. The grades of mineralized zones were low (typically <0.5% combined Ni and Cu) and no further work was completed. The area was not explored following the Voisey's Bay discovery, because the mineral rights were retained by Kennecott Canada. No further work was completed until 2006, when Altius Minerals acquired the rights and completed additional drilling.

The mineralization at Fraser Lake was described by Dyke *et al.* (2004), based on a study of six drillholes. Essentially four rock types were identified, *i.e.*, coarse-grained olivine norite to troctolite, melatroctolite, fine-grained

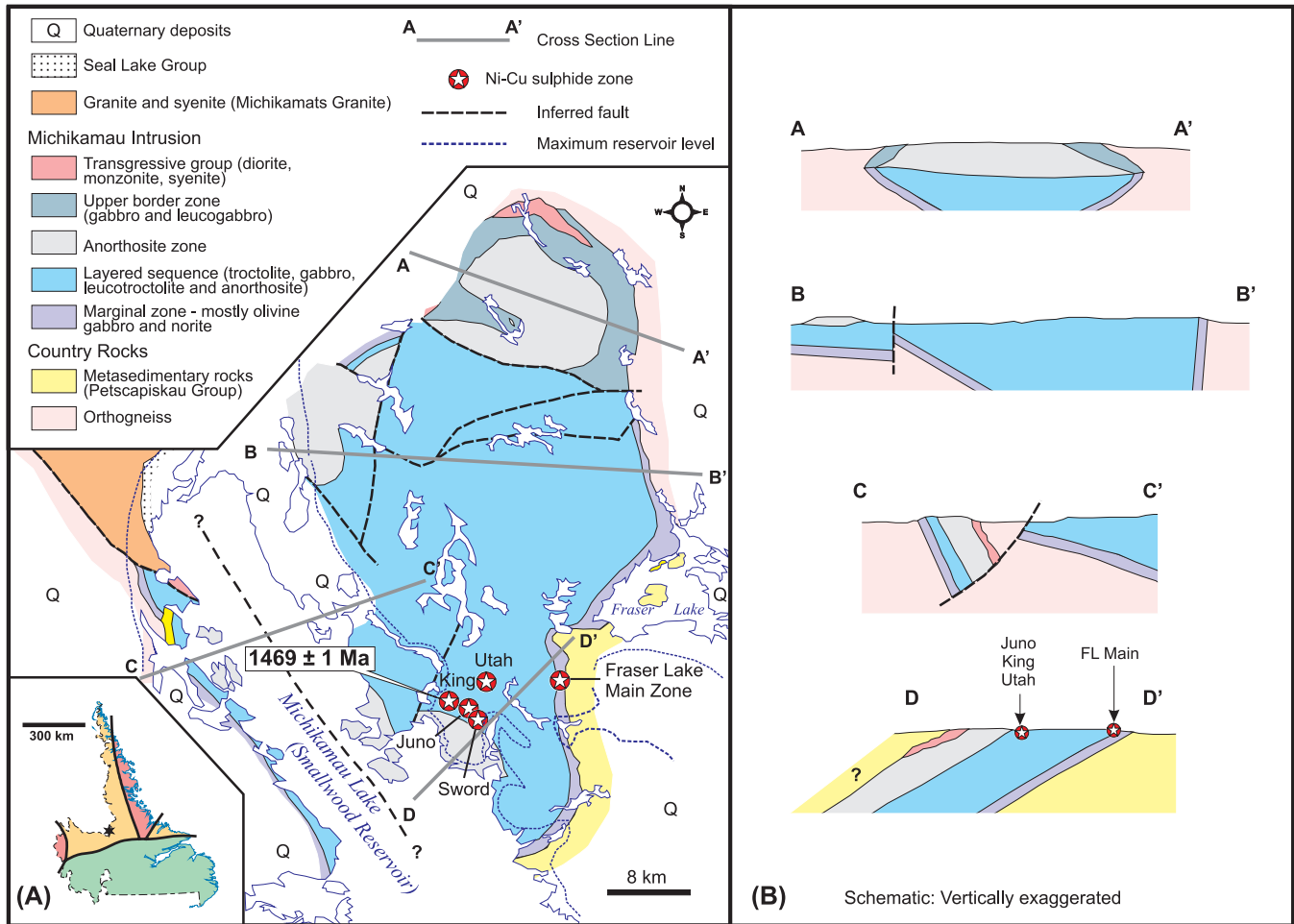


Figure 3. (A) Geological map of the Michikamau Intrusion, after Emslie (1968), showing the locations of magmatic sulphide mineralization discussed in this report. (B) Schematic cross-sections of the inferred geometry of the Michikamau Intrusion, along lines indicated in part (A); modified after Emslie (1965). Note that the shorelines shown on this map predate creation of the Smallwood Reservoir, of which Michikamau Lake is now a part. The maximum extent of the modern reservoir is indicated as a separate line, and much of the southwestern section of the intrusion is now submerged.

norite, and a banded to foliated norite. The last was interpreted as a metamorphosed border series to the intrusion, rather than its country rocks. Contrary to conclusions drawn during exploration, drilling did not actually penetrate the lower contact of the intrusion. The sulphide mineralization occurs mostly in troctolite and melatroctolite, and consists of disseminated to patchy sulphides that have an interstitial habit suggestive of a late-crystallizing magmatic origin. The sulphides are mostly pyrrhotite, with fine exsolved pentlandite and minor chalcopyrite. Sulphide metal contents (calculated following Kerr, 2001) average 0.6% to 0.8% Ni, and 0.4% to 1.3% Cu, with some slight differences according to host-rock type (Dyke *et al.*, 2004). These low sulphide metal contents explain the generally low absolute Ni and Cu contents. The mineralized olivine norite and troctolite contain diffuse, partially digested country-rock inclusions consisting largely of calcic plagioclase and spinel. These are similar to digested inclusions described by Li and Naldrett

(2001) from the Voisey's Bay intrusion, which were there interpreted to record extensive assimilation of country rocks, possibly leading to the exsolution of the sulphide liquid. However, sulphur isotope analyses (reported by Smith, 2006) do not show the negative values suggestive of metasedimentary sources.

Smallwood Reservoir Area

The southwest section of the Michikamau Intrusion is exposed adjacent to the shores of the Smallwood Reservoir, although much of the area mapped by Emslie (1968) is now submerged (Figure 3). Exploration by Brilliant Mining in 2005 was, in part, prompted by the report of Dyke *et al.* (2004) on the Fraser Lake area. An airborne EM survey by Brilliant Mining revealed several conductive anomalies, associated with positive magnetic responses. Ground prospecting identified local sulphide-bearing subcrop, but

most conductors were obscured by surficial deposits (Carpenter, 2005). Subsequent drilling in 2006 and 2007 intersected disseminated sulphide mineralization at four of these target areas (Juno, King, Sword and Omaha zones; Figure 3). The grades of the mineralization varied from <0.1% Ni to 1.33% Ni, and <0.1% to 1.62% Cu (Finnegan, 2006). The best intersection was 11.3 m, averaging 0.71% Ni, 0.45% Cu and 0.12% Co (Brilliant Mining, press release, October 4, 2007).

The only published descriptions of the mineralization in this area are some general comments by Kerr (2007b), but more detailed information (now available) is in the assessment report by Finnegan (2006). Drillcore from the 2006 program is now available in the provincial core library, and a more detailed descriptive account will be presented elsewhere; the following summary is based largely on examination of drillcore in 2007 and 2009.

The distribution of mineralized zones (Figure 3) suggests that sulphides are present at more than one level within the west-dipping layered series, but the characteristics of mineralization and host rocks vary little between these locations. In most cases, the host rocks are coarse-grained, leucocratic troctolites and olivine-norites that resemble those described from the east side of the intrusion (Dyke *et al.*, 2004). However, magmatic layering is not seen in core, and there are no ultramafic cumulates or foliated border zone norites. The mineralized intervals likely sit at significantly higher levels within the stratigraphy of the intrusion than those on the eastern side (Figure 3). It is possible that the host rocks are layered, but perhaps on a scale larger than the relatively short drillholes completed during exploration. The sulphides display well-developed interstitial textures and, where semimassive to massive, euhedral crystals of silicate minerals (olivine, pyroxene and plagioclase) are suspended within them. Inclusions are rare in the holes examined, and most of those that were seen are cognate and mafic in composition, and do not represent assimilated country-rock xenoliths. Drillholes MK-06-01 and MK-06-02, from the Juno zone, contain intervals of very coarse-grained, leucocratic noritic pegmatite that appear to be gradational into surrounding rocks that contain interstitial sulphides. This pegmatitic material was used for geochronological studies (see below). Calculated sulphide metal contents (see Kerr, 2001) are provided by Finnegan (2006). These show generally higher tenors than equivalent samples from the Fraser Lake area. Sulphide Ni contents range from 0.5% to 1.9% Ni, and sulphide Cu contents range from 0.1% to 2.3% Cu. The database from exploration samples (Finnegan, 2006) indicates some systematic variation in sulphide tenors between discrete geographic locations, implying variations in the silicate magma to sulphide liquid ratio (R-factor) during development of the sulphides. The most metal-rich sul-

phides come from the Sword North zone (approaching 2% Ni) whereas those from the Juno zone average around 1% Ni (Finnegan, 2006).

EVENING LAKE INTRUSION(S)

Geological Relationships

The area around Evening Lake (Figure 4) includes several discrete bodies of mafic rocks that intrude metasedimentary rocks of the Kaniapiskau Supergroup in the Gagnon terrane. Amongst these country rocks are the sulphide-bearing shales, siltstones and derived schistose rocks of the Attikamagen and Menihek formations (Figure 4). The two largest mafic units, which extend northeastward from Evening Lake, are associated spatially with quartzites of the Sims Formation, suggesting that their emplacement was, at least, locally controlled by the basal unconformity of this sequence. Mafic rocks in this area were described in general terms by Ware and Wardle (1979) and Rivers (1982), and more recently by Kerr (2007). Some descriptive and geometric information is also provided in assessment reports concerning drilling results (*e.g.*, French and Janes, 2005a, b), and in a NI 43-101 technical report filed as part of another report (Wilton, *in* French, 2005). Due to poor exposure, the three-dimensional geometry of these mafic intrusions remains largely unknown, and the shallow drilling to date does not illuminate this problem. However, drillholes completed at the EIW prospect (*see* below) mostly terminate in metasedimentary rocks interpreted to be Menihek Formation, implying that the gabbro is sheet-like, and likely capped by the Sims Formation quartzites. Minor textural and compositional variations are difficult to discern in the field, but are apparent in drillcore. Nevertheless, the mafic rocks are monotonous in texture and composition, comprising olivine gabbro with ophitic to subophitic textures. The olivine is a variably serpentinized cumulus phase, and secondary amphibole is widely developed in areas of local shearing. A distinctive pale pink dioritic to monzonitic variant is also present, and contains prismatic primary amphibole; this is interpreted as an evolved (possibly residual) magma, but is in many cases gradational with 'normal' gabbro. Layering is not observed in the field, but subtle modal variation is visible in drillcore, suggesting that it is likely present. Local xenolith-rich zones also occur adjacent to this contact, but xenoliths are little-metamorphosed and do not display reaction or assimilation textures; they appear to be of local derivation.

Magmatic Sulphide Mineralization

Mineralized gabbro at Evening Lake was discovered by Karl Krats and his colleagues, who were prospecting for Pb and Zn mineralization in the metasedimentary rocks. This

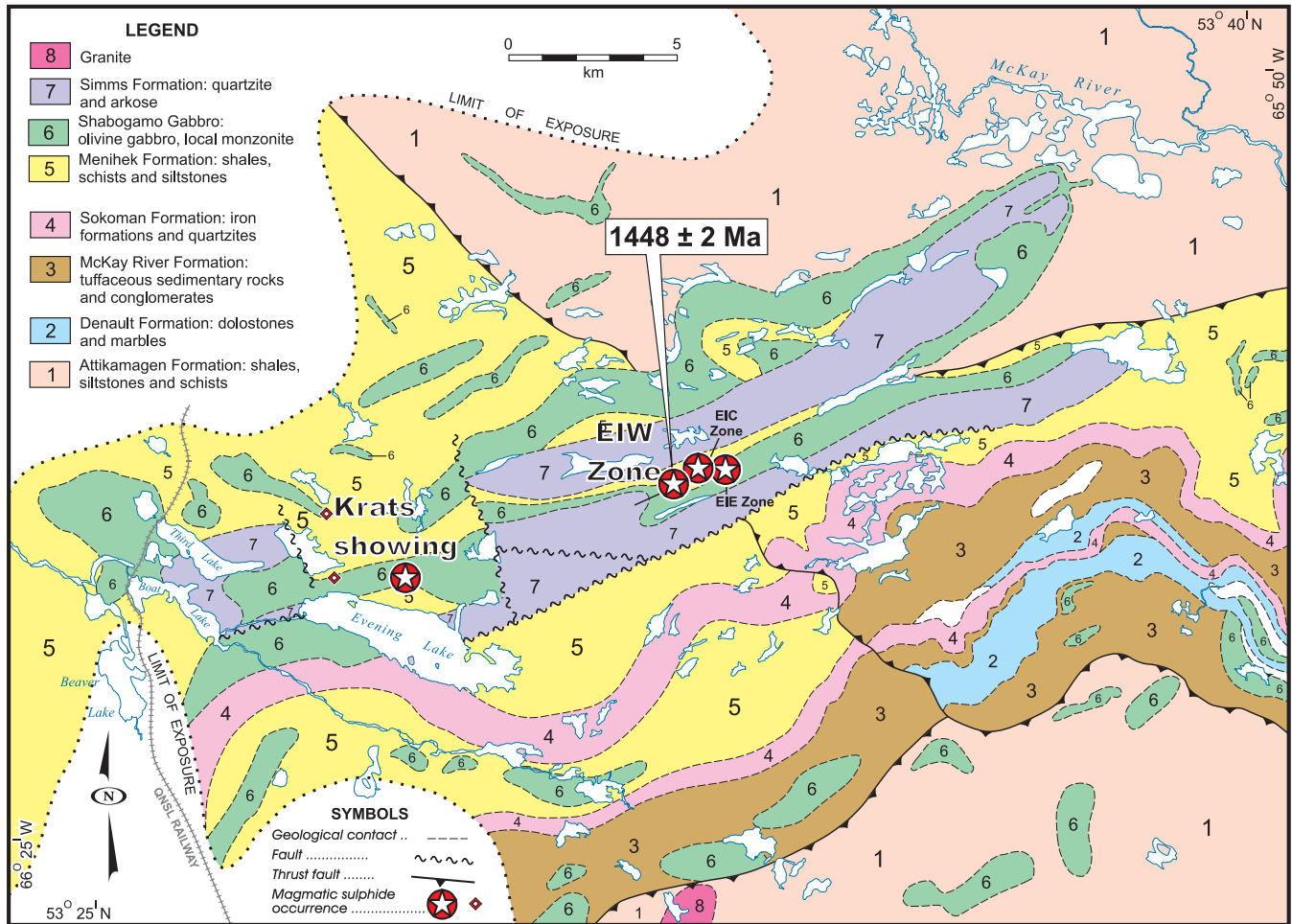


Figure 4. Geological map of the area around Evening Lake, modified after a similar figure presented by Kerr (2007), with additional information on locations of sulphide mineralization.

initial discovery led to the involvement of BHP-Billiton, and later Gallery Resources, in a wider exploration program throughout the area shown in Figure 4, which located traces of sulphides in several other areas (Muntanion, 2002). An airborne EM and magnetic survey completed in 2003 revealed numerous conductors, and the most prominent of these was subsequently tested by drilling in 2004 and 2005. Several holes over a strike length of 1.5 km encountered disseminated sulphides; the best intersections were at the location known as E1W (Janes and French, 2005; French and Janes, 2005; French, 2005). However, the grades were generally low (<0.5% combined Ni + Cu).

The Krats showing is described in assessment reports (Krats, 2000, 2001; Muntanion, 2002) and also by Kerr (2007). It consists of disseminated pyrrhotite and chalcopyrite in medium-grained gabbro, which occurs in angular blocks interpreted to be derived from an underlying frost-heaved outcrop. Absolute grades from surface sampling range up to 1.2% combined Ni and Cu, and sulphide metal

contents range from 0.9% to 1.6% Ni, and 0.3% to 1.5% Cu (Krats, 2001; Kerr, 2006). However, the Krats showing remains undrilled, largely because it lacks a strong associated conductor.

The mineralization in the E1W area is summarized in assessment reports (Janes and French, 2005; French and Janes, 2005), and was also described by Kerr (2007) as part of a regional assessment. Core from the prospect is now partly stored within the provincial core library, and the following description is based largely on examination of this material in 2005 and 2006. The mineralization consists of disseminated sulphides, largely pyrrhotite with minor chalcopyrite, hosted by medium-grained olivine gabbro. The zone of sulphides is situated close to, but not directly at, the basal contact with the metasedimentary country rocks. The habit of the sulphides is interstitial, indicating a syngenetic origin. Due to the limited drilling, the exact attitudes of the sulphide zone and the basal contact of mafic intrusion cannot easily be constrained, but it appears to be flat-lying and

possibly gently folded (Janes and French, 2005). Subsequent drilling located similar mineralization at two other locations (E1C and E1E) over a total strike length of 1.5 km (Figure 4), which implies significant lateral extent along strike (Janes and French, 2005b). Sulphide metal contents calculated using the method of Kerr (2001) are modest, ranging from 0.4% to 0.9% Ni and 0.2% to 1.2% Cu (Kerr, 2006; Wilton, *in* French, 2005). Inspection of assay data listed in assessment reports indicates significant variation in Ni/Cu ratios, which is here interpreted to reflect mobilization of Cu, perhaps due to later alteration effects noted locally in the drillcore.

MOUNT FYNE INTRUSION

Geological Relationships

The Mount Fyne intrusion is the largest mafic body known within the Molson Lake terrane, and extends for some 80 km from west of Churchill Falls to Ossokmanuan Lake (Figure 2). The country rocks to the intrusion are complex orthogneisses and metaplutonic rocks of granitoid composition; no metasedimentary units are known in the area. The intrusion is best exposed in the area of Mount Fyne itself, where it is described by Nunn and Christopher (1983) and Wardle (1985). Elsewhere, it is generally poorly exposed, except along the Trans-Labrador highway and surrounding areas. The intrusion includes both gabbroic and noritic rocks, but the most common variants are olivine gabbro and melanocratic troctolite. The rocks of the Mount Fyne intrusion have experienced a greater degree of Grenvillian metamorphism than compositionally equivalent rocks in the Gagnon terrane, and they exhibit corona textures. However, coronas are for the most part incipient, consisting of thin orthopyroxene rims on olivines, and do not obscure the original ophitic to subophitic textures or granular cumulus olivine. The primary textures are closely similar to the textures observed in the Evening Lake intrusion, and the rocks are compositionally similar. No widespread magmatic layering has been recognized within the intrusion, although it was locally observed in roadside outcrops, as were younger dykes of finer grained gabbro. In general, the rocks are coarser grained than those of the Evening Lake intrusion, and display more obvious local grain-size variations. Patchy leucocratic amphibole-rich pockets are present, and these resemble the dioritic variants noted in the Evening Lake intrusion. Compositional variants of the gabbro were noted in regional mapping of the area (*e.g.*, Nunn and Christopher, 1983; Wardle, 1985), but these are difficult to trace and correlate due to paucity of exposure.

Magmatic Sulphide Mineralization

To date, the Mount Fyne intrusion has received only limited exploration attention from exploration companies,

but Karl Krats and his colleagues prospected the area over a period of several years. Disseminated sulphides were encountered in several areas within the body, notably between the Esker Road and the Trans-Labrador highway, and around Mount Fyne (Krats, 2002, 2006). In most cases the amount of sulphides is small (<2%) and related Ni or Cu enrichment is modest, with total Ni + Cu <1000 ppm. Not all mineralized samples come from bedrock, but angular float of local derivation abounds in unexposed areas. The best results from prospecting were 0.13% Ni and 0.11% Cu, and several other samples contained up to 1000 ppm Ni and 800 ppm Cu (Krats, 2002). Due to the small amount of sulphides, no attempt was made to calculate sulphide metal contents, as these would be subject to significant uncertainty, especially in olivine-bearing variants (Kerr, 2001). From an exploration viewpoint, the Mount Fyne intrusion is associated with lake-sediment Ni, Cu, Pt and Pd anomalies (McConnell, 2005), and the presence of MgO-rich troctolitic rocks with elevated Ni contents suggests that it has potential for magmatic sulphides, should other conditions required for their formation be met. Exploration in the best-exposed part of the intrusion is further complicated by the presence of several power lines, which impede EM surveys that represent the logical next step in its evaluation.

U–Pb GEOCHRONOLOGY

The U–Pb ages for the Evening Lake intrusion and the Michikamau Intrusion were obtained at the Geological Survey of Canada laboratory in 2007 and 2009, respectively. The investigation of the Michikamau and Evening Lake intrusions was undertaken to establish the age of associated magmatic sulphide mineralization, and to test the hypothesis that they might represent the same period of magmatism, which was permitted by previous geochronological data (Krogh and Davis, 1973; James, 1994; Connelly *et al.*, 1996). The age determination from the Mount Fyne intrusion, discussed here, was completed at the Jack Satterly Geochronology Laboratory at the Royal Ontario Museum in 1993, and originally reported in an unpublished report (Table 1; Krogh, 1993).

SAMPLE PROCESSING AND ANALYTICAL PROCEDURES

For all samples, heavy minerals were separated by standard procedures including crushing, grinding, and physical separation using a Wilfley Table and heavy liquid techniques. Further separation of mineral species was accomplished using a Frantz isodynamic magnetic separator. Zircon and/or baddeleyite fractions were then hand-picked, and zircons were abraded using the air-abrasion technique of Krogh (1982), aside from fractions Z1 and Z2 in the Mount Fyne sample. Analyses at the GSC laboratory followed the

Table 1. U–Pb geochronological data; see text for discussion

Fraction ¹	Description ²	Wt. ug	U ppm	Pb ³ ppm	²⁰⁶ Pb/ ²⁰⁴ Pb	Pb ⁵ pg	Isotopic Ratios ⁶				²⁰⁶ Pb ²³⁸ U	±1SE Abs	Corr. ⁷ Coeff.	²⁰⁷ Pb ²⁰⁶ Pb	±1SE Abs	Ages (Ma) ⁸		²⁰⁷ Pb ²³⁵ U	±2SE	²⁰⁷ Pb ²⁰⁶ Pb	±2SE	% Disc
							²⁰⁸ Pb/ ²⁰⁶ Pb	²⁰⁷ Pb/ ²³⁵ U	²⁰⁶ Pb Abs	²⁰⁶ Pb ±1SE												
KC-Z-08-01 (Z9770): Michikamau anorthosite (DDH MK-06-02; UTM 437005E/6016010N, depth of ~ 63.5 m)																						
BdA (B:1)	Br,Clr,Frag,rFr,fln,M3°	24	203	49	9891	8	0.006	3.23117	0.00453	0.25442	0.00030	0.00030	0.947	0.09211	0.00004	1461.3	3.1	1464.7	2.2	1469.6	1.8	0.6
BdB (B:1)	Br,Clr,Frag,rFr,M3°	12	151	36	18962	1	0.004	3.22917	0.00378	0.25440	0.00024	0.00024	0.929	0.09206	0.00004	1461.1	2.4	1464.2	1.8	1468.6	1.7	0.6
BdD (B:1)	Br,Clr,Frag,rFr,fln,M3°	4	137	33	5781	1	0.003	3.22969	0.00394	0.25439	0.00025	0.00025	0.912	0.09208	0.00005	1461.1	2.5	1464.3	1.9	1469.0	2.0	0.6
BdE (B:1)	Br,Clr,Frag,rFr,fln,M3°	3	208	50	2355	4	0.004	3.22565	0.00426	0.25410	0.00025	0.00025	0.868	0.09207	0.00006	1459.6	2.5	1463.3	2.0	1468.8	2.6	0.7
AKGC-06-02 (Z9218): Monzonitic gabbro, Evening Lake intrusion (DDH E1W5; UTM 690735E/5944900N, depth of 319.5 to 326.5 m)																						
A1 (Z: 18)	Co, Clr, Eu, Tab, El, Dia	15	256	77	2581	12	0.320	3.11578	0.00406	0.24809	0.00023	0.00023	0.857	0.09109	0.00006	1428.6	2.4	1436.6	2.0	1448.4	2.7	1.5
B1 (Z: 30)	Co, Clr, fFr, rln, Eu, Tab, El, Dia	15	222	69	1635	12	0.340	3.18307	0.00484	0.25323	0.00025	0.00025	0.766	0.09117	0.00009	1455.1	2.6	1453.1	2.3	1450.1	3.7	-0.4
B2 (Z: 28)	Co, Clr, fFr, rln, Eu, Tab, El, Dia	15	147	44	5989	7	0.300	3.13425	0.00367	0.24981	0.00022	0.00022	0.932	0.09100	0.00004	1437.5	2.3	1441.1	1.8	1446.5	1.8	0.7
B3 (Z: 30)	Co, Clr, fFr, rln, Eu, Tab, El, Dia	15	193	58	2817	6	0.300	3.11713	0.00399	0.24815	0.00022	0.00022	0.861	0.09111	0.00006	1428.9	2.3	1436.9	2.0	1448.8	2.6	1.5
B5 (Z: 14)	Co, Clr, fFr, rln, Eu, Tab, El, Dia	10	247	73	1396	26	0.290	3.13676	0.00488	0.24937	0.00024	0.00024	0.812	0.09123	0.00009	1435.2	2.4	1441.8	2.4	1451.4	3.7	1.2
C1 (Z: 23)	Co, Clr, fFr, rln, Eu, Tab, El, Dia	13	140	42	14683	2	0.300	3.12916	0.00356	0.24915	0.00022	0.00022	0.936	0.09109	0.00004	1434.1	2.3	1439.9	1.8	1448.4	1.7	1.1
GN-04-036G: Gabbro, Mount Fyne intrusion, near Ossokmanuan Control Structure (UTM 363465E/5923730N, approximate)																						
Z1 (Z: 19)	needles	58	198	58	17840	10	.332	2.92654	0.00590	0.23817	0.00050	0.00050	0.881	0.08912	0.00009	1377.2	2.6	1388.8	1.5	1406.7	2.1	2.3
Z2 (Z: 11)	tabular	110	124	35	13287	16	0.276	3.03213	0.00524	0.24428	0.00045	0.00045	0.845	0.09002	0.00009	1409.0	2.3	1416.0	1.3	1426.0	2.1	1.3
Z3 (Z: 5)	blocky fragments	44	255	68	17370	10	0.151	3.13672	0.00475	0.25039	0.00039	0.00039	0.836	0.09086	0.00008	1440.5	2.0	1441.7	1.2	1443.6	1.9	0.3

Notes:

¹Bd=Baddeleyite, Z=zircon. Number in brackets refers to the number of grains in the analysis.²Fraction descriptions: Co=Colourless, Br=Brown, Clr=Clear, fFr=Few Fractures, rFr=Rare Fractures, fln=Few Inclusions, rln=Rare Inclusions, Frag=Fragment, Tab=Tabular, M3=Magnetic@1.8A 3°SS.³Radiogenic Pb⁴Measured ratio, corrected for spike and fractionation⁵Total common Pb in analysis corrected for fractionation and spike⁶Corrected for blank Pb and U and common Pb, errors quoted are 1 sigma absolute; procedural blank values for this study ranged from <0.1–0.1 pg for U and 1 pg for Pb; Pb blank isotopic composition is based on the analysis of procedural blanks; corrections for common Pb were made using Stacey-Kramers compositions;

Procedural blanks for the analyses from Mount Fyne intrusion are estimated at 0.5 pg U and 2 pg Pb, based on data initially reported by Krogh (1993)

⁷Correlation Coefficient; value of 0.8 assumed for Mount Fyne intrusion samples for age calculation purposes.⁸Corrected for blank and common Pb, errors quoted are 2 sigma in Ma.

UTM locations for diamond drill-holes are the collar locations, and do not correspond exactly with surface projection of sample locations for inclined holes.

protocols outlined by Parrish *et al.* (1987). Treatment of analytical errors followed Roddick (1987) and regression analysis used a modified version of the method of York (1969). Errors on the ages are reported at 2 sigma levels (Table 1), and error ellipses in concordia diagrams indicate 2 sigma uncertainties (Figures 5 to 7). Analytical procedures for the Mount Fyne data, described by Krogh (1993), are essentially the same, although analytical errors and procedural blanks are larger than for the more recent GSC data (*see* Table 1 notes). Recalculation of the Mount Fyne data after Ludwig (2001) gave essentially the same results reported by Krogh (1993).

GEOCHRONOLOGICAL RESULTS

Michikamau Intrusion

It took three attempts to resolve the age of this rock unit. An initial small sample (about 10 cm of NQ drillcore) was collected in 2007, from a very coarse-grained pegmatitic variant of the host rock in hole MK-06-02 at 37 m depth. The sample contained a small amount of red-brown rutile; however, extremely low U contents for the rutile resulted in data that were not useable. A second (slightly larger) sample from the same location was then processed in the hope that it might contain zircon and/or baddeleyite, but no material suitable for dating was recovered. The third and final attempt used about 2 m of split drillcore from slightly deeper in the same drillhole (63.5 m depth), again representing a very coarse-grained pegmatitic version of the host rock. Small amounts of high-quality baddeleyite crystals were recovered (inset of Figure 5). Four single-grain baddeleyite fractions gave essentially identical near-concordant results ($\leq 0.7\%$ discordant, Table 1). A weighted mean of the $^{207}\text{Pb}/^{206}\text{Pb}$ ages of all the analyses is calculated to be 1469 ± 1 Ma (MSWD = 0.23, probability = 0.88; Figure 5). This age of 1469 ± 1 Ma is interpreted to record the time of crystallization for the Michikamau Intrusion.

Evening Lake Intrusion

The Evening Lake intrusion was sampled from archived drill core in the Goose Bay drillcore library, representing drillhole E1W5. The sampled rock type is a relatively evolved dioritic phase of the intrusion, which here occurs below gabbroic rocks that contain minor sulphide mineralization. This compositional variant was chosen because of the higher probability of finding zircon. The close association between this rock type and the mineralized olivine gabbro in outcrops and drillcore indicates that they are closely related, and it is thus an appropriate target for geochronology.

The sample AKGC-06-02 (z9218) yielded abundant high-quality zircon, which was well-faceted, euhedral, and

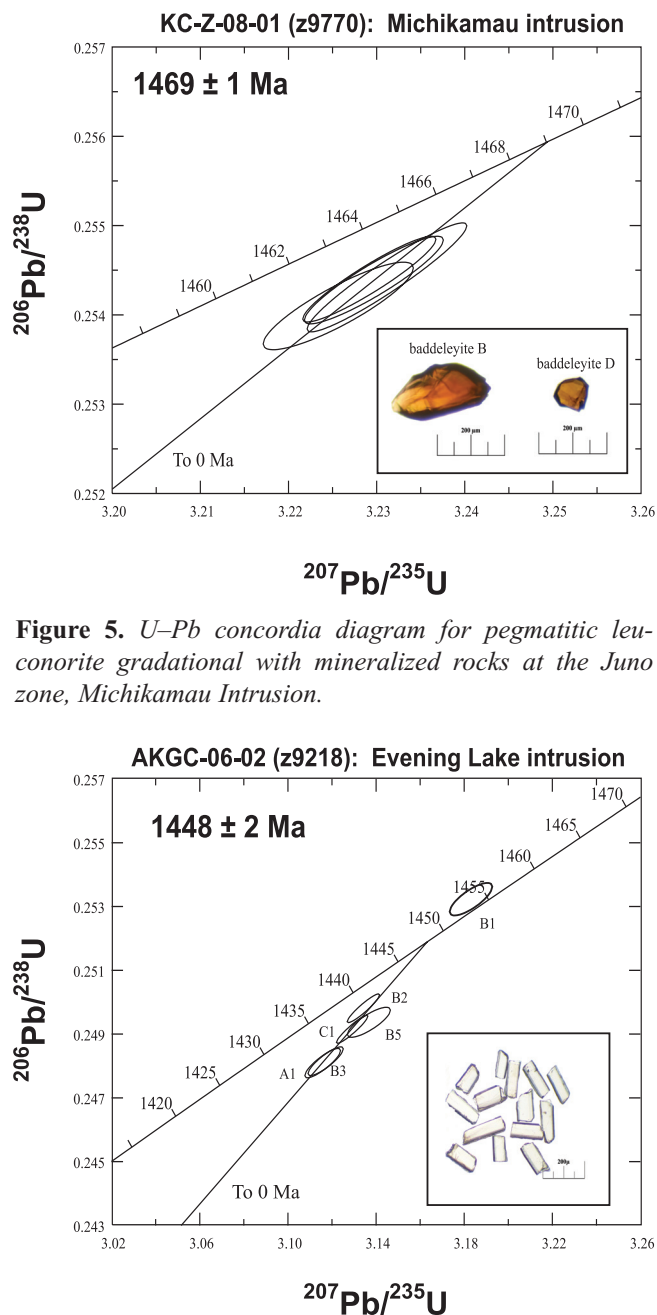


Figure 5. *U–Pb concordia diagram for pegmatitic leuconorite gradational with mineralized rocks at the Juno zone, Michikamau Intrusion.*

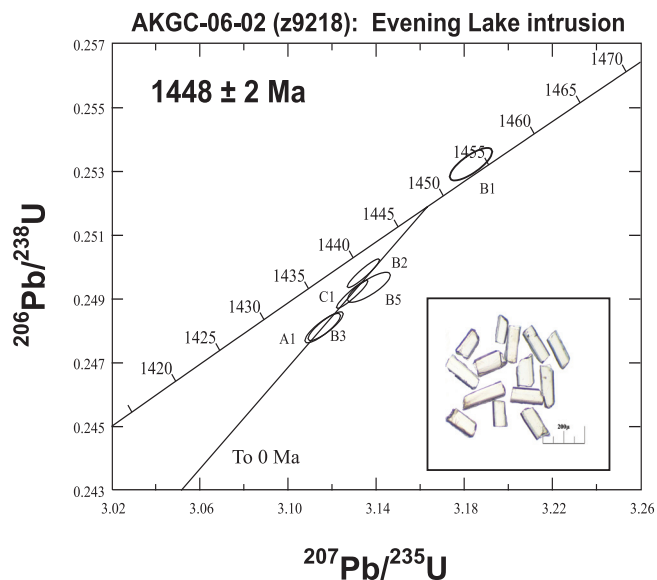


Figure 6. *U–Pb concordia diagram for monzodioritic variant of the Evening Lake intrusion at the E1W magmatic sulphide prospect.*

had a flat, tabular morphology (inset of Figure 6). Six multi-grain fractions of zircon were analyzed. One fraction plots very close to (but slightly above) concordia; the remainder vary from 0.7 to 1.5% discordant (Table 1). A linear regression of all six analyses, which has a lower intercept fixed at the origin, has an upper intercept of 1448.2 ± 1.2 Ma (MSWD = 1.4, probability = 0.2; Figure 6). A date of 1448 ± 2 Ma is interpreted as the crystallization age of the gabbro,

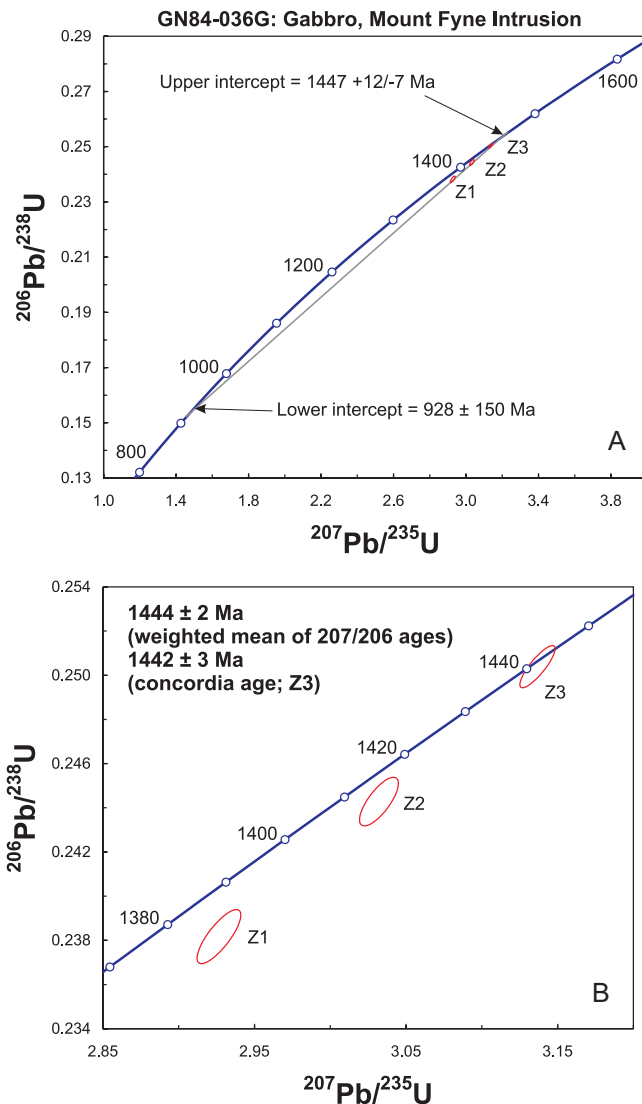


Figure 7. U–Pb concordia diagrams for gabbro of the Mount Fyne intrusion, Ossokmanuan Lake, southwest of Churchill Falls; (A) general plot showing upper and lower intercept ages; (B) detailed plot showing data from individual fractions.

and the time of formation of the magmatic sulphide mineralization.

Mount Fyne Intrusion

The sample from the Mount Fyne intrusion was collected in 1984 by G. Nunn, but was not analyzed until 1993. It was collected from a rock quarry just north of the Ossokmanuan control structure (G. Nunn, personal communication, 2008). The following description of the results is paraphrased from Krogh (1993). The sample (GN84063G) yielded abundant colourless euhedral to skeletal zircon crystals and fragments of larger crystals. Some of the grains had

a flat, tabular morphology akin to that described from the Evening Lake sample. Three multigrain fractions ranged from virtually concordant to about 14% discordant. Taken as a group, these define a linear array projecting to $1447 \pm 12/-7$ Ma, with a lower intercept at *ca.* 928 Ma (Figure 7a). However, the results from the small abraded blocky fragments (Z3) are essentially concordant within error, and have a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1443.6 ± 1.9 Ma; this result is not significantly affected by the choice of lower intercept. However, the overlap of fraction Z3 with the concordia curve actually yields a slightly younger age of 1442 ± 3 Ma (method of Ludwig, 2003). Taking all these results into account, the conservative estimate of 1444 ± 4 Ma (Krogh, 1993) remains the best estimate of the time of crystallization (Figure 7b). The lower intercept of *ca.* 928 Ma suggests that some Pb loss is related to the Grenvillian Orogeny.

DISCUSSION

This investigation was prompted by questions related to the age(s) of magmatic sulphide mineralization in western Labrador, but the results also have implications in the context of regional geological patterns.

Geochronological results from the Michikamau and Evening Lake intrusions indicate temporally discrete magmatic episodes at *ca.* 1469 and *ca.* 1448 Ma, respectively, which both gave rise to magmatic sulphide mineralization. The *ca.* 1444 Ma age from the Mount Fyne intrusion suggests that it is also linked to the younger episode, and the most conservative estimate of the age is within error of the Evening Lake result. The ages of 1448 to 1444 Ma overlap with less precise U–Pb ages of $1452 \pm 15/-13$ Ma (Connelly *et al.*, 1995) and $1459 \pm 23/-22$ Ma (Connelly and Heaman, 1993) obtained from gabbroic rocks in the western part of the Molson Lake terrane. One of the objectives of this study was to test the idea of a temporal link between the mineralized Shabogamo Gabbro and the Michikamau Intrusion, which was permitted by previous data. However, the new data rule out such a link, as the age for the Michikamau Intrusion is at least 20 Ma older than the Shabogamo Gabbro. Nevertheless, there may still be a wider causal connection between this mafic magmatism and the development of large anorthositic complexes over a longer time period, as discussed elsewhere by Gower *et al.* (1991).

The magmatic sulphide mineralization in the *ca.* 1469 Ma Michikamau Intrusion is the earliest mineralization of this type identified in the Mesoproterozoic rocks of Labrador. The *ca.* 1448 and 1444 Ma ages from the Evening Lake and Mount Fyne intrusions similarly define magmatic sulphide mineralization in this time interval, at least 100 Ma prior to the development of sulphide mineralization at Voisey's Bay and Pants Lake in northeastern Labrador.

Although the relationship between emplacement age and mineral potential is likely not a simple one, the results confirm that older Mesoproterozoic plutonic suites across Labrador represent viable exploration targets for orthomagmatic Ni–Cu sulphide deposits.

On a more detailed level, the age of 1469 ± 1 Ma for the Michikamau Intrusion now provides the best estimate for the time of emplacement of this body. Interestingly, it is similar to an unpublished zircon age of 1464 ± 4 Ma obtained by Krogh (1993) from a metamorphosed tonalite dyke that cuts the Petskapiskau Group on Rusty Island, about 10 km northeast of the Fraser Lake sulphide prospect (Figure 3); monazite from the same sample gave a nearly concordant age of 1469 ± 2 Ma. The location with respect to the inferred contact of the Michikamau Intrusion suggests that the age may have been reset by contact metamorphic effects, rather than recording crystallization of the dyke (Gower and Krogh, 2002; G. Nunn, personal communication, 2009). The new data reported here from the intrusion itself support this interpretation, and confirm that the Michikamau Intrusion is the oldest of several large mafic to anorthositic suites in central Labrador. However, precise age data are still lacking for the Harp Lake intrusion and the Mistastin intrusion (Figure 1). The former is constrained only by an imprecise U–Pb determination of *ca.* 1450 Ma, from a crosscutting granitoid rock (Emslie, 1980), and the latter constrained only by an unpublished *ca.* 1420 Ma age noted by Emslie and Stirling (1993). Both represent obvious candidates for new geochronological studies.

The age from Evening Lake confirms the assignment of this mafic body to the Shabogamo Gabbro, and provides the first precise age determination from a mafic intrusion traditionally assigned to the Shabogamo Gabbro within the Gagnon terrane in Labrador. The close similarity between this result and the age from the Mount Fyne intrusion in the Molson Lake Terrane affirms the long-suspected temporal and genetic link between mafic intrusions in the autochthonous foreland and deeper level parautochthonous terranes of the Grenville Province. However, it remains possible that older magmatic suites could exist elsewhere in the foreland region.

The results from this study confirm that more than one age grouping of Mesoproterozoic mafic rocks in Labrador has potential for magmatic sulphide deposits, but we caution that age is not by itself an indication of mineral potential, or lack thereof. Many other factors are critical in the generation of magmatic sulphide deposits (*e.g.*, Naldrett, 1999). These include (but are not restricted to), the primary magma compositions, the initial Ni and Cu contents, the fractionation history, and the access of the magma to potential external sources of sulphur. The latter is commonly considered a crit-

ical element, as magmas rarely contain sufficient sulphur to develop a sulphide liquid at early stages in their fractionation, when metals remain abundant within them. In this context, the apparent differences in prospectivity between the Evening Lake and Mount Fyne intrusions may be significant. These two intrusions are of essentially the same age, and have similar compositions; in fact, Mount Fyne is generally more primitive and Ni-rich than Evening Lake (Kerr, 2006). Present information suggests that sulphide mineralization in the Mount Fyne intrusion is minor in extent compared to that at Evening Lake. The most fundamental contrasts between these two intrusions are the interpreted relative depths of emplacement and the nature of their country rocks. The Evening Lake intrusion was emplaced at shallow levels into sulphide-bearing metasedimentary rocks of the Menihek and Attikamagen formations, whereas the Mount Fyne intrusion is largely surrounded by orthogneisses and granites that lack sulphides. In this particular tale of two intrusions, the contrasts in geological environment may ultimately be more important in assessing their relative mineral potential than a simple consideration of their age equivalence.

ACKNOWLEDGMENTS

The late Karl Krats is thanked for introducing the senior author to magmatic sulphides in western Labrador, and for his enthusiastic field assistance and good company in 2005 and 2006. Brad Dyke is thanked for his efforts in his more detailed thesis study of mineralization at Fraser Lake, which made an important contribution to our knowledge, and Ges Nunn and Charles Gower are thanked for information about the geological context and implications of samples collected in the 1980s. The staff of the Geochronology Laboratory at the GSC are thanked for their assistance in generating the U–Pb data. The initial manuscript was greatly improved by suggestions for revision by Charles Gower.

REFERENCES

- Amelin, Y., Li, C. and Naldrett, A.J.
1999: Geochronology of the Voisey's Bay complex, Labrador, Canada, by precise U–Pb dating of coexisting zircon, baddeleyite and apatite. *Lithos*, Volume 47, pages 33–51.
- Burgess, J.R.
1993: Third year assessment report on the Fraser Lake property, Newfoundland. Unpublished assessment report by Kennecott Canada Inc. Geological Survey File [013L/0077].
- Carpenter, R.
2005: First year assessment report on airborne geo-

- physics and prospecting on Brilliant Mining Corporation's Labrador nickel properties. Brilliant Mining Corporation, unpublished assessment report. LAB/1424
- Connelly, J.N. and Heaman, L.
1993: U-Pb geochronological constraints on the tectonic evolution of the Grenville Province, western Labrador. *Precambrian Research*, Volume 63, pages 123-142.
- Connelly, J.N., Rivers, T. and James, D.T.
1995: Thermotectonic evolution of the Grenville Province of western Labrador. *Tectonics*, Volume 14, pages 202-217.
- Dyke, B., Kerr, A and Sylvester, P.J.
2004: Magmatic sulphide mineralization at the Fraser Lake prospect (NTS map area 13L/5), Michikamau Intrusion, Labrador. *In Current Research. Newfoundland and Labrador Department of Natural Resources, Geological Survey, Report 04-1*, pages 7-22.
- Emslie, R.F.
1965: The Michikamau anorthositic intrusion, Labrador. *Canadian Journal of Earth Sciences*, Volume 2, pages 385-399.

1968: The geology of the Michikamau Intrusion, Labrador (13L, 23I). *Geological Survey of Canada, Paper 68-57*, 85 pages.

1980: Geology and petrology of the Harp Lake Complex, central Labrador: An example of Elsonian magmatism. *Geological Survey of Canada, Bulletin 293*, 136 pages.
- Emslie, R.F. and Stirling, J.A.R.
1993: Rapakivi and related granitoids of the Nain Plutonic Suite: Geochemistry, mineral assemblages and fluid equilibria. *Canadian Mineralogist*, Volume 31, pages 437-446.
- Finnegan, C.
2006: Second year assessment report on diamond drill hole program and prospecting on Brilliant Mining Corporation's Labrador nickel projects. Unpublished assessment report, Brilliant Mining Corporation, Geological Survey File, 34 pages.
- Frarey, M.J. and Duffell, S.
1964: Revised stratigraphic nomenclature for the central part of the Labrador Trough. *Geological Survey of Canada, Paper 64-25*, 13 pages.
- French, V.A.
2005: Supplementary work assessment report on airborne geophysical surveying, NI 43-101 report, geology, geochemistry and petrography research, interpretations and compilations. Unpublished assessment report for Gallery Resources. Geological Survey File [LAB 1418], 117 pages.
- French V.A. and Janes, K.
2005: Work assessment report on diamond drilling, prospecting and compilation, Shabogamo Project, western Labrador. Unpublished assessment report for Gallery Resources. Geological Survey File [LAB 1422], 147 pages.
- Gower, C.F.
2003: Implications of reassessed $^{40}\text{Ar}/^{39}\text{Ar}$ and K/Ar geochronological data for Grenvillian orogenesis in the eastern Grenville Province. *In Current Research. Newfoundland Department of Mines and Energy, Geological Survey, Report 03-1*, pages 15-35.
- Gower, C.F. and Krogh, T.E.
2002: A U-Pb geochronological review of the Proterozoic history of the eastern Grenville Province. *Canadian Journal of Earth Sciences*, Volume 39, pages 795-829.
- Gower, C.F., Rivers, T. and Brewer, T.S.
1991: Middle Proterozoic mafic magmatism in Labrador, eastern Canada. *Geological Association of Canada, Special Paper 38*, pages 485-506.
- Hoffman, P.F.
1988: United Plates of America, the birth of a Craton: Early Proterozoic assembly and growth of Laurentia. *Annual Reviews of Earth and Planetary Sciences*, Volume 16, pages 543-603.
- James, D.T.
1994: Geology of the Grenville Province in the Lac Joseph and Ossokmanuan Lake areas (23A/NW and 23H/SW), western Labrador. Newfoundland Department of Mines and Energy, Geological Survey, Report 94-2, 58 pages.
- James, D.T. and Mahoney, K.L.
1994: Structural, metamorphic and intrusive relations in the hinterland of the eastern Churchill Province, western Labrador. *In Current Research. Newfoundland and Labrador Department of Mines and Energy, Geological Survey, Report 94-1*, pages 371-387.

- Janes, K. and French, V.A.
2005: Work assessment on diamond drilling, prospecting, and compilations forming part of the Shabogamo Project, western Labrador. File LAB/1398
- Kerr, A.
1999: Magmatic Ni-Cu sulphide mineralization in central and northern Labrador: A report on 1999 field activities. Newfoundland Department of Mines and Energy, Geological Survey, Report of Activities for 1999, pages 48-51.

2001: The calculation and use of sulfide metal contents in the study of magmatic ore deposits: A methodological analysis. *Exploration and Mining Geology*, Volume 10, pages 289-301.

2003: Nickeliferous gabbroic intrusions of the Pants Lake area, Labrador, Canada: Implications for the development of magmatic sulfides in mafic systems. *American Journal of Science*, Volume 303, pages 221-258.

2006: Magmatic sulphide mineralization in mafic plutonic rocks of western Labrador. Newfoundland Department of Natural Resources, Geological Survey, Report of Activities for 2006, pages 33-36.

2007: Mafic igneous rocks in western Labrador: A regional assessment of potential for magmatic Ni-Cu $\pm$ PGE mineralization. In *Current Research*. Newfoundland and Labrador Department of Natural Resources, Geological Survey, Report 07-1, pages 145-167.
- Kerr, A. and Smith, J.L.
2007: Magmatic sulphide mineralization in Labrador: A summary of exploration results and survey activities in 2007. Newfoundland and Labrador Department of Natural Resources, Geological Survey, Report of Activities for 2007, pages 8-10.
- Kerr, A., Krogh, T.E., Corfu, F., Scharer, U., Gandhi, S.S. and Kwok, Y.Y.
1992: Episodic Early Proterozoic granitoid plutonism in the Makkovik Province of the eastern Canadian Shield: U-Pb geochronological data and geological implications. *Canadian Journal of Earth Sciences*, Volume 29, pages 1166-1179.
- Krats, K.
2000: Geological assessment report, claim licence number 6989M, 7108M. Newfoundland Department of Mines and Energy, Geological Survey, File 23G/09/0251.

2001: Geological assessment report, claim licence number 7591M, 7843M. Newfoundland Department of Mines and Energy, Geological Survey, File 23G/09/0257.

2002: Geological assessment report, first year: Trans Labrador Highway and Mount Fyne property. Unpublished prospecting report. Geological Survey, File [023H/0112].

2006: First year assessment report on the Mount Fyne properties, Twin Falls area, western Labrador. Unpublished prospecting report. Geological Survey, File [023H/0121].
- Krogh, T.E.
1982: Improved accuracy of U-Pb zircon ages by the creation of more concordant systems using an air abrasion technique. *Geochimica et Cosmochimica Acta*, Volume 46, pages 637-649.

1993: Report on Labrador geochronology, 1992-93. Newfoundland Department of Mines and Energy, Geological Survey, File [LAB 0977].
- Krogh, T.E. and Davis, G.L.
1973: The significance of the inherited zircons on the age and origin of igneous rocks - an investigation of the ages of the Labrador adamellites. *Carnegie Institute of Washington Yearbook*, Volume 72, number 1630, pages 610-613.
- Li, C., Lightfoot, P.C., Amelin, Y. and Naldrett, A.J.
2001a: Contrasting petrological and geochemical relationships in the Voisey's Bay and Mushuau Intrusions, Labrador, Canada: Implications for ore genesis. *Economic Geology*, Volume 95, pages 771-801.
- Li, C. and Naldrett, A.J.
2001: Melting reactions of gneissic inclusions with enclosing magma at Voisey's Bay, Labrador, Canada: Implications for ore genesis. *Economic Geology*, Volume 95, pages 801-815.
- Ludwig, K.R.
2001: Users manual for ISOPLOT/EX, new 2.49: A geochronological toolkit for Microsoft Excel. Berkely Geochronology Centre, Special Publication 1a, 55 pages.
- McConnell, J.W.
2005: Lake sediment and water survey for copper, nickel and platinum group elements across the Ossok Mountain Intrusive Suite, western Labrador. New-

- foundland and Labrador Department of Natural Resources, Geological Survey, File LAB/1397, 55 pages.
- Muntanion, H.
2002: Assessment report: 2001 reconnaissance of the Shabogamo gabbro suite for Ni-Cu-(PGE) potential, southern Labrador, Canada. BHP Billiton Diamonds Inc., unpublished assessment report. Newfoundland and Labrador Department of Natural Resources, Geological Survey, File LAB/1377, 31 pages.
- Naldrett, A.J.
1999: World-class Ni-Cu-PGE deposits: key factors in their genesis. *Mineralium Deposita*, Volume 34, pages 227-240.
- Nunn, G.A.G.
1982: Regional geology east of Michikamau Lake, central Labrador. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 82-1, pages 149-168.
- Nunn, G.A.G. and Christopher, A.
1983: Geology of the Atikonak River area, Grenville Province, western Labrador. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 83-1, pages 107-114.
- Parrish, R.R., Roddick, J.C., Loveridge, W.D. and Sullivan, R.W.
1987: Uranium-lead analytical techniques at the Geochronology Laboratory, Geological Survey of Canada. Geological Survey of Canada, Paper 87-2, pages 3-7.
- Rivers, T.
1982: Preliminary report on the geology of the Gabbro Lake and McKay River map areas (23H/11 and 23H/12), Labrador. Newfoundland Department of Mines and Energy, Geological Survey, Report 82-2, 27 pages.
- Roddick, J.C.
1987: Generalized numerical error analysis with applications to geochronology and thermodynamics. *Geochimica et Cosmochimica Acta*, Volume 51, pages 2129-2135.
- Smith, R.L.
2006: The basal gabbro subdivision and associated magmatic nickel-copper sulphide mineralization of the Pants Lake Intrusion, Labrador, Canada. Unpublished M. Sc. Thesis, Memorial University, St. John's, NL, 116 pages.
- Thein, A.M. and Rudd, J.
1992: Assessment report on Fraser Lake property, Labrador. Unpublished assessment report, Kennecott Canada Inc. Geological Survey File [013L/05/0075].
- Wardle, R.J.
1985: Geology of the Churchill Falls area. Newfoundland Department of Mines and Energy, Geological Survey, Report 85-2, 69 pages.
- Ware, M.J. and Wardle, R.J.
1979: Geology of the Sims - Evening Lake area, western Labrador with emphasis on the Helikian Sims Group. Newfoundland Department of Mines and Energy, Geological Survey, Report 79-5, 22 pages.
- York, D.
1969: Least squares fitting of a straight line with correlated errors. *Earth and Planetary Science Letters*, Volume 5, pages 320-324.

Note: Geological Survey file numbers are included in square brackets.

