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Evolution of Palaeoproterozoic mafic intrusions located within the thermal aureole of the Sudbury Igneous Complex, Canada: Isotopic, geochronological and geochemical evidence

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Abstract—Impact cratering and their resultant geological phenomena are recognised as significant factors in the lithological and biologic evolution of the earth. Age-dating of impact events is critical in correlating cause and effects for these catastrophic processes. The Falconbridge and Drury Township (Twp) intrusions were emplaced at the contact between Neoarchaean basement and Palaeoproterozoic volcanosedimentary rocks, and also lie at the southeast and southwest edges of the Sudbury Igneous Complex (SIC), within its thermal contact aureole. The Falconbridge Twp intrusion is dated at 2441 ± 3 Ma by U-Pb zircon, with evidence of Archaean inheritance from its host granitoids. Granitoids from the southernmost Abitibi Subprovince are dated here between 2670 ± 11 Ma for an undeformed Algoman granite, and 2696 ± 18 Ma for a foliated granitoid, consistent with existing data from the Abitibi Greenstone Belt and from the Wawa Subprovince. Major and trace element geochemical evidence, common-Pb isotopic compositions, and ε_{Nd}^{2440} values between 0 and −1 are all consistent with a Palaeoproterozoic origin for the Falconbridge Twp intrusion, and support inclusion in the East Bull Lake-type suite of leucogabbroic plutons and sills.

In contrast, the Drury Twp intrusion gives a U-Pb zircon age of 1859 ± 13 Ma, coincident with the date of SIC-emplacement. While the major and trace element compositions are comparable to the Falconbridge data, the Drury displays significant heterogeneity in ε_{Nd}^{2440}, with values ranging from +3.7 to −0.1, and contains more radiogenic Pb isotopic compositions. Field, geochemical and isotopic evidence clearly distinguishes this intrusion from constituents of the SIC itself, and indicates that the Drury too is a Palaeoproterozoic intrusion. This requires that apparently unshocked, undeformed magmatic-looking zircon has been grown or reset in a postmagmatic setting. This has significant implications for the identification of mantle-derived magmas and crustal remelts associated with large impact craters. A resetting mechanism involving aggressive hydrothermal alteration of zircon facilitated by halogen-complexing is proposed, inducing rapid, postshock lead loss and subsequent annealing. *Copyright © 2005 Elsevier Ltd*

1. INTRODUCTION

In recent years both the concept and the prominence of impact phenomena as agents of geological change has become progressively more widely recognised, from the early work of Dietz (1959, 1960, 1961, 1964, 1972) to the present (e.g., see Dressler (1984); Grieve et al. (1995) and Reimold and Gibson (1996) for summaries). Of particular interest are the large impact structures with projected original diameters on the order of 200 to 300 km such as at Vredefort (Therriault et al., 1995), Sudbury (Grieve, 1994), Morokweng (Corner et al., 1997) and Chicxulub (Morgan and Warner, 1999). A wide range of geological phenomena have been attributed to the emplacement of these large features, including mass extinction events in the case of Chicxulub (largely on the basis of the coincidence of the timing of impact and the Cretaceous-Tertiary boundary at ca. 65 Ma), exposure of middle to lower crustal rocks through postimpact doming and subsequent erosion as at Vredefort (e.g., Hart et al. 1990a, 1990b), and concentration of major metal deposits at Sudbury (e.g., Golightly, 1994).

Of particular importance in the evaluation of these structures is the determination of reliable geochronometry, of both impact-initiated juvenile crustal or mantle melts and their protoliths. While the geochronology of impact melt rocks or shocked felsic crustal basement rocks is relatively straightforward, in cases where impact melts have interacted with their host rocks over prolonged periods, either in the form of magmatic or hydrothermal systems, the systems become much more complex. Recent geochronological studies on mafic rocks proximal to impact environments such as Sudbury (Corfu and Lightfoot, 1996) and Vredefort (Moser, 1997) involving the dating of mafic components in or associated with proximal, brecciated, hornfelsed, or otherwise deformed basement rocks, frequently contain both shocked, preimpact (by definition) zircon and syn-impact zircon with euhedral, prismatic, colourless, typically igneous morphologies. These have been interpreted in both cases, somewhat controversially, as the products of syn- or postimpact mafic igneous activity, represented by the euhedral prismatic zircons, which have acquired shocked zircons by inheritance from adjacent felsic or granitic country rocks.

The paragenesis of these rocks is particularly critical in environments where mafic to ultramafic rocks hosted by otherwise largely felsic or siliceous material comprising impact melt sheets and their host rocks represent the best candidates and therefore the best potential evidence for mantle-derived

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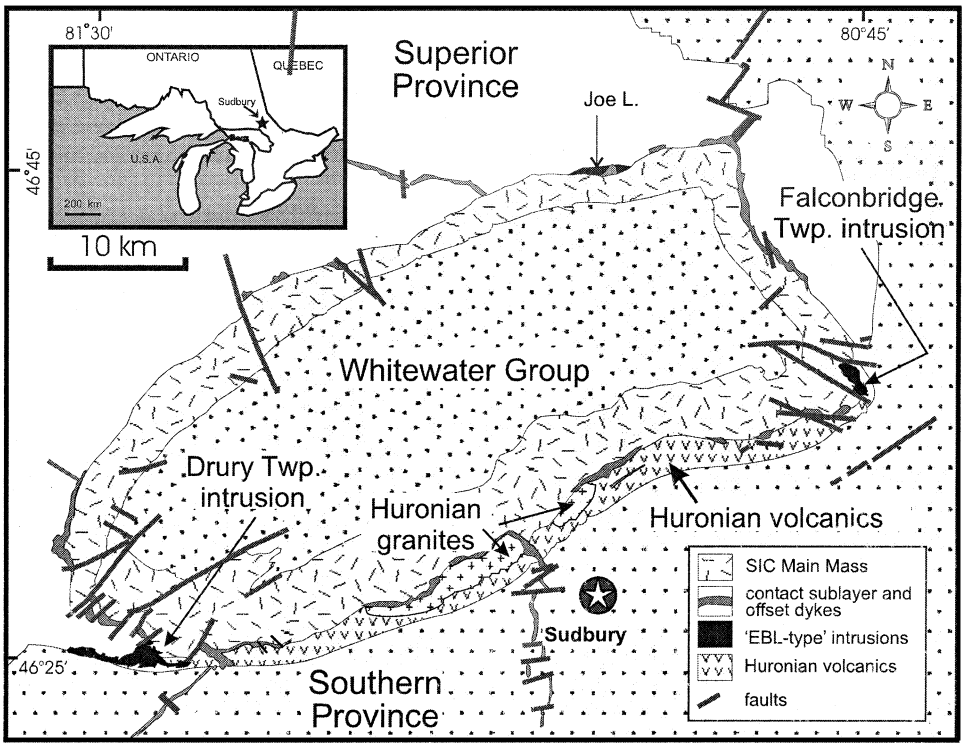


Fig. 1. Geological map showing the locations of the Drury and Falconbridge Township intrusions relative to the Sudbury Igneous Complex and Southern and Superior Province basements. EBL = East Bull Lake; SIC = Sudbury Igneous Complex; Twp = Township. (See text for further explanation).

components to impact assemblages. In cases such as Sudbury which contain extensive Ni-Cu-PGE mineralization, which is typically associated with mantle-derived magmatism (i.e., hosted by komatiites or layered mafic intrusions), the presence or absence of a mantle contribution is absolutely critical to ore paragenesis models, both with regards to the source of the metals and of the sulphur (in the case of sulphide ores, as opposed to oxide ores such as chromitite).

The ca. 1850 Sudbury Igneous Complex (SIC), located astride the boundary between the southernmost Archaean Superior Province and the Palaeoproterozoic Southern Province (Fig. 1), represents the largest single source of nickel in the world, and is generally believed to have originated as a result of impact-induced cataclysmic melting of local crustal country rock (e.g., Dietz, 1972; Grieve, 1994). While the SIC is largely underlain by Archaean gneissic rocks of the Levack Gneiss Complex (e.g., McGrath and Broome, 1994; Hearst et al., 1994) which are unmineralized where they are exposed at surface, Huronian mafic basaltic to diabasic rocks comprise a large part of the country rocks along the southern margin of the SIC and an important component of the contact sublayer of the SIC (Prevec, 2000; Prevec et al., 2000), where the bulk of the nickel sulphide is hosted. Two Palaeoproterozoic mafic intrusive suites within the Southern Province are known to contain significant Cu-Ni-PGE sulphides locally, shown in Figure 2. These are the ca. 2480–2450 Ma East Bull Lake-type leucogabbronoritic Huronian-aged plutons and sills (James et al., 2002; Peck et al., 1993, 1995) and the ca. 2220 Ma Nipissing Gabbros (Lightfoot and Naldrett, 1996).

Sills identified with the older, Huronian-aged intrusive suite on the basis of field petrologic criteria have been intruded into Archaean country rocks immediately adjacent to the SIC (Fig. 1) in Drury (Card, 1978), Falconbridge (Thomson, 1957) and Wisner (Dressler, 1984) Townships (Twp). These intrusions provide a means of evaluating the effects of the emplacement of the SIC onto the mafic potential proto-ore footwall rocks. To determine the potential relevance of these intrusions as possible proto-ore hosts for the SIC, the origin of two of these intrusions is investigated using their petrology, major and trace element geochemistry, U-Pb zircon geochronology and Sm-Nd isotope geochemistry. The geochronology of texturally distinct members of the southernmost Archaean granitic rocks has also been constrained using U-Pb zircon geochronology. The Drury and Falconbridge Twp intrusions are compared with one another and with mafic components of and within the SIC, to establish the relationship between the intrusions and the SIC melt rocks and inclusions therein.

2. REGIONAL GEOLOGY

The vast majority of the volume of both the Huronian and Nipissing plutonic suites have been emplaced into the volcanics and sediments of the Southern Province, although members of both suites have been identified within the marginal zones of the adjacent geological provinces, consisting of granitoids and gneisses of the Abitibi Subprovince and Archaean foreland gneisses of the Grenville Province, a heterogeneous assemblage which has been broadly grouped together as the Ramsey-Algoma Granitoid Complex (Jackson and Fyon, 1991). The mafic plutons and sills are broadly aligned in an east-west orien-

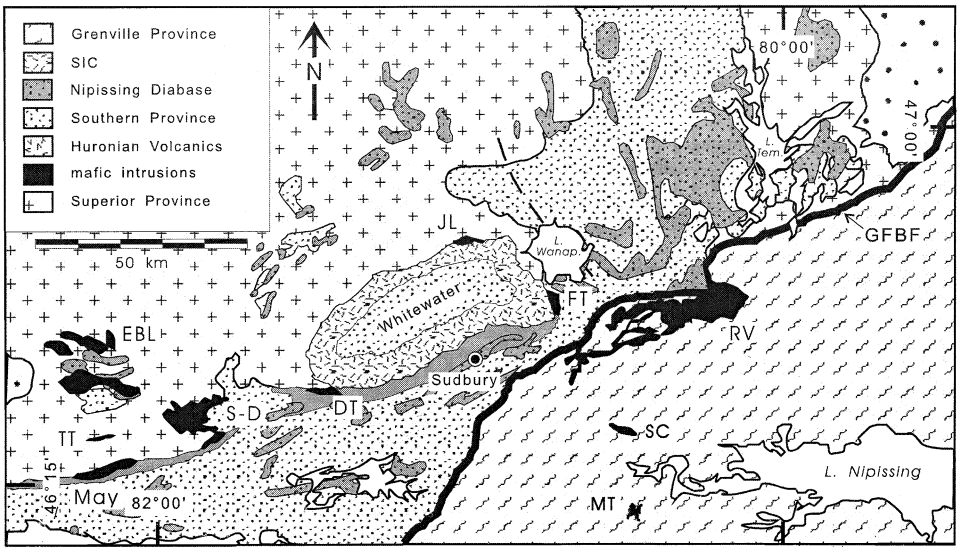


Fig. 2. Geological map of the southern Superior Province, showing the extent of the EBL-suite of intrusions, along with the position of selected younger anorthosites. EBL = East Bull Lake, TT = Tennyson Township (Twp), May = May Twp, *S*-D = Shakespeare-Dunlop, DT = Drury Twp, JL = Joe Lake, FT = Falconbridge Twp, RV = River Valley, SC = St Charles, MT = Mercer Twp, GFBF = Grenville Front Boundary Fault, Whitewater = Whitewater Group sediments.

tation in the Sudbury area, consistent with prevailing Kenoran (ca. 2650 Ma) and younger Penokean (ca. 1900–1700 Ma) crustal fracturing and faulting directions. The Huronian intrusive suite consists of three large intrusions (East Bull Lake and Shakespeare-Dunlop in the west and River Valley in the east) and a large number of smaller sills lying in between (Fig. 2). Small intrusions tentatively identified with this suite have been identified 200 km to the north (Fort Knox) and 300 km to the west (St. Joseph's Island). This suite has also been tentatively genetically related to both the basal Huronian basalts and the Matachewan dyke swarm (e.g., Fahrig et al., 1987; Vogel et al., 1998). Three leucogabbroic sills have been identified in the footwall rocks to the SIC, located in Drury, Falconbridge and Wisner Townships. (The Wisner Twp intrusion is also commonly referred to as the Joe Lake Intrusion.)

The small hornblende-feldspar body in Falconbridge Township is about two kilometres long and half a kilometre wide, elongated in a north-south direction, shown in Figure 3a. The primary mineralogy of the Falconbridge Township intrusion is very poorly preserved, such that the rock was initially designated a hornblende-syenite (Thomson, 1957). He describes coarse-grained amphiboles, secondary quartz and orthoclase, sodic plagioclase, and xenoliths of pillow-basaltic lavas. It is bounded to the north by Archaean granites, to the west by the norite of the SIC, and to the south by Huronian basaltic volcanics. Thompson (1957) interpreted the hornblende-syenite as intrusive into the Huronian Supergroup and predating the SIC.

The smaller of the two intrusions included in this study is located in eastern-central Drury Township, shown in Figure 3b. The actual extent of the intrusion is difficult to determine, as it was originally mapped as a hornblende-syenite phase of the basal Huronian volcanics (Card, 1965), whose exposure begins in western Drury Township and continues eastwards around the southern margin of the Sudbury Structure. The "hornblende-syenite" crops out in an area of about five by two kilometres in eastern Drury Township (Card, 1965), and was not initially identified by the same author in the adjacent township (Denison) to the east (Card, 1965). This unit, later identified as an intrusive (Card, 1978), intrudes the Algoman Birch Lake Batholith to the north, and is bounded to the south by Nipissing Gabbro and basal Huronian volcanics (Card, 1965; Card, 1978). The Drury Twp metagabbro is a leucocratic, massive to locally well-lineated rock largely composed of saussuritised plagioclase and chloritised hornblende. It is crosscut by breccias thought to be associated with the emplacement of the SIC (Card, 1965; Rousell, 1984) and by mafic dykes which have been tentatively correlated with the ca. 2220 Ma Nipissing Gabbros (Card, 1965, 1978), and xenoliths showing the same distinctive coarse-grained leucogabbroic texture have been recognized in the overlying basalts (Card, 1978). Both the Drury and Falconbridge sills reside within fault-bounded blocks (Dressler, 1984a) showing evidence of both lateral and vertical displacement. Despite the fact that the compilation map produced for the Sudbury area (Dressler, 1984b) classifies both the Drury and Falconbridge (and Wisner Township) intrusions as Late Archaean, rather than Palaeoproterozoic, this map was designed with a focus on the SIC itself, rather than the country rocks, and it is clear from Card (1978) that the Drury Township body is interpreted as being affiliated with the post-Abitibi East Bull Lake and Shakespeare-Dunlop magmatic suite.

3. METHODOLOGY

Fresh (unweathered) samples of at least 10 kg were obtained from the two mafic intrusions (14 samples) and two granitoids (2 samples) by sledgehammering from outcrop, sawn and crushed to <300 mesh powder at the University of Alberta, with precautions taken to minimise contamination, including using paint-free saw blades,

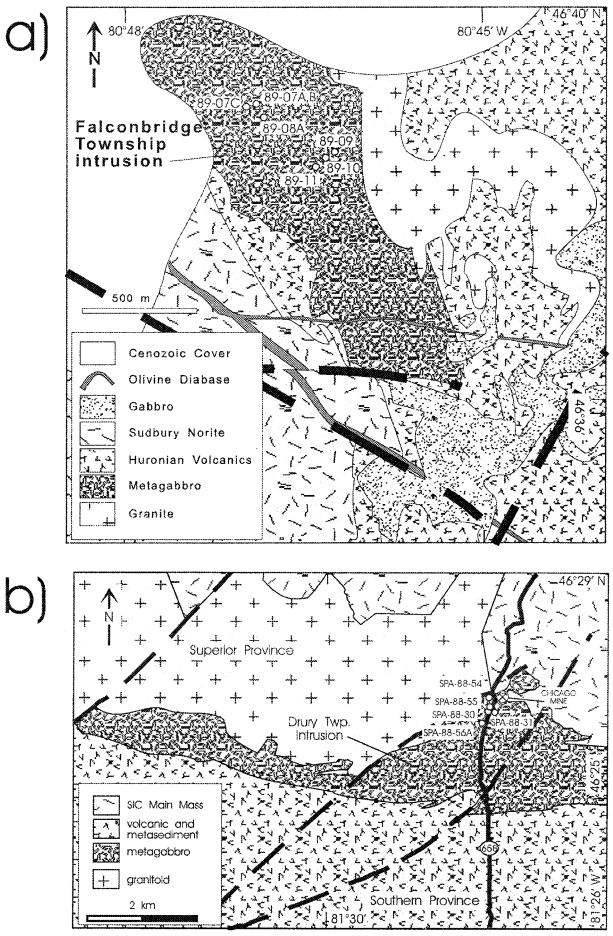


Fig. 3. Geological setting and sample locations for a) the Falconbridge Township intrusion and b) the Drury Township intrusion.

water-based rather than oil-based lubricants, and precontamination and rigorous cleaning of crushing equipment (see Prevec, 1993 for details). Representative splits of 5–10 g were sent for geochemical analysis. Major elements were determined by X-ray fluorescence (XRF) analysis at the Geological Survey of Canada (Ottawa, Canada), and trace elements by inductively-coupled plasma—mass spectometry (ICP-MS) at the Geology Department, University of Cape Town, South Africa (Table 1A and B). Zircons were extracted from coarsely-crushed samples using a combination of the Wilfley Table, heavy liquids (tetrabromoethane and methylene iodide), and Frantz magnetic separation. Zircon extraction and U-Pb isotopic analyses (Table 2a) for the Falconbridge Twp samples were conducted at the Geological Survey of Canada by the senior author on a Finnigan MAT 261 nine-collector solid-source mass spectrometer, following the sample preparation, analytical and data reduction procedures of Parrish et al. (1987). Zircons from the Drury Twp and granitoid samples were separated and selected by the senior author at the University of Alberta, and U-Pb isotopic analyses were carried out at the Research School of Earth Sciences at the Australian National University, Canberra, Australia, on the Sensitive High-Resolution Ion-Microprobe ("SHRIMP") by Dr Halfdan Baadsgaard. Ages, given in Table 2b, were derived from spot analyses on individual grains (as opposed to multiple spots on any one individual grain). Drury Twp zircons were also polished and etched with hydrofluoric acid at the G.S.C. and examined by SEM at the Université du Québec à Montréal and for cathodiluminescence at the University of the Witwatersrand. Samples for whole-rock isotopic analysis experienced dissolution of 100–250 mg sample powders (<300 mesh) in high pressure steel or teflon bombs using a sequence or combination of hydrofluoric, nitric and hydrochloric acids. Sm-Nd isotopic analyses (Table 3) were carried out by the senior author at the Ministry of Northern Development and Mines (MNDM) Geoservices Centre in Sudbury, Ontario. Isotopic ratios were determined on a VG Sector multi-collector thermal ionization mass spectrometer (TIMS). See Table 3 caption for further details. Whole-rock common lead isotopic analyses were conducted at the University of Alberta on a VG Micromass 30 single collector TIMS machine. See Table 4 caption for further details.

4. PETROLOGY

The mineralogy of both the Drury and Falconbridge suites is characterized by greenschist grade metaleucogabbroic compositions. Plagioclase is characterized by fine-grained hornfelsed-textured pseudomorphs of feldspar or saussuritized equivalents after the igneous primocrysts. The suite from Falconbridge Twp consists of amphibole and plagioclase, or alterations thereof. Relict cumulate textures involving plagioclase and pseudomorphs of amphibole after clinopyroxene are well-preserved. Primary plagioclase is often preserved as grain cores, but is generally variably altered to fine-grained muscovite and epidote, and has otherwise largely been replaced by fine-grained anhedral plagioclase, leaving grain interiors which may show remnant albite twinning. Within the fine-grained feldspar, coarser-grained rosettes of plagioclase are common, usually adjacent to relict coarser grains. Amphibole is pale brownish-green and weakly pleochroic, and forms pseudomorphs after preexisting clinopyroxene, preserving two-pyroxene exsolution lamellae and opaque exsolution textures. A thin rim of more pleochroic green amphibole surrounds the pseudomorphs. Assemblages of dark- to olive-green amphibole, chlorite or biotite and opaque minerals may represent relict olivine. Calcite and coarse-grained epidote also occur. In the more heavily altered samples, plagioclase has been completely replaced by fine- and coarse-grained epidote, clinozoisite and muscovite, and the amphiboles are polygranular aggregates. Veins of coarse-grained quartz, characterized by linear grain boundaries and the absence of undulatory extinction, cross-cut earlier textures.

The Drury Twp samples are all altered to the extent that no original plagioclase has been preserved, and the amphibole is in relatively poor condition as well. Relict cumulate textures pseudomorphic after plagioclase laths and intercumulus clinopyroxene are distinct locally. Plagioclase has been recrystallized and entirely replaced by fine-grained epidote, clinozoisite and muscovite, constituting 60 to 75 modal percent of the rock. Plagioclase, where preserved, occurs as fine-grained, decussate-textured aggregates. Pale green to colourless pleochroic amphibole occurs as coarse grains which may show simple twinning, but commonly occurs as coarse aggregates of fibrous grains. Amphibole is commonly rimmed by a weakly radially-oriented chlorite layer. Coarse-grained epidote and anhedral titanite occur, associated with alteration of plagioclase and amphibole, respectively. Apparent oxidized subhedral pseudomorphs after femic minerals occur, consisting of linear assemblages of opaques, rutile, and calcite, rimmed by fine-grained amorphous oxides. Amorphous oxides apparently pseudomorphing titanite also occur. Late fractures may be filled with quartz, chlorite, hydrous iron oxides or nothing at all.

Table 1A. Major and trace element compositions for Falconbridge Township (Twp) sill samples, analysed by XRF (majors) and ICP-MS (trace) as described in the methodology section and in the caption below Fig. 1B.

Element/I.D.	89-07A	89-07B	89-07C	89-08A	89-08B	89-09	89-10	89-11A	89-11B	89-12B	89-13
Falconbridge Twp.											
SiO_2	50.40	51.40	49.50	50.30	50.90	49.90	49.90	50.40		51.30	51.20
TiO_2	0.18	0.37	0.21	0.45	0.37	0.29	0.32	0.23		0.71	0.70
Al_2O_3	22.70	15.20	21.10	21.10	15.70	16.30	15.00	18.60		24.30	23.80
Fe_2O_3	1.68	1.87	1.71	1.95	1.87	1.79	1.82	1.73		2.21	2.20
FeO	3.62	7.32	5.03	4.72	6.15	8.11	8.17	5.64		3.05	3.15
MnO	0.09	0.17	0.11	0.12	0.15	0.19	0.19	0.14		0.07	0.06
MgO	4.79	7.86	6.02	4.52	8.33	8.01	7.82	6.34		2.49	2.74
CaO	12.02	11.39	11.00	11.59	12.80	10.22	11.35	10.98		10.21	10.06
Na_2O	2.60	2.10	2.60	2.60	1.90	2.30	2.00	2.70		3.90	4.00
K_2O	0.56	0.71	0.75	0.60	0.40	0.43	0.52	1.07		0.75	0.71
P_2O_5	0.02	0.07	0.03	0.05	0.04	0.02	0.02	0.03		0.12	0.08
H_2O	1.10	1.60	2.30	1.80	1.70	2.60	2.50	2.30		0.70	1.00
Mg #	62.47	60.88	62.02	55.42	65.47	59.50	58.69	61.08		46.83	48.77
Sc	18.7	40.7	23.0	20.6	39.8	31.6	43.7	30.2	31.4	9.19	12.1
V	88.6	164	103	159	198	160	186	118	125	79.7	90.6
Cr	134	214	201	97.9	608	317	104	136	140	51.7	54.0
Co	29.0	49.8	33.9	32.4	44.3	51.5	52.5	37.7	39.9	21.4	23.0
Ni	53.9	103	81.4	62.2	118	127	85.3	83.1	84.1	29.5	30.5
Cu	29.4	101	108	61.1	39.1	164	149	47.9	38.1	12.4	10.5
Rb	15.7	31.5	14.3	8.89	12.0	9.92	14.1	29.4	29.3	5.61	5.16
Sr	279	185	271	326	189	220	243	271	258	804	752
Y	4.28	13.1	4.82	8.76	9.81	5.82	8.36	5.42	5.87	7.40	7.03
Zr	7.96	26.8	10.6	18.3	16.3	5.39	10.3	10.1	13.0	4.59	11.6
Nb	0.48	1.72	0.45	1.55	0.96	0.32	0.52	0.51	0.57	3.06	2.48
Cs	1.10	2.20	0.45	0.50	0.52	0.13	0.15	0.35	0.30	0.15	0.14
Ba	127	214	161	99.1	85	141	147	289	292	365	253
La	1.87	5.23	2.14	5.69	3.76	1.80	2.29	2.47	2.91	5.92	5.97
Ce	4.39	13.4	4.54	12.2	8.36	3.79	5.18	5.11	6.12	15.1	13.0
Pr	0.55	1.71	0.58	1.51	1.10	0.50	0.71	0.66	0.77	2.00	1.70
Nd	2.30	7.36	2.48	6.35	4.93	2.26	3.34	2.80	3.24	8.60	7.30
Sm	0.55	1.77	0.59	1.40	1.24	0.60	0.93	0.69	0.75	1.79	1.55
Eu	0.39	0.60	0.35	0.55	0.46	0.41	0.47	0.43	0.44	1.10	1.07
Gd	0.61	1.97	0.69	1.37	1.44	0.75	1.15	0.83	0.89	1.65	1.50
Tb	0.10	0.33	0.12	0.23	0.24	0.13	0.20	0.14	0.15	0.23	0.22
Dy	0.69	2.17	0.79	1.47	1.62	0.92	1.37	0.94	1.01	1.38	1.32
Ho	0.15	0.47	0.17	0.31	0.35	0.21	0.30	0.20	0.22	0.27	0.26
Er	0.46	1.40	0.52	0.94	1.05	0.63	0.91	0.61	0.65	0.75	0.73
Tm	0.068	0.20	0.077	0.14	0.15	0.10	0.13	0.088	0.095	0.10	0.10
Yb	0.46	1.36	0.52	0.93	1.01	0.67	0.89	0.60	0.65	0.65	0.64
Lu	0.070	0.21	0.077	0.14	0.15	0.10	0.13	0.090	0.10	0.10	0.093
Hf	0.23	0.73	0.29	0.54	0.48	0.20	0.31	0.30	0.34	0.18	0.35
Ta	0.17	0.20	0.10	0.15	0.16	0.12	0.12	0.081	0.076	0.21	0.16
Pb	4.04	4.32	3.85	4.37	2.48	32.0	6.00	4.10	5.42	2.06	2.19
Th	0.26	1.36	0.30	0.86	0.77	0.14	0.29	0.54	0.51	0.29	0.32
U	0.048	0.20	0.055	0.19	0.16	0.031	0.064	0.087	0.086	0.075	0.093
$(Ce/Yb)_{Cl}$	2.4	2.5	2.2	3.4	2.1	1.4	1.5	2.2	2.4	5.9	5.2
Cu/Ni	0.55	0.98	1.33	0.98	0.33	1.29	1.75	0.58	0.45	0.42	0.35

5. GEOCHEMISTRY

Both the Drury and Falconbridge intrusions are of broadly basaltic geochemical affinity, with around 50 wt.% SiO_2,15–24 wt.% Al_2O_3, and 10–12 wt.% CaO (Table 1). The two most variable major elements are aluminum and magnesium, demonstrating an inverse correlation in abundances between ~2.5 wt.% MgO and 24 wt.% Al_2O_3 to over 8 wt.% MgO and 10 wt.% Al_2O_3. The major element compositions of the two intrusions are broadly overlapping, although the Drury Twp. samples are typically more alkaline, as shown in AFM and Harker classification diagrams for basalts (Fig. 4a and b, respectively) from Irvine and Baragar (1971). Overall, the major and trace element compositions are relatively homogeneous within and between both intrusions (Table 1). Three of the Drury Twp. samples (88–54, 55, 56A) are olivine normative, as are four of the Falconbridge Twp. samples (89–07C, 09, 10, 11). Both intrusions show similar trace element compositional distributions, as displayed on a primitive mantle-normalised spidergram (Fig. 5a). Relative to primitive mantle and to typical basaltic reservoirs, the intrusions are large-ion lithophile and alkaline-earth element enriched, typical of crustally-emplaced mantle-derived magmas, but relatively depleted (or less enriched) in high field strength elements, as denoted by the negative spikes in Th, U, Nb, Ta, Zr and Hf. Phosphorus and the light rare earth elements are also depleted relative to the overall trend. The REE are characterised by LREE enrichment relative to chondrites (Fig. 5b), with rel-

Table 1B. Major and trace element compositions for the Drury Township (Twp) sill samples, analysed by XRF (majors) and ICP-MS (trace) as described in the methodology section and in the caption below.

Element/I.D.	88-31	88-32	88-54	88-55	88-56A
Drury Twp.					
SiO_2	51.80	51.00	50.90	46.80	50.70
TiO_2	0.57	0.29	0.21	0.16	0.21
Al_2O_3	16.90	20.60	21.10	25.10	20.90
Fe_2O_3	2.07	1.79	1.71	1.66	1.71
FeO	5.16	5.59	4.67	3.45	3.86
MnO	0.11	0.13	0.09	0.08	0.11
MgO	7.60	4.50	4.79	4.52	5.21
CaO	10.27	10.83	9.01	11.60	11.41
Na_2O	2.70	3.20	3.80	2.40	3.20
K_2O	0.81	0.40	1.02	1.30	0.64
P_2O_5	0.10	0.04	0.02	0.01	0.01
H_2O	1.30	2.10	2.70	2.90	2.40
Mg #	65.87	52.70	57.89	61.94	63.23
Sc	21.4	25.0	20.5	9.69	26.7
V	104	129	93.5	55.7	124
Cr	76.8	51.6	126	75.2	98.5
Co	27.1	34.1	19.2	29.5	31.9
Ni	86.4	53.7	93.8	125	62.2
Cu	104	58.8	56.8	11.4	19.5
Rb	16.4	7.10	25.1	34.9	15.8
Sr	347	278	376	338	264
Y	4.80	8.71	4.46	3.52	4.28
Zr	9.06	14.6	13.7	11.9	7.60
Nb	0.81	1.30	3.27	0.93	0.47
Cs	0.64	0.22	0.52	0.64	0.35
Ba	191	125	334	467	205
La	2.37	4.55	3.94	2.25	1.48
Ce	4.87	10.3	8.02	4.60	3.34
Pr	0.60	1.28	0.90	0.56	0.43
Nd	2.57	5.34	3.51	2.27	1.93
Sm	0.60	1.25	0.67	0.48	0.51
Eu	0.43	0.66	0.34	0.34	0.37
Gd	0.70	1.33	0.71	0.54	0.61
Tb	0.12	0.22	0.12	0.085	0.10
Dy	0.78	1.45	0.76	0.58	0.71
Ho	0.17	0.31	0.16	0.12	0.16
Er	0.50	0.92	0.49	0.37	0.46
Tm	0.074	0.13	0.070	0.053	0.068
Yb	0.50	0.89	0.47	0.35	0.46
Lu	0.074	0.13	0.070	0.052	0.068
Hf	0.26	0.43	0.36	0.27	0.19
Ta	0.15	0.15	0.11	0.15	0.10
Pb	3.22	2.97	2.87	3.19	3.54
Th	0.50	0.50	0.85	0.49	0.20
U	0.066	0.095	0.18	0.072	0.064
$(Ce/Yb)_{Cl}$	2.5	3.0	4.4	3.3	1.9
Cu/Ni	1.20	1.10	0.61	0.09	0.31

Major elements in weight percent (wt.%), trace elements in ppm. 89-11A, B are duplicate analyses. Mg# = (MgO)/(MgO + FeO). FeO calculated from $Fe_2O_3 = TiO_2 + 1.5$ after Irvine and Baragar (1971). XRF data were calibrated against international standard MRG-1 (Abbey, 1981), as well as a Geological Survey of Canada (G.S.C.) benchmark standard from the University of Alberta, GSC B-1, and G.S.C. internal standards 177-88-56, 177-88-57, 177-88-58, 163-89-45 and 163-88-46. A duplicate and a triplicate analysis of a granite and a gabbro (respectively) were also obtained, giving 2 reproducibilities of 0.7 wt.% or better for SiO_2, and 0.1 wt.% or better for all the other major elements. Data are provided in Prevec (1993) and are available from the senior author on request. Trace element data were calibrated as described in Le Roex et al. (2001).

atively flat HREE profiles, and positive Eu anomalies which are inversely proportional in size to REE abundance.

6. GEOCHRONOLOGY

One sample from each of the two sills was selected for extraction of accessory minerals for U-Pb geochronology on the basis of representative and relatively least-deformed petrology.

Sample SPA-89-08A from the Falconbridge Twp. intrusion is a coarse-grained amphibole-plagioclase rock with cumulate texture pseudomorphs well-preserved, from the north end of the intrusion (UTM zone 17, 517730E, 5162135N). The zircons were without exception of extremely poor quality. Although euhedral grain shape was not uncommon, grains were red-brown and usually opaque or very weakly transluscent. No shock features were identified. Four populations were identified

Table 2a. U-Pb analytical data for "conventional" U-Pb zircon isotopic analyses.

Fraction, Size*	Wt. · g	U ppm	Pb[a] ppm	Pb[b] pg	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$ Age (Ma)
Falconbridge Twp. Gabbro, SPA-89-08A								
A,+105,NM5,o,s	11	566	274	455	0.3800 ± .12	7.283 ± .37	0.13902 ± .30	2215.1 ± 10
BA,−105,NM5,cd,s	2	3693	2154	12	0.4472 ± .09	9.811 ± .10	0.15913 ± .03	2446.4 ± 1.0
BB,−105,NM5,o,(5)	9	772	419	29	0.4463 ± .09	10.248 ± .10	0.16654 ± .03	2523.2 ± 1.0
CA,−105,NM5,o,(4)	3	962	597	27	0.4608 ± .08	11.167 ± .10	0.17577 ± .04	2613.4 ± 1.2
CB,−105,NM5,cd,fr,(5)	5	134	72	10	0.4696 ± .10	11.289 ± .11	0.17435 ± .04	2599.9 ± 1.5
HA,150,NM10,br,f,s	174	152	86	35	0.4504 ± .09	9.787 ± .11	0.15761 ± .04	2430.2 ± 1.5
HB,−150,NM10,br,f,s	133	177	94	15	0.4512 ± .09	9.809 ± .10	0.15767 ± .04	2430.8 ± 1.3
HC,−150,NM10,br,f,s	258	79	42	28	0.4496 ± .09	9.751 ± .10	0.15730 ± .04	2426.8 ± 1.5
G,−150,NM10,cl,f,(3)	123	6.0	2.2	18	0.1683 ± 1.2	1.730 ± 4.7	0.07457 ± 4.2	1057 + 162/−180

Errors are 1 std. error of mean in % except $^{207}Pb/^{206}Pb$ age errors which are 2 std. errors in Ma.
Pb* = Radiogenic Pb.
NMn = Non-magnetic at n degrees of tilt.
br = brown; cd = clouded; cl = clear; f = fragment; fr = fractured; o = opaque; s = single grain analysis (n) = number of grains in multigrain analysis.
[a] Numbers (i.e. +105, −105) indicate zircon size larger or smaller than given diameter, in microns.
[b] Total common Pb in analysis in picograms.

within this sample. Fraction A was a single, euhedral, opaque, relatively coarse, dark reddish-brown grain. Population B consisted of ten dark orangy-brown, subhedral to rounded euhedral grains with distinct darker clouded cores. Two fractions were analysed from this population, consisting of a single grain (fraction BA) which was distinctly more transluscent than the other grains in this population, five of which were analysed as fraction BB. Population C consisted of reddish transluscent euhedral grains (fraction CA) or grain fragments (fraction CB).

All fractions were highly discordant, with $^{207}Pb/^{206}Pb$ ages ranging from 2215 Ma to 2613 Ma (Fig. 6a). A regression through three points (fractions A, BB and CB), used as a reference line, indicates an Archaean upper intercept and a Sudbury-aged (ca. 1850 Ma) lower intercept. Populations B and C show late Archaean $^{207}Pb/^{206}Pb$ ages consistent with an Archaean provenance, with the exception of fraction BA, which lies above this reference discordia and has a $^{207}Pb/^{206}Pb$ age of 2446 Ma. As fraction BA represented both a distinct physiologic type and the only grain not indicating an Archaean provenance, a new fraction of the most transluscent grains remaining was extracted, abraded and analysed (populations G and H). Three of the newly selected grains (fractions HA, HB, HC) define a discordia with an upper intercept at 2441 ± 3 Ma (Ludwig Model 1 solution, with an M.S.W.D. of 1.7) and a relatively imprecise Grenville-aged (ca. 1000 Ma) lower intercept (986 ± 30 Ma) defined by grain G, as shown in Figure 6a inset.

The zircon data indicate a large amount of inheritance from an Archaean component, probably ca. 2700 Ma, as represented by the euhedral dark-coloured grains. Subsequent Huronian-aged growth represented by the more transluscent, paler-coloured subhedral zircon is interpreted as representing the crystallization age. Episodic lead-loss corresponding to both SIC and Grenville-aged thermal events is represented.

Table 2b. U-Pb analytical data for SHRIMP U-Pb zircon isotopic analyses.

Spot I.D.	U ppm	Th ppm	Pb ppm	^{204}Pb ppb	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$ Age (Ma)
Drury Twp. intrusion SPA-88-56A (204-corrected)							
9-1	176	412	88	1	0.3260 ± 64	5.06 ± 12	1842 ± 19
10-1	142	248	65	4	0.3265 ± 65	5.13 ± 14	1862 ± 28/−29
11-1	166	454	88	1	0.3262 ± 64	5.12 ± 12	1862 ± 18
12-1	212	168	82	2	0.3338 ± 65	5.20 ± 12	1847 ± 18
13-1	250	652	129	1	0.3209 ± 62	5.08 ± 11	1879 ± 15
14-1	191	353	89	2	0.3273 ± 64	5.17 ± 11	1864 ± 18
15-1	632	207	209	6	0.3226 ± 62	5.02 ± 10	1846 + 8/−9
Algoman Granitoid SPA-88-18 (204-corrected)							
25-1	114	48	66	3	0.519 ± 11	13.29 ± 30	2705 ± 12
26-1	160	73	81	0	0.507 ± 10	12.88 ± 28	2693 ± 10
27-1	129	44	74	3	0.521 ± 11	13.25 ± 30	2694 ± 12
Abitbi Foliated Granitoid SPA-88-17 (208-corrected)							
1-1	100	31	51	15	0.4593 ± 73	11.59 ± 22	2680 ± 15
2-1	115	40	61	30	0.4668 ± 72	11.65 ± 22	2662 ± 14
3-1	169	88	94	41	0.4765 ± 69	11.90 ± 21	2663 ± 14
4-1	139	48	77	26	0.4949 ± 73	12.53 ± 22	2685 + 12/−13
5-1	129	53	74	19	0.5069 ± 77	12.68 ± 23	2666 ± 14
6-1	120	50	67	31	0.4861 ± 76	12.14 ± 23	2663 ± 15

Table 3. Sm-Nd whole rock isotopic data.

Sample #	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	$\varepsilon_{Nd}(2.44)$	$\varepsilon_{Nd}(1.85)$	$f_{Sm/Nd}$	T_{CHUR}	T_{DM}
Drury Twp.									
SPA-88-32	1.354	5.721	0.1430	0.511765	−0.2	−4.3	−0.2731	2465	2789
SPA-88-54	0.813	3.971	0.1237	0.511647	3.6	−2.0	−0.3712	2061	2375
SPA-88-55	0.531	2.346	0.1367	0.511753	1.6	−3.0	−0.3051	2238	2573
SPA-88-56A	0.493	1.889	0.1579	0.512120	2.1	−0.9	−0.1973	2027	2543
Falconbridge Twp.									
SPA-89-07A	0.542	2.251	0.1456	0.511797	−0.4	−4.3	−0.2599	2494	2825
SPA-89-07B	1.639	6.825	0.1451	0.511795	−0.3	−4.2	−0.2622	2479	2810
SPA-89-07C	0.575	2.302	0.1509	0.511882	−0.4	−3.9	−0.2329	2503	2860
SPA-89-08A	1.295	5.722	0.1368	0.511630	−0.9	−5.5	−0.3048	2549	2833
SPA-89-08B	1.146	4.391	0.1577	0.511963	−0.9	−3.9	−0.1983	2623	2998
SPA-89-09	0.630	2.267	0.1679	0.512145	−0.6	−2.8	−0.1463	2597	3069
SPA-89-10	0.978	3.440	0.1718	0.512225	−0.2	−2.2	−0.1264	2519	3062
SPA-89-10*	0.839	2.943	0.1724	0.512216	−0.6		−0.1238	2628	3146
SPA-89-11	0.753	2.953	0.1542	0.511903	−1.0	−4.3	−0.2126	2620	2973
SPA-89-11*	0.745	2.913	0.1546	0.511924	−0.7		−0.2140	2572	2938

ε_{Nd} values and model ages calculated using equations of DePaolo and Wasserburg (1976), chondritic values of $^{143}Nd/^{144}Nd = 0.512638$ and $^{147}Sm/^{144}Nd = 0.1967$ (Jacobsen and Wasserburg, 1980), and depleting mantle of DePaolo (1981). Analyses were normalized to $^{146}Nd/^{144}Nd = 0.7219$. A mixed ^{149}Sm-^{150}Nd mixed spike was prepared and calibrated, giving values for BCR-1 (split 39) of 28.7 ppm Nd, 6.61 ppm Sm, and $^{147}Sm/^{144}Nd = 0.1395 \pm 0.0019$ on seven replicate dissolutions. Sm and Nd extracted using the standard combination of cation exchange and Biobead-HDEHP column chromatography. Over the period of this study La Jolla Nd gave a value of $^{143}Nd/^{144}Nd = 0.511839 \pm 0.000019$ (2 σ on n = 7) and Ames Nd metal gave $^{143}Nd/^{144}Nd = 0.511958 \pm 0.000016$ (2 σ on n = 31). Within-run analytical uncertainties on $^{143}Nd/^{144}Nd$ were $\pm$ 0.000015 or better at 95% C.I.

Sample SPA-88-56A from the Drury Twp intrusion is a chloritized, epidotized amphibole-plagioclase metagabbro from the north-central part of the intrusion (UTM zone 17, 464000E, 5141600N). Some relict igneous cumulate textures are preserved. The zircons obtained were dark brown and relatively extensively fractured, although commonly subhedral with three or four crystal faces preserved. Grains were generally translucent, and while some zoning was observed, no obvious evidence for cores was noted. SHRIMP U-Pb analyses of seven spots produced a cluster of points around concordia with an average $^{207}Pb/^{206}Pb$ age of 1859 $\pm$ 13 Ma (2σ) (Fig. 6b) (a Ludwig Model 1 regression forced through the origin, with an M.S.W.D. of 0.63). All analyses are within 2σ imprecision of one another and of the regression, although analysis 13-1 shows a small amount of evidence for a possible small inherited component, as reflected by a $^{207}Pb/^{206}Pb$ age of 1879 $\pm$ 15 Ma (2σ). The zircons are not typical of those derived in metamorphic, hydrothermal growth environments, show no evidence of shock features such as planar lamellae or "raspberry textures" (e.g., Krogh et al., 1984; Krogh et al., 1993; Kamo et al., 1996), and were initially interpreted as representative of the igneous crystallization age of the sill.

Zircons were also extracted from two country rock granitoids to provide some reference for southernmost Superior Province crust. The two samples are from the polybatholithic terrain described as Ramsey-Algoman granitoids, but are here referred to as Algoman and Abitibi granitoids, field designations used (by K.D. Card, pers. comm. 1988) to distinguish between typically relatively unde-

Table 4. Pb-Pb whole-rock isotopic data.

Sample	$^{206}Pb/^{204}Pb$ SE	$^{207}Pb/^{204}Pb$ SE	$^{208}Pb/^{204}Pb$ SE
Falconbridge Twp.			
89-07A	15.3949 $\pm$ 0.0017	15.2196 $\pm$ 0.0026	35.5154 $\pm$ 0.0087
89-07B	16.1353 $\pm$ 0.0034	15.2773 $\pm$ 0.0072	36.5317 $\pm$ 0.0083
89-08A	15.9206 $\pm$ 0.0035	15.2753 $\pm$ 0.0034	36.2213 $\pm$ 0.0096
89-09	17.2778 $\pm$ 0.0034	15.5359 $\pm$ 0.0040	37.1994 $\pm$ 0.0077
89-10	15.6541 $\pm$ 0.0028	15.2925 $\pm$ 0.0048	35.4085 $\pm$ 0.0124
89-11	15.7111 $\pm$ 0.0017	15.2676 $\pm$ 0.0026	35.6696 $\pm$ 0.0077
Drury Twp.			
88-31	16.5510 $\pm$ 0.0021	15.4384 $\pm$ 0.0021	37.7014 $\pm$ 0.0076
88-32	16.2356 $\pm$ 0.0013	15.3871 $\pm$ 0.0015	37.0033 $\pm$ 0.0045
88-54	16.5265 $\pm$ 0.0039	15.4289 $\pm$ 0.0027	36.7725 $\pm$ 0.0080
88-55	15.9612 $\pm$ 0.0025	15.3643 $\pm$ 0.0027	36.4920 $\pm$ 0.0102
88-56A	16.1204 $\pm$ 0.0023	15.3676 $\pm$ 0.0025	36.3478 $\pm$ 0.0066

Pb was extracted using anion exchange column chromatography with HCl-H_2O. NBS 981 gave values of $^{206}Pb/^{204}Pb = 16.934 \pm 0.009$ (2 SE), $^{207}Pb/^{204}Pb = 15.942 \pm 0.009$ and $^{208}Pb/^{204}Pb = 36.720 \pm 0.038$ (Duke, 1993). Total Pb procedural blanks on the order of 0.1 ng were compensated for by dissolving large sample volumes (400–1000 mg) in normal reagent volumes in order to maximise sample to blank ratios. SE are standard errors.

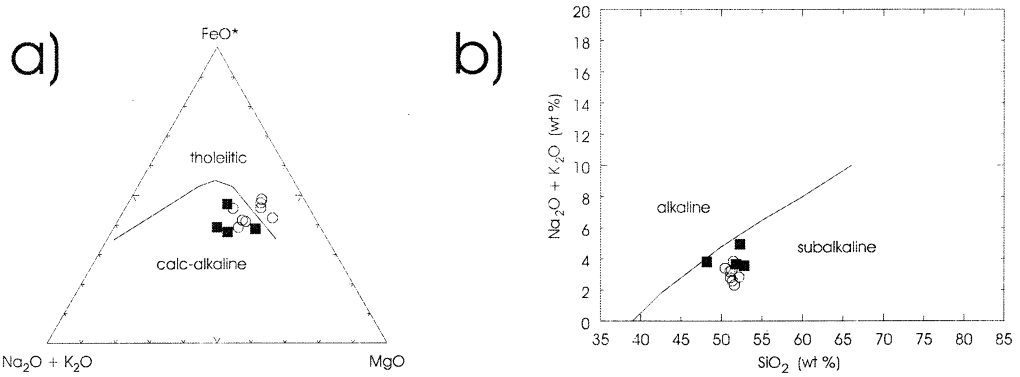


Fig. 4. Major element compositional variation in the Drury (filled squares) and Falconbridge Twp. samples (open circles), shown in a) an AFM diagram, and b) a Harker Diagram, both from Irvine and Baragar (1971).

formed and foliated rocks, respectively. Sample SPA-88-18 ("Algoman") is a pink sodic biotite granite with a greenschist facies metamorphic overprint. This sample was obtained from ~6 km northwest of the East Bull Lake intrusion (UTM 17, 400955E, 5148875N). Zircons were pale pink, euhedral to subhedral clear grains, with minor inclusions of apatite and occasional length-normal fracturing. Grain dimensions varied from equant to weakly acicular (3:1 aspect ratios). SHRIMP analyses of six spots produced a discordant array which produced a Ludwig Model 1 regression age of 2670 ± 22 Ma (M.S.W.D. = 0.24) and an average $^{207}Pb/^{206}Pb$ age of 2670 ± 11 Ma (all errors as 2σ; Fig. 6c). Sample SPA-88-17 ("Abitibi") is a well-foliated tonalite located immediately to the north of the East Bull Lake intrusion (UTM zone 17, 407125E, 5145650N). Sparse zircon yields resulted in the analysis of only three grains from this sample, which were euhedral, pale pink, prismatic grains. Some evidence of internal structure including zoning, extensive fracturing, and possible cores was observed in grain fragments which were not analysed. SHRIMP U-Pb analyses from three spots produced a cluster of points overlapping concordia, with an average $^{207}Pb/^{206}Pb$ age of 2696 ± 18 Ma (2σ), also shown in Figure 6c (Ludwig Model 1 forced through the origin, with M.S.W.D. = 0.19).

The ca. 2670 Ma age for the Algoman granite is interpreted as an igneous crystallization age, with the discordance attributable to non-episodic lead-loss over time. Using any of the regressions and associated 2σ imprecisions presented, the two granites are of equivalent age, within the error limits. However, the apparent older age range for the Abitibi granite is consistent with the petrographic textural evidence.

7. ISOTOPE GEOCHEMISTRY

7.1. Sm-Nd Isotopes

Sm-Nd isotopic variation for samples from the two sills are presented in Table 3. The Falconbridge samples show a very restricted range at 2.44 Ga, with ε_{Nd}^{2440} all between 0 and −1. In contrast, the small number of Drury samples show significant heterogeneity, with ε_{Nd}^{2440} values ranging from + 3.7 to −0.1. The Drury samples cannot be modelled at any age to give a homogeneous ε_{Nd} range. This is best demonstrated on an isochron diagram (Fig. 7), where the Falconbridge samples define an isochron at 2464 ± 150 Ma, with an M.S.W.D. of 2.2 (Ludwig Model 3 solution), in agreement with the U-Pb age, while the Drury samples plot near or above this regression, consistent with heterogeneity induced by variable LREE-depletion. A regression through the Drury Twp samples gives a very poorly constrained age of ca. 2070 Ma.

7.2. Pb-Pb Isotopes

Whole-rock Pb isotopic compositions are provided in Table 4. The samples can be broadly divided into three groups, consisting of 1) the Falconbridge samples excluding sample 89-09; 2)

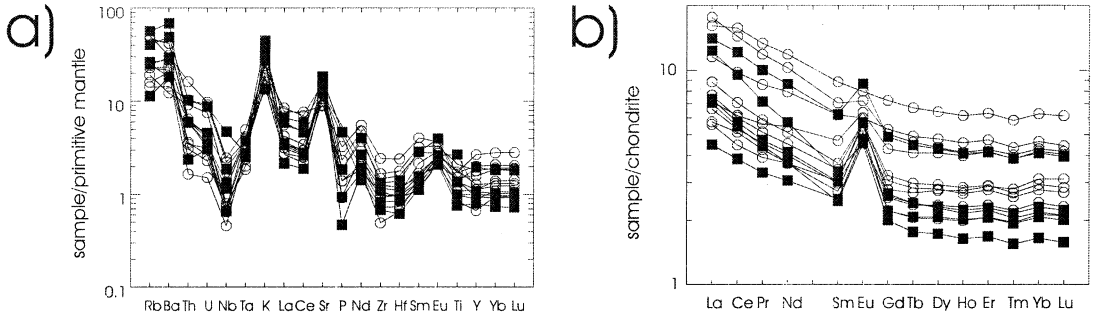


Fig. 5. Trace element variations in the Drury (filled squares) and Falconbridge Twp. samples, shown in a) a spidergram, normalised to primitive mantle, by convention, and b) a chondrite-normalised REE profile. See text for discussion. Symbols as in Figure 4.

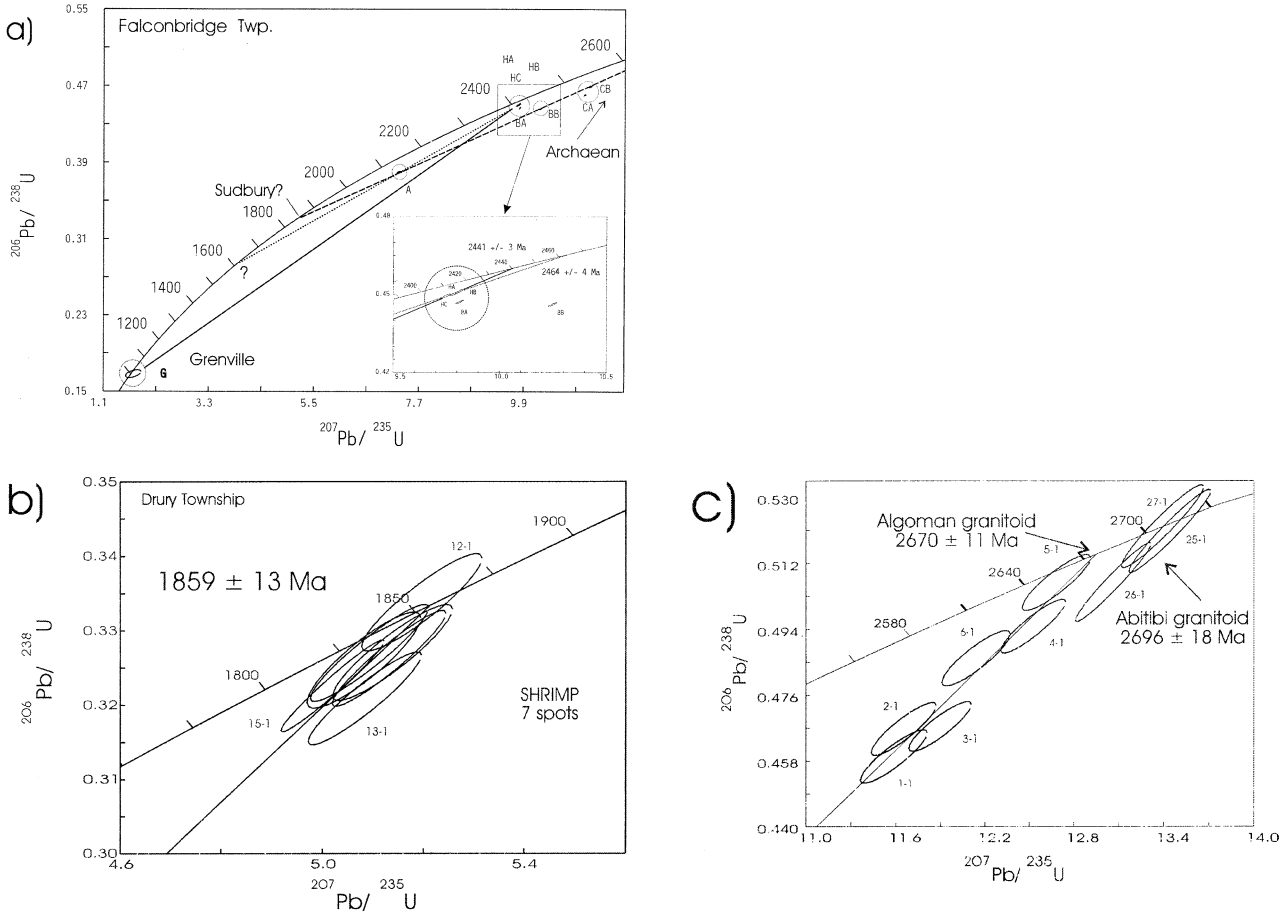


Fig. 6. U-Pb zircon concordia plots for a) Falconbridge and b) Drury Twp. intrusions, as well as from the granitoid (c) and 'Algoman' and 'Abitibi' granitic gneissic basement samples.

the Drury samples, and 3) sample 89-09, which has more radiogenic values than the rest. The two suites of samples defined subparallel arrays (Fig. 8) with ca. 2100 Ma regression ages, and all samples together give a late Archaean (ca. 2677 ± 450 Ma, using a Ludwig Model 2 regression) age. The samples all lie very near to the Stacey-Kramers bulk earth evolution line (not shown), approximating Mesoproterozoic bulk earth (1850–900 Ma). These implied model ages are artifacts of the elevated μ values ($^{238}U/^{204}Pb$) in the samples, and must be assumed to have no age significance as such. The implications of the elevated μ will be discussed below.

8. DISCUSSION

8.1. Pre-1850 Ma Provenance

8.1.1. Tectonic setting

Suites of Palaeoproterozoic mafic rocks in the Southern Province are shown in Figure 2, including the East Bull Lake-type intrusives, the Nipissing Diabases and the Huronian basaltic volcanics. The Drury and Falconbridge Twp intrusions are clearly spatially comparable with the EBL-suite intrusions, straddling the contact between Superior Province granitoids to the north and Southern Province volcanics and sediments to the south. There are a number of Palaeoproterozoic mafic dyke swarms in the map area which are not shown, both in the Superior and Southern Province. These are, however, relatively unhelpful from the point of view of geochemical comparison, since their compositions, where geochemical data are available, are typically highly variable and probably very strongly influenced by local host-rock contamination (e.g., Boily and Ludden, 1990; Nelson et al., 1990), although it has been suggested more recently that elements of primary plume signature may be preserved in Hf/Zr ratios in the Matachewan dyke swarm (Phinney and Halls, 2001). While this is less true of the Nipissing Diabases and Huronian volcanics, they are also strongly affected by combined crustal assimilation-fractional crystallisation processes, such that isotopically and compositionally primitive compositions are extremely rare in the former case (e.g., Lightfoot et al., 1993) and unknown in the latter (e.g., Jolly et al., 1992).

8.1.2. Chemical evidence

Both the Drury and Falconbridge intrusions have a broadly basaltic compositional affinity. Beyond this, there are various indications of geochemical variation within the Drury and Falconbridge Twp. intrusions which are consistent with either

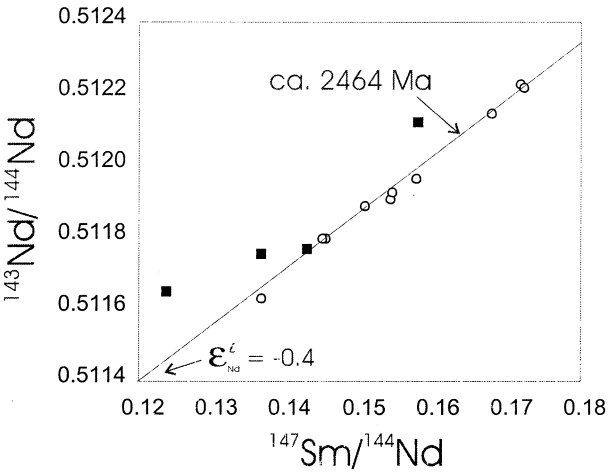


Fig. 7. Sm-Nd isochron diagram, displaying errorchron for Falconbridge Twp samples, and scatter for Drury samples. Analytical imprecisions are smaller than plotted symbols. Symbols as in Figure 4.

variations in the proportions of crystals and trapped liquid, or crustal contamination, or a combination of the two processes. The relative consistency in ε_{Nd}^{2440} values for Falconbridge in particular suggests that crustal contamination by Archaean basement is not a significant factor in inducing compositional variation. The inverse correlation of Mg and Al is most readily explained in terms of variations in plagioclase content. In the absence of significant crustal contamination, the decrease in Eu-anomaly with increasing REE abundance (Fig. 5a) is consistent with variations in trapped liquid-crystal proportions. Finally, the relative depletion in HFSE and LREE observed in the spidergrams (Fig. 5b) suggests that the sampled parts of the intrusions represent the lower portions, such that the upper, more incompatible-enriched members may have been removed by erosion, as has been observed in the more western intrusions in the EBL-type suite (e.g., Vogel et al., 1999).

The Drury and Falconbridge compositions therefore clearly cannot be evaluated directly with reference to parent liquids, particularly in the case of the major elements. This is consistent with interpretations of the geochemical variation observed in the Huronian-aged Palaeoproterozoic leucogabbronoritic intrusions (the EBL-type suite) further to the west (e.g., Prevec, 1993; Vogel et al., 1998; James et al., 2002). In the absence of chilled marginal phases or unambiguous feeder dykes for the Drury and Falconbridge intrusions, it is beyond the scope of this study to establish the cogenesis of the Huronian intrusions using modelled geochemical criteria. Nonetheless, for provenancing purposes, comparisons may be made with the associated Palaeoproterozoic intrusions.

Trace and major element compositions can be used to distinguish the Drury and Falconbridge Twp. intrusions from all magmatic (as opposed to xenolithic) components of the SIC and to infer a genetic association with the Huronian rocks. The compositional fields for various contemporaneous and/or proximal intrusions can also be usefully compared in terms of their incompatible element abundances. In Figure 9, the trace element compositional range for the Drury and Falconbridge intrusion samples are compared to those of these other Proterozoic suites, and to the SIC, using the HFSE, the REE and Cu/Ni ratios. Data for the EBL-suite are from Prevec (1993), for the Nipissing from Lightfoot and Naldrett (1996), for the Huronian basalts from Prevec (1993) from the Stobie and Elsie Mountain Formations near Sudbury, and Tomlinson (1996) for the Thessalon sequence further west. SIC data are from Lightfoot et al. (1997) and Prevec et al. (2000), and include not only various representative components of the SIC Main Mass, including the norites and granophyre, but also the contact sublayer, offset dykes, and the pyroxenitic and basaltic inclusions found within these latter two, marginal facies. It is evident that all components of the SIC are significantly enriched in LREE and HFSE relative to the Drury and Falconbridge bodies, and all the other Palaeoproterozoic mafic rocks but the most contaminated Huronian basalts. Note that the least-contaminated Huronian basalts are not the basal flows, which are typically among the most contaminated (e.g., Jolly et al., 1992), but rather those higher in the sequence, such as Unit 6 of Tomlinson (1996). In addition to relatively flat REE profiles (e.g., $(Ce/Yb)_N$ ratios of around 2.5, as compared to those for SIC main mass rocks from ~7 to 9), the positive Eu anomalies in the Drury and Falconbridge intrusions are distinct from the negative or absent Eu anomalies in SIC rocks. The Drury and Falconbridge rocks are also HFSE-poor relative to most of their Palaeoproterozoic counterparts, and are in fact comparable to the anorthosites in terms of HFSE abundance, although they are distinguished from them by flatter REE-profile slopes (as reflected by the Ce/Yb ratio). The Drury and Falconbridge samples overlap only the more depleted members of the EBL-suite, and of the Huronian volcanics in the Sudbury area.

If the compositional fields for SIC rocks and associated country rock are plotted in terms of their LREE abundance (as reflected by Ce content) and LREE/HREE ratio (as represented by chondrite-normalized Ce/Yb ratio), the sills display lower REE abundances than all of the associated rock types but identical LREE/HREE ratios to the Huronian basaltic rocks. Plagioclase accumulation should produce cumulates with lower

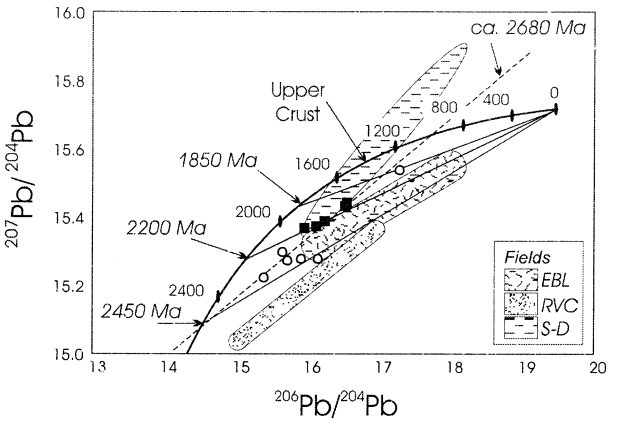


Fig. 8. Pb-Pb isotopic compositions for the Falconbridge and Drury Twp. samples. The slope regression line for all samples (dashed), isochrons for 2450 Ma (the probable intrusive age), 2200 Ma (Nipissing Diabase intrusion) and 1850 (SIC emplacement), the Upper Crust reservoir of Zartman and Doe (1981), and fields for the East Bull Lake, Shakespeare-Dunlop (Prevec, 1993) and the River Valley (Ashwal and Wooden, 1989) intrusions are provided for reference (see text for discussion). Analytical imprecisions are smaller than plotted symbols. Symbols as in Figure 4.

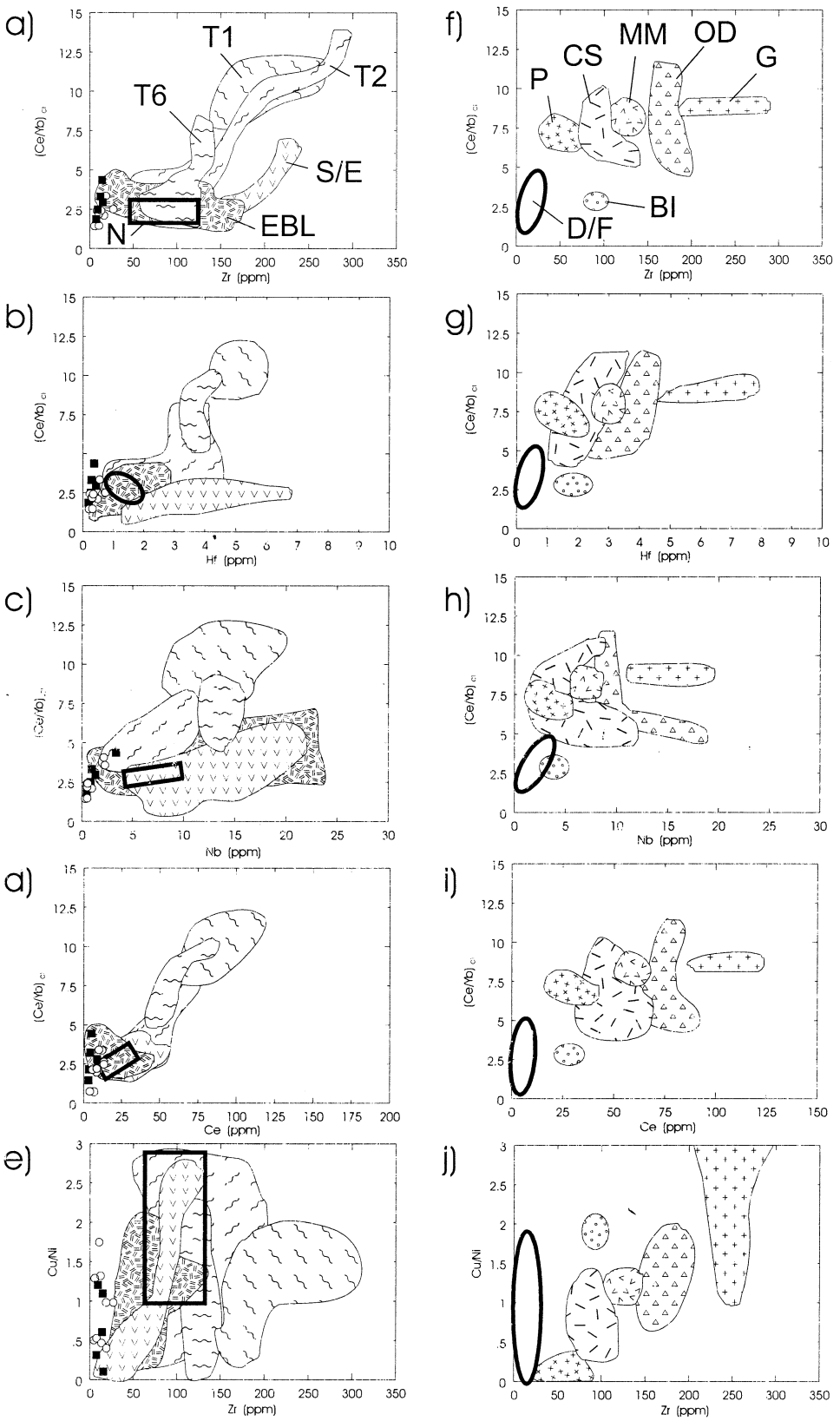


Fig. 9. (*a-j*). Comparative geochemical diagrams, contrasting the incompatible element abundances and Cu/Ni ratios of Falconbridge and Drury Twp. samples with those from a variety of Palaeoproterozoic to Mesoproterozoic mafic intrusive suites and the SIC. See text for references and explanations. The Drury (filled squares) and Falconbridge (open circles) are plotted as in previous diagrams in Figure 9 (a-e). and are indicated for reference as a bold ellipse (labelled D/F) on the SIC data field plots (Fig. 9. f-j). Other data fields are abbreviated as follows (as labelled in Fig. 9 a and f): For 9 (a-e): EBL = East Bull Lake-suite; N = average Nipissing Diabases; S/E = Huronian basalts from the Sudbury area, from the Elsie Mountain and Stobie Formations; T1, T2 and T6 = Huronian basalts from the Thessalon area, Units 1, 2 and 6. For Figure 9 (f-j), showing reference fields for SIC compositions, BI = basaltic inclusions; CS = Contact Sublayer; G = Granophyre; MM = Main Mass norite; OD = Offset Dykes; P = pyroxenite inclusions. See text for data sources.

REE abundances than in the parental magma, as the crystal-liquid partition coefficients for the REE are less than one for plagioclase and the pyroxenes in basaltic compositions (e.g., Hanson, 1980). While clinopyroxene accumulation in particular can lower the LREE/HREE ratio of a cumulate, the leucogabbroic sills have significantly less pyroxene than SIC rocks of equivalent MgO content. This suggests that the sills are very unlikely to have been derived by accumulation from an SIC parental magma, but could readily have been derived from a Huronian basalt-like parent.

8.1.3. Isotopic evidence

At the time of SIC emplacement (ca. 1850 Ma), the Falconbridge and Drury samples were isotopically distinct from the SIC main mass samples. Table 3 shows $\varepsilon_{Nd}{}^{1850}$ ranging between −0.9 and −5.5 for the sills, which contrasts significantly with SIC values of $\varepsilon_{Nd}{}^{1850}$ of around −9 (e.g., Faggart et al., 1985; Dickin et al., 1996; Prevec et al., 2000). Conversely, the Drury and Falconbridge samples exactly overlap the ranges for other Palaeoproterozoic mafic suites or their least contaminated end-members, with $\varepsilon_{Nd}{}^{1850}$ between about −2 and −5 (summarised by Prevec et al., 2000). The ε_{Nd} isotopic data therefore support a Palaeoproterozoic, non SIC-related origin for the Drury and Falconbridge intrusions, consistent with the geochemical data distributions.

At 2440 Ma, both the Drury and Falconbridge Township intrusions are at least as depleted as the least-contaminated members of the EBL-suite, with $\varepsilon_{Nd}{}^{i}$ around 0 to −1 (e.g., Ashwal and Wooden, 1989; Nelson et al., 1990; Prevec et al., 2000), which contrast with the more contaminated values of $\varepsilon_{Nd}{}^{2440}$ between −4.5 to −4.9 from basal Huronian basalts (Jolly et al., 1992). No Drury Twp. samples are more enriched than this characteristic Palaeoproterozoic near-chondritic Nd isotopic signature, albeit with scatter towards more depleted values. The Drury scatter can be interpreted in two ways. First, crustal contamination of a depleted mantle-derived magma with an $\varepsilon_{Nd}^{2440} > +3.7$ (close to the depleting mantle of DePaolo, 1981). Although depleted mantle signatures have been recognised in Neoarchaean (ca. 2700 Ma and older) greenstone belts (e.g., Cattel et al., 1984) and in Mesoproterozoic (ca. 1.4 Ga) anorthosite massifs (e.g., Ashwal et al., 1986), they have not been identified in Palaeoproterozoic mafic rocks in eastern Canada, nor in their potentially correlative rocks in the Fennoscandian Sheild (summarised in Prevec, 2003). Also, although they are olivine normative and slightly poorer in LREE, the most isotopically depleted Drury Twp. rocks are not significantly petrologically or geochemically distinctive in such a way that would suggest the preservation of a more primitive parental magma composition. The alternative is that the Sm-Nd systematics have been upset, and that open system behaviour has been induced by secondary heating and/or fluid movement. However, the resetting cannot have been sufficient to significantly remobilise the REE, as the REE profiles still reflect magmatic behaviour broadly consistent with the igneous petrology.

The lead isotope systematics show distinct groupings which may be relevant in this context. A pervasive crustal contribution to all the samples may be assumed, whether during emplacement or at the source, as implied by the near-chondritic Nd isotopic signatures. The Archaean xenocrystic zircons in the Falconbridge samples require some crustal assimilation, certainly. In light of this, the lead isotopic data in Figure 8 have been plotted with reference to the Upper Crust reservoir of Zartman and Doe (1981) as a more relevant reference than a bulk earth upper mantle reservoir curve. The Drury and Falconbridge data can be compared with existing lead data from other Palaeoproterozoic intrusions, consisting of the East Bull Lake, Shakespeare-Dunlop, and River Valley plutons (see Fig. 8 caption for references). Each of these datasets define subparallel linear arrays with different μ ranges and differing crustal contributions. The River Valley data are less radiogenic than the rest, consistent with its emplacement into (and presumably contamination by) parautochthonous Grenville Province crust, which may be slightly younger, on average, despite being reworked Archaean crust. The East Bull Lake and Shakespear-Dunlop data largely underlie the Drury and Falconbridge Twp data, albeit with larger ranges consistent with more extensive sampling of larger, better preserved intrusions.

Based on the Upper Crust reservoir, isochrons have been plotted for ca. 2.44 Ga, 2.2 Ga, and 1.85 Ga (Fig. 8). The 2.44 Ga isochron, representing the probable intrusion age, appears to be consistent with Falconbridge Twp samples of varying μ value. Consistent with their very consistent Nd isotopic signatures, this suggests pervasive crustal contamination at the time of intrusion. The Drury Twp samples appear to be nearly colinear with the 2.2 Ga isochron (as also reflected by the Drury regression age of ca. 2.1 Ga), which is contemporaneous with the emplacement of the Nipissing Diabase suite (e.g., Corfu and Andrews, 1986; Noble and Lightfoot, 1992), some of which may crosscut the Drury Twp intrusion itself, and a distinct thermal and locally hydrothermal event within the Southern Province. It seems likely that the Drury Twp and perhaps some of the Falconbridge Twp samples may have been affected by mobilisation of U and Pb during the Nipissing event. One Falconbridge sample (89-09), and perhaps some of the Drury Twp samples, appears to have been affected by SIC-induced U-Pb remobilisation at 1.85 Ga. The implication of the lead is that the Drury Twp samples have been much more strongly affected by post-2.45 Ga events than have the Falconbridge Twp samples.

8.1.4. Geochronological evidence

The isotopic characteristics of zircons from the Falconbridge Twp. intrusion infer an Early Proterozoic emplacement age with significant late Archaean component. Possible sources of xenocrystic zircon include Abitibi granitoids and detrital grains from Huronian sediments, and higher-grade Levack gneiss-type material (representing potential lower crust in the Sudbury area). The observation that the inheritance clearly predates 2440 Ma material favours an Archaean age (as opposed to a younger Palaeoproterozoic Creighton-Murray Granite age) for the granitoid which hosts the intrusion on its east flank, although the inheritance may reflect deeper-level contamination. The new granitoid ages in this study are somewhat younger than the previous southernmost Superior Province age dates from the Wawa Subprovince to the northwest, but are consistent with or older than “latest” Abitibi Subprovince zircon ages (e.g., Corfu et al., 1989; Meldrum et al., 1997; Ames et al.,

1998), interpretable in the context of ca. 2.6 Ga terrane closure and suturing ages (e.g., Jackson and Fyon, 1991).

8.2. Geochronological Implications

The ca. 1850 Ma "Sudbury-age" (cf. Krogh et al., 1984) for the Drury Twp. intrusion is therefore enigmatic. Circumstantial field evidence including the presence, throughout the Drury intrusion, of shock metamorphic breccias thought to be related to the emplacement of the Sudbury Structure ("Sudbury breccias"; Card, 1965) requires that the emplacement of the Drury Twp. intrusion predates that of the SIC. Shock breccias associated with meteorite impacts are considered to occur in the very early stages of crater development, associated with primary shock wave propagation (e.g., Grieve, 1994), well before the crystallisation of the melt sheet or the hypothetical emplacement of discrete impact-induced (mantle?) melts. Cross-cutting 'Nipissing Diabase-type' dykes infers an Early Proterozoic (pre-2.2 Ga) origin for the Drury Twp intrusion. Detailed mapping by Card (1965) clearly shows dykes cross-cutting the northwestern contacts between the Drury Twp intrusion and its granitic footwall. The change in the intrusive character of these dykes from narrow dykes within the granites to broad sills in the Southern Province, to the south of the Drury Twp intrusion, is readily attributable to a correspondence of intrusive habit and nature of the intruded host rock between crystalline basement (the Archaean granites) and horizontal volcanosedimentary strata (the Southern Province).

In addition, the tectonic setting, geochemical compositions, Sm-Nd and Pb-Pb isotopic compositions all indicate a pre-SIC origin for the Drury Twp intrusion. The observation that the Falconbridge Twp. intrusion zircon population is almost exclusively composed of Archaean inherited material, combined with its petrographic and lithological similarity to the Drury Twp. body suggests that an early Proterozoic intrusion age might be accommodated for Drury if relatively little zircon growth occurred at the time of intrusion, such that the population observed is a product of secondary zircon growth related to the emplacement of the Sudbury Structure.

REE isotopic-systematics, typically utilized to monitor crustal contamination and/or source characteristics due to their relative immobility, may be influenced by the migration of fluorine- and chlorine-enriched fluids outwards from the base of the intrusion into the footwall. Halogen-bearing fluids have been invoked to account for the outward migration (away from the basal SIC contact) and emplacement of Cu-PGE-enriched liquids deep into the footwall of the SIC (Farrow et al., 1994; McCormick et al., 2002; Hanley and Mungall, 2003). Cu/Ni ratios are shown in Figure 9 (e, j), demonstrating first that they provide no useful discriminatory information regarding provenance, but also showing some evidence for significant depletion in Cu in some of the Drury samples, producing Cu/Ni ratios as low as 0.09 in sample SPA-88-55 (Table 1). The presence of halogen-rich fluids would not only provide a potential carrier for otherwise relatively immobile metals such as the PGE (e.g., Boudreau and McCallum, 1992), but also may have provided a carrier for the REE, which are known to be soluble in halogen-rich solutions. This is especially evident at high (i.e., magmatic and late magmatic) temperatures, such as has been reported in the Stillwater (e.g., Meurer and Boudreau, 1996) and Bushveld (e.g., Mathez, 1989; Willmore et al., 2000) layered mafic intrusive complexes, where REE mobility is manifested in apatites particularly. Late-magmatic temperatures may well have existed in the proximal aureole to the SIC, as predicted by thermal modelling of the sub-SIC footwall during cooling of an impact melt sheet (Prevec and Cawthorn, 2002).

It is unclear what effect, if any, this deuteric activity might have on zircon geochronology. Halogen-bearing fluids, even at high temperatures, are not recognised as demonstrating any notable effects on U-Pb systematics in zircon, although it is reasonable to assume that Pb-Cl complexing might enhance lead-loss effects where fluid access to the zircon occurred. This explanation is superficially unlikely to satisfy a circumstance such as the Drury Twp data, where there is essentially no evidence of a pre-SIC signature preserved in the dated sample.

One possible mechanism for impact-induced postmagmatic zircon involves the growth of new zircon associated with granophyric intergrowths, a characteristic textural feature of both SIC rocks and thermally metamorphosed country-rock inclusions entrained within it (e.g., Lightfoot et al., 1997), and representative of subsolidus intergrowth or potentially sequestered early-melts. Industrious attempts to identify impact-contemporaneous zircon associated with granophyric blebs in mafic rocks from the Vredefort impact were, however, unsuccessful (D. Moser, *private communication*, 1999), and this hypothesis remains effectively unexamined, in the face of negative evidence. Alternatively, Schärer and Deutsch (1990) and Deutsch and Schärer (1990) concluded, on the basis of natural and experimental results (respectively) that shock metamorphism induces progressive lead loss, but does not, itself, "reset" the U-Pb systems in zircon (or monazite). It is therefore proposed that even in the absence of obvious shocked textures in zircons, rapid lead loss may have taken place, aggressively facilitated by hot, possibly halogen-rich fluids, and disguised by subsequent high temperature annealing. This is suggested on the basis of the purely circumstantial evidence provided. Neither scanning electron microscope nor cathodoluminescence examinations of the Drury Township zircons undertaken by the senior author revealed any evidence of shock lamellae or structure other than typical igneous growth zoning.

An alternative to secondary growth or resetting of zircons is that the Drury Twp intrusion represents an impact-induced wholesale remelt of a preexisting Palaeoproterozoic intrusion which existed at the site of the SIC. This would be possible only if the crosscutting dykes and breccias are not Nipissing and impact pseudotechylites, respectively, but are later features. It would also require that the Drury represents the sole manifestation of SIC-induced melt which has remained a discrete entity, with no geochemical evidence for mixing with the SIC liquids themselves. Lastly, the extensive metamorphism of the Drury has not affected the adjacent SIC, and must be assumed to reflect earlier, Penokean metamorphism. The approximately syn-SIC-aged Penokean Orogeny is not manifested by magmatic activity anywhere in Ontario (e.g., van Breemen and Davidson, 1988; Prevec, 1995), unlike further to the southwest (e.g., Sims et al., 1989), so it is considered to be equally unlikely that the Drury Twp represents the sole manifestation of Penokean melting, locally. Therefore, a total magmatic origin for the Drury Twp intrusion is considered to be extremely unlikely.

A pre-SIC origin for the Drury and Falconbridge Twp intrusions, despite a zircon age to the contrary in the former case, supports an endogenic origin for the metals in the SIC. Specifically, the absence of unambiguous evidence for juvenile mantle-derived material at 1850 Ma requires that the SIC is constituted from preexisting crustal materials. The proximity of the Drury and Falconbridge bodies to the SIC margin strongly suggests that metal budget calculations for the bulk SIC must take into account the inclusion of constituents of both the EBL- and Nipissing suites of Palaeoproterozoic intrusions, all of which are Cu-Ni-PGE-bearing and may significantly affect the metal mass-balance of the system.

9. SUMMARY AND CONCLUSIONS

The Drury and Falconbridge Twp intrusions represent remnants of sills or plutons into which the SIC has been emplaced at 1850 Ma, via a catastrophic shock and thermal event. The two sills are geochemically and tectonically consistent with the suite of leucogabbroic rocks which comprise the East Bull Lake-type intrusions, straddling the northern margin of the Southern Province boundary. The sills both lie within the contact aureole of the SIC, by which they are crosscut. Sm-Nd and Pb-Pb isotopic evidence, as well as zircon geochronology, support this association in the case of the Falconbridge Twp intrusion, which shows Palaeoproterozoic signatures with some Archaean inheritance, and minor thermal overprint from the nearby Grenville thrust event. In contrast, the Drury Twp intrusion displays scattered Sm-Nd systematics, potentially younger (ca. 2200 Ma) Pb-Pb compositions, and SIC-aged (ca. 1850 Ma) zircons, with no significant evidence for either Palaeoproterozoic (ca. 2450 Ma), Archeaean or Grenvillian signatures. While it cannot be entirely ruled out that the Drury Twp intrusion may be a member of the Nipissing Diabase suite, the incompatible trace element geochemical data favour a ca. 2450 Ma affiliation, and an 1850 Ma origin is deemed completely implausible. Either interpretation requires an anomalous mechanism to explain the U-Pb zircon systematics, for which a combination of shock-induced lead loss and comprehensive annealing is proposed, facilitated by a high-temperature, halogen-enriched fluid-bearing environment in the immediate vicinity of the SIC.

Regardless of the exact mechanism, the implication of impact ages in preimpact rocks, combined with similar results from other mafic rocks associated with Sudbury and Vredefort, suggests that zircon geochronology in these specialised but geologically significant settings must be interpreted with great care. The identification of syn- vs. preimpact mafic intrusions has significant implications relating to the source of potentially metalliferous magmas, and to the structural and compositional nature of the crust at the time of impact.

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