Polyorogenic reworking of ore-controlling shear zones at the South Range of the Sudbury impact structure: A telltale story from *in situ* U-Pb titanite geochronology

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Abstract

The post-impact orogenic evolution of the world-class Ni-Cu-PGE Sudbury mining camp in Ontario remains poorly understood. New temporal constraints from ore-controlling, epidote-amphibolite facies shear zones in the heavily mineralised Creighton Mine (Sudbury, South Range) illuminate the complex orogenic history of the Sudbury structure. *In situ* U-Pb dating of shear-hosted titanite grains by LA-ICP-MS reveals new evidence for shear zone reworking during the Yavapai (ca. 1.77 – 1.7 Ga), Mazatzalian - Labradorian (1.7 – 1.6 Ga), and Chieflakian - Pinwarian (1.5 – 1.4 Ga) accretionary events. The new age data show that the effects of the Penokean orogeny (1.9 – 1.8 Ga) on the structural architecture of the Sudbury structure have been overestimated. At a regional scale, the new titanite age populations corroborate that the Southern Province of the Canadian Shield documents the same tectonothermal episodes that are recorded along orogenic strike within the accretionary provinces of the southwestern United States.

Introduction

The 1.85 Ga Sudbury impact structure is a heavily mineralised, multi-ring impact structure, located at the crossroad of three Precambrian structural provinces at the Southern edge of the Canadian Shield (Krogh et al., 1982, Pye et al., 1984). The structure hosts vast reserves and resources of Ni-Cu-Platinum Group Element (PGE) mineralisation (Ames and Farrow., 2007) and has been the subject of a massive collection of research over the

last 120 years, however, questions remain about the structural evolution that led to the present-day geometry of the crater units and the orebodies that they host.

Accretionary and collisional events during and after the Sudbury impact event, led to the accretionary growth and crustal assembly of the Laurentia craton (Hoffman.,1988, Whitmeyer and Karlstrom., 2007). This accretionary evolution is documented in the north-central U.S. and the wider Great Lakes region with five temporally distinct events characterised as the: (a) Penokean (1.89 to 1.83 Ga; Sims et al., 1989), (b) Yavapai (1.77 to 1.7 Ga; Piercey et al., 2007), (c) Mazatzalian-Labradorian (1.7 to 1.6 Ga; Bailey et al., 2004), and (d) Chieflakian-Pinwarian events (1.5 to 1.4 Ga; Corfu and Easton., 2000) followed by pre-collisional events and the terminal collisional Grenvillian orogeny (*sensu stricto* 1090 – 980 Ma; Rivers., 2008).

The effects of these different events on the tectonothermal evolution of the Southern Province and the Sudbury impact structure have not been well understood. It has widely reported that the impact structure underwent orogenic deformation chiefly during the Penokean orogeny (Brocoum and Dalziel., 1974, Boerner et al., 2000). However, in the wider Lake Superior region, different folding episodes and the unroofing of gneiss domes, that had previously been attributed to the Penokean orogeny, are more likely associated with significantly younger orogenic overprints (Van Schmus, 1976, Schneider et al., 2004, Schulz and Cannon, 2007).

To elucidate the orogenic timeline at the South Range of the Sudbury structure and resolve in more detail the potential effects of Post-Penokean orogenic events, different ore-controlling shear zones from the deepest levels of Creighton Mine (**Figure 1**) were selected for detailed petrographic-microtectonic analysis and *in-situ* U-Pb titanite geochronology with the main aims to: (a) bracket the timing of events that induced shear zone operation/reworking, (b) characterise microstructures and syn-kinematic assemblages of the ore-controlling shear zones and (c) place, where possible, new temporal constraints on the tectonic remobilization of shear-controlled Ni-Cu-PGE sulphide ore bodies at the South Range of the Sudbury structure.

Geological setting of the Sudbury impact structure

The Sudbury impact structure (**Figure 1**) straddles the margin of the Archaean Superior Province and Paleoproterozoic Huronian Supergroup, and is one of the largest and oldest known impact structures on the planet. Three major units are recorded in the Sudbury impact structure: (a) the pseudotachylitic Sudbury Breccia, (b) the Sudbury Igneous Complex and (c) the Whitewater Group (Pye et al., 1984 and references therein). The Sudbury

structure is bounded at the north (North Range) by a complex of Neo-Archaeon tonalitic gneisses whereas at the south (South Range) is underlain by a complex of plutons, volcanosedimentary, and siliciclastic units of the Huronian Supergroup that belong to the Southern Province (Fairbairn et al., 1969). The post-impact metamorphic evolution of the Sudbury area is characterised by greenschist to epidote-amphibolite facies conditions with the maximum P-T conditions ($P = 4\text{--}5$ kbar, $T = 550\text{--}600^{\circ}\text{C}$, Fleet et al., 1987) recorded in the South Range, in spatial association with a system of moderately south-dipping, top-to-the-NW ductile and brittle thrusts known as the South Range Shear Zone (**Figure 1**) (Fleet et al., 1987, Shanks and Schwerdtner, 1991, Riller, 2005).

Figure 1

Shear zone families in the Creighton Deep Mine

Creighton Mine is located at the South Range of the Sudbury basin, within an embayment of the Sudbury Igneous Complex that hosts more than 200 Mt of Ni-Cu-PGE mineralization (**Figure 1**) (Lightfoot, 2017). The majority of the magmatic ore bodies in Creighton Mine are located either within a noritic unit with ultramafic inclusions (Sublayer) at the base of the Sudbury Igneous Complex, or in association with Huronian metamafic and plutonic bodies within the footwall. Mylonitic shear zones are spatially associated with sulphide ore bodies at different depths of Creighton Mine (**Figure 2**). The two shear zone families that were selected in this study are the 118 and the Hodder/315 system. The 118 system is characterized by steeply-dipping, ENE-striking, biotite-rich tectonites that are exposed at depths greater than 2.5 km below the surface (O'Donnell, 1979). The steeply dipping shear zones of Creighton deep Mine have been structurally correlated with a major transcurrent system of shear zones in the Southern Province, the Murray fault zone (Snelling et al., 2013). The latter is the easternmost continuation of an Archaean suture zone, the Great Lakes Tectonic Zone, that reactivated during the Yavapai interval accretionary event at ca. 1.76 Ga (Sims et al., 1980, Riller et al., 1999, Tohver et al., 2007).

The 118 system intersects at low angle the mineralised basal contact of the Sudbury Igneous Complex and comprises the following shear zones: (a) the Fresh Air Raise (FAR), (b) the Plum, (c) the 402, (c) the Return Air Raise (RAR), (d) the Northwest (NW) and (e) the North of NW shear zones (Snelling et al., 2013). In contrast, the Hodder/315 system is a structurally-distinct family of south-dipping mineralised shear zones with listric geometry that becomes prevalent at the deeper levels of the mine. Based on the orientation of shear fabrics and

supporting drillcore data, the Hodder/315 family of shear zones constitutes the down-dip extension of shear zones that belong to the network of the South Range Shear Zone (**Figures 1 and 2**).

Figure 2

Petrographic characterisation and microstructures

RAR and Plum shear zones (steeply-dipping family)

Biotite and hornblende grains dominate the mineral assemblage and define a penetrative planar fabric in the RAR shear zone (**Figure 3a**). Within lower strain domains of the shear zone, cm-scale alternations of biotite and hornblende-rich bands are observed. In high-strain domains, titanite grains are observed as euhedral grains in textural equilibrium with hornblende and biotite grains, whereas in lower strain domains they occur as anhedral grains with ilmenite cores and patchy zoning (**Figure 3b**).

In the Plum shear zone, quartzofeldspathic protomylonitic domains and meta-mafic mylonitic domains are observed. The quartzofeldspathic domain characterised by the assemblage: $Qz-Bt-Hbl-Pl-Ep \pm Aln \pm Ttn \pm Ap \pm Zrn \pm Po \pm Ccp$. Feldspar porphyroclasts show core and mantle microstructures with localization of chalcopyrite grains in the recrystallized mantles (**Figure 3c**), and contain linear bands with preferential recrystallization relative to adjacent intra-grain domains that also host Ccp grains. In lower-strain metamafic domains, hornblende, chalcopyrite, and pyrrhotite grains define locally a folded fabric (**Figure 3d**).

315 shear zone (shallow-dipping family)

The 315 shear zone comprises biotite-rich mylonites with the assemblage: $Bt-Qz-Hbl-Pl-Po-Ccp \pm Pn \pm Cal \pm Ttn \pm Zr$. Biotite laths, calcic amphiboles, and sulphide grains define a folded fabric (**Figure 3e**) that is locally transposed to a penetrative high-strain fabric defined chiefly by biotite grains (**Figure 3f**). Titanite grains are observed in reflected light as anhedral masses with patchy zoning and only locally in textural equilibrium with fabric-forming phases.

Figure 3

Sampling and methodology

Forty-eight samples were selected from different drillcores that intersect the RAR, Plum, and 315 shear zones at different depths below the 7800 level (2.37 km) of the Creighton Mine. Drillcore photographs and mineral assemblages from representative mylonitic samples of each drillcore are provided in **File 1** and **Table 1 (Supporting information)**, respectively. Nine mylonitic samples were selected for U-Pb titanite geochronology after detailed petrographic inspection. Titanite grains were targeted in reflected light maps of polished thin sections and imaged using backscatter electron (BSE) microscopy using different scanning electron microscopes at the University of Portsmouth (UK). U-Pb isotopic analyses (**Table 2, supporting information**) on selected titanite grains were performed using an ASI RESolution 193 nm ArF excimer laser coupled to a quadrupole Agilent 7500cs ICP-MS or PlasmaQuant Elite ICP-MS at the University of Portsmouth, UK. Instrumental setup and analytical conditions are provided in **Table 3 (Supporting information)**. Instrumental mass bias was corrected by sample-standard bracketing using the matrix-matched Khan titanite as the primary standard (ID-TIMS age of 522.2 ± 2.2 Ma, Heaman et al., 2009). To check the accuracy and precision of the analyses a variety of quality control secondary standards were interspersed between the unknowns, yielding results within uncertainty of the accepted reference values (**File 2; Supporting information**).

Electron beam imaging of titanite grains (Backscatter electron microscopy)

RAR and Plum shear zones

Titanite grains in the RAR shear zone are classified into two populations based on textural differences between the low and high-strain domains. Titanite grains within the low-strain domains are anhedral, show patchy zoning in BSE, and host ilmenite inclusions (**Figure 4a**). Titanite grains within the higher strain domains are in textural equilibrium with fabric-forming silicates, host ilmenite and apatite inclusions, and locally show recrystallization and polycrystalline amalgamation (**Figure 4b**).

Figure 4

In the Plum shear zone, the titanite grains are also characterised by patchy zoning, ilmenite cores, and subhedral patchily zoned apatite inclusions (**Figure 4c**). Euhedral rims that are darker in BSE images show sharp boundaries with biotite flakes. Crystal-plastic microstructures, such as sub-grains decorated by μm -scale darker films in BSE images, are locally recorded in titanites (**Figure 4d**). Other relatively abundant accessory phases that were detected include fractured zircons, and allanite grains that overgrow patchily zoned apatite grains.

315 shear zone

Titanite grains within the 315 shear zone exhibit overgrowth zoning (discontinuous core and rim domains with variable BSE response) (**Figure 4e**) and also show patchy zoning and ilmenite inclusions (**Figure 4f**). The patchily zoned grains locally show a strong shape-preferred orientation and are observed in textural equilibrium with biotite flakes. Local amalgamation of smaller patchily zoned euhedral grains is also observed.

***In situ* U-Pb titanite geochronology (Laser ablation – inductively coupled plasma – mass spectrometry)**

RAR and 315 shear zones

Forty U-Pb isotopic analyses were performed on anhedral, patchily-zoned titanite grains from the low-strain domains of the RAR shear zone. The analysed grains have low uranium contents, with a range of U concentrations from 1.16 to 6.74 ppm. The spread of U-Pb ratios defines a U-Pb isochron line in Tera-Wasserburg space that yields a regressed lower intercept $^{238}\text{U}/^{206}\text{Pb}$ date of 1730 ± 66 Ma (2σ , $n = 40$, MSWD = 2.2) (**Figure 5a**). The intersection of this regression line with the y-axis yields an initial $^{207}\text{Pb}/^{206}\text{Pb}$ isotopic ratio of 0.98 ± 0.04 . Twenty-eight additional analyses on euhedral titanite grains from the higher strain domains of the RAR shear zone, with average U concentration 14.48 ppm, define a regressed U-Pb isochron line with a lower intercept date of 1622 ± 25 Ma (2σ , $n = 28$, MSWD = 1.8) (**Figure 5b**). The initial $^{207}\text{Pb}/^{206}\text{Pb}$ isotopic composition of the younger population is estimated at 0.85 ± 0.16 and overlaps within uncertainty with that of the older population.

Thirteen U-Pb isotopic analyses ($n = 13$) were performed on titanites from one biotite-rich mylonite of the 315 shear zone. Eight analyses on grains with patchy zoning, with average uranium concentration of 21 ppm, yielded a lower intercept date of 1750 ± 39 (2σ , $n = 8$, MSWD = 0.83) with an initial $^{207}\text{Pb}/^{206}\text{Pb}$ isotopic ratio estimated at 0.92 ± 0.14 (**Figure 5c**). Five analyses from core and rim domains of the titanite population with

overgrowth zoning yielded a lower intercept date of 1656 ± 41 Ma (2σ , $n = 5$, $MSWD = 0.43$) with an initial $^{207}\text{Pb}/^{206}\text{Pb}$ ratio of 0.91 ± 0.09 (**Figure 5d**).

Figure 5

Plum shear zone

Twenty-eight U-Pb isotopic analyses were performed on patchily zoned titanite grains with ilmenite cores from two low-strain quartzofeldspathic samples of the Plum shear zone. The grains have average U concentration of 7 ppm and define on Tera-Wasserburg space a single U-Pb isochron with a regressed lower intercept $^{238}\text{U}/^{206}\text{Pb}$ date of 1453 ± 33 Ma (2σ , $n = 28$, $MSWD = 1.5$) (**Figure 6**). The initial $^{207}\text{Pb}/^{206}\text{Pb}$ isotopic composition of the analysed grains is estimated at 0.96 ± 0.02 .

Figure 6

Discussion and conclusions

The oldest titanite age populations of ca. 1.73 - 1.75 Ga in the RAR and 315 shear zones corroborate within analytical uncertainty a reactivation episode at ca. 1.75 Ga and provide further evidence for the orogenic deformation of the South Range during the Yavapai-interval event (Raharimarefa et al., 2014). Furthermore, the youngest age populations in the RAR and 315 shear zones showcase the reworking of shear fabrics at ca. 1.65 Ga, corroborating previous studies that highlight the effects of Mazatzalian – Labradorian orogeny in mines of the South Range (Bailey et al., 2004, Papapavlou et al., 2017).

However, the youngest age population of ca. 1.45 Ga, in the Plum shear zone provides, for first time, robust evidence that Huronian footwall rocks of the South Range underwent a Pre-Grenvillian thermal event. This event is well documented in proximity to the Grenville Front and is characterised as the Chieflakian – Pinwarian

event (Haggart et al., 1993, Krogh, 1994, Corfu and Easton, 2001). Taking into consideration the presence of ore remobilization textures (e.g. **Figures 3c and 3d**) and crystal-plastic deformation in the dated titanite grains of the Plum shear zone (e.g. **Figure 4d**), the ca. 1.45 Ga date possibly represents the youngest major event of sulphide kinesis in the mining camp.

On a regional scale, various geochronological studies demonstrate that the Proterozoic crust in the North American midcontinent has a similar tectonothermal evolution to the Proterozoic crust in accretionary provinces of southwestern United States (Holm et al., 1998, Holm et al., 2005, Van Schmus et al., 2007). The three age populations of ca. 1.75, 1.65 and 1.45 Ga in the three epidote-amphibolite-facies shear zones of Creighton Mine document reactivation, which possibly occurred as a response to far-field orogenic processes during the successive docking of various accretionary provinces to the southeast-facing Laurentia convergent margin. The new chronological constraints of this study cast doubt on the effects of Penokean orogeny (1.9 – 1.8 Ga) to the orogenic deformation of the Sudbury crater and ore systems, and illuminate a complex post-impact orogenic history.

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Figure captions

Figure 1. Simplified geological map of the Sudbury impact structure and adjacent lithotectonic provinces modified from Ames et al., (2008). The white rectangle highlights the Creighton Mine at the South Range of the Sudbury structure.

Figure 2. Model cross-section of Creighton Deep Mine constructed in DataMine that depicts the orientation relationships of the examined shear zones of the 118 and Hodder/315 families and their location relative to ore bodies. Note that the sulphide ore bodies are projected onto the model cross section.

Figure 3. Photomicrographs from the the RAR, Plum, and 315 shear zone samples that show: (a) a penetrative fabric in S-L tectonites of the RAR shear zone defined by hornblende and biotite grains; (b) the boundary between two domains with different fabric intensity on the RAR shear zone, with the lower strain domain (right) containing a titanite porphyroclast with weak shape-preferred orientation, and the higher strain domain containing a higher abundance of biotite and amphibole grains with a penetrative fabric; (c) a feldspar porphyroclast in the Plum shear zone that exhibits recrystallization in the rims (core and mantle microstructure) and within linear intragranular wedge-shaped bands (indicated with red triangles), with chalcopyrite (Ccp) grains preferentially located along the dynamically recrystallized rims of the feldspar porphyroclasts; (d) folded fabric in the Plum shear zone defined by hornblende grains, with sulphide grains with strong shape preferred orientation also defining the folded fabric; (e) folded fabric in the 315 shear zone defined by hornblende, quartz, and sulphide grains; (f) penetrative fabric defined by biotite in the 315 shear zone, with a band of recrystallized feldspar at the lower part of the photograph (mineral abbreviations based on Whitney and Evans, 2010).

Figure 4. Backscatter electron (BSE) images of titanite grains from the RAR, Plum and 315 shear zones that show: (a) anhedral titanite grain with patchy zoning and ilmenite core from the low-strain domains of the RAR shear zone; (b) a titanite grain with ilmenite inclusions from the high-strain domains of the RAR shear zone that is in textural equilibrium with fabric-forming biotite, and has sharp optical contacts between titanite and biotite matrix; (c) patchily zoned titanite grains with ilmenite and apatite inclusions from the Plum shear zone, with apatite grains that also show patchy zoning and are overgrown by allanite grains; (d) a titanite grain with ilmenite inclusions from the Plum shear zone, with subgrains that are decorated by darker films with anastomosing geometry; (e) a sector zoned titanite grain from the 315 shear zone with discontinuous core-mantle-rim domains that exhibit variable response in BSE; (f) a patchily zoned titanite grain with ilmenite inclusions from the 315 shear zone that shows a strong shape preferred orientation and is in textural equilibrium with fabric-forming biotite.

Figure 5. Tera-Wasserburg U-Pb concordia diagrams that show isotopic data from: (a) titanite grains hosted within the low-strain domains of the RAR shear zone; (b) titanite grains hosted with the higher strain domains of the RAR shear zone that contain more radiogenic Pb and show less spread in Tera-Wasserburg space; (c) titanite grains with patchy zoning from the 315 shear zone; (d) titanite grains with sector zoning from the 315 shear zone.

Figure 6. Tera-Wasserburg U-Pb concordia diagram that shows U-Pb isotopic data from titanite grains of the Plum shear zone.

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Whitewater Group

- Turbidite and siltstone
- Argillite and siltstone
- Suevitic breccia

Sudbury Igneous Complex

- Granophyre
- Quartz gabbro
- Norite
- Quartz diorite
- Ni-Cu-PGE ore

Footwall units and adjacent provinces

- Huronian metasediments and metamafic rocks
- Plutonic bodies
- Grenville Province
- Southern Province
- Superior Province

Structural boundaries and faults

- South Range Shear Zone
- Faults
- Grenville Front