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

Yujian Wang, C. Michael Lesher*, Peter C. Lightfoot, Edward F. Pattison, and J. Paul Golightly
Mineral Exploration Research Centre, Harquail School of Earth Sciences, Goodman School of Mines, Laurentian University, Sudbury P3E 2C6, Canada

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 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 wehrlite 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

---

1 GSA Data Repository item 2018137, Figure DR1 (trace element patterns of four groups), and Table DR1 (results of aPv calculations), is available online at http://www.geosociety.org/datarepository/2018/or on request from editing@geosociety.org.
texture, where olivine grains have been deformed into aggregates of small domains having 1°–5° (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 373572) 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 (An45) 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 An53–55 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 oxygen atoms in the “ring-breathing” modes of symmetric stretching in T-O-T linkages (T = Si4+, Al3+) (e.g., Matson et al., 1986; Freeman et al., 2008). Therefore, variations in T-O-T bond angles (i.e., disorder of TO4 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 (An93) 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 emission 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., Fo91-96 and 3992–621 ppm Ni). This is distinctly different from olivine in residual mantle peridotite (Fo92-98 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 Hibberson 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-clinoxyroxene-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 MPa 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
Acknowledgments

We thank K. Schulz, J. Mungall, and J. Darling for very generous access to their drill core samples and thin section material. The dominant cumulate and poikilitic textures provided insights into the structural evolution of the Sudbury region, which in turn provided an understanding of the origin of the Sudbury Igneous Complex. This research was supported by the Natural Sciences and Engineering Research Council of Canada, and a China Scholarship Council award to Wang.

Conclusions

Shock mosaicism of olivine and partial isotropization of plagioclase in olivine-bearing mafic and ultramafic inclusions in the Sublayer of the Sudbury Igneous Complex suggests an upper to middle crustal origin for these inclusions, not a very shallow (e.g., Darlington et al., 2010) or very deep (e.g., Mungall et al., 2004) excavation depth. The absence of any higher-pressure inclusions mitigates against an interpretation of deep impact.

References Cited

Carter, N.L., Raleigh, C.B., and Decarli, P.S., 1968, The evolution of olivine in sublayer rocks: Journal of Geophysical Research, v. 73, p. 5391–5406, https://doi.org/10.1029/JB073i016p05391.

Stöfler, D., Ostertag, R., Jannes, C., Pfannschmidt, G., Gupta, P.R., Simon, S.B., Papike, J.I., and Beauchamp, R.H., 1986, Shock metamorphism and petrography of the Shergotty achondrite: Geochimica et Cosmochimica Acta, v. 50, p. 889–903, https://doi.org/10.1016/0016-7037(86)90371-6.

Stöfler, D., Keil, K., and Scott, E.R.D., 1991, Shock metamorphism of ordinary chondrites: Geochimica et Cosmochimica Acta, v. 55, p. 3845–3867, https://doi.org/10.1016/0016-7037(91)90078-J.

Stauber, S.M., LaGatta, A.B., Martín-Del Pozzo, A.L., and Langmuir, C.H., 2008, Evidence from high-Ni olivines for a hybridized peridote/pyroxenite source for orogenic anesides from the central Mexican Volcanic Belt: Geochimisty Geophysics Geosystems, v. 9, p. 1–33, https://doi.org/10.1029/2007GC001583.

Velder, B., Syono, Y., Kikuchi, M., and Boyer, H., 1989, Raman microprobe study of synthetic dia- plactic plagioclase feldspars: Physics and Chemistry of Minerals, v. 16, p. 436–441, https://doi.org/10.1007/BF00197013.

Wang, Y., Lesher, C.M., Lightfoot, P.C., Patterson, E.F., and Golightly, J.P., 2016, Shock metamorphic features of olivine, orthopyroxene, and plagioclase in phlogopite-bearing ultramafic-mafic inclusions in Sublayer Sudbury Igneous Complex, Sudbury, Canada: Abstract 5082 presented at the 35th International Geological Congress, Cape Town, South Africa, 27 August–4 September.

Winardi, S., and Mereu, R.F., 1997, Crustal velocity structure of the Superior and Grenville provinces of the southeastern Canadian Shield: Canadian Journal of Earth Sciences, v. 34, p. 1167–1184, https://doi.org/10.1139/e97-094.

Zibetna, L., Green, E.C.R., and Blundy, J.D., 2017, Multiple-reaction geobarometry for olivine-bearing igneous rocks: The American Mineralogist, v. 102, p. 2349–2366, https://doi.org/10.2138/am-2017-6154.

Manuscript received 21 November 2017
Revised manuscript received 10 February 2018
Manuscript accepted 13 February 2018
Printed in USA

GEOLOGY