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The formation of the Sudbury breccia in the North Range of the Sudbury impact structure

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ABSTRACT

In the North Range of the ca. 1.85 Ga Sudbury impact structure, massive bodies of Sudbury breccia cut across the Archean Levack gneiss complex and Early Proterozoic Matachewan diabase dykes. The complex underlies the Sudbury Igneous Complex (SIC), which represents an impact melt sheet that lined the floor of the impact crater. The breccia occurs as 1–100 m wide irregular bodies that contain rounded clasts of diabase and tonalitic and dioritic Levack gneiss within a fine-grained to aphanitic, black to dark grey matrix. Mineral chemical analyses and Rietveld analyses based on X-ray diffraction patterns show that the breccia matrix contains microclasts of magnesiohornblende, oligoclase, and quartz, surrounded by metamorphic andesine laths, actinolite, Kfeldspar, albite, and chlorite, which crystallized during cooling of the SIC. On binary oxide-SiO_2 diagrams, breccia values plot on a compositional mixing line between those of the more felsic tonalitic gneiss and the more mafic dioritic gneiss and diabase. The breccia has concentrations in rare earth elements (REEs) intermediate between those of the dioritic and tonalitic gneisses and a REE pattern with a negative slope that is less pronounced than those of the gneisses. This is due to the addition of a minor diabase component that has a slightly negative REE slope, suggesting that the breccia is a mix of comminuted tonalitic gneiss, dioritic gneiss, and minor diabase. Comminution and cataclasis of these source rocks occurred along pre-existing anisotropies and fractures that formed and were reactivated during the growth and collapse of the transient crater. The comminuted materials mixed together as large bodies of breccia that were injected in dilational sites that opened during the upward expansion and collapse of the crater.

1. Introduction

The formation of large impact craters occurs in three stages: contact-compression, excavation, and modification of the impact crater (Melosh, 1989; French, 1998). During initial contact, the rocks in the contact zone between the colliding projectile and impacted rocks are strongly compressed generating a shock wave that propagates through the impacted rocks. The contact-compression stage ends when the projectile has transferred all its kinetic energy to the impacted rock and has been melted and vaporized because of the enormous pressures and associated temperatures generated during the impact. During the excavation stage, the expanding shock wave sets the impacted rocks in motion producing a subsonic excavation flow that expands the crater to the size of a short-lived transitory crater, called the transient crater. The transient crater comprises an excavated zone where the target rocks are brecciated, melted, and ejected outside of the crater, and a lower displaced zone where the target rocks are compressed downward and outward beneath the floor of the transient crater. The modification stage begins when the transient crater reaches its maximum size and starts collapsing due to gravitational instability of its rims and simultaneous rebound of the crater floor. The collapse of the rims of the crater occurs along normal faults forming ring structures that increase the final diameter of the crater. The three impact stages grade into one another. The contact-compression and excavation stage occur in seconds to minutes, and the modification stage occurs over a period of 30 min or less for a crater of the size of Sudbury although isostatic readjustment of the crater likely continued for several thousand years after the impact (Stöffler et al., 1994).

The ca. 1.85 Ga Sudbury impact structure (Fig. 1) is one of the largest terrestrial impact structures after Vredefort in South Africa and possibly Chicxulub in Mexico. It is interpreted as a 200–260 km diameter multiring impact basin, similar to those observed on the moon (Grieve et al., 1991; Stöffler et al., 1994; Deutsch et al., 1995; Spray et al., 2004). The Sudbury Igneous Complex (SIC), known worldwide for its Ni–Cu magmatic deposits, occupies the center of the structure. It formed as an impact melt sheet that differentiated

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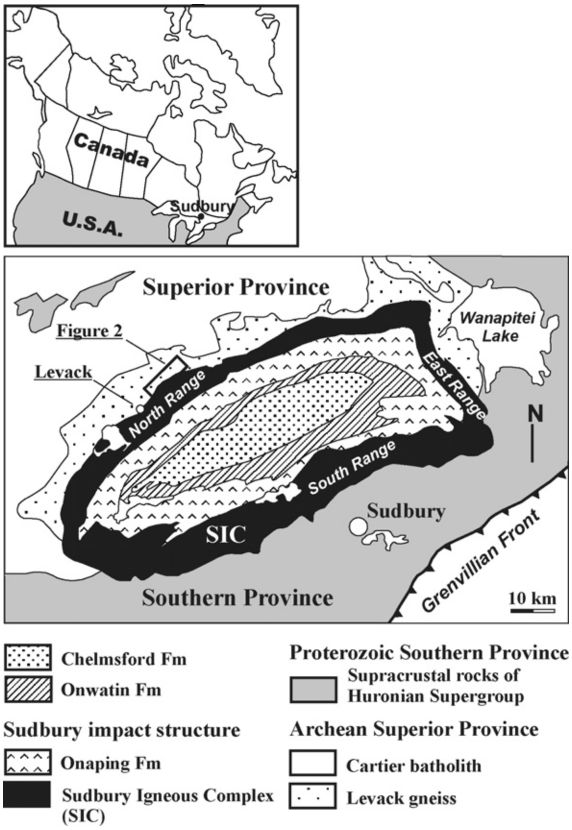

Fig. 1. Simplified geological map of the Sudbury impact structure, modified after Ames et al. (2005). Map of Canada with location of Sudbury.

into layers of norite, quartz gabbro, and granophyre during cooling beneath a ~2 km thick blanket of ejectas, fallback breccias, and iridium bearing plume collapse breccias of the Onaping Formation (Peredery, 1972; Ames et al., 1998, in press; Mungall et al., 2004), which insulated the SIC from surface (Grieve et al., 1991; Pope et al., 2004; Zieg and Marsh, 2005). Post-impact sedimentation buried the Onaping Formation impactites under mudstone of the Onwatin Formation and turbiditic sandstone of the Chelmsford Formation.

The Sudbury impact structure is geographically divided into the North Range, the South Range, and the East Range (Fig. 1). In the North and East Ranges, the SIC is in contact with the Archean Levack gneiss complex and Cartier Batholith of the Superior Province, whereas in the South Range, it is in contact with ca. 2.3–2.4 Ga plutons and Huronian Supergroup supracrustal rocks of the Early Paleoproterozoic Southern Province. Shatter cones and Sudbury breccia are volumetrically the most conspicuous, impact-generated, outcrop scale structures in the impacted rocks below the SIC (Dietz and Butler, 1964; Guy Bray, 1966; Dressler, 1984; Peredery and Morrison, 1984; Müller-Mohr, 1992; Ames and Farrow, 2007). Sudbury breccia is a pseudotachylitic breccia that originated by comminution and possibly melting of the impacted rocks during the excavation and modification stages of the impact (Dietz and Butler, 1964; Dressler, 1984; Müller-Mohr, 1992; Thompson and Spray, 1994; Spray and Thompson, 1995; Spray, 1997; Scott and Benn, 2002; Legault et al., 2003; Rousell et al., 2003; Dressler and Reimold, 2004; Riller, 2005). Although considerable research has been done on impact breccias in general (see reviews by Reimold, 1995, 1998; Dressler and Reimold, 2004; Reimold and Gibson, 2005), several questions remain on the relative importance of cataclasis, frictional melting, and shock melting in the formation of these breccias, on the origin of the fractures and faults hosting the breccias, and on the scale of mobilization or injection of breccias during an impact event. Whether zones of breccias played active roles in facilitating the expansion and collapse of craters or are simply passive shock metamorphic products is another interesting question requiring further research. To answer some of these questions, we mapped the distribution of the Sudbury breccia, its orientations and internal structures, in a 2 km wide by 7 km long area immediately underlying the SIC in the North Range (Fig. 1). We analyzed the major and trace element composition of the breccia and host rocks and mapped changes in the attitude of pre-impact Archean structures to determine how footwall rocks behave on map scale during large impacts. This area was chosen because Sudbury breccia is more abundant immediately below the SIC, and the North Range escaped the post-impact reverse faulting event that imbricated the South Range (Rousell, 1984; Shanks and Schwerdtner, 1991). Our results suggest that Sudbury breccia in the North Range formed by cataclasis in the displaced zone of the transient crater during outward expansion and inward collapse of the crater. It represents a comminuted mix of two main source rocks, tonalitic and dioritic Levack gneiss, which was injected in dilatational zones and fractures that opened during collapse and rebound of the crater floor.

2. Geology of the Levack gneiss complex in the North Range

The study area extends from the Levack embayment, a semicircular trough in the footwall contact of the SIC, to the town of Levack 7–8 km to the west (Fig. 2). It comprises the current and past-producing Longvack, Coleman, Levack, and McCreedy mines. The deposits consist of massive Ni–Cu magmatic ore zones located at the base of the SIC and adjacent underlying footwall rocks, and vein-type Cu–Ni-PGE (i.e. platinum group element) and disseminated low-sulphide high-PGE ore zones that are generally associated with Sudbury breccia bodies that cut through the Levack gneiss complex.

The Archean Levack gneiss complex is an assemblage of banded and migmatitic tonalitic, granodioritic, and dioritic gneisses with interspersed small metapyroxenite and gabbroic bodies and minor paragneisses (Langford, 1960; Card, 1994). Tonalitic to granodioritic gneiss is the dominant rock unit in the study area. It consists of plagioclase, clinopyroxene, quartz, biotite, and hornblende, with lesser orthopyroxene, garnet, apatite, and magnetite. Discontinuous bodies of dioritic gneisses occur within the tonalitic gneiss. Dioritic gneiss differs from the tonalitic gneisses by a greater abundance of orthopyroxene and clinopyroxene and by a lesser abundance or lack of quartz. Metapyroxenite forms small, <50 m thick, massive slivers that are composed almost exclusively of brown hornblende with minor clinopyroxene, plagioclase, biotite, apatite, and magnetite.

A continuous penetrative gneissic foliation is observed across the Levack gneiss complex. It is defined by plagioclase ± quartz felsic bands, alternating with mafic bands that are richer in clinopyroxene, hornblende, biotite, ±orthopyroxene. The gneissic foliation is steeply dipping and show similar orientation patterns across the map area. On stereonet diagrams, poles to foliation show small circle distributions with cone axes plotting in the northeast stereonet quadrant for structural domains A and B and in the northwest quadrant for structural domain C (Fig. 2). These orientation patterns result from the superposition of two or more generations of folds overprinting the gneissic foliation (Legault, 2008).

The Levack gneiss complex has primary ages ranging between 2711 ± 7 and 2635 ± 5 Ma (Ames et al., in press). The time of upper amphibolite to granulite facies metamorphism and deformation is constrained between ca. 2647 Ma, the age of a pegmatite and a mafic granulite, and ca. 2644 Ma, the age of a cross-cutting massive granite (Krogh et al., 1984; Ames et al., in press). This