**THE SUDBURY STRUCTURE: AN EMERGING PERSPECTIVE; R.A.F. Grieve[1], D. Stöffler[2] and A. Deutsch[2], [1]Geol. Surv. Canada, Ottawa, Canada, [2]Institut für Planetologie, Münster, Germany**

<u>INTRODUCTION</u> The Sudbury Structure covers an area > 15,000 $km^2$ and is a collective term for the, presently elliptically shaped, Sudbury Igneous Complex (SIC), the interior Sudbury Basin (SB) and the surrounding brecciated basement rocks of the Superior and Southern Provinces of the Canadian Shield. Previous work ascribed its origin to impact with the formation of a crater in the 50 to 100 km size range, followed by igneous intrusion to account for the SIC. While the impact origin has many adherents, volcanic origins are still proposed (1). Thus, the Structure remains controversial and it is the only terrestrial impact structure with a component of internally generated magmatism. Based on recent field work and analysis by the Münster group (e.g., 2, 3), in cooperation with the Ont. Geol. Surv. (B. Dressler), and a better understanding of cratering processes (4, 5,), we have come independently to equivalent conclusions regarding the Sudbury Structure. Namely, the original impact structure was larger than previously believed and the SIC, together with the Basal Member of the overlying Onaping Formation, represent an impact melt system.

<u>SIZE</u> While we recognize that large craters are less efficiently excavated than smaller craters, we have attempted to derive the size of the original impact structure by analogy. The relevant observations are: (i) downfaulted outliers of Huronian supracrustal cover rocks ~ 20-25 km from the outer edge of the SIC. Such outliers are generally considered to have originated outside the transient cavity rim. If the predeformation center of the crater is assumed to be the center of the SB, this constrains the transity cavity radius to ≤ 50-55 km. (ii) breccia dikes (Sudbury Breccia) extending out for ~ 35 km from the edge of the SIC. Comparison with breccia occurrences at other structures (4) suggests a transient cavity radius of 50-55 km. (iii) Shatter cones, indicative of shock pressures ≥ 2 GPa up to 20 km from the SIC. Shatter cones occur just inside the transient cavity at other structures, constraining the transient cavity radius to ≥ 50 km. (iv) Planar features in quartz, recording pressures of ≥ 6 GPa, up to 8 km from the SIC. At Charlevoix (D = 55 km), shock pressures in this range occur at ~ 0.7 of the transient cavity radius. By analogy, the transient cavity radius is again constrained to ~ 55 km. These constraints and estimates are all consistent and suggest a transient cavity diameter in 100 km range. Depending on the relationship between transient and final diameters (6, 7), this translates to a final crater diameter of 175-200 km. This is larger than most previous estimates (8, 9, 10) but is similar to some more recent estimates (3, 11).

<u>IGNEOUS COMPLEX</u> A characteristic of complex craters in crystalline targets is an annular impact melt sheet within the crater. When not present, its absence is ascribed to erosion. If one accepts that the Onaping Formation is a polymict breccia, largely analogous to a fall back breccia, then it corresponds to a unit that normally overlies a melt sheet. Erosion, therefore, cannot be invoked and the melt sheet must also be present. The only viable candidate for such a melt sheet is the SIC. Previously, the SIC was rejected as an impact melt as its volume was in excess of that expected for the Sudbury event (9, 10). Using the relation Volume of Melt = $3.8 \times 10^{-4} D^{3.4}$ (12), the expected volume of melt is ~ $2 \times 10^4$ $km^3$. Thus, more than sufficient melt is available for the SIC, present estimated volume of $3\text{-}4 \times 10^3$ $km^3$ (9), to be an erosional remnant of a melt sheet.

The lithological stratigraphy at Sudbury is generally consistent with this hypothesis: basement with indications of structural uplift (granulite facies Levack Gneisses), which is cut by breccia dikes (Sudbury Breccia) and impact melt dikes (Offset Dikes), overlain by a parautochthonous mega-breccia (Footwall Breccia), then basal melt with lithic debris (Sublayer), coarser grained clast free melt (Main Mass of SIC), a capping of clast-rich melt (Basal Member, Onaping Formation), and finally a sequence of suevite-like clastic matrix breccias (Grey, Green and Black Members, Onaping Formation).

Also consistent is the unusual chemistry of the SIC, with its high $SiO_2$ and $K_2O$ content and enrichment in light REE compared to other mafic layered intrusions. The high radiogenic Sr component and the large negative $\epsilon_{Nd}$ values are compatible with a crustal source and an Archean model age (13, 14). Proponents of an igneous origin for the SIC ascribe these chemical affinities to major (> 50%) crustal contamination (15). This would require the SIC to be superheated, which is not a characteristic of endogenic igneous rocks, but rather of impact melt rocks. If the SIC is a melt sheet, its composition should mirror the target rocks. The main lithologies at Sudbury are 5-10 km of Proterozoic supracrustal rocks (Huronian Supergroup), overlying Archean granite-greenstone terrain (Abitibi Subprovince) and high grade gneisses (Levack Complex). Least-squares mixing models produce a statistically acceptable mix for the average SIC composition from ~ 95% average Abitibi granite-greenstone and 5% Huronian sediment, without the need for an admixture of a mantle-derived igneous component. An equally acceptable mix can be obtained from 55% granite, 42% mafic metavolcanics and 3%

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felsic metavolcanics (Table 1). The first mix may be more geologically reasonable, as Huronian clasts are characteristic of the upper part of the SIC (the granophyre) and the melt breccia of the Basal Member of the Onaping Formation. Similarly, the bulk of material melted in an impact event comes from a volume at and below the maximum depth of penetration. For a Sudbury-sized event that would be in the 5-10 km range, i.e., below the Huronian Supergroup. Thus, the volume melted would be largely in Archean basement, which is consistent with mixing model results and the isotopic data.

As relative melt volume increases with crater size (15), the melt volume at Sudbury would be a substantial fraction of the transient cavity volume, with the depth of melting greater than the transient cavity floor. Thus, the melt would be relatively clast free and there would be no central positive topographic peak, which are characteristics of the SIC and the Structure, respectively. Local contact zones and their variation and apparent contradictory age relations for the Sublayer and main body of the SIC and the Basal Member of the Onaping Formation have analogies at other large melt sheets and represent minor flow contacts and internal cooling boundaries formed as the SIC cooled and responded to relatively late structural adjustments. The SIC is a differentiated melt complex. This is not a characteristic of terrestrial impact melt sheets analysed to date. The SIC, however, is the largest known melt sheet. It would cool more slowly than smaller sheets analysed previously and would tend to differentiate. Furthermore, endogenic models for the SIC call for in situ differentiation (16). If a SIC magma can differentiate, so can a SIC impact melt sheet.

CONCLUSIONS An impact origin for the SIC has important ramifications. It removes much of the complication in the geologic history of the area and allows the Structure and its associated lithologies to be interpreted within a single process. Observations at the Structure have a direct analogy to planetary studies, with it representing the best preserved, possibly multi-ring, impact basin on the Earth. It also means that clast-free, igneous textured rocks, which form a differentiated sequence, can be produced in a basin-sized impact event. This blurs the simple textural distinction between endogenic and impact melts and has important implications for the interpretation of "igneous" lunar highland rocks. It may also have consequences for the recently recognized problem of the paucity of impact melt rocks older than 3.9 b.y. (17) in the geologic record of the moon.

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| TABLE 1 | Components | | Igneous Complex | | Components | | | Igneous Complex | |
|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 3 | 8 |
| $SiO_2$ | 63.5 | 84.1 | 64.3 | 64.6 | 71.3 | 55.0 | 70.6 | 64.3 | 64.4 |
| $TiO_2$ | 0.7 | 0.2 | 0.8 | 0.7 | 0.5 | 1.1 | 0.5 | 0.8 | 0.7 |
| $Al_2O_3$ | 16.0 | 9.7 | 14.9 | 15.7 | 15.8 | 15.7 | 15.1 | 14.9 | 15.7 |
| $FeO_T$ | 6.3 | 1.5 | 6.7 | 6.1 | 2.2 | 10.8 | 4.2 | 6.7 | 5.9 |
| MnO | 0.1 | 0.01 | 0.1 | 0.1 | 0.7 | 0.2 | 0.1 | 0.1 | 0.1 |
| MgO | 3.2 | 0.5 | 2.9 | 3.1 | 0.7 | 5.7 | 1.7 | 2.9 | 2.9 |
| CaO | 4.8 | 0.2 | 4.1 | 4.5 | 2.0 | 8.0 | 3.1 | 4.1 | 4.6 |
| $Na_2O$ | 3.0 | 2.5 | 3.3 | 3.3 | 4.0 | 2.8 | 3.0 | 3.3 | 3.5 |
| $K_2O$ | 1.96 | 1.4 | 2.9 | 1.9 | 3.4 | 0.5 | 1.6 | 2.9 | 2.1 |
| % in mix | 95 | 5 | | | 55 | 42 | 3 | | |
| Reduced $\chi^2$ | | | 0.40 | | | | | 0.63 | |

1. Average Abitibi orogenic belt, 2. Lorrain arkose, 3. Average Sudbury Igneous Complex, 4. Calculated mix from 1 and 2, 5. Average local Sudbury Granite, 6. Average Superior Province mafic metavolcanic, 7. Average Superior Province felsic metavolcanic, 8. Calculated mix from 5, 6 and 7.