Shock metamorphic features in mafic and ultramafic inclusions in the Sudbury Igneous Complex: Implications for their origin and impact excavation

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ABSTRACT
The lowermost, discontinuous parts of the impact-generated Sudbury Igneous Complex (Canada), comprising the Sublayer and Offset Dikes, are distinguished from overlying Main Mass norite rocks by the presence of abundant inclusions and Ni-Cu-PGE (PGE—platinum group element) sulfide mineralization. The majority of the felsic to mafic inclusions appear to be derived from the exposed country rocks, but the volumetrically important olivine-bearing mafic and ultramafic inclusions have only very rare equivalents in the surrounding country rocks. We record the discovery of abundant shock metamorphic features (e.g., mosaicism in olivine; strong fracturing and partial isotropization of plagioclase) in the olivine-bearing mafic and ultramafic inclusions consistent with a shock pressure of 20–30 GPa. Olivine compositional data are inconsistent with a local country rock or mantle origin for these inclusions. Abundant plagioclase, the absence of garnet or Mg-spinel, and calculated low pressures (<500 MPa) provide evidence for derivation of the inclusions from unexposed mafic-ultramafic intrusions in the upper to middle crust that were disrupted during formation of the transient crater, incorporated into the impact melt sheet, and preserved because of their relatively refractory compositions. These observations support models involving intermediate, rather than very deep or very shallow, excavation for the Sudbury impact event.

INTRODUCTION
The Sudbury Igneous Complex is located at the boundary between the Archean Superior Province and the Paleoproterozoic Southern Province in northeastern Ontario, Canada. It is one of the world’s oldest, largest, and best-exposed meteorite impact structures (e.g., Grieve and Therriault, 2000) and contains one of the world’s largest magmatic Ni-Cu-PGE (PGE—platinum group element) sulfide deposits (e.g., Lightfoot, 2016). Although there is evidence that the country rocks have been deformed by hyper-velocity impact (e.g., French, 1967), the proposed depth of impact has ranged from deep (as much as 40 km; e.g., Mungall et al., 2004) to shallow (<12 km; e.g., Darling et al., 2010). A better estimation of excavation depth is important in establishing the evolution of the Sudbury impact crater, the contributions of different rock units to the impact melt sheet, and the sources of metals in the associated world-class Ni-Cu-PGE sulfide deposits. Previous studies focused on geochemical and/or isotopic analyses of the impact melt sheet itself (Offset Dike margins, averaged Main Mass lithologies, or glass shards contained in the overlying Onaping Formation breccias). All of these studies invoke significant degrees of impact homogenization of, and post-impact modification by, the country rocks. The approach taken here is new. We have studied the shock metamorphic record in the refractory olivine-bearing mafic and ultramafic inclusions from the Sublayer and the Offset Dikes, which we argue are direct samples of the target rocks and provide better constraints on the depth of the impact process.

BACKGROUND
The Sublayer occurs discontinuously within embayments and troughs along the basal contact of the Sudbury Igneous Complex and contains a similar inclusion population to the Offset Dikes, which occur as concentric and radial dikes that extend as much as 20 km into the country rocks (e.g., Pattison, 1979; Lightfoot, 2016). The Sublayer and the Offset Dikes host, or are directly associated with, most of the contact and offset Ni-Cu-PGE ores in the Sudbury structure. As a result, they are important not only from a petrogenetic perspective, but also from an economic perspective.

The Sublayer and the Offset Dikes contain abundant inclusions, including felsic to mafic inclusions derived from local country rocks (Huronian metabasalts and metasediments, East Bull Lake mafic to anorthositic intrusions, and Nipissing mafic intrusions), and also abundant olivine-bearing mafic and ultramafic inclusions with only rare, poorly described potential equivalents in the surrounding country rocks (Naldrett et al., 1984). Some olivine melanorite inclusions have well-preserved igneous textures and are believed to have cognate origins involving contributions from (1) unspecified more primitive magmas (Corfu and Lightfoot, 1996), (2) mantle-derived magmas (e.g., Lightfoot et al., 1997), and/or (3) melted mantle-derived mafic country rocks (e.g., Prevec et al., 2000); however, most of the ultramafic inclusions have been proposed to be exotic (e.g., Pattison, 1979; Golightly, 1994). The olivine-bearing mafic and ultramafic inclusions range in size from centimeters to tens of meters, are typically rounded to subrounded, and are dominated by cumulate and poikilitic igneous textures. The lithologies include dunite and feldspar peridotite, pyroxenite, amphibole pyroxenite, olivine melanorite, and olivine gabbro, most of which contain 1%–10% phlogopite. The inclusions can be divided into four lithological, textural, and geochemical groups (see Fig. DR1 in the GSA Data Repository1).

SHOCK METAMORPHIC FEATURES
Shock metamorphic features are recognized in multiple samples in all four groups. Four group I feldspar peridotite inclusions are characterized by undulose extinction and partial isotropization of plagioclase. All 14 samples of group II wehlrite inclusions are characterized by dynamic recrystallization or shock mosaicism of olivine. Three group III olivine- and amphibole-bearing orthopyroxenite contain kink-banded phlogopite. Two group IV olivine melanorite inclusions display mosaicism of olivine and potentially “decorated” planar deformation features (PDFs) in orthopyroxene. This paper focuses mainly on mosaicism of olivine and partial isotropization of plagioclase.

Shock Mosaicism of Olivine
Olivine in heavily shocked rocks (20–30 GPa) is commonly characterized by mosaic...
The absence of any preferred orientation of disorientations (sometimes up to 20°) disorientations (Carter et al., 1968). The precise mechanism of mosaicism has not been established, but may be a result of intense fracturing and plastic flow on the scale of the crystal structure (Carter et al., 1968). The subsequent to irregular domains of impact mosaicism differ from plastic polygonization, which is characterized by slip bands, deformation lamellae, and kink bands (e.g., Raleigh, 1968); from dynamic recrystallization, which is characterized by subgrain rotation and dislocation glide (e.g., Falus et al., 2011); and from static recrystallization, which is characterized by more uniform grain sizes with 120° angles (e.g., Ragan, 1969).

Mosaicism is present in olivine in group II and IV inclusions. Sample 373555, a group IV inclusion from the Foy Offset, is a representative example where olivine occurs as 1–2 mm elliptical aggregates that exhibit smooth margins against the surrounding recrystallized plagioclase groundmass (Figs. 1A and 1B). The absence of any preferred orientation of the recrystallized olivine grains, or evidence of boundary migration of the elliptical olivine assemblages, precludes a strain-dependent (dynamic) recrystallization process. Although a few olivine subgrains exhibit 120° triple junctions, the wide range in sizes (10–200 μm) and wide variety of irregular grain shapes and contacts are unlikely to have been generated solely by static recrystallization. As a result, we suggest that primary olivine underwent shock mosaicism, which gave rise to variably small distortions of the crystal lattice, and was then thermally recrystallized during post-shock recovery and/or during incorporation into the Sublayer magma.

In addition, orthopyroxene also contains potential PDFs, which occur as pervasive parallel fractures (1–2 μm wide, 3–5 μm spaced) that are partially decorated by aligned fluid inclusions (Wang et al., 2016).

Shock mosaicism and PDFs usually form at a pressure of 20–30 GPa (Stöffler et al., 1991).

**Shock Metamorphism of Plagioclase**

Plagioclase is a common intercumulus phase in most ultramafic inclusions. Plagioclase in group I inclusions displays undulose extinction, pervasive fractures, and partial isotropization (Figs. 1C and 1D). The fractures are narrow (typically <3 μm wide), but variably spaced (typically 5–30 μm), occur in multiple orientations, and generally cut through plagioclase grains. Most are filled with unidentified Mg- and Fe-rich phases. Although different from the closed planar fractures and PDFs in typical shocked plagioclase (e.g., Chao 1967), the complex and open fracture networks observed in the plagioclase in Sublayer inclusions have been reported in shocked plagioclase in the Stannern meteorite (Czech Republic) and Peace River meteorite (Alberta, Canada) (Chen and Gorsey, 2000). The inhomogeneity on a micron scale, where glass and crystalline materials both occur, is common in shocked terrestrial rocks and meteorites (e.g., Kitamura et al., 1977).

We investigated unshocked and shocked plagioclase in a representative ultramafic inclusion (sample 373582) using micro-Raman spectroscopy. The analyses were performed using a Renishaw inVia Reflex Raman spectrometer at Surface Science Western in London, Ontario (Canada) using analytical procedures described by Fritz et al. (2005). Unshocked plagioclase (An$_{55}$) in a reference quartz gabbro sample from the Main Mass of the Sudbury Igneous Complex exhibits characteristic Raman bands at 188.9, 480.0, and 508.3 cm$^{-1}$, and a minor band at 797.0 cm$^{-1}$. Full widths at half maximum (FWHM) of the key 480.0 and 508.3 cm$^{-1}$ bands are 25.5 and 19.0 cm$^{-1}$, respectively (Fig. 2).

Shocked plagioclase is stoichiometric An$_{55-53}$ with no obvious zoning, and is characterized by pronounced short-frequency (<450 cm$^{-1}$) Raman bands peaking at 182.9 and 281.7 cm$^{-1}$ (spectrum 373582-1 in Fig. 2) and 186.6, 282.3, and 405 cm$^{-1}$ (spectrum 373582-2 in Fig. 2). The 405 cm$^{-1}$ band displays pronounced shoulders on both sides. The medium-frequency bands (450–520 cm$^{-1}$) exhibit decreasing width around 480 cm$^{-1}$ (FWHM = 20.8 cm$^{-1}$ in 373582-1, and 10.5 cm$^{-1}$ in 373582-2) and merge into the major band at 506.3 cm$^{-1}$ (373582-1) or 504.4 cm$^{-1}$ (373582-2). This phenomenon has been recorded in the Raman spectra of plagioclase in Martian meteorites (Fritz et al., 2005). Bands in the 450–520 cm$^{-1}$ range are attributed to the motion of bridging oxygens atoms in the “ring-breathing” modes of symmetric stretching in T-O-T linkages ($T$ = Si$^{4+}$, Al$^{3+}$) (e.g., Matson et al., 1986; Freeman et al., 2008). Therefore, variations in T-O-T bond angles (i.e., disorder of TO$_4$ tetrahedra) will affect the positions of medium-range bands. The observed variations in short and intermediate frequencies cannot be regarded as diagnostic of shock metamorphism because variations in composition and crystal orientation may also cause artificial variations in band properties (i.e., band broadening or reduced intensities). However, a longer-frequency band around 580 cm$^{-1}$ (580.8 cm$^{-1}$ in 373582-1, 584.4 cm$^{-1}$ in 373582-2) emerges as a shoulder on the band near 500 cm$^{-1}$. This shoulder is assigned to symmetric stretching vibrations of
three-membered Al-O ring structure, indicating the increased portion of this ring structure in pressure-induced amorphous CaAl2Si2O8 (Daniel et al., 1997). This band appeared in synthetic anorthite after being experimentally shocked to 30 GPa (Velder et al., 1989). Additionally, both shocked plagioclases analyzed in this study exhibit a pronounced broad band at 999.6 cm⁻¹ (373582-1) or 993.6 cm⁻¹ (373582-2), which has been observed in shocked anorthite (An₉₀) in lunar meteorite NWA773 (Freeman et al., 2008). The occurrence of this broad, medium-intensity band around 1000 cm⁻¹ in the spectra is diagnostic of the presence of CaAl2Si2O8 glass (Daniel et al., 1995, 1997). Thus, the Raman spectra indicate shock-induced partial isotropization of plagioclase at a pressure of 26–29 GPa (Stöffler et al., 1986).

MINERAL COMPOSITIONS

Olivine is commonly the first silicate mineral to crystallize from mafic-ultramafic magmas and therefore provides insights into deciphering the early crystallization history of the magmas and the characteristics of the magma source. Wavelength-dispersive X-ray spectrometric analyses of olivine in 56 olivine-bearing mafic and ultramafic inclusions (using an electron probe microanalyzer) reveals that the olivines display a wide range of composition (i.e., Fo₉₀₋₉₈ and 3992–621 ppm Ni). This is distinctly different from olivine in residual mantle peridotite (Fo₉₃₋₉₈ and 3000–1500 ppm Ni; Pearson et al., 2004). Notably, some individual samples contain olivine that is characterized by very high Ni contents (3992–3010 ppm), up to 1500 ppm higher than the dominant olivines with similar Fo contents (Fig. 3), and similar to the high values in olivine in basalts derived from pyroxenitic sources (e.g., Ni-rich olivines from the central Mexican volcanic belt [CMVB] in Fig. 3). The dominant olivines commonly form clusters defined by individual samples and/or samples from the same locations, but vary greatly between different samples and locations (Fig. 3). The variations in olivine compositions are not consistent with fractional crystallization or magma mixing, which would generate systematic trends, suggesting that the olivine-bearing mafic and ultramafic inclusions are derived from multiple crustal target sources with different compositions.

**GEOBAROMETRY**

The absence of garnet or Mg-spinel and the universal presence of plagioclase in the inclusion assemblages imply a depth <30 km (Green and Hibbleson 1970). In order to more precisely estimate the depth of derivation, we selected several olivine-bearing mafic and ultramafic inclusions from multiple localities that exhibited textural and mineral-chemical evidence of being in chemical equilibrium, and applied the olivine-clinopyroxene-plagioclase (Ol-Cpx-Pl) barometer of Ziberna et al. (2017) (see Table DR1 in the Data Repository). The results suggest that all of the inclusions equilibrated between 210 ± 112 MPa and 410 ± 157 MPa at depths between 7.7 ± 4.1 km and 14.9 ± 5.7 km, assuming a geobarometric gradient of 27.5 ± 1.4 km⁻¹ (equivalent to an average crustal density of 2800 kg m⁻³, consistent with the abundance of mafic intrusive rocks in the Huronian and Archean sequences). Given the widely accepted crustal thickness of 37–38 km in the Sudbury region (Winardhi et al., 2004 00 6008 00 1000 1200.
and Mereu, 1997) and the overwhelming upper crustal signature (after allowance for the great abundance of mafic intrusions in the Sudbury region) in the impact melt (Lightfoot, 2016), this suggests an upper to middle crustal origin for the inclusions, not a very shallow (e.g., Darling et al., 2010) or very deep (e.g., Mungall et al., 2004) excavation depth. The absence of any higher-pressure inclusions militates against an interpretation of deep impact.

CONCLUSIONS

Shock mosaicism of olivine and partial isotropization of plagioclase in olivine-bearing mafic and ultramafic inclusions in the Sublayer and the Offset Dikes provide near-unequivocal evidence for shock metamorphism at 20–30 GPa, and therefore an exotic origin of the inclusions. The dominant cumulate and poikilitic textures and low forsterite contents of olivine in all inclusions preclude the inclusions being direct samples of the subcontinental lithospheric mantle. The estimated low to moderate pressure of all samples and the absence of any higher-pressure samples support an upper to middle crust origin for these inclusions, and therefore a shallow to intermediate rather than deep impact depth.

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