GEOLOGICAL SURVEY OF CANADA
OPEN FILE 7856

Targeted Geoscience Initiative 4: Canadian Nickel-Copper-Platinum Group Elements-Chromium Ore Systems — Fertility, Pathfinders, New and Revised Models

New field observations and U-Pb ages in the Sudbury area: toward a detailed cross-section through the deformed Sudbury Structure

Wouter Bleeker[1], Sandra L. Kamo[2], Doreen E. Ames[1], and Don Davis[2]

[1]Geological Survey of Canada, Ottawa, Ontario
[2]University of Toronto, Toronto, Ontario

2015

Recommended citation

Bleeker, W., Kamo, S.L., Ames, D.E., and Davis, D., 2015. New field observations and U-Pb ages in the Sudbury area: toward a detailed cross-section through the deformed Sudbury Structure, *In:* Targeted Geoscience Initiative 4: Canadian Nickel-Copper-Platinum Group Elements-Chromium Ore Systems — Fertility, Pathfinders, New and Revised Models, (ed.) D.E. Ames and M.G. Houlé; Geological Survey of Canada, Open File 7856, p. 151–166.

Contribution to the Geological Survey of Canada's Targeted Geoscience Initiative 4 (TGI-4) Program (2010–2015)

TABLE OF CONTENTS

Figures

Tables

New field observations and U-Pb ages in the Sudbury area: toward a detailed cross-section through the deformed Sudbury Structure

Wouter Bleeker[1]*, Sandra L. Kamo[2], Doreen E. Ames[1], and Don Davis[2]

[1]Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario K1A 0E8
[2]Jack Satterly Geochronology Laboratory, University of Toronto, 22 Fussell Street, Toronto, Ontario M5S 3B1
*Corresponding author's e-mail: wbleeker@nrcan.gc.ca

ABSTRACT

The Sudbury area straddles the transition from the Archean Superior structural province to the Paleoproterozoic Southern province. To the south it is flanked by younger Proterozoic belts and finally the ca. 1 Ga Grenville Front. It is unique in that it also hosts the deformed remnants of one of the largest and oldest preserved impact structures in the geological record, the ~300 km diameter Sudbury Structure. This structure is characterized by a differentiated melt sheet, commonly referred to as the Sudbury Igneous Complex (SIC), which at or near its base hosts one of the largest concentrations of Ni-Cu-PGE sulphides on the planet. These metal-rich sulphides have formed the basis for an extensive mining industry since nickel was first discovered during railway construction in 1883. Despite more than a century of research, many geological questions remain unresolved in this fascinating area.

Here we present new field observations and preliminary U-Pb zircon and baddeleyite ID-TIMS results on a suite of about 20 critical samples that help resolve some long-standing geological questions. Many rock units in the Sudbury area have experienced significant shock metamorphism, which has increased the complexity of the Pb-loss patterns of their zircon crystals. Therefore, a key rationale for the present study was to apply "chemical abrasion" pre-treatment to single best-preserved zircon crystals, or fragments thereof, to reduce or eliminate young Pb loss and allow us to see through the shock-induced Pb loss.

We show that the Joe Lake Gabbro below the North Range is an Archean metagabbro, consistent with observed field relationships. Foliated granite on the Southeast Range is also Archean, requiring that metavolcanic rocks it intruded are Archean as well and not part of the basal Huronian rift succession. We present the first robust age on the Creighton Granite, showing it to be a folded subvolcanic sill and the magma chamber to the overlying Copper Cliff Rhyolite. Together, the Creighton Granite and Copper Cliff Rhyolite represent a single felsic magmatic system 2455–2460 Ma in age, which developed in the immediate aftermath of the main pulse of Matachewan mafic magmatism at ca. 2460 Ma. Magma mingling structures near the base of the Creighton Granite sill demonstrate the intimate relationship with Matachewan mafic magmas.

We have dated a number of mafic dyke swarms in the area, both pre- and post-dating the SIC. Among these is the first recognition of a ca. 2507 Ma dyke swarm in the Sudbury area. Furthermore, we present several ages on the SIC and its offset dykes, including a weighted mean ^{207}Pb/^{206}Pb age of 1849.7 ±0.2 Ma for a high-MgO norite in the South Range, and a precise concordant baddeleyite age of 1848.5 ±0.8 Ma for the radial Pele dyke on the North Range. The latter likely represents the youngest and final dyke injection of the offset dyke system into the fractured footwall of the SIC.

INTRODUCTION: NEW GEOCHRONOLOGY OF THE SUDBURY AREA

About 20 samples from across the wider Sudbury area were selected for U-Pb geochronology (Table 1, Fig. 1). These samples address a number of critical rock units and geological relationships. Some units, such as the Joe Lake Gabbro, North Range, had not been previously dated and their origin was subject to debate (e.g. Archean versus an early intrusive pulse of the Matachewan event). Others had poorly resolved ages (e.g. Creighton Granite), or were known to be artificial groupings based on varied field relationships (e.g. the "Trap dykes").

We also aimed to tackle, at the highest precision, the time scale of igneous crystallization and cooling of the Sudbury Igneous Complex (SIC), and to resolve some of the controversies surrounding which dykes are part

---

Bleeker, W., Kamo, S.L., Ames, D.E., and Davis, D., 2015. New field observations and U-Pb ages in the Sudbury area: toward a detailed cross-section through the deformed Sudbury Structure, *In:* Targeted Geoscience Initiative 4: Canadian Nickel-Copper-Platinum Group Elements-Chromium Ore Systems — Fertility, Pathfinders, New and Revised Models, (ed.) D.E. Ames and M.G. Houlé; Geological Survey of Canada, Open File 7856, p. 151–166.

Table 1. Preliminary results on samples from the Sudbury area.

#	Rock Unit	Sample No.	Easting (mE)	Northing (mN)	Description	New U-Pb Age (Ma)	Comment	Method^1	Event	References
1	Joe Lake Gabbro	BNB-12-094	497330	5178808	Foliated metagabbro in footwall of SIC, cut by Sudbury Breccia	**ca. 2660**	Minimum; age of metamorphism	U-Pb, zircon	Levack Gneiss Complex	This study
2	Crosscutting pegmatite	BNB-12-095	497323	5178800	Pink granitic pegmatite dyke, shallow dipping and undeformed, cuts metagabbro	**2648 ±9**		U-Pb, zircon	Cartier Granite suite	This study
3	Late Archean granite	BNB-13-052	518496	5161806	Archean granite, moderately foliated, cuts mafic volcanic rocks	**2676 ±7***	Minimum: 2653 ±7	U-Pb, zircon	Late Archean granite, pre-Cartier	This study
4	"Pyroxenite dyke"	BNB-13-087A	453291	5162853	Mafic dyke, cutting Cartier Granite, and itself cut by megacrystic Matachewan diabase dyke	**2507 ±4***	Minimum: 2479 ±3	U-Pb, baddeleyite	Early Matachewan or Mistassini?	This study
5	"Tailings Pond Gneiss"	BNB-13-058	490094	5147118	Migmatitic gneiss, relict compositional banding in paleosome, probably paragneiss	*Not yet analyzed*	Detrital zircon population		Basal Huronian clastics	See Petrus (2014) for LA-ICP-MS data on zircons from a similar sample
6	Falconbridge Twp Intrusion	BNB-13-051	517882	5162308	Coarse anorthositic gabbro, steeply dipping layering, cuts Archean granite		No datable minerals recovered		Matachewan LIP, East Bull Lake suite?	This study; see Prevec & Baadsgaard (2005)
7	Gabbro sill enclave	BNB-13-093	485966	5144629	Coarse metagabbro enclave in brecciated Creighton Granite, along Lively regional road	**2476 ±7***	Both zircon and baddeleyite	U-Pb, zircon	Early Matachewan sills	This study
8	Matachewan dykes	BNB-08-130	452847	5289123	Large mafic dykes, north-northwest-trending, near Gogama	2460 ±2		U-Pb, baddeleyite	Matachewan LIP, main pulse	Bleeker et al. (2012); Halls et al. (2005)
9a	Creighton Granite	BNB-12-058	490094	5147118	Coarse-grained porphyritic granite/granodiorite, from approximate middle of granite sill	**2464 ±35***	Minimum: 2437 ±2	U-Pb, zircon	Matachewan LIP, felsic pulse	This study; see also Frarey et al. (1982) and Smith (2002)
9b	Creighton Granite	BNB-12-060A	486067	5141778	Second sample of Creighton Granite, west side of Hwy 144 Bypass, near top of sill	2433 ±4	Minimum	U-Pb, zircon	Matachewan LIP, felsic pulse	This study
10	Murray Granite	BNB-12-059	496735	5150992	Pink biotite granite, homogeneous, along railway cut	**2460 ±6***	Minimum: 2448 ±3	U-Pb, zircon	Matachewan LIP, felsic pulse	This study; see also Krogh et al. (1996)
11a	Copper Cliff Rhyolite	BNB-12-064	488430	5141367	Rhyolite tuff, crudely bedded, Lively area, large outcrops north of Hwy 17	2465 ±14* (2455-2460)	Minimum: 2455 ±3	U-Pb, zircon	Matachewan LIP, felsic pulse	This study; see also Krogh et al. (1984); Ketchum et al. (2013)
11b	Copper Cliff Rhyolite	BNB-12-098	489311	5141660	Massive flow-banded rhyolite near top of unit, Lively area, outcrop north of Hwy 17	2426 ±3	Minimum	U-Pb, zircon	Matachewan LIP, felsic pulse	This study
	Creighton & Copper Cliff	BNB-12-058, 060A, 064			Combined regression through Creighton Granite (4) and Copper Cliff (3) data	2464 ±12*	Combined (n=7, MSWD=3.1)	U-Pb, zircon	Matachewan LIP, felsic pulse	This study
	Creighton & Copper Cliff	BNB-12-058, 060A, 064			Combined regression through Creighton Granite (3) and Copper Cliff (3) data	**2459 ±7***	Combined (n=6, MSWD=1.9)	U-Pb, zircon	Matachewan LIP, felsic pulse	This study
12	Nipissing Sill	BNB-13-048A	502367	5142640	Large, more magnetic late-stage pegmatoidal melt pod in Nipissing Diabase	2215 ±1	Minimum	U-Pb, zircon & baddeleyite	Nipissing (Senneterre, Ungava)	This study; see also Corfu & Andrews (1986); Noble & Lightfoot (1992)
13a	Pre-SIC mafic dykes (Ia)	BNB-12-022	358234	5128148	Large mafic dyke cutting Huronian Supergroup	2116 ±5	Preliminary	U-Pb, baddeleyite	Marathon LIP	Bleeker & Chamberlain, unpublished data; see also Halls et al. (2008)
13b	Pre-SIC mafic dykes (Ib)	BNB-12-028B	331657	5135079	Large mafic dyke cutting Huronian Supergroup	2105 ±5	Preliminary	U-Pb, baddeleyite	Marathon LIP	Bleeker & Chamberlain, unpublished data
14	Pre-SIC mafic dykes (II)	BNB-12-025	353644	5122629	Large mafic dyke cutting Huronian Supergroup	ca. 1930	Preliminary	U-Pb, baddeleyite	New event for southern Superior	Bleeker & Chamberlain, unpublished data
15	Mafic norite	BNB-13-007	484226	5146795	Black Norite with high MgO, higher up in "norite stratigraphy", along Hwy 144 Bypass	**1849.7 ±0.2**	Weighted mean (n=4, MSWD=1.2)	U-Pb, evaporation & ID-TIMS	SIC meltsheet, early	This study; see also Davis (2008), Krogh et al. (1984)
16	"Crowfoot" granophyre	BNB-14-010	484495	5150103	Coarse latest crystallizing granophyre, South Range, along Hwy 144 Bypass	*in progress*		U-Pb, zircon	SIC meltsheet, final crystallization	
17	Hess Offset, quartz diorite	BNB-13-088A	449037	5160679	Outer main phase of quartz diorite, trench across Hess Offset dyke, no sulphides	**1849.1 ±0.9**	Upper intercept	U-Pb, baddeleyite	Early offset dyke injection into footwall	This study; see also Corfu & Lightfoot (1996)
18	Cascaden Offset, quartz diorite	BNB-13-089	458169	5162474	Quartz diorite dyke, fine- to medium-grained, ~10–12 m wide, northwest of SIC	*in progress*		U-Pb, baddeleyite	Offset dyke injection into footwall	Dave Smith, Wallbridge Mining Inc., pers. comm. (2013)
19	Pele Offset, evolved diorite	BNB-13-090B	477219	5178116	Evolved more felsic diorite, with plagioclase phenocrysts, from centre of dyke	1848.5 ±0.8	One concordant precise analysis	U-Pb, baddeleyite	Final, cooler offset dyke injection	This study
20	Trap dykes (III)	BNB-13-047E	502530	5142589	Late-stage granophyric melt pod in ~10 m-wide "Trap dyke"	1748 ±5	Preliminary	U-Pb, zircon	Trap dyke swarm	This study
21	Felsite dyke, undeformed	BNB-13-049	502340	5142616	Crosscutting felsic dyke, fine-grained matrix, small feldspar, biotite and quartz phenocrysts	**1766 ±9**	Youngest single zircon grain	U-Pb, zircon	Cutler Batholith suite?	This study; see also Davidson et al. (1992)

Notes:

1: CA-ID-TIMS on single zircons or small fragments thereof, unless otherwise noted.

*: Upper intercept based on discordant array with 1850 Ma lower intercept.

Ages noted in bold font are preferred interpretations of the data.

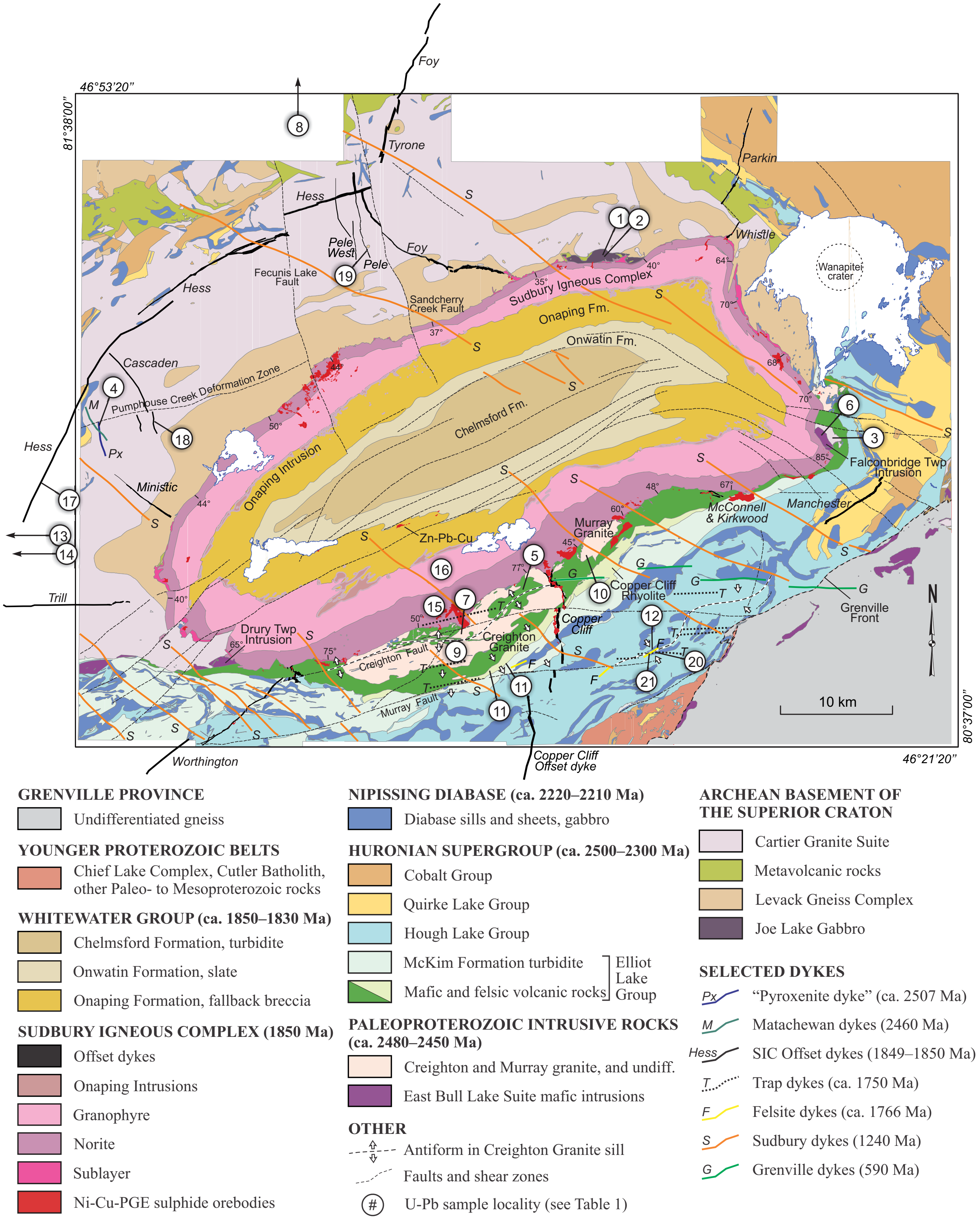


Figure 1. Map of the Sudbury area (adapted from Ames and Farrow, 2007), with locations of samples marked. Numbers 1 to 21 correlate with Table 1.

of the "offset dyke" system of the SIC versus unrelated older dyke sets.

Collectively, these ages will help to sharpen the geological framework for this unique area, and they will be incorporated into an updated and expanded version of the digital map compilation for the area (Ames et al., 2006; 2008a,b). Furthermore, they help constrain a detailed regional geological cross-section that will accompany an updated version of this map (Bleeker et al., 2013, 2014a,b).

RATIONALE

With several important geochronological questions unresolved in this area, a key rationale for the present study was to apply some critical innovations in high-precision ID-TIMS U-Pb geochronology. These include micro-sampling of complex zircon crystals, made possible by low-Pb blank levels of ~0.2–0.5 pg, and "chemical abrasion" pre-treatment of the selected single zircon fragments (Mattinson, 2005, 2011), to reduce or eliminate young Pb loss and thereby allowing us to see through the shock-induced Pb loss.

Obtaining precise ages on some of the pre-SIC target rocks has proven difficult due to most zircons having experienced substantial Pb loss at multiple times, notably at 1850 Ma or shortly thereafter, in response to the impact event (Dietz, 1964; Dietz and Butler, 1964; Bray et al., 1966; Pye et al., 1984; Faggart et al., 1985; Grieve et al., 1991; Spray et al., 2004) and the associated shock metamorphism (e.g. Krogh et al., 1996), but also at younger times (e.g. multiple Proterozoic events). Discordance patterns are further complicated by variable degrees of recent Pb loss, making many upper intercept age interpretations uncertain and non-unique. An important example is the age of the Creighton Granite, a major unit in the footwall of the South Range of the SIC (Fig. 1) that, despite several previous U-Pb studies (Frarey et al., 1982; Smith, 2002), has remained controversial due to variably discordant and scattered data points. Does this granite represent a relatively unique magmatic event in this part of the Superior craton at ca. 2330 Ma (Frarey et al., 1982), or at ca. 2375 Ma (Smith, 2002)? Or are these ages merely a function of unresolved Pb-loss complexity from damaged zircons?

A definitive answer to questions like these will only come from more concordant data on single zircons, avoiding mixing of discordant ages and minimizing projection to the concordia curve. Thus, the ever increasing ability to analyse smaller and better preserved single zircon grains, or only highest quality fragments thereof, and to improve their concordance through chemical abrasion, may finally resolve some of the long-standing age questions. By applying these techniques we have now resolved the age of the Creighton Granite to ca. 2460 Ma, consistent with this intrusion being a high-level subvolcanic sill and magma chamber of the Copper Cliff Rhyolite Formation, for which we have obtained a similar age.

On another level, the time scale of igneous crystallization and cooling of the ~3–5 km-thick Sudbury melt sheet represents another important question. We are tackling this by selecting first and last crystallizing phases of the SIC and subjecting their igneous zircons to an evaporative pre-treatment (similar to Davis, 2008) prior to high-precision ID-TIMS analysis of the annealed and most robust remnants of the crystals. This method holds the potential to resolve crystallization ages of distinct phases of the SIC down to an uncertainty level of ca. 0.1–0.2 Ma (2σ). Resolving this question of the time scale of cooling will inform advanced modeling studies of the dynamic and igneous evolution of the melt sheet.

SAMPLES, PRELIMINARY RESULTS, AND INTERPRETATION

Below we discuss preliminary results obtained on our U-Pb sample suite. Some samples are still in progress, whereas the odd sample failed to produce a suitable mineral separate or was otherwise aborted or temporarily set aside. In general, the samples and resulting ages will be discussed from oldest to youngest and with reference to Table 1. Locations of all samples are shown in Figure 1, with precise GPS coordinates (±4 m) given in the table.

In terms of interpretation, in some cases fully concordant results were obtained and interpretation of a final age is straightforward, with the uncertainty reflecting 95% confidence limits of the data. In other cases, where discordance was improved upon (relative to previous studies) but not fully eliminated, the data can be discussed in terms of a "minimum age" and a "preferred upper intercept age". The minimum age is provided by the ^{207}Pb/^{206}Pb age of the least discordant zircon analysis (barring inheritance). In some cases, for instance the new 2437 ±2 Ma minimum age for the Creighton Granite, such ages already provide a strong guide toward the final answer and eliminate previously proposed age interpretations.

In a number of samples, multiple discordant data points require some judgement in the choice of regression and a corresponding upper intercept calculation. Such discordant data commonly fit a discordia line with an 1850 Ma lower intercept (e.g. Krogh, 1984; Krogh et al., 1996), i.e., the age of impact and shock-induced Pb loss. Where appropriate, we thus calculate an upper intercept based on such a model. In some samples, however, alternative regressions and upper intercepts are suggested by the data.

1. Joe Lake Gabbro, Immediate Footwall to Part of the North Range

Many small rounded and clear zircon crystals were separated from the Joe Lake Gabbro. Field observations showed this gabbro to be a variably foliated metagabbro (Fig. 2a), with a foliation that merged with that of the surrounding Levack Gneiss Complex (Card, 1994). We thus interpret the Joe Lake Gabbro as an Archean metagabbro and the zircons most likely represent metamorphic zircon growth during deformation. Concordant and near concordant data indicate an age of high-grade metamorphism and zircon growth at ca. 2660 Ma. Interestingly, the zircons did not show any obvious shock damage (fracturing, pervasive cloudiness). The Joe Lake Gabbro is an Archean metagabbro and not part of the Paleoproterozoic East Bull Lake suite.

2. Crosscutting Pegmatite Dykes, Joe Lake Area

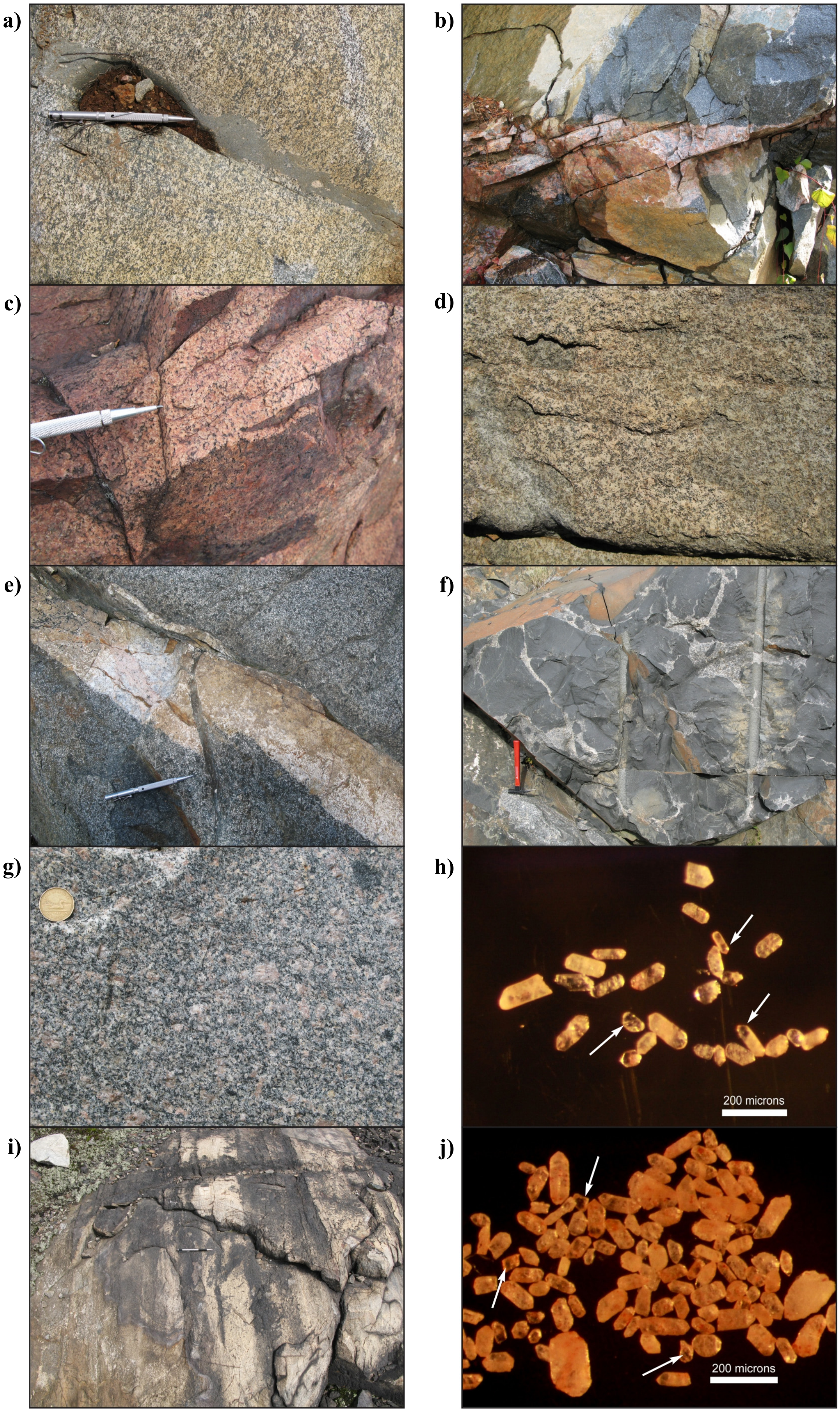
The Joe Lake metagabbro is crosscut by several parallel, shallow dipping, and essentially undeformed pink granite pegmatite dykes (Fig. 2b). These dykes post-date the penetrative fabric of the host metagabbro and represent a late (latest?) granitic phase intruding the Levack Gneiss Complex. Data for four zircon grains are variably discordant but collinear, yielding an upper intercept age of 2648 ±9 Ma, which is interpreted as the crystallization age of this late granite pegmatite, in agreement with the slightly older metamorphic age of the host metagabbro. The data allow some latitude in the choice of lower intercept, but they do not strongly project to a lower intercept of 1850 Ma; i.e., there is no overriding control from shock-induced Pb loss. This duplicates observations in the previous sample. These pegmatite dykes, in a broad sense, are probably part of the ca. 2642 Ma Cartier Granite complex (Card, 1994; Meldrum et al., 1997) that dominates the area north of the SIC, and they post-date essentially all of the penetrative Archean deformation in the Levack Gneiss Complex. Wodicka (1997) reported similar age constraints on deformation as part of a larger geochronological data set on the northern footwall of the SIC.

3. Late Archean Granite, Southeast Range, Falconbridge Township

In Falconbridge Township, near the southeastern apex of the folded SIC, we dated a foliated biotite granite (Fig. 2c). This granite intrudes metavolcanic rocks, and is itself intruded by the crudely layered anorthositic gabbro body of the "Falconbridge Township Intrusion" (Thomson, 1957; Dressler, 1984; see also section 6, *Falconbridge Township Intrusion,* below). On the present compilation map of the Sudbury Structure (Ames et al., 2006, 2008b), volcanic rocks surrounding the foliated granite body are identified as lower Huronian mafic volcanic rocks (Stobie Formation). However, multiple single zircon analyses indicate a late Archean age for this granite, with a minimum age of ca. 2653 Ma. The near concordant data fit a discordia line to an 1850 Ma lower intercept and, using this model, provide a 2676 ±7 Ma upper intercept age. Clearly this granite is part of the Archean basement below the Huronian rift succession and the mafic volcanic rocks it intruded must also be Archean, rather than early Huronian. Remapping of this area is required to redefine the Archean-Huronian unconformity. In contrast to the North Range samples discussed above (1 and 2), the zircon data of this late Archean granite indicate strong shock metamorphism, in agreement with the presence of major bodies of Sudbury Breccia in the immediate area. This can be interpreted, qualitatively, in terms of an order of magnitude stronger shock intensity in this area compared to that in the northern footwall of the SIC near Joe Lake. In other words, the Falconbridge Township area must be significantly closer to the centre of the impact than the Joe Lake area.

4. "Pyroxenite Dyke", North Range: A Sudbury Igneous Complex-Related Offset Dyke?

This unit is a ~50 m-wide mafic dyke of melanocratic gabbro to pyroxenite that intrudes the Cartier Granite complex, ~10 km northwest of the northwestern flank of the SIC (Fig. 2d; see Fig. 1 for location). There was some question whether this dyke might represent a radially oriented "offset dyke" (D. Smith, Wallbridge Mining, pers. comm., 2013). Field investigation by the first author uncovered the crosscutting contact of a plagioclase megacrystic Matachewan dyke, with the latter dyke chilled against the "pyroxenite dyke". Hence the "pyroxenite dyke" is older than ca. 2460 Ma. Baddeleyite crystals separated from this dyke indicate a minimum age of 2479 ±3 Ma. Several of the discordant fractions show a linear array that is consistent with an 1850 Ma lower intercept. Using this model, the upper intercept age is 2507 ±4 Ma. This allows the possibility that ca. 2510 Ma dykes (e.g. Mistassini event; Fahrig and West, 1986; Ernst and Bleeker, 2010) are present in this part of the Superior craton. Alternatively, this dyke may represent a primitive early pulse of the Matachewan event (cf. Heaman, 1997). It is interesting to note that a detrital zircon of similar age (2497 ±10 Ma) has been reported from basal Huronian sediments further west (a quartz wacke of the Livingstone Creek Formation; see Craddock et al., 2013), providing additional evidence for a zircon source, and thus magmatic activity, predating the Matachewan event in the southern Superior craton.


a)
b)
c)
d)
e)
f)
g)
h)
200 microns
i)
j)
200 microns

5. "Tailings Pond Gneiss"

A migmatitic gneiss, intruded by granitic leucosome veins, occurs in an outcrop in the middle of the large tailings pond west of the Copper Cliff smelter complex. The question was whether this gneissic rock represents an Archean basement inlier on the South Range. On closer inspection and after slabbing of the samples, it was revealed that this gneiss represents a high-grade metasandstone or wacke with relict graded bedding, and not an Archean orthogneiss. Its overall character suggests a high-grade metamorphic lower Huronian rift sandstone that is part of the migmatitic envelope to the Creighton Granite sill (near the inferred hot base of this large sill). A heterogeneous detrital zircon population separated from this sample supports this interpretation. We have not yet analyzed any of these zircons, which likely represent a varied Archean provenance. Any provenance interpretation is likely to be complicated by "smearing" of ^{207}Pb/^{206}Pb ages due to varied degrees of 1850 Ma Pb loss, even if chemical abrasion is successful in eliminating most of the young Pb loss. Additional data on this "gneiss" can be found in Petrus (2014).

6. Falconbridge Township Intrusion

This is one of two intrusions (Falconbridge and Drury) thought to be of early Huronian age. They are dominated by layered anorthositic gabbro. Their ages are currently not well constrained but Prevec and Baadsgaard (2005) suggested an age of ca. 2441 Ma for the Falconbridge intrusion based on complexly discordant zircon data. Unfortunately, our sample of the Falconbridge intrusion did not yield any datable minerals. We may revisit these intrusions in the near future. However, we are aware of at least one independent study aiming to date the Drury Township Intrusion.

7. Coarse Gabbro Enclave in Creighton Granite

The Creighton Granite intruded the lower Huronian succession. The granite includes rafts of metamorphosed siltstone, graded wacke, and arenite, as well as mafic sills of probable Matachewan age. Near the Creighton Mine, in what we infer is the base of the folded Creighton Granite sill (Fig. 1), a large gabbro inclusion or enclave is surrounded by Creighton Granite (Fig. 2e). From the various mafic rocks in this area, this gabbro was the coarsest grained and thus most likely to yield datable minerals. Mineral separation of a ~10 kg sample yielded both skeletal primary zircon grains and baddeleyite. The latter mineral showed overgrowths of polycrystalline zircon and produced complex data. Chemically abraded skeletal zircons are somewhat discordant, defining a linear array consistent with an 1850 Ma lower intercept. Based on this model, the data indicate an upper intercept age of 2476 ±7 Ma, in agreement with recently published ages for other early Huronian intrusions, such as the River Valley intrusion (James et al., 2002 and references therein).

8. Matachewan Dykes, Main Pulse

As part of a separate study, the timing of the main pulse of Matachewan dykes north of Sudbury has been refined. Ages show a tight clustering around 2460 Ma. (Bleeker et al., 2012; see also Halls et al., 2005; cf. Heaman, 1997). Dykes of this age typically carry ubiquitous calcic plagioclase megacrysts, indicating some residence time of the magma in a large lower or mid-crustal magma chamber. They are clearly younger than the ca. 2480 Ma early pulse of the Matachewan event (e.g. Krogh et al., 1984; James et al., 2002) that led to the East Bull Lake Suite of layered intrusions. We include this age here in Table 1 because it is important for the age interpretation of other units along the South Range of the SIC. Main pulse Matachewan dykes are ubiquitous in basement to the north of the SIC but are not known to crosscut the Creighton Granite and lower Huronian formations such as the Copper Cliff Rhyolite. Crosscutting northerly trending mafic dykes would be immediately apparent in these felsic units. Their absence thus constrains Huronian felsic magmatism to younger than 2460 Ma.

9. Creighton Granite

We sampled the main phase of the Creighton Granite (Fig. 2g), a coarse-grained, variably K-feldspar porphyritic granite to granodiorite (e.g. Dutch, 1979;

Figure 2 (opposite page). Photographs of selected samples. **a)** Foliated metagabbro of the ca. 2660 Ma Joe Lake Gabbro, immediate footwall to parts of the North Range of the Sudbury Igneous Complex (SIC) and host to the WD16 deposit. The foliation in the metagabbro is cut by a Sudbury Breccia dykelet. **b)** Shallow-dipping pink pegmatite that cuts across the foliation of the Joe Lake metagabbro, dated at ca. 2648 ±9 Ma. **c)** Late Archean foliated biotite granite, Falconbridge Township, dated at ca. 2676 ±7 Ma. **d)** Close-up of the "pyroxenite dyke" north of the SIC, dated at ca. 2507 Ma. **e)** Metagabbro enclave in Creighton Granite, dated at ca. 2476±7 Ma. Gabbro is cut by granitic dykelet. **f)** Magma mingling and hybridization between ca. 2460 Ma mafic magma and Creighton Granite felsic magma. **g)** Porphyritic Creighton Granite, main phase, dated at ca. 2460 Ma. **h)** Examples of zircons from the Creighton Granite, after annealing. Small clear grain fragments that were analyzed are highlighted (see arrows). **i)** Bedded crystal tuff of the Copper Cliff Rhyolite Formation, with a minimum age of 2455 ±3 Ma. **j)** Example of zircons from the Copper Cliff crystal tuff, with clear fragments that were analyzed highlighted. Combined age for the Creighton Granite and Copper Cliff Rhyolite is 2455–2460 Ma.

Table 2. U-Pb data for Creighton Granite and Copper Cliff Rhyolite samples.

Sample Number	**Weight** (µg)	**U** (ppm)	**Th/ U**	**PbC** (pg)	**^{206}Pb/ ^{204}Pb** measured	**^{207}Pb/ ^{235}U**	**2 σ**	**^{206}Pb/ ^{238}U**	**2 σ**	**Error Corr**	**^{207}Pb/ ^{206}Pb/**	**2 σ**	**^{206}Pb/ ^{238}U Age** (Ma)	**2 σ**	**^{207}Pb/ ^{235}U Age** (Ma)	**2 σ**	**^{207}Pb/ ^{206}Pb Age** (Ma)	**2 σ**	**Disc** (%)
BNB-12-058 *Creighton Granite (K-feldspar porphyritic granodiorite; GPS#2093: 46°26'23.04"N, 81°11'15.65"W)*																			
z1	0.2	377	0.47	0.5	4594	9.904	0.030	0.4540	0.0012	0.897	0.15823	0.00021	2412.8	5.3	2425.9	2.8	2436.9	2.3	1.2
z2	0.8	100	0.47	0.5	4811	9.484	0.030	0.4437	0.0013	0.851	0.15501	0.00026	2367.3	5.9	2386.0	2.9	2401.9	2.9	1.7
z3	0.2	675	0.51	0.4	9284	8.848	0.022	0.4279	0.0009	0.925	0.14998	0.00015	2296.2	4.0	2322.5	2.3	2345.7	1.7	2.5
BNB-12-060A *Creighton Granite (K-feldspar porphyritic granodiorite; GPS#2107: 46°25'45.96"N, 81°10'52.85"W)*																			
z1	na	na	0.58	8.0	376	9.175	0.108	0.4353	0.0014	0.787	0.15289	0.00144	2329.4	6.2	2355.7	10.8	2378.5	16.1	2.5
z2	na	na	0.44	3.1	1631	9.630	0.036	0.4424	0.0011	0.761	0.15785	0.00038	2361.6	5.1	2400.0	3.4	2432.8	4.1	3.5
BNB12-064 *Copper Cliff Rhyolite Formation (crystal tuff; GPS#2131: 46°25'32.80"N, 81°09'02.09"W)*																			
z1	0.3	28	0.68	0.3	727	9.902	0.144	0.4576	0.0060	0.923	0.15694	0.00088	2429	27	2426	13	2422.9	9.5	-0.3
z2	0.8	45	0.45	0.2	4834	10.008	0.046	0.4569	0.0020	0.956	0.15884	0.00021	2426.1	8.8	2435.5	4.2	2443.4	2.3	0.9
z3	0.3	125	0.63	0.2	6059	10.067	0.049	0.4564	0.0020	0.938	0.15995	0.00027	2423.9	8.9	2440.9	4.5	2455.2	2.8	1.5
z4	1.0	13	0.77	0.5	751	10.148	0.103	0.4617	0.0039	0.896	0.15942	0.00073	2447	17	2448	9	2449.5	7.7	0.1
BNB12-098 *Copper Cliff Rhyolite Formation (flow-banded rhyolite: GPS#2205: 46°25'42.34"N, 81°08'20.83"W)*																			
z1	1.0	14	0.30	0.8	389	4.589	0.127	0.3161	0.0029	0.603	0.10531	0.00245	1771	14	1747	23	1720.0	43.0	-3.4
z2	na	na	0.53	3.4	450	8.296	0.025	0.3828	0.0009	0.841	0.15718	0.00026	2089	4	2264	3	2425.6	2.8	16.2
z3	na	na	0.45	10	1369	9.607	0.302	0.4386	0.0027	0.952	0.15886	0.00407	2344	12	2398	29	2443.6	43.6	4.8

Notes:

All zircon grains have been thermally annealed and etched in HF (Mattinson, 2005).

Th/U calculated from radiogenic ^{208}Pb/^{206}Pb ratio and ^{207}Pb/^{206}Pb age assuming concordance.

PbC is total common Pb assuming the isotopic composition of laboratory blank.

^{206}Pb/^{204}Pb corrected for fractionation and common Pb in spike.

Pb/U ratio corrected for fractionation, common Pb in the spike, and blank.

Error Corr is correllation coefficients of X-Y error on the concordia plot.

Correction for ^{230}Th disequilibrium in ^{206}Pb/^{238}U and ^{207}Pb/^{206}Pb assuming Th/U of 4.2 in the magma.

Disc is percent discordance for the given ^{207}Pb/^{206}Pb age.

Frarey et al., 1982; Smith, 2002), in two places along Highway 144, west of Lively. Although zircon is relatively abundant, it is poorly preserved, in part due to fracturing as a result of the shock metamorphism and subsequent alteration. Previous studies have shown that it is difficult to obtain concordant data from this unit (e.g. Smith, 2002). We dated rare, small, unaltered crystal fragments (Fig. 2h) that were chemically abraded prior to U-Pb analysis. This strategy indeed produced more concordant results than previous studies but none of the data are fully concordant (Table 2, Fig. 3). However, the data define a linear array consistent with an 1850 Ma lower intercept. The least-discordant grain indicates a minimum age of 2437 ±2 Ma, eliminating the possibility that this granite might be younger than 2400 Ma (cf. Frarey et al., 1982; Smith, 2002; Raharimahefa et al., 2014). Collectively, the data suggest an upper intercept age of ca. 2460 Ma, an age that is similar to that of the nearby Murray Granite (see below, and Krogh et al., 1996). It allows a simple interpretation of the field relationships in which the Creighton Granite is a subvolcanic sill and the magma chamber to the overlying and chemically similar Copper Cliff Rhyolite Formation. Magma-mingling structures and hybridization with mafic magmas were observed near the base of the sill (Fig. 2f) and indicate a close and essentially contemporaneous relationship with mafic magmas low in the Huronian rift succession. South of the Creighton Granite and evidently part of the felsic magmatic system, intrusive bodies of finer grained granite porphyry were observed at an intermediate stratigraphic level between the top of the Creighton Granite sill and the overlying Copper Cliff Rhyolite.

10. Murray Granite

A similar approach as above applied to the Murray Granite yielded three new analyses that are more concordant than but collinear with previously reported results (Krogh et al., 1996). One of our analyses overlaps the concordia curve and indicates a minimum age of 2448 ±3 Ma. An upper intercept age calculated including these new data is 2460 ±6 Ma, consistent with the field relationships described above (i.e. absence of Matachewan dykes). The more discordant data indicate the strong control imparted by 1850 Ma Pb loss, i.e., further evidence for the intense shock-induced Pb loss in this part of the South Range, as documented and described in detail by Krogh et al. (1996).

11. Copper Cliff Rhyolite

We separated zircons from two different samples of the Copper Cliff Rhyolite Formation, a layered crystal-rich tuff from near the middle of the formation (Fig. 2i) and a massive flow-banded rhyolite near the top of the formation, both from the Lively area. Although zircons were abundant, nearly all are of poor quality (Fig. 2j). Three small fragments from the crystal tuff nevertheless plot toward the upper end of the discordant array (Fig. 3). The most precise of these is 1.5% discordant and yields a minimum age of 2455 ±3 Ma. A regression of all the data (Copper Cliff plus Creighton, n=7), from 1850 Ma, yields an upper intercept age of 2464 ±12 Ma with a mean square weighted deviation (MSWD) of 3.1. Eliminating one point from this regression (n=6) yields a better fit (MSWD<2.0) and more precise upper intercept age of 2459 ±7 Ma. This regression also fits the least discordant data from earlier studies of the

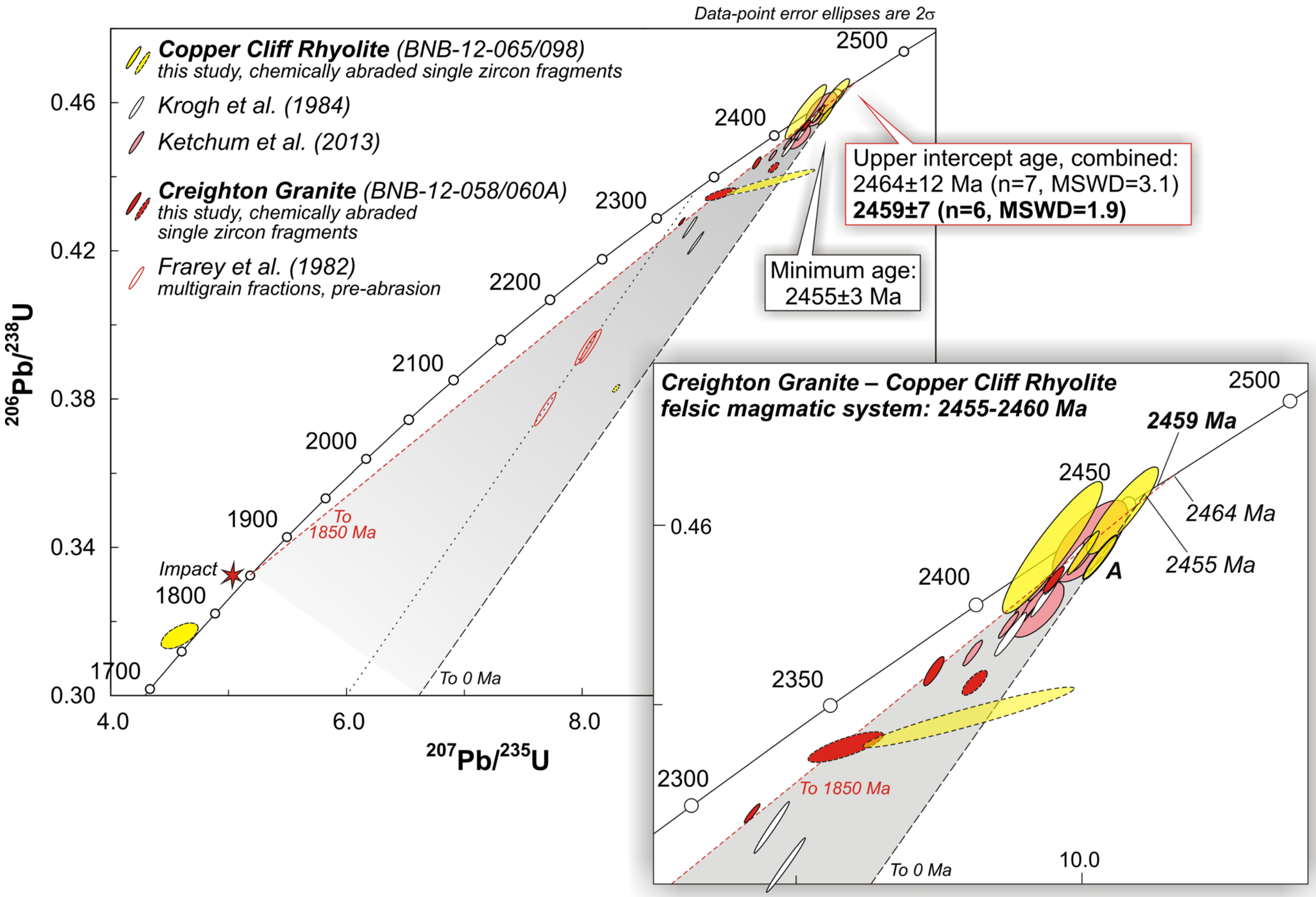


Figure 3. U-Pb concordia diagram of Creighton Granite (red ellipses) and Copper Cliff Rhyolite (yellow and other ellipses) zircon data. Data from Krogh et al. (1984; open ellipses) and Ketchum et al. (2013; pink ellipses) are also shown. The various data sample the complex Pb-loss field (shaded grey) bounded by the shock metamorphism-induced discordia line (red dashed line) to 1850 Ma and various younger episodes of Pb loss, and finally the chord to the origin defined by recent Pb loss. Large multi-grain zircon fractions of Frarey et al. (1982), from an early pre-air abrasion study on the Creighton Granite (open red ellipses), sample the middle of this field, averaging various degrees of Pb loss and processes. Due to the severity of the Pb loss, only the clearest grain fragments pre-treated by chemical abrasion get close to the apex of the Pb-loss field and approach the primary crystallization age. The ^{207}Pb/^{206}Pb age of our most precise and least discordant datum from the Copper Cliff crystal tuff sample (A in inset) constrains a minimum age of 2455 ±3 Ma. The majority of the chemically abraded zircon data plot on or near the discordia with the 1850 Ma lower intercept, the age of shock-induced Pb loss. The upper intercept of this discordia is 2464 ±12 Ma or 2459 ±7 Ma if one analysis is eliminated from the regression. Together with field relationships, the age of the combined Creighton Granite and Copper Cliff Rhyolite magmatic system can be constrained to 2455–2460 Ma, immediately following the main pulse of Matachewan mafic magma input at ca. 2460 Ma.

Copper Cliff Rhyolite (Krogh et al., 1984; Ketchum et al., 2013) and is the most precise age estimate that can be interpreted from our data. Together with the constraint from the Matachewan dykes, and also considering the new age of the nearby Murray Granite, 2460 ±6 Ma, we suggest that the age of the Copper Cliff Rhyolite and Creighton Granite magmatic system is 2455–2460 Ma. This is slightly older and more precise than previous estimates for the age of the Copper Cliff Rhyolite (Krogh et al., 1984; see also Ketchum et al., 2013). All our results are consistent with a sharply timed peak of felsic magmatism at ca. 2455–2460 Ma, immediately following the main pulse of Matachewan mafic magma input at ca. 2460 Ma. One zircon from the flow-banded rhyolite gave a younger age near the time of impact. This analysis is reversely discordant and plots at the young end of the mixing line from 2464 to 1850 Ma. This small equant grain (~50 µm) appears to have recrystallized as a consequence of the impact event, which would have reset its U-Pb systems at 1850 Ma.

12. Nipissing Diabase Sill, South of the Sudbury Igneous Complex, Conformable in Mississagi Formation Quartzite

We sampled one of the main Nipissing Diabase sills south of the SIC (Fig. 1). The sill is conformable with layering (i.e. bedding) in the surrounding Mississagi Formation quartzite, and both are folded into a tight east-plunging syncline. These observations are inconsistent with suggestions of a pre-Nipissing folding event in the area, the so-called "Blezardian orogeny"

(Frarey et al., 1982; Stockwell, 1982). The diabase sill hosts several late-stage pegmatoidal pods from which baddeleyite and skeletal zircon were extracted. U-Pb data for both minerals define a 2215 ±1 Ma upper intercept age with a lower intercept anchored at 0 Ma, which we interpret as a minimum age for the time of intrusion. If the grains were affected by some earlier Pb loss, a slightly older upper intercept in the 2215–2220 Ma range is possible. This new result is in agreement with previous age estimates on Nipissing Diabase (Corfu and Andrews, 1986; Noble and Lightfoot, 1992; see also Buchan et al., 1993).

13. Pre-Sudbury Igneous Complex Mafic Dykes, I

Rocks along the South Range are intruded by a variety of mafic dykes that post-date the Creighton Granite. Apart from the much younger and unmetamorphosed "Sudbury" olivine diabase dykes (e.g. Krogh et al., 1987), all of these are metamorphosed, in broad terms allowing an age range from ca. 2450 Ma to ca. 1600 Ma. On closer inspection, some of these metadiabase dykes are affected by Sudbury Breccia formation, whereas others post-date Sudbury Breccia and crosscut all SIC units. Trends of the metadiabase dykes vary from 040 to 100°, also suggesting more than one event. Many of these dykes have been referred to as "Trap dykes". The older of these dykes are difficult to date because they are typically less than 15 m wide and fully recrystallized. In a separate study, we have dated approximately east-west-trending diabase dykes well to the west of the SIC, and these were shown to be ca. 2105–2116 Ma (Bleeker and Chamberlain, in prep.), i.e., they belong to the Marathon large igneous province (Fahrig and West, 1986; Halls et al., 2008). We therefore suggest that dykes of this age likely extend into the Sudbury area and represent some of the pre-SIC dykes.

14. Pre-Sudbury Igneous Complex Mafic Dykes, II

Similar to the mafic dykes described above, and again well west of the SIC, a more northwesterly trending set of mafic dykes was also dated, yielding a preliminary baddeleyite age of ca. 1900–1950 Ma (Bleeker and Chamberlain, in prep.). Again, we suspect this event to be represented in the Sudbury area.

15. Mafic High-MgO Norite, Sudbury Igneous Complex

This unit consists of a dark, MgO-rich norite high in the norite "stratigraphy" of the South Range (Lightfoot and Zotov, 2005). It contains both baddeleyite and newly formed skeletal zircons. Zircon grains were pretreated by evaporating off labile Pb at high temperature, in vacuum within a mass spectrometer. The remainder of the grains were then dissolved and subjected to standard ID-TIMS analysis. Geological discordance cannot be determined by this method because of the Pb evaporation step but this does not disturb $^{207}Pb/^{206}Pb$ ages, which may represent the magmatic age if disturbed Pb was completely eliminated. Four analyses, each involving multiple zircons pretreated by evaporation, fully overlap and yield a precise weighted mean of 1849.7 ±0.2 Ma, with an MSWD of 1.16, representing the zircon crystallization age in this part of the norite stratigraphy. This age is comparable to ages obtained by Davis (2008).

16. Last Crystallizing Granophyre Phase, the "Crowfoot" Granophyre, Sudbury Igneous Complex

We consider the very coarse "Crowfoot" granophyre as a likely candidate for the last water- and incompatible element-enriched residual melt phase of the SIC. Using a similar strategy as described above for the norite, we hope to obtain a highly precise age for this stage of the crystallization history, thus constraining the overall time span of igneous crystallization and cooling of the SIC. Only crosscutting granitic dykes represent potentially younger melt phases (derived from melting of the footwall?), and could potentially add further insights. Work on these units is in progress.

17. Hess Offset Dyke, Outer Inclusion-Free Quartz Diorite ("QD")

As part of on-going efforts to date some of the recently uncovered offset dykes, we dated a homogeneous outer quartz diorite phase of the concentric Hess Offset dyke (Wood and Spray, 1998), in a new exploration trench northwest of the SIC. This particular sample was partly meant as a benchmark for other offset dyke data sets. The sample contained fresh unaltered baddeleyite. Four nearly concordant fractions define an age of 1849.1 ±0.9 Ma (regression through 0 Ma). This age is in agreement with the high-precision age on the norite (see section 15, *Mafic High-MgO Norite, Sudbury Igneous Complex,* above), and with previous U-Pb zircon and baddeleyite ages on offset dykes (Corfu and Lightfoot, 1996; Osterman et al., 1996).

18. Cascaden Offset Dyke, Northwest of the Sudbury Igneous Complex

The Cascaden dyke, which is also located to the northwest of the SIC, is a suspected radial offset dyke. It was discovered by Wallbridge Mining geologists. It is ~10–12 m wide and trends ~330º, with a subvertical attitude. It consists of fine-grained, somewhat more evolved, quartz diorite with a field appearance similar to that of other offset dykes. We have identified baddeleyite in thin section and U-Pb dating of this dyke is in progress.

19. Pele Offset Dyke, North of the Sudbury Igneous Complex

This interesting ~28 m-wide dyke is more evolved than typical South Range quartz diorite dykes. It is radial, essentially vertical, and clearly chilled against granitic country rocks. It contains small platy plagioclase phenocrysts, which near the margin are aligned in the magmatic flow. Evidently this dyke, if part of the SIC offset dyke system, was injected late and no longer was superheated, with plagioclase on the liquidus during emplacement and phenocrysts having grown to ~5 mm. A sample from the medium-grained centre of this dyke yielded baddeleyite, one fraction of which is fully concordant with a precise age of 1848.5 ±0.8 Ma. From this we conclude that this dyke is indeed part of the offset dyke system and one of the last dykes to be injected into the footwall. The precise age of this more evolved dyke provides a hint of the young end of the SIC crystallization time scale, with an overall duration on the order of ~0.5 to 1.0 Myr, from 1849.7 ±0.2 Ma to 1848.8 ±0.8 Ma. This estimate of the overall time scale of the high-temperature part of the thermal evolution is consistent with, but more precise than, that provided by hydrothermal titanite from overlying Onaping Formation breccia (1848.4 +3.80/-1.8 Ma, see Ames et al., 1998).

20. Post-Sudbury Igneous Complex "Trap Dykes", III, South Range of the Sudbury Igneous Complex

Metadiabase dykes, with sheared margins but otherwise essentially undeformed, form a distinct swarm of approximately east-west-trending diabase dykes across the South Range (Fig. 1). They cut across the SIC, the offset dykes, and some of the Ni-sulphide orebodies (P. Lightfoot, pers. comm.), and they also post-date most if not all of the folding in the SIC and Huronian Supergroup. Yet they are fully metamorphic in character, i.e., characterized by fully recrystallized metamorphic mineral assemblages. They must be significantly younger than 1850 Ma, yet old enough to see the regional metamorphism across the South Range. We have identified both micro-baddeleyite and late-stage zircon in these typically 5–15 m-wide dykes and dating is in progress. Our preliminary age, based on chemically abraded zircons, is 1748 ±5 Ma. We suggest that the name "Trap dykes" or "Trap dyke swarm" be reserved for these post-SIC dykes. They most likely relate to a post-Penokean rifting event in the evolving margin of southeastern Laurentia.

21. Northeast-trending Felsite Dykes

A distinct suite of very fine-grained, weakly porphyritic felsic dykes intrudes across the South Range. (Fig. 1). They are granitic in composition, with small phenocrysts of quartz, feldspar, and black biotite in a very fine-grained quartzofeldspathic matrix. They are near vertical, with a northeasterly trend, and are essentially undeformed, showing only minor faulting with quartz vein development. They post-date the Trap dyke swarm. Dating of these dykes is complicated by inheritance, as demonstrated by one of our samples, but a single concordant zircon analysis indicates a maximum age of intrusion at 1766 ±9 Ma. If confirmed, this would represent the onset of the post-Penokean granitoid events documented further south (e.g. Davidson et al., 1992; Sullivan and Davidson, 1993; Davidson and van Breemen, 1994; see also Corfu and Easton, 2001). The relatively undeformed character of these dykes near the SIC indicates that essentially all deformation of the South Range was in place by ca. 1766 Ma.

CONCLUSIONS

New U-Pb ages are presented on a suite of ~20 samples from the Sudbury area, together with new field observations. Some of the age data are preliminary or still in progress.

On the North Range of the SIC, our field observations and age data show that the Joe Lake Gabbro is a metagabbro unit within the Levack Gneiss Complex. It is not part of the East Bull Lake suite of early Huronian layered intrusions. As the latter intrusions were emplaced along the Archean-Paleoproterozoic unconformity, an early Huronian age for the Joe Lake Gabbro would severely limit the possible amount of impact excavation along the North Range. Now that the Joe Lake Gabbro is shown to be an Archean metagabbro, this constraint is removed, allowing significant differential uplift of the high-grade Levack Gneiss Complex to be part of the impact process.

Levels of shock metamorphism in zircons from the North Range footwall are much lower than on the South Range, suggesting that "ground zero" of the impact was well to the south, most likely in the Frood-Stobie to Copper Cliff area, just south of the (preserved) SIC proper. A preliminary analysis of all shatter cone data (e.g. Bray et al., 1996) also points to this area as the centre of the impact (W. Bleeker, unpubl. data). This suggests that all of the preserved SIC melt sheet merely represents an erosional remnant of one flank of a much larger melt sheet (Bleeker et al., 2014a). This has important implications for how to best interpret the overall "stratigraphy" of the SIC, for interpretation of the seismic section (Milkereit and Green, 1992; Wu et al., 1995), and for the final size of the impact structure (e.g. Spray et al., 2004). Nearly all previous studies have implicitly assumed that the centre of the impact is within in the preserved extent of the SIC.

On the southeastern limb of the SIC, we have dated a foliated granite as late Archean. The mafic volcanic rocks it intruded must therefore also be Archean, rather than basal Huronian (cf. compilation maps of the area: Dressler, 1984; Ames et al., 2006). A similar conclusion probably also applies to the Skead pluton somewhat further north. These findings require remapping of the area to better define the Archean–Paleoproterozoic unconformity. The layered anorthositic gabbro of the Falconbridge Township intrusion did not yield datable minerals and remains relatively poorly dated (Prevec and Baadsgaard, 2005).

Using chemical abrasion, the age of the Murray Granite has been refined to 2460 ±6 Ma, slightly younger and more precise than the previous estimate of 2477 ±9 Ma (Krogh et al., 1996), and in better agreement with field relationships.We also present the first robust and relatively precise age on the Creighton Granite, at 2455–2460 Ma, based on combined U-Pb data and field relationships. Analysis of six chemically abraded zircon crystal fragments from both the Creighton Granite and the Copper Cliff Rhyolite yield a combined upper intercept age of 2459 ±7 Ma. Our observations show that the Creighton Granite is a folded sill-like body that likely acted as the high-level magma chamber to the Copper Cliff Rhyolite Formation. Tight folding and tilting of this sill and the surrounding Huronian rift succession predated the impact and subsequent emplacement of the SIC. Magma-mingling structures show that the Creighton Granite interacted with mafic magmas, low in the Huronian rift structure, during and following the main pulse of Matachewan magmatism at 2460 Ma.

A tightly folded Nipissing Diabase sill has been dated at 2215 ±1 Ma. It is fully conformable with surrounding Huronian strata on the South Range, inconsistent with the concept of a pre-Nipissing "Blezardian orogeny". The main rationale for the Blezardian orogeny was the idea that deformation and intrusion of granite plutons, such as the Creighton Granite, thought to be ca. 2.3 Ga in age, terminated the depositional history of the Huronian succession (Frarey et al., 1982; Stockwell, 1982). None of these ideas are supported by present evidence. The Creighton Granite is an early Huronian 2455–2460 Ma rift-related granite, not an orogenic granite pluton; folding of the Huronian succession did not commence until well after emplacement of Nipissing Diabase sills and sheets with the onset of Penokean accretion and collision events at ca. 1860 Ma. Other observations that have contributed to the concept of a Blezardian orogeny can all be explained without a significant pre-Nipissing deformation event. For instance, saucer-shaped Nipissing sills locally may appear to crosscut Huronian strata and, after superimposed Penokean deformation, could easily lead to confusing field relationships.

Several new ages on "offset dykes" have been obtained (Hess, Pele), resolving that the radial Pele dyke is indeed part of the offset dyke system. The Pele dyke likely represents the youngest and last phase of SIC offset dyke injection. It carries phenocrysts, hence it was no longer superheated, and it was injected as a regular magmatic dyke, with chilled and relatively straight contacts. Its age of 1848.5 ±0.8 Ma provides a hint of the overall time scale of melt-sheet evolution and crystallization on the order of 0.5–1.0 Myr. A new highly precise ^{207}Pb/^{206}Pb age, obtained by a hybrid technique (see also Davis, 2008), dates zircon crystallization in South Range high-MgO norite at 1849.7 ±0.2 Ma.

Other dykes have been shown to be part of unrelated older dyke sets. We present the first evidence of a ca. 2507 Ma swarm in this part of the Superior craton, an age similar to that of the Mistassini swarm farther to the northeast. Other dykes west of Sudbury have been dated at ca. 2105–2116 Ma and ca. 1900–1950 Ma (Bleeker and Chamberlain, in prep.). The former, which we call the Blind River dykes, are part of the Marathon large igneous province. The latter define a new event in the southern Superior craton. Continental breakup along the southern margin of the Superior craton only occurred after most of these dyke swarms were emplaced, making the entire Huronian Supergroup an intra-continental rift and sag succession (Bleeker and Ernst, 2006; Ernst and Bleeker, 2010) and not a long-lived passive margin succession as commonly portrayed (e.g. Bennett et al., 1991; Young et al., 2001).

Trap dykes, a name we restrict to ~east-west-trending post-SIC dykes across the South Range, have a preliminary zircon age of 1750 Ma. Having identified both baddeleyite and zircon in these dykes, their U-Pb dating is in progress. They post-date most if not all of the folding of Huronian strata (and SIC) across the South Range and must be related to a post-Penokean rifting event in the evolving margin of southeastern Laurentia. Nevertheless, they are fully metamorphic and (statically) recrystallized. They are cut by a younger suite of essentially undeformed felsite dykes that have a preliminary age of 1766 ±9 Ma.

ACKNOWLEDGEMENTS

We thank Dave Smith and Joshua Bailey, from Wallbridge Mining Company, and Peter Lightfoot, from Vale, Sudbury, for helpful discussions and sharing some of their knowledge of the Sudbury Structure. Dave Smith guided us to some of their properties and pointed out possible offset dykes of interest. Peter

Lightfoot provided the sample of the MgO-rich norite. Mike Easton of the Ontario Geological Survey is thanked for discussion and critical reading of the manuscript. Proof reading of the final manuscript by Tony LeCheminant is also gratefully acknowledged. Elizabeth Ambrose handled the final editing and layout of the manuscript.

REFERENCES

Ames, D.E. and Farrow, C.E.G., 2007. Metallogeny of the Sudbury Mining Camp, Ontario. *In:* Mineral Deposits of Canada: A Synthesis of Major Deposit Types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods, (ed.) W.D. Goodfellow; Geological Association of Canada, Mineral Deposits Division, Special Publication No. 5, p. 329–350.

Ames, D.E., Watkinson, D.H., and Parrish, R.R., 1998. Dating of a regional hydrothermal system induced by the 1850 Ma Sudbury impact event; Geology, v. 26, p. 447–450.

Ames, D.E., Singhroy, V., Buckle, J., Davidson, A., and Molch, K., 2006. Integrated bedrock geology – Radarsat – Digital elevation data of Sudbury, Ontario. Geological Survey of Canada Open File 4571. Scale 1: 75,000.

Ames, D.E., Davidson, A., and Wodicka, N., 2008a. Geology of the giant Sudbury polymetallic mining camp, Ontario, Canada; Economic Geology, v. 103, p. 1057–1077.

Ames, D.E., Card, K., Wodicka, N., and Davidson, A., 2008b. 100K Geological map of the Sudbury mining camp and Surrounding area, Ontario, Canada; Supplement to Ames, D.E. and Wodicka, N., 2008, Geology of the Giant Sudbury Polymetallic Mining Camp, Ontario, Canada; Economic Geology, v. 103, p. 1057–077.

Bennett, G., Dressler, B.O., and Robertson, J.A., 1991. The Huronian Supergroup and associated intrusive rocks. *In:* Geology of Ontario; Ontario Geological Survey, Special Volume 4, Part 1, p. 549–592.

Bleeker, W. and Ernst, R.E., 2006. Short-lived mantle generated magmatic events and their dyke swarms: The key unlocking Earth's palaeogeographic record back to 2.6 Ga. *In:* Dyke Swarms—Time Markers of Crustal Evolution: Selected Papers of the Fifth International Dyke Conference, Rovaniemi, Finland, 31 July – 3 August, 2005 (also Fourth International Dyke Conference, Kwazulu-Natal, South Africa 26–29 June, 2001) (ed.) E. Hanski, S. Mertanen, T. Rämö, J. Vuollo; A.A. Balkema, Rotterdam, p. 3–26.

Bleeker, W., Hamilton, M.A., Ernst, R.E., and Söderlund, U., 2012. Resolving the age structure of the Matachewan event: Magmatic pulses at ca. 2445–2452 Ma, 2458–2461 Ma, and 2475–2480 Ma; unpublished CAMIRO Reports A96, A97, and A98, 17 p.

Bleeker, W., Kamo, S., and Ames, D.E., 2013. New field observations and U-Pb age data for footwall (target) rocks at Sudbury: Towards a detailed cross-section through the Sudbury Structure, *In:* Extended Abstracts; Large Meteorite Impacts and Planetary Evolution V Meeting, 5-8 August, Sudbury, Ontario, Lunar Planetary Institute contribution No. 1737, p. 13.

Bleeker, W., Kamo, S., Ames, D.E., 2014a. Towards a detailed geological cross-section of the deformed Sudbury impact basins: New observations and new geochronology (Presentation); Ontario Exploration and Geoscience Symposium, November 3-4, 2014, Sudbury.

Bleeker, W., Kamo, S., Ames, D., and Smith, D., 2014b. New U-Pb ages for some key events in the Sudbury area, including the Creighton Granite and Joe Lake metagabbro, *In:* Abstracts; Geological Association of Canada, Annual Meeting, May 21-23, Fredericton, New Brunswick, Abstract Volume 37, p. 32–33.

Bray, J.G, and Geological Staff, 1966. Shatter cones at Sudbury; The Journal of Geology, v. 74, p. 243–245.

Buchan, K.L., Mortensen, J.K., and Card, K.D., 1993. Northeast-trending Early Proterozoic dykes of southern Superior Province: multiple episodes of emplacement recognized from integrated paleomagnetism and U-Pb geochronology; Canadian Journal of Earth Sciences, v. 30, p. 1286–1296.

Card, K.D., 1994. Geology of the Levack gneiss complex, the northern footwall of the Sudbury structure, Ontario, *In:* Canadian Shield; Geological Survey of Canada, Current Research 1994-C, p. 269–278. doi:10.4095/193807

Corfu, F. and Andrews, A.J., 1986. A U-Pb age for mineralized Nipissing diabase, Gowganda; Canadian Journal of Earth Sciences, v. 23, p. 107–109.

Corfu, F. and Easton, R.M., 2001. U-Pb evidence for polymetamorphic history of Huronian rocks underlying the Grenville Front tectonic zone east of Sudbury, Ontario; Chemical Geology, v. 172, p. 149–171.

Corfu, F. and Lightfoot, P.C., 1996. U-Pb geochronology of the sublayer environment, Sudbury igneous complex, Ontario; Economic Geology, v. 91, p. 1263–1269.

Craddock, J.P., Rainbird, R.H., Davis, W.J., Davidson, C., Vervoort, J.D., Konstantinou, A., Boerboom, T., Vorhies, S., Kerber, L., and Lundquist, B., 2013. Detrital zircon geochronology and provenance of the Paleoproterozoic Huron (~2.4–2.2 Ga) and Animikie (~2.2–1.8 Ga) basins, southern Superior Province; The Journal of Geology, v. 121, p. 623–644. doi:10.1086/673265

Davidson, A. and van Breemen, O., 1994. U-Pb ages of granites near the Grenville Front, Ontario, *In:* Radiogenic Age and Isotopic Studies: Report 8; Geological Survey of Canada, Current Research 1994-F, p. 107–114.

Davidson, A., van Breemen, O., and Sullivan, R.W., 1992. Circa 1.75 Ga ages for plutonic rocks from the Southern province and adjacent Grenville Province: what is the expression of the Penokean orogeny? *In:* Radiogenic Age and Isotopic Studies, Report 6; Geological Survey of Canada, Paper 92-2, p. 107–107.

Davis, D.W., 2008. Sub-million-year age resolution of Precambrian igneous events by thermal extraction–thermal ionization mass spectrometer Pb dating of zircon: Application to crystallization of the Sudbury impact melt sheet; Geology, v. 36, p. 383–386.

Dietz, R.S., 1964. Sudbury structure as an astrobleme; Journal of Geology, v. 72, p. 412–434.

Dietz, R.S. and Butler, L.W., 1964. Shatter-cone orientation at Sudbury, Canada; Nature, v. 204, p. 280–281.

Dressler, B.O., 1984. Sudbury geological compilation; Ontario Geological Survey, Precambrian Geology Series, Map 2491, scale 1:50,000.

Dutch, S.I., 1979. The Creighton pluton, Ontario: an unusual example of a forcefully emplaced intrusion; Canadian Journal of Earth Sciences, v. 16, p. 333–349.

Ernst, R.E. and Bleeker, W., 2010. Large igneous provinces (LIPs), giant dyke swarms, and mantle plumes: Significance for breakup events within Canada and adjacent regions from 2.5 Ga to the Present. *In:* Special Issue on the theme LITHOPROBE—parameters, Processes, and the Evolution of a Continent. LITHOPROBE Contribution 1482 and Geological Survey of Canada Contribution 20100072; Canadian Journal of Earth Sciences, v. 47, p. 695–739, doi:10.1139/E10-025

Fahrig, W.F. and West, T.D., 1986. Diabase dyke swarms of the Canadian Shield; Geological Survey of Canada, Map 1627A, scale 1:4,973,900.

Faggart, B.E., Basu, A.R., and Tatsumoto, M., 1985. Origin of the Sudbury complex by meteoritic impact: Neodymium isotopic evidence; Science, v. 230, p. 436–439.

Frarey, M.J., Loveridge, W.D., and Sullivan, R.W., 1982. A U-Pb zircon age for the Creighton Granite, Ontario, *In:* Current Research, Part C; Geological Survey of Canada, Paper 82-1C, p. 129–132.

Grieve, R.A., Stöffler, D., and Deutsch, A., 1991. The Sudbury Structure: Controversial or misunderstood?; Journal of Geophysical Research: Planets (1991–2012), v. 96, p. 22753–22764.

Halls, H.C., Stott, G.M. and Davis, D.W., 2005. Paleomagnetism, geochronology and geochemistry of several Proterozoic mafic dike swarms in northwestern Ontario; Ontario Geological Survey, Open File Report 6171, 59 p.

Halls, H.C., Davis, D.W., Stott, G.M., Ernst, R.E., and Hamilton, M.A., 2008. The Paleoproterozoic Marathon large igneous province: new evidence for a 2.1 Ga long-lived mantle plume event along the southern margin of the North American Superior Province; Precambrian Research, v. 162, p. 327–353.

Heaman, L.M., 1997. Global mafic magmatism at 2.45 Ga: Remnants of an ancient large igneous province?; Geology, v. 25, p. 299–302.

James, R.S., Easton, R.M., Peck, D.C., and Hrominchuk, J.L., 2002. The East Bull Lake intrusive suite: Remnants of a ~2.48 Ga large igneous and metallogenic province in the Sudbury area of the Canadian Shield; Economic Geology, v. 97, p. 1577–1606.

Ketchum, K.Y., Heaman, L.M., Bennett, G., and Hughes, D.J., 2013. Age, petrogenesis and tectonic setting of the Thessalon volcanic rocks, Huronian Supergroup, Canada; Precambrian Research, v. 233, p. 144–172.

Krogh, T.E., Davis, D.W., and Corfu, F., 1984. Precise U-Pb zircon and baddeleyite ages for the Sudbury area, *In:* The Geology and Ore Deposits of the Sudbury Structure (ed.) E.G. Pye, A.J. Naldrett, and P.E. Giblin; Ontario Geological Survey, Special Volume 1, p. 431–447.

Krogh, T.E., Corfu, F., Davis, D.W., Dunning, G.R., Heaman, L.M., Kamo, S.L., Machado, N., Greenhough, J.D., and Nakamura, N., 1987. Precise U-Pb isotopic ages of diabase dikes and mafic to ultramafic rocks using trace amounts of baddeleyite and zircon, *In:* Mafic dyke swarms, (ed.) H.C. Halls and W.F. Fahrig; Geological Association of Canada, Special Paper 34, p. 147–152.

Krogh, T.E., Kamo, S.L, and Bohor, B.F., 1996. Shock metamorphosed zircons with correlated U-Pb discordance and melt rocks with concordant protolith ages indicate an impact origin for the Sudbury structure, *In:* Earth Processes: Reading the Isotopic Code (ed.) A. Basu and S. Hart; American Geophysical Union, Geophysical Monograph 95, p. 343–353.

Lightfoot, P.C. and Zotov, I.A., 2005. Geology and geochemistry of the Sudbury Igneous Complex, Ontario, Canada: Origin of nickel sulfide mineralization associated with an impact-generated melt sheet; Geology of Ore Deposits, v. 47, p. 387–420.

Mattinson, J.M., 2005. Zircon U–Pb chemical abrasion ("CA-TIMS") method: combined annealing and multi-step partial dissolution analysis for improved precision and accuracy of zircon ages; Chemical Geology, v. 220, p. 47–66.

Mattinson, J.M., 2011. Extending the Krogh legacy: development of the CA-TIMS method for zircon U-Pb geochronology; Canadian Journal of Earth Sciences, v. 48, p. 95–105.

Meldrum, A., Abdel-Rahman, A.F., Martin, R.F., and Wodicka, N., 1997. The nature, age and petrogenesis of the Cartier Batholith, northern flank of the Sudbury Structure, Ontario, Canada; Precambrian Research, v. 82, p. 265–285.

Milkereit, B. and Green, A., 1992. Deep geometry of the Sudbury structure from seismic reflection profiling; Geology, v. 20, p. 807–811.

Noble, S.R. and Lightfoot, P.C., 1992. U-Pb baddeleyite ages for the Kerns and Triangle Mountain intrusions, Nipissing Diabase, Ontario; Canadian Journal of Earth Sciences, v. 29, p. 1424–1429.

Osterman, M., Schärer, U., and Deutsch, A., 1996. Impact melt dikes in the Sudbury multi-ring basin (Canada): Implications from uranium-lead geochronology on the Foy Offset Dike; Meteoritics & Planetary Science, v. 31, p. 494–501.

Petrus, J., 2014. Mineralogical, chemical and isotopic evolution of impact bombarded rocks and minerals; Ph.D. thesis, Laurentian University, Sudbury, Ontario, 269 p.

Prevec, S.A. and Baadsgaard, H.B., 2005. Evolution of Paleoproterozoic mafic intrusions located within the SIC thermal aureole: Isotopic, geochronological and geochemical evidence; Geochimica et Cosmochimica Acta, v. 69, p. 3653–3669.

Pye, E.G., Naldrett, A.J., Giblin, P.E. (ed.), 1984. The geology and ore deposits of the Sudbury Structure; Ontario Geological Survey, Special Volume 1, 603 p.

Raharimahefa, T., Lafrance, B., and Tinkham, D.K., 2014. New structural, metamorphic, and U–Pb geochronological constraints on the Blezardian Orogeny and Yavapai Orogeny in the Southern Province, Sudbury, Canada; Canadian Journal of Earth Sciences, v. 51, p. 750–774.

Smith, M.D., 2002. The timing and petrogenesis of the Creighton pluton, Ontario: An example of felsic magmatism associated with Matachewan igneous events; M.Sc. thesis, University of Alberta, Edmonton, Alberta, 123 p.

Spray, J.G., Butler, H.R., and Thompson, L.M., 2004. Tectonic influences on the morphometry of the Sudbury impact structure: Implications for terrestrial cratering and modeling; Meteoritics & Planetary Science, v. 39, p. 287–301.

Stockwell, C.H., 1982. Proposals for time classification and correlation of Precambrian rocks and events in Canada and adjacent areas of the Canadian Shield, Part 1: A time classification of Precambrian rocks and events; Geological Survey of Canada, Paper 80-19, 135 p.

Sullivan, R.W. and Davidson, A., 1993. Monazite age of 1747 Ma confirms post-Penokean age for the Eden Lake complex, Southern Province, Ontario, *In:* Radiogenic Age and Isotopic Studies: Report 7; Geological Survey of Canada, Paper 93-2, p. 45–48.

Thomson J.E., 1957. Geology of Falconbridge Township. Ontario; Department of Mines Annual Report, v. 66, 36 p.

Young, G.M., Long, D.G., Fedo, C.M., and Nesbitt, H.W., 2001. Paleoproterozoic Huronian basin: product of a Wilson cycle punctuated by glaciations and a meteorite impact; Sedimentary Geology, v. 141, p. 233–254.

Wodicka, N., 1997. Sudbury structure: Northern footwall rocks and Sudbury Igneous Complex. *In:* Timmins to Sudbury transect: New Insights into the Regional Geology and the Setting of Ore Deposits, (ed.) D.E. Ames, W. Bleeker, K.B. Heather, and N. Wodicka; Geological Association of Canada–Mineralogical Association of Canada, Joint Annual Meeting, Ottawa '97, Field Trip Guidebook B6, 133 p.

Wood, C.R. and Spray, J.G., 1998. Origin and emplacement of offset dikes in the Sudbury impact structure: Constraints from Hess; Meteoritics & Planetary Sciences, v. 33, p. 337–347.

Wu, J., Milkereit, B., and Boerner, D.E., 1995. Seismic imaging of the enigmatic Sudbury Structure; Journal of Geophysical Research, v. 100, p. 4117–4130.