SOLIDIFICATION OF THE SUDBURY IMPACT MELT BODY AND NATURE OF THE OFFSET DIKES - THERMAL MODELING.

B. A. Ivanov[1], A. Deutsch[2], M. Ostermann[2], and A. Ariskin[3];[1]Inst. f. Dynamics of Geospheres, Russian Acad. Sci., Moscow, Russia 117939 (baivanov@glasnet.ru); [2]Inst. f. Planetologie, Univ. Münster, D-48149 Münster, Germany (deutsca@uni-muenster.de); [3]Vernadsky Inst. f. Geochemistry and Analytical Chemistry, Russian Acad. Sci., Moscow, Russia 117334 (ariskin@glasnet.ru).

Summary. The Sudbury Igneous Complex (SIC) is interpreted as the solidified impact melt body of the 1.850 Ga Sudbury Structure. We present first results of thermal modeling for this about 250 km seized multi-ring impact structure: Cooling of the impact melt sheet form the initial temperature of 2000k below liquidus at 1450K lasted about 100 ka, and below the solidus at 1270K, about 300 ka. The Offset Dikes, consisting of differentiated melt material, were formed within 500 ka after the impact event. Uncertainties to these time constraints are on the order of a factor two.

Introduction. The Sudbury Igneous Complex (SIC), together with the clast-rich sequences on top (Basal Member - Onaping Formation) and bottom (Sublayer) are convincingly interpreted as the solidified impact melt body of the about 250 km seized, 1.850 Ga Sudbury multi-ring impact structure [1]. Post-impact tectonism resulted in deformation of this melt body, and overthrusting of the South Range [2, 3], finally yielding an elliptically shaped bowl - the SIC. According to LITHOPROBE investigations the maximum depth of this bowl is 6 km below present surface [e.g., 2, 4].

Reconstruction of the deformation allows to restore the initial geometry of the SIC as melt sheet with a thickness of about 2.5 km covering the inner depression of the Sudbury crater with a diameter of approximately 60 km, and overburden by about 3 km of impact-related breccias and post-crater deposits [1]. The SIC is the largest known terrestrial impact melt sheet with an estimated volume of 1 to 2.5 x 10^4 km^3. The principle difference of the impact melt pool at Sudbury to impact melt layers in smaller craters is that due to its large size, solidification took much longer time. This time was sufficient to allow chemical differentiation of the initially rather homogeneous melt into the three main lithologies of the SIC: a thick upper layer of Granophyres, underlain by Quartz-Gabbro and quartz-rich Norites.

In this context, it is interesting to note that the geochemical composition of the material solidified in the Offset Dikes around the main SIC body match that of the Norite [5]. This observation indicates that Offset Dike formation occurred not simultaneously with the cratering event but only after the onset of differentiation during late stage adjustments of the crater basement. We can, however, imagine an alternative origin of the Offset Dikes. They may represent fractures in the crater floor, filled from above with impact melt. This possibility would imply an melt pool, initially much larger than the SIC at its present erosional level. In favor of the latter hypothesis is the presence of concentric Offset Dikes, which strike parallel to the outer margin of the SIC. To judge between these alternatives requires additional geochemical work on Offset samples in combination with proper modeling of the original crater morphology and the cooling history of the melt pool.

Thermal modeling. We made simple estimates (1D implicite numerical code) to evaluate the cooling history of the SIC body. The geometrical constraints of the model are three flat layers, *i.e.*, (i) overburden material with a thickness of 2.5 km , resting on (ii) a 2.5 km thick melted layer, which in turn is underlain by (iii) rocks of the lower crust, uplifted by about 20 km above pre-impact level. The surface boundary conditions of layer (i) are held constant at a temperature of 300K; temperature within layer (i) ranges from 300K ("cold breccia") to 850K ("hot suevite"). Melt layer (ii) has an initial temperature of 1800 to 2000K. For layer (iii) a constant temperature of 500K was assumed from the interface with the SIC down to the "undisturbed" depth of 20 km. More exact estimates of a sub-crater temperature field should take into account shock heating, and modification of the geothermes during the crater rebound. Thermal constants used in our calculations were those, which have been used for thermal modeling of the Manicouagan crater [6].

We obtained the following results for the impact melt layer of the Sudbury Structure: The time needed for a decrease of the initial temperature below the liquidus point (assumed at 1450K) is about 100 ka, and below the solidus point (assumed at 1270K), about 300 ka. In contrast, this time span is only 1 ka for the 200 m thick melt sheet of the Manicouagan structure [6].

Our result simply reflects the $[length]^2/[time]$ scaling. A factor of 2 is assigned as minimum uncertainty to the solidification time of the SIC due to uncertainties in thermal properties and boundary conditions. 2D or 3D thermal modeling, and convective heat transfer inside the melted body also can modify the numbers, however, the order of magnitude from our simple estimate will remain unchanged. It is, therefore, concluded that Offset Dike's formation should have occurred no later than 0.25 to 0.5 Ma after the impact; this estimate is much tighter than recent high-precision dating results. U-Pb crystallization ages of zircon and baddeleyite, separated from quartz-dioritc lithologies of the Foy Offset Dike [7], and in the main body of the SIC [8] are identical within the given error limits of +4/-3 Ma (2σ). Present available geochronological methods are not sufficient for still better resolving the succession of events; whereas, thermal modeling yields a more detailed time frame.

Another useful outcome of the modeling are the temperature estimates for the contact of the melt pool with crater floor lithologies, and for rocks beneath this contact. Mineralogical estimates, based on geothermometry, indicate a maximum temperature of up to 1300K close to the contact, and of 850K, 1.2 km below. First results of thermal modeling (Fig. 1) give ~1200K for the lower SIC/Footwall contact. The temperature 1.2 km below the contact gradually grows and reaches the maximum of 950K only 400 ka after the impact. This temperature compares well with geothermometric estimates of 850K. Future fitting of model and observational data will allow to set strict constraints for the whole scenario of the Sudbury crater formation. In this context, evaluating maximum temperatures in country rocks close to the Offsets is an important goal of future petrological investigations. Such temperatures will help to approve or reject the aforementioned possibility of Offset formation at the bottom of a much larger impact melt pool.

Thermal modeling allows us to follow with geochemical modeling of the SIC differentiation using the COMAGMAT phase equilibria model [10] and the bulk SIC composition given by [11] as initial conditions. Principal, yet preliminary results are: (i) the liquidus is definitely below 1150C (the modeled value is 1115C), (ii) Orthopyroxene is a liquidus phase, whereas, plagioclase is the third crystallizing phase. The question arises if the observed plagioclase is a cumulative or intercumulus phase. If plagioclase is cumulative, we should change dynamic parameters of the model in order to obtain cumulative "norites". This problem is important for understanding the thermal and geochemical evolution induced by giant impacts in the terrestrial and lunar crust [12].

Outlook. Several important questions raise from the outlined thermal scenario. We will concentrate on these problems in our ongoing study:

1. How is the overburden material stabilized on top of the >2.5 km liquid impact melt layer, with a diameter in excess to 60 km?

2. If Offset Dikes are formed indeed only during SIC differentiation (i.e., delayed by several thousands of ka), what was the mechanical reason to open breccia-filled fractures and to inject the dike-forming melt?

3. Are there field indications and/or petrological data to prove that Offset Dikes are really dikes yet not melt-filled fractures in the basement of a larger, now eroded part of the melt sheet?

Acknowledgments. This work is supported by DFG grants De 401/9 and 436 RUS to A.D. Part of this work was done during a scientific visit of B.A. Ivanov at Münster.

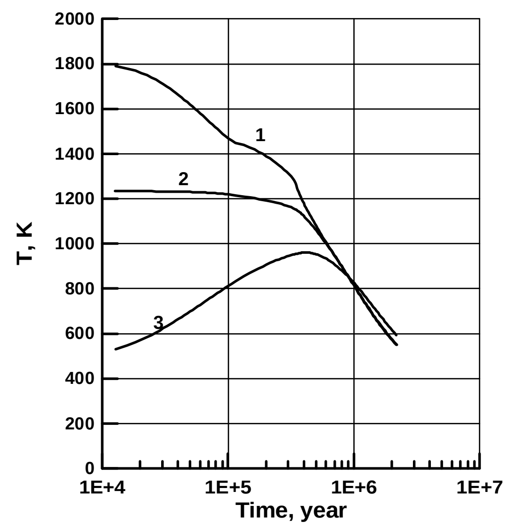

FIGURE 1. The modeled cooling history of SIC. **1** - maximal temperature inside the initially melted body; **2** - temperature at the lower SIC boundary; **3** - temperature 1.2 km below the lower SIC boundary.

References.

[1] Stöffler, D., et al. (1989) *Meteoritics 24*, 398; Grieve, R.A.F., et al. (1991) *JGR 96*, 22753-22764; Deutsch, A. et al. (1995) *Geol. Rundschau 84*, 697-709;
[2] Milkreit B., et al. (1994) *GRL 21*, 931-934;
[3] Shanks, W.S. and Schwerdtner, W.M. (1991) *Can. J. Earth Sci. 28*, 1677-1686;
[4] Deutsch, A. and Grieve, R.A.F. (1994) *GRL 21*, 963-966;
[5] Ostermann, M. (1996) *Ph. D. Thesis, WWU Münster*, 168 pp;
[6] Onorato, P.L.K. et al. (1978) *JGR 83*, 2789-2798;
[7] Ostermann, M. et al. (1996) *MAPS 31*, 494-501;
[8] Krogh, T.E. et al. (1984) Ont. Geol. Surv. Spec. Vol. 1, 431-446;
[9] Lakomy, R. (1990) *Meteoritics 25*, 195-207;
[10] Ariskin, A.A. et al. (1993) *Computers & Geosci. 19*, 1155-1170;
[11] Collins, W.H. (1934) *Trans.Royal Soc. Canada 38*, 335-350;
[12] Warren, P.H., et al. (1996) *Geol. Soc. Amer. Spec. Pap. 307*, 105-124.