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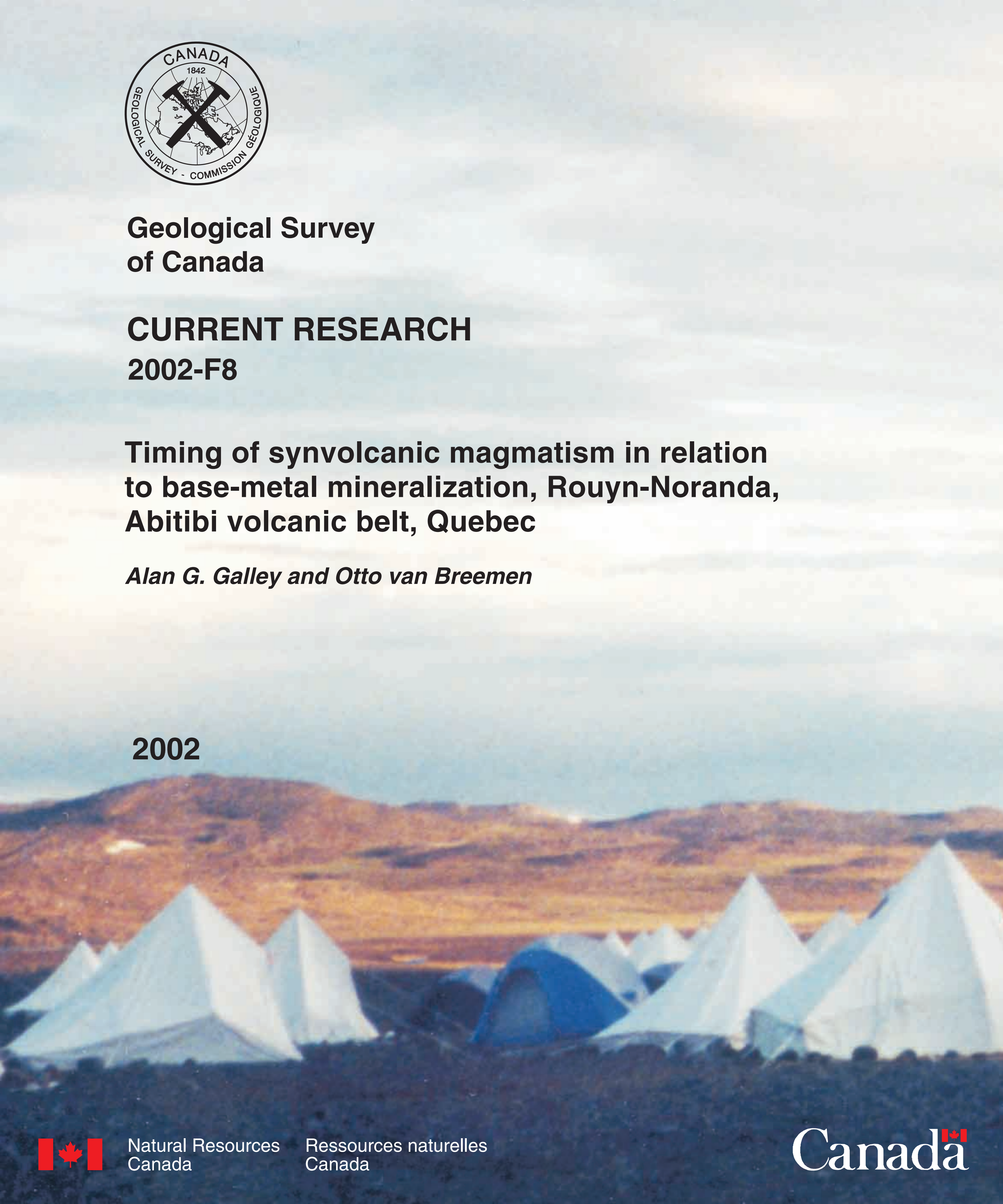

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Timing of synvolcanic magmatism in relation to base-metal mineralization, Rouyn-Noranda, Abitibi volcanic belt, Quebec

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Abstract: Uranium-lead zircon dating was carried out on the 2700 Ma Flavrian–Powell subvolcanic intrusive complex in the Noranda cauldron-hosted volcanogenic massive sulphide camp in order to determine the temporal relationship between intrusion-hosted Cu-Mo and volcanic-hosted massive-sulphide mineralization. The youngest trondhjemite phase of the Flavrian–Powell subvolcanic intrusive complex has an age of 2700 +3/-2 Ma, whereas a quartz porphyritic aplite dyke that crosses the Cu-Mo-Au-mineralized St. Jude intrusive breccia pipe returned an age of 2697 ± 2 Ma, similar to the post-cauldron Cléricy rhyolite. In conjunction with published dates on the Flavrian–Powell subvolcanic intrusive complex, these ages restrict the main emplacement events of the intrusive complex to less than 2 million years, and disassociate the volcanogenic massive sulphide mineralization related to the 2700 Ma magmatic event from the 2697 Ma late porphyry-type mineralization. The latter date coincides with the age of late Blake River Group volcanism and magmatism that hosts the Bousquet camp Au-(Cu) vein and auriferous volcanogenic massive sulphide deposits.

Résumé : Dans le camp minier de Noranda, où des gisements de sulfures massifs volcanogènes sont encaissées dans une structure de caldeira, une datation du complexe intrusif subvolcanique de Flavrian-Powell (env. 2 700 Ma) a été effectuée par la méthode U-Pb sur zircon afin de déterminer la relation chronologique entre les minéralisations de Cu-Mo présentes dans l'intrusion et les minéralisations de sulfures massifs contenues dans la succession volcanique. La phase trondhjémitique la plus récente du complexe intrusif subvolcanique de Flavrian-Powell a été datée à 2 700 +3/-2 Ma, tandis qu'un dyke d'aplite à phénocristaux de quartz qui recoupe la colonne de brèche intrusive de St. Jude, hôte d'une minéralisation de Cu-Mo-Au, a livré un âge de 2 697 ± 2 Ma. Celui-ci est comparable à l'âge de la rhyolite de Cléricy, qui est pour sa part postérieure à la succession de la caldeira. Combinés aux résultats de datations antérieurement publiés pour le complexe intrusif subvolcanique de Flavrian-Powell, ces âges restreignent les principaux événements de mise en place du complexe intrusif à un intervalle de moins de 2 millions d'années et dissocient la minéralisation de sulfures massifs volcanogènes liée à l'épisode magmatique de 2 700 Ma de la minéralisation tardive de type porphyrique datant de 2 697 Ma. Ce dernier âge coïncide avec celui de l'activité volcanique et magmatique du Groupe de Blake River, lequel est l'hôte des gisements filoniens à minéralisation de Au-(Cu) et des gisements de sulfures massifs volcanogènes à minéralisation aurifère du camp minier de Bousquet.

INTRODUCTION

Ten of the twelve volcanogenic massive sulphide camps in the Superior Province contain comagmatic and coeval subvolcanic intrusions of sufficient size to have been responsible for initiating and sustaining deposit-forming hydrothermal activity (Galley, 2000). Of these ten, eight are low-Al, low-K, quartz diorite–tonalite–trondhjemite intrusive complexes typical of extensional settings in oceanic-arc environments. The dominantly felsic composition of the volcanogenic massive sulphide-related composite intrusions increases the possibility for the generation of base-metal-rich magmatic fluids in a porphyry-type environment. These fluids could migrate from the cooling intrusion to mix with the seawater-dominated hydrothermal convection system, thereby enhancing its metal content. Examples of volcanogenic massive sulphide-related intrusions with porphyry-type mineralization include the Beidelman Bay intrusion in the Archean Sturgeon Lake volcanogenic massive sulphide camp of Ontario (Friske, 1974; Poulsen and Franklin, 1981), the Flavrian–Powell intrusion in the Archean Noranda camp of Quebec (Goldie et al., 1979; Kennedy, 1985), the Sneath Lake intrusion in the Paleoproterozoic Snow Lake camp of Manitoba, and the Jörn intrusion in the Skellefte volcanogenic massive sulphide district of Sweden (Walford and Franklin, 1982; Weihed and Schöberg, 1991). These intrusive systems could therefore be considered as submarine equivalents of the porphyry-epithermal continuum advocated by Sillitoe et al. (1996) and Hannington et al. (1997).

The temporal relationship between intrusion and volcanic-hosted base-metal mineralization was first examined in the Archean Sturgeon Lake volcanogenic massive sulphide camp (Galley et al., 2000). The result was the recognition of porphyry dikes that were emplaced during Cu-Mo mineralization of the Beidelman Bay subvolcanic intrusive complex. The Beidelman Bay intrusion has an age of 2733.8 +1.4/–1.3 Ma (Davis and Trowell, 1982), which is comagmatic and coeval with the overlying felsic volcaniclastic strata at 2735 ± 1.2 Ma (Davis et al., 1985). The felsic volcaniclastic strata are host to several volcanogenic massive sulphide deposits. The porphyry dikes associated with the Cu-Mo mineralization have a U-Pb zircon age of 2720.5 +3.5/–3.0 Ma (Galley et al., 2000). The porphyry-style mineralization is therefore considerably younger than the phases of the intrusion that are coeval with overlying, volcanogenic massive sulphide-hosting, felsic volcaniclastic strata.

It was then decided to test for differences in age between Cu-Zn-(Au) volcanogenic massive sulphide mineralization within the Archean Noranda volcanogenic massive sulphide camp and Cu-Mo mineralization within the spatially associated, coeval, Flavrian–Powell subvolcanic intrusive complex. This communication describes the results of dating this mineralizing event in relation to the formation of the massive-sulphide deposits in the overlying Noranda cauldron succession.

FLAVRIAN–POWELL SUBVOLCANIC INTRUSIVE COMPLEX

The Flavrian–Powell intrusive complex (FPIC; Fig. 1) is a 56 km^2 body emplaced along the base of the Noranda cauldron within the Blake River Group of the Archean southern Abitibi volcanic belt (Peloquin et al., 1990; Gibson and Watkinson, 1990). The Noranda cauldron is host to 17 volcanogenic massive sulphide deposits, including the 54 Mt Horne mine (Gibson and Watkinson, 1990). The Flavrian–Powell subvolcanic intrusive complex was first recognized as being comagmatic with its host volcanic succession by Goldie (1976). This conclusion is supported by geochemical studies by Kennedy (1985) and Paradis et al. (1988).

The Flavrian–Powell subvolcanic intrusive complex consists of an early quartz-diorite phase that is now present only as pendants and xenoliths within the younger phases and is compositionally similar to the andesite-dyke swarm that fed andesite flows within the overlying Noranda cauldron (Gibson, 1989; Fig. 2). This was followed by intrusion of a number of tonalite sills, which in turn were intruded by a succession of xenolithic to massive trondhjemite sills (Goldie et al., 1979; Kennedy, 1985; Richard, 1999). The trondhjemitic phases are geochemically identical to volcanogenic massive sulphide-hosting rhyolite within the overlying cauldron succession (Paradis et al., 1988). The tonalite-trondhjemite phases were intruded by the Eldrich diorite phase, which was then followed by the emplacement of a trondhjemitic stock within the core of the intrusive complex. The southern part of the Flavrian–Powell subvolcanic intrusive complex is crossed by aphyric to porphyritic trondhjemite dyke swarms, some of which are feeders to post-cauldron rhyolite flows (Setterfield et al., 1995). Another felsic porphyry dyke swarm was intruded along the western margin of the composite intrusion. The last magmatic activity affecting the Flavrian–Powell subvolcanic intrusive complex was intrusion of a series of late Archean, north-northwest-trending diorite dikes that transect all previous intrusive phases.

Mortensen (1993) sampled both the tonalite and trondhjemite phases of the Flavrian–Powell subvolcanic intrusive complex. The sample of the tonalite phase contained abundant medium to dark pinkish brown, stubby to elongate, strongly zoned zircon grains. Four analyses were moderately to strongly discordant, with two fractions yielding ^{207}Pb/Pb^{206} ages of 2705.5 ± 1.7 Ma and 2709.7 ± 1.3 Ma. The Four Corners rhyolite, which is stratigraphically below the Flavrian–Powell subvolcanic intrusive complex, returned a date of 2700.9 +1.4/–1.1 Ma. A sample of massive, white, early trondhjemite yielded an upper intercept age of 2700.8 +2.6/–1.0 Ma, which is consistent with the age of the underlying Four Corners rhyolite (Mortensen, 1993). Kennedy (1985) suggested that the late trondhjemite core to the Flavrian–Powell subvolcanic intrusive complex was younger due to the presence of a contact-metamorphic halo, a feature that is rare in high-level intrusions. He suggested an age of around 2690 Ma to coincide with a discordant ^{207}Pb/^{206}Pb age of 2685.8 Ma for the nearby Lac Dufault granodiorite (Gariépy and Allègre, 1985), whose western phase is also surrounded by an extensive contact-metamorphic halo.

Re-examination of the biotite-rich halo around the late trondhjemite phase indicates that it is not a product of contact metamorphism, but rather is due to a metasomatic event that generated a series of amphibole-biotite-apatite-sulphide veins representing volatile exsolution associated with crystallization of the late-stage trondhjemite core. This is important for two reasons. Firstly, it negates any correlation with the contact metamorphism that accompanied the emplacement of the 2690 Ma Lac Dufault granodiorite, and therefore brings into question the actual age of late-stage magmatism associated with the Flavrian–Powell subvolcanic intrusive complex. Secondly, the presence of the vein-rich halo suggests that the late-stage trondhjemite had the potential to generate porphyry-type base-metal mineralization. This possibility is further evidenced by the fact that the Cu-Mo mineralization hosted by the Flavrian–Powell subvolcanic intrusive complex was demonstrated by Kennedy (1985) to be associated with a trondhjemite stock of similar composition to the late trondhjemite core.

Several other observations are relevant regarding the timing of the Flavrian–Powell subvolcanic intrusive complex phases relative to volcanogenic massive sulphide-related hydrothermal activity. Oxygen-isotope evidence indicates that the quartz-diorite and tonalite phases underwent the most intense, high-temperature alteration associated with the formation of a sub-seafloor convective hydrothermal system within the Noranda cauldron (Kennedy, 1985; Cathles, 1993). The subsequent early trondhjemite phase shows less evidence for seawater-related hydrothermal alteration, and its upper contact transects the main volcanogenic massive sulphide-hosting horizon within the cauldron (Fig. 2). The

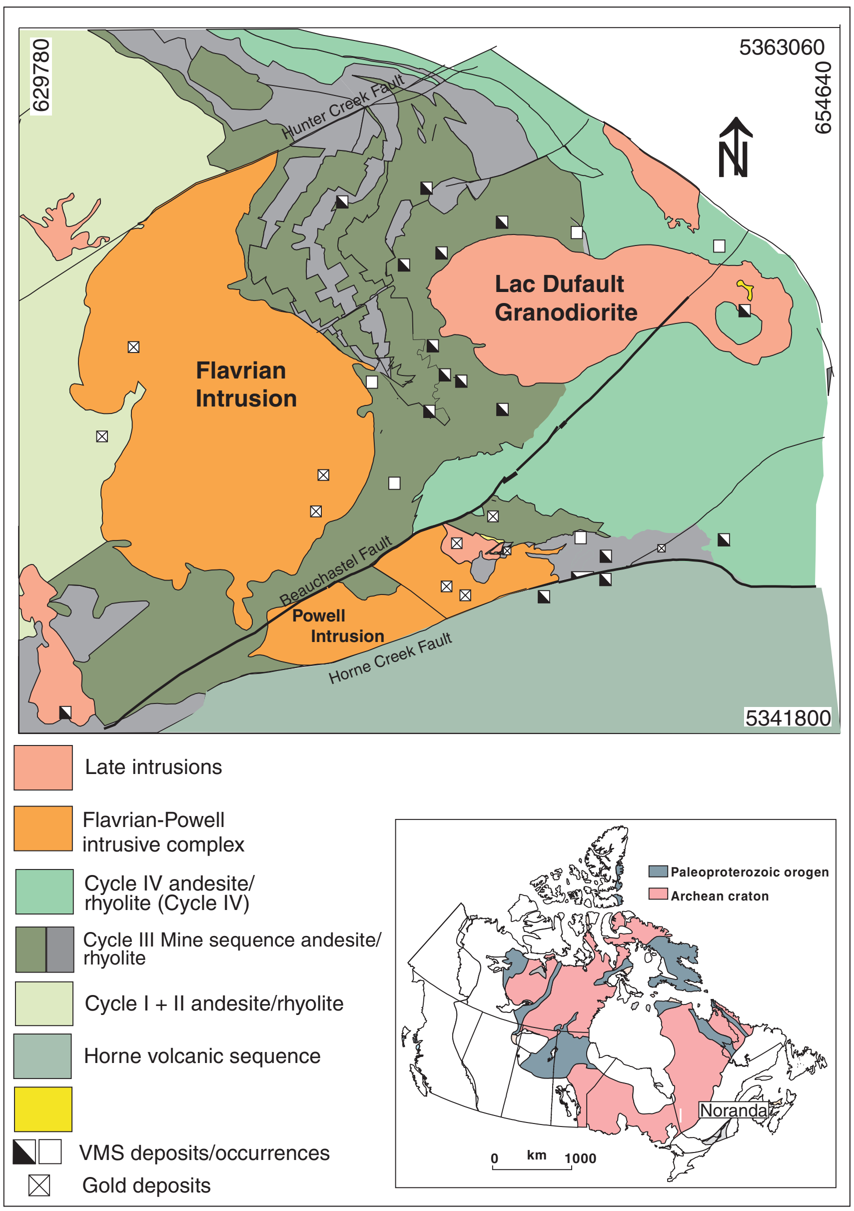

Figure 1.

Location of the Paleoarchean Noranda volcanogenic massive sulphide camp and associated Flavrian–Powell intrusive complex (modified from Gibson and Watkinson, 1990). The 2990 Ma Lac Dufault pluton postdates early deformation and has an extensive contact-metamorphic halo. Stratigraphy and enclosed Flavrian–Powell synvolcanic intrusions dip 20–40° to the east.

late-stage trondhjemite that occupies the core of the Flavrian–Powell subvolcanic intrusive complex shows no evidence of high-temperature, seawater-related hydrothermal activity. It would therefore appear that the quartz-diorite and tonalite phases of the Flavrian–Powell subvolcanic intrusive complex were associated with development of the volcanogenic massive sulphide-related hydrothermal activity within the Noranda cauldron. The overprinting, early trondhjemite phase is moderately altered and was emplaced during the late stages of the volcanogenic massive sulphide-related hydrothermal activity. The unaltered, late trondhjemite phase completely postdated volcanogenic massive sulphide formation within the cauldron.

INTRUSION-HOSTED CU-MO MINERALIZATION

The Flavrian–Powell subvolcanic intrusive complex contains two occurrences of Cu-Mo mineralization. The Don–Rouyn occurrence is situated within the early trondhjemite phase near the southern, faulted margin of the complex (Fig. 2). It is described by Goldie et al. (1979) and Jébrak et al. (1997) as having characteristics of a small porphyry system, with a zoned mineralization pattern, varying outward from bornite-pyrite to chalcopyrite-pyrite, around a strongly silicified core. Its small size (36 Mt of 0.15% Cu) made it uneconomic, but its silicified core was mined for smelter flux. The second intrusive-related sulphide-mineral occurrence is hosted by the St. Jude intrusive breccia, located on the western margin of the composite intrusion and measuring 600 m in diameter (Fig.3, 4). This mineralized intrusive breccia has a pyrite-chalcopyrite-bornite-molybdenite-rich core and a pyrite-sphalerite-galena-rich margin. The breccia pipe is bordered to the west by an extensive felsic porphyry dyke swarm that hosts numerous Zn-Pb-Cu-Ag-Au vein showings (Kennedy, 1985; Carrière, 1992). The breccia has a biotite-rich potassic core and sericite-rich phyllic margin, typical of many mineralized porphyry systems (Fig. 4). Kennedy (1985) noted that the core of the pipe contains a trondhjemite plug of similar mineralogy and texture to that of the late trondhjemite core to the main Flavrian–Powell subvolcanic intrusive complex.

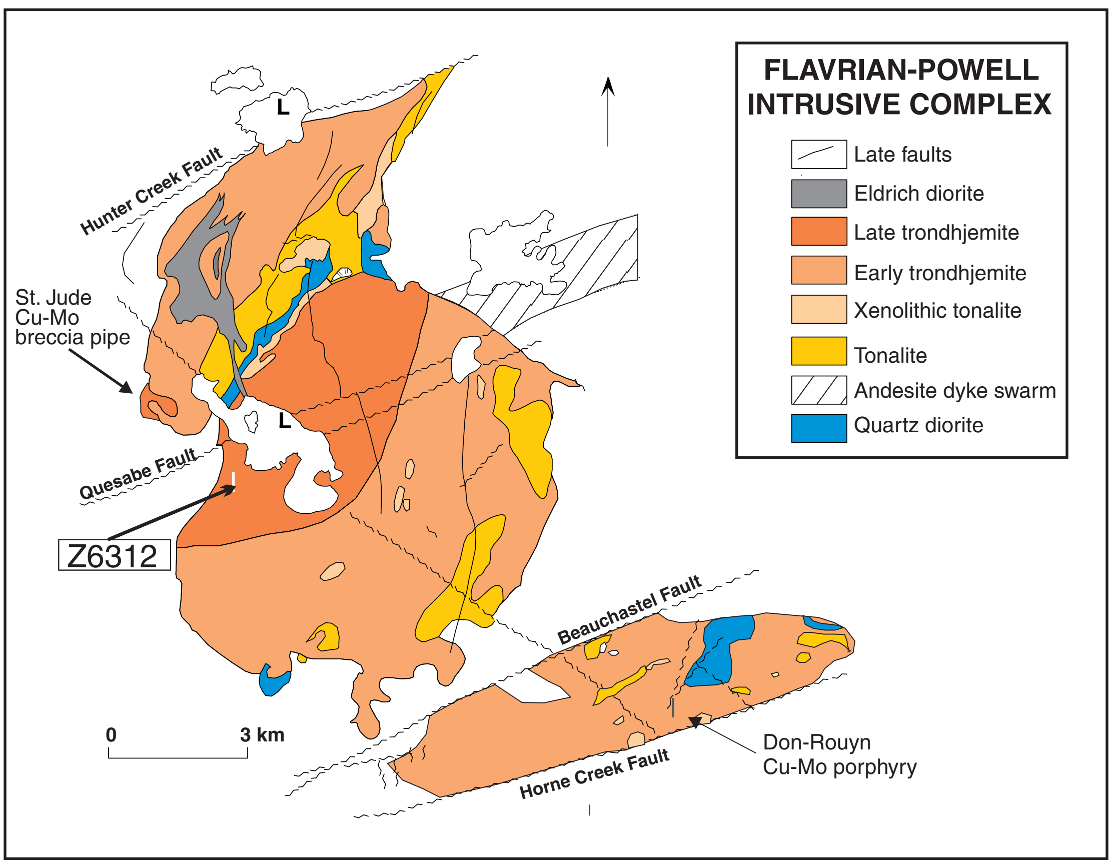

Figure 2. Geology of the Flavrian–Powell intrusive complex. The present configuration of the intrusive complex, as two parts, is due to early, north-verging thrust faulting. Note the locations of the Don–Rouyn Cu-Mo porphyry occurrence and the sulphide-mineralized St. Jude intrusive breccia pipe. Note also the location of geochronology sample 99GIA-036 from the late trondhjemite phase of the subvolcanic intrusive complex.

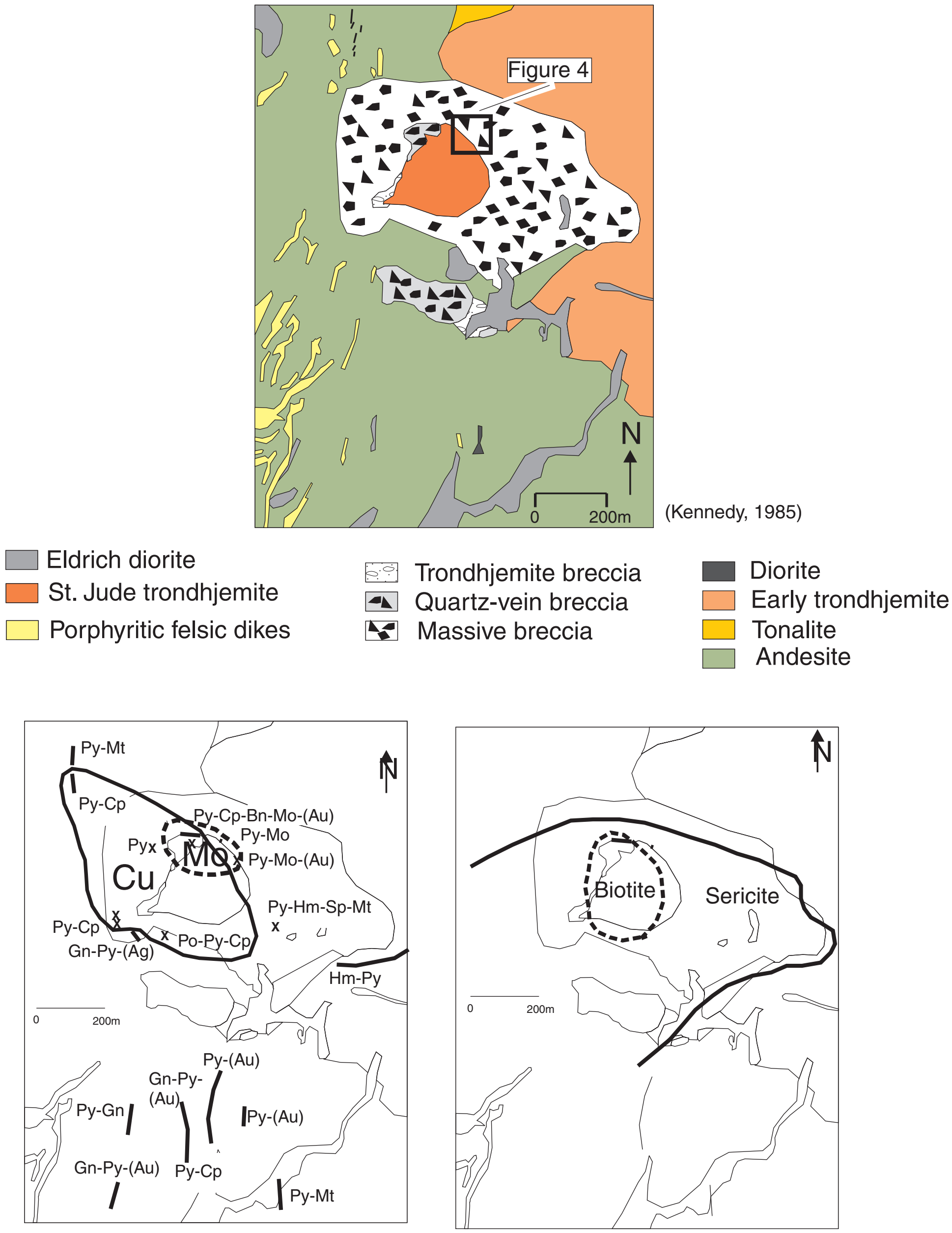

*Figure 3. Series of diagrams from Kennedy (1985) depicting the various characteristics of the St. Jude intrusive-hydrothermal breccia pipe and associated porphyry dyke swarm. Upper diagram shows the general geological setting along the west margin of the Flavrian–Powell subvolcanic intrusive complex (*see *Fig. 2 for location inset). Lower left diagram indicates the general metal zonation centred on the breccia pipe, and the location of various sulphide-rich vein sets on the breccia periphery and associated with a quartz porphyry dyke swarm. Lower right diagram indicates the distribution of biotite-rich (potassic) and sericite-rich (phyllic) alteration typical of high-temperature magmatic mineralizing systems. Bn, bornite; Cp, chalcopyrite; Gn, galena; Hm, hematite; Mo, molybdenite; Mt, magnetite; Po, pyrrhotite; Py, pyrite; Sp, sphalerite.*

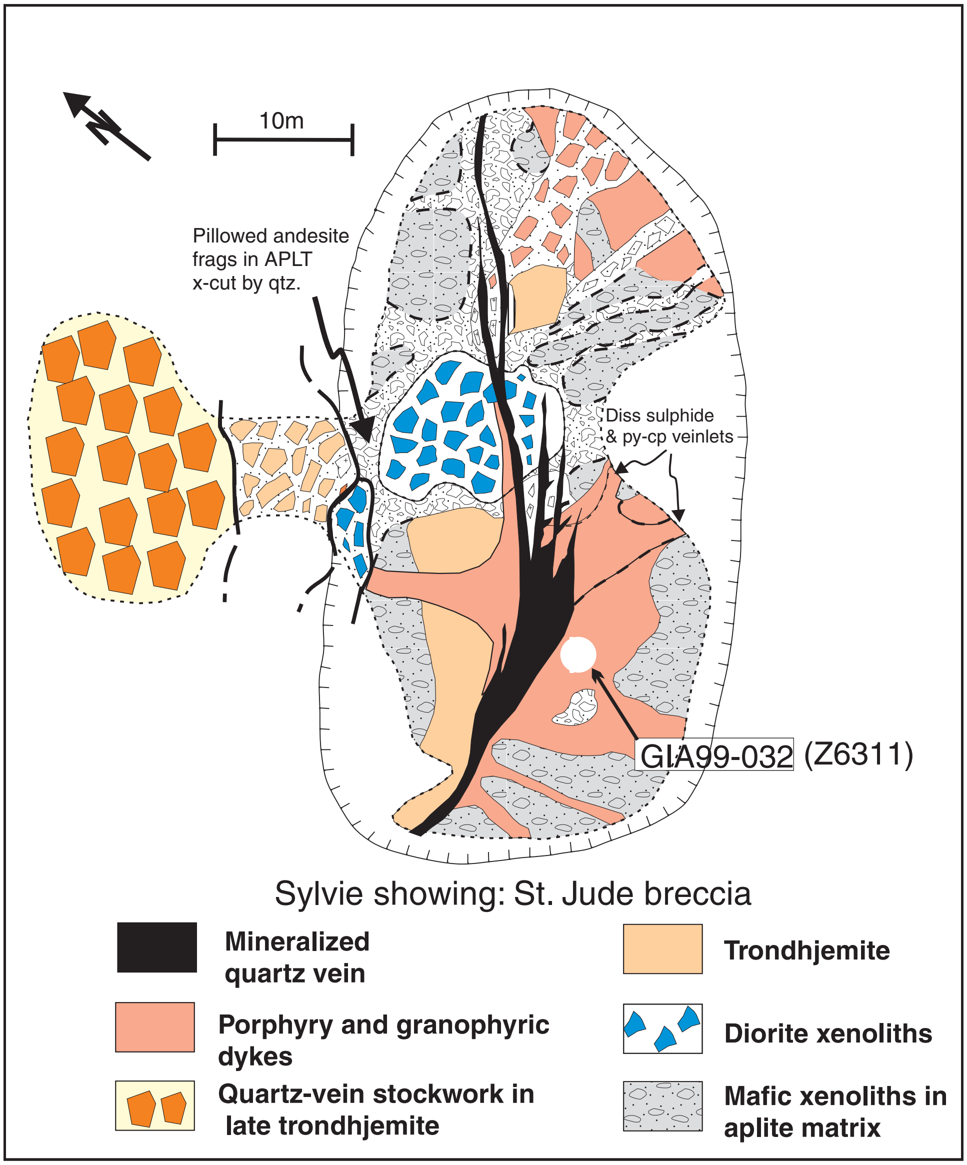

Figure 4. *Detailed sketch map generated during examination of the Sylvie occurrence within the St. Jude breccia pipe. Sample z6311 was taken from the youngest intrusive phase associated with the breccia pipe.*

The St. Jude breccia pipe consists of a number of nested intrusive-breccia units that were shown by Kennedy (1985) to transect and incorporate the felsic quartz-feldspar porphyry dyke swarm that strikes north-northeast along the west margin of the Flavrian–Powell subvolcanic intrusive complex. The clast-supported breccia units contain blocky xenoliths of the andesitic wallrocks, along with fragments of aphyric to porphyritic felsic intrusive. The margins of the small body of trondhjemite show evidence for in situ brecciation and inclusion in the surrounding intrusive breccia. The breccia units are crossed by a bifurcating, Mo-bearing quartz vein that, in turn, is transected by an aphyric aplite dyke.

GEOCHRONOLOGICAL SAMPLES

Two geochronology samples were selected in order to bracket the age of the Cu-Mo mineralization within the St. Jude breccia. The zircon fractions were strongly abraded (Krogh, 1982). Analytical techniques for measuring U-Pb isotopes in zircon at the GSC are summarized by Parrish et al. (1987) and Roddick (1987). Isotopic data are presented in Table 1 and plotted on Figure 5. Age uncertainties are given at the 95% confidence level.

The first sample (z6311) is a fine-grained, quartz porphyritic and highly granophyric, light grey aplite that transects most of the breccia types within the Sylvie mineralized

Table 1. U-Pb zircon isotope analytical data.

Fraction[1]	Weight[2] mg	U ppm	Pb[3] ppm	$^{206}Pb/^{204}Pb$ [4]	Pb[5] pg	$^{208}Pb/^{206}Pb$ [6]	$^{207}Pb/^{235}U$ [6]	$^{206}Pb/^{238}U$ [6]	$^{207}Pb/^{206}Pb$ [6]	$^{207}Pb/^{206}Pb$ [7]	Disc[8]
GIA-99-032: aphyric dyke, Lac Flavrian Complex (z6311; lat. 48.3183°N, long. 79.2322°E)											
A, +105, M3	11	98	58	3359	10	0.137	13.205±0.12	0.5182±0.10	0.18483±0.05	2697±2	0.24
B, -74, M3	7	89	53	1979	10	0.148	13.169±0.13	0.5167±0.10	0.18485±0.06	2697±2	0.53
D1, M5	6	70	41	2107	7	0.143	13.015±0.13	0.5111±0.11	0.18467±0.06	2695±2	1.53
GIA-99-036: medium-grained trondhjemite, Lac Flavrian complex (z6312; lat. 48.3033°N, long. 79.2083°E)											
A1, +50-100, M1	6	44	26	883	10	0.133	13.336±0.19	0.5218±0.15	0.18536±0.11	2701±4	-0.24
B1, +50-100, M1	7	53	31	266	46	0.14	12.960±0.38	0.5091±0.23	0.18465±0.28	2695±9	1.9
C1-A, +50-150, N1	8	51	30	4202	2	0.133	13.166±0.13	0.5160±0.11	0.18507±0.05	2699±2	0.76
D1-A, +50-75, N1	8	25	15	248	27	0.135	13.472±0.41	0.5266±0.39	0.18555±0.23	2703±8	-1.1

[1] size ranges indicated are in microns; M and N refer to magnetic or non-magnetic at side slope indicated in degrees and 1.8 A current in Frantz isodynamic separator
[2] error on weight is ±1 mg
[3] radiogenic Pb
[4] measured ratio corrected for spike and Pb fractionation of 0.09 ± 0.03 %AMU
[5] total common Pb on analysis corrected for fractionation and spike
[6] corrected for blank Pb and U, common Pb; errors quoted are 1s in percent
[7] age error quoted is 2 standard errors (in Ma)
[8] discordance in per cent along a discordia to origin

exposure, but is itself truncated by smaller breccia dikes (Fig. 3, 4). The aplite hosts one-third of the exposed length of a mineralized quartz vein mineralized with molybdenite-pyrite-chalcopyrite. Zircons are clear and colourless, and have minor clear inclusions. They are stubby, simple bipyramidal prisms with sharp terminations. Regression analysis of the three single-grain data points yields an upper intercept age of 2697 ± 2 Ma and a lower intercept age of ca. 270 Ma (Fig. 5A), with a mean square of weighted deviates (MSWD) of 0.17 (York, 1969).

The second sample (z6312) is a massive, pink, equigranular trondhjemite from the core of the Flavrian–Powell subvolcanic intrusive complex (Fig. 2). This phase contains around 5% rounded mafic xenoliths. The sample is from the same outcrop sampled by Richard (1999), and was taken to determine the youngest date for the last major magmatic event associated with the subvolcanic intrusion. Zircons are clear and colourless prisms with length:breadth ratios ranging from 2:1 to 4:1. Uranium concentrations in these zircons are low. Regression of all four data points yields an upper intercept age of 2700 +3/–2 Ma and a lower intercept age of ca. 425 Ma (Fig. 5B), with a MSWD of 0.62.

DISCUSSION

The age of the Four Corners rhyolite (2700.9 +1.4/–1.1 Ma) and the early trondhjemite phase of the Flavrian–Powell subvolcanic intrusive complex (2700.8 +2.6/–1.0 Ma) are nearly identical, with a minimum age of 2699.8 Ma. This confirms the synvolcanic age of the early phases of the complex and their temporal association with the volcanogenic massive sulphide mineralization in the Noranda cauldron. The 2700 +3/–2 Ma age for the unaltered late trondhjemite core of the Flavrian–Powell subvolcanic intrusive complex indicates a minimum age of 2698 Ma for volcanogenic massive sulphide-related hydrothermal activity. The age of the aplite associated with late stages of Cu-Mo mineralization within the St. Jude breccia pipe (2697 ± 2 Ma) coincides with the age of the Cléricy rhyolite (2697 +1.3/–0.7 Ma; Mortensen, 1993), which is part of the post–Noranda cauldron volcanic succession. Although there is an overlap in the age ranges calculated for the main trondhjemite phases of the Flavrian–Powell subvolcanic intrusive complex and the Cu-Mo-related aplite dyke, the closer age relationship between the latter and the post-cauldron Cléricy rhyolite would suggest a slight difference in age between volcanogenic massive sulphide and intrusion-hosted base-metal mineralization in the Noranda mining camp.

The Cu-Mo mineralization hosted by the 2697 Ma St. Jude breccia represents the last synvolcanic magmatic activity associated with the Flavrian–Powell subvolcanic intrusive complex, and is similar in age to the 2698 Ma post-cauldron volcanism that marks the upper part of the Blake River Group. Low-Al, low-K quartz diorite–tonalite–trondhjemite intrusions are not usually associated with porphyry-type base-metal mineralization. This is due to the inherently low water contents of tonalitic melts (<2 weight %) and low metal contents of high silica trondhjemitic melts (Whitney, 1977; Christiansen and Keith, 1996). There are examples of oceanic-arc granitoid suites hosting Cu-Mo mineralization (Kesler et al., 1975), but these suites are commonly in more evolved, calc-alkalic Phanerozoic arcs (Lang and Titley, 1998).

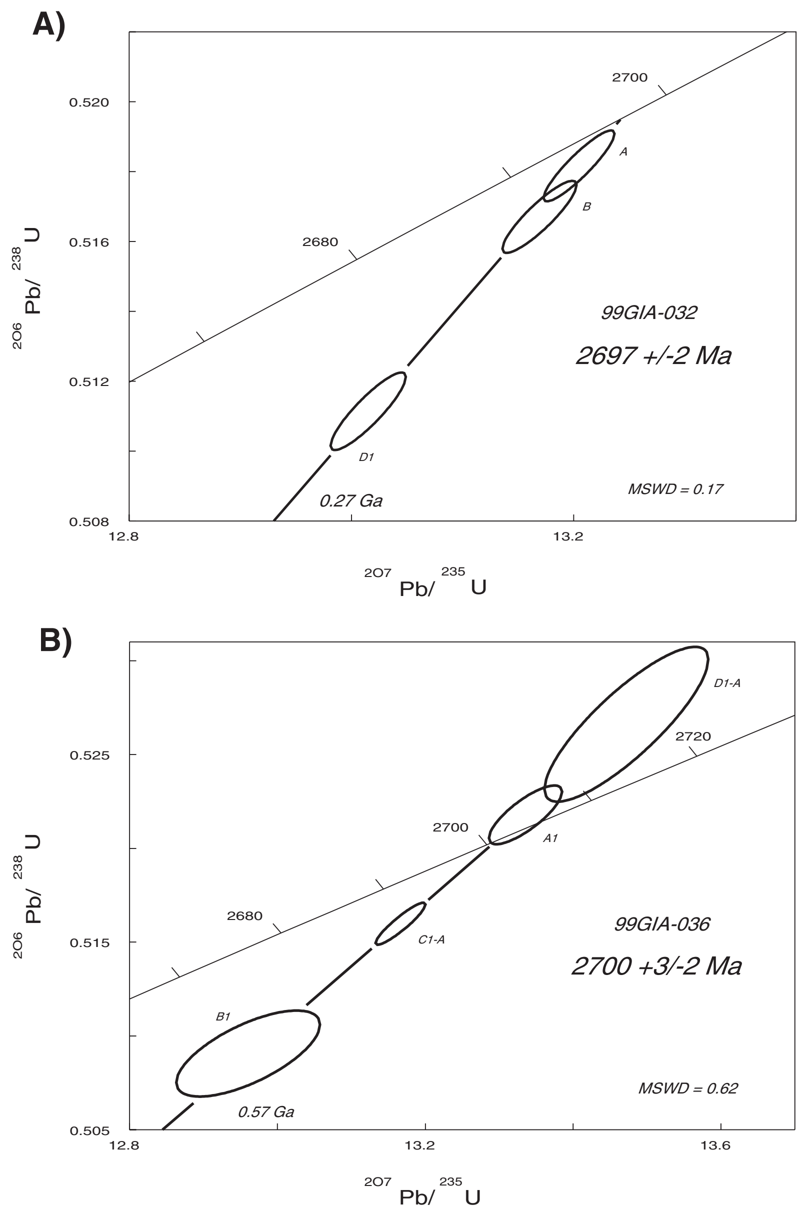

Figure 5. *Concordia plots for* ***A)*** *sample z6311 of porphyritic aplite associated with the St. Jude breccia pipe, and* ***B)*** *sample z6312 taken from the late trondhjemite core of the Flavrian–Powell subvolcanic intrusive complex.*

The intrusion of a highly porphyritic felsic dyke swarm into the St. Jude intrusive breccia pipe suggests an association with a highly fractionated magma chamber. As fractionation is considered a major factor in the generation and collection of metal-rich magmatic fluids (Lowenstern, 1994; Hedenquist et al., 1998), it is possible that late-stage, intermediate to felsic magmas of the Blake River Group were relatively rich in volatiles. This ability for the late-stage felsic magmas of the Blake River Group to produce metal-enriched volatiles may have implications for the origin of the Cu-Au vein and auriferous volcanogenic massive sulphide deposits hosted by 2698 Ma volcanic strata and associated intrusions within the Blake River–hosted Bousquet mining camp.

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