HORNBLENDE THERMOBAROMETRY OF IMPACT MELT ROCKS: A CASE STUDY FROM THE RATHBUN OFFSET DIKE, SUDBURY IMPACT STRUCTURE, CANADA. A. Kawohl[1], [1]Institute of Geography and Geology, University of Würzburg, Germany (alexander.kawohl@uni-wuerzburg.de)

Introduction: Many studies before have used conventional amphibole geothermobarometry in order to constrain the depth of emplacement or the level of erosion of calc-alkaline plutonic rocks. Primary igneous calcic amphibole has also been reported for some terrestrial impact structures, including the Vredefort Impact Structure (South Africa) [1] and the Sudbury Impact Structure (Canada) (e.g., [2,3]). In both cases, amphibole (hornblende) occurs mainly as an accessory mineral within the allochthonous impact melt rocks that are thought to be derived from an initially coherent, but now deeply eroded, impact melt sheet.

Here, I present the first mineral chemical data for primary igneous hornblende from the Sudbury Impact Structure and explore whether this amphibole is suited for geothermobarometry, and what the results can tell us about the depth of emplacement of impact melt dikes within large terrestrial impact structures, and the pre-erosional extent and thickness of the Sudbury impact melt sheet in particular.

Samples: The rock samples used for this study were collected in outcrop from the recently discovered Rathbun Offset Dike [3], 15 km east of the Main Mass of the Sudbury Igneous Complex. The Rathbun Offset Dike is only one of several impact melt dikes (locally termed Offset Dikes) that occur in well-defined geometric outcrop patterns within the brecciated basement beneath the ~200 km Sudbury Impact Structure. With a combined strike length of 130 km and an estimated volume of 10 km^3, these dikes are the largest examples of their kind on planet Earth. They are generally believed to have formed when allochthonous impact melt was injected into the fractured crater floor very shortly after the impact (e.g., [3,4]), and they are considered equivalent to the Granophyre Dikes at Vredefort [5].

In terms of geochemistry, the rock samples from the Rathbun Offset Dike are calc-alkaline and andesitic [3], which is typical of an impact melt rock resulting from large-scale bulk melting and homogenization of Precambrian continental crust. In terms of petrography, the samples are classified as inclusion-bearing quartz diorite; they contain abundant lithic clasts (gabbro, wacke) of the local country rock, embedded in a phaneritic quartz dioritic matrix (Fig. 1A). This quartz dioritic matrix is holocrystalline, has an ophitic texture, and consists of 45 vol% plagioclase, 35 vol% quartz, and 20 vol% amphibole; accessory minerals are biotite, ilmenite, magnetite, and apatite (Fig 1B). Plagioclase is pseudomorphically replaced by saussurite, and amphibole and biotite are partially altered to chlorite. Most of the amphibole, however, is fresh, subhedral, with a pleochroism from beige brown to olive green.

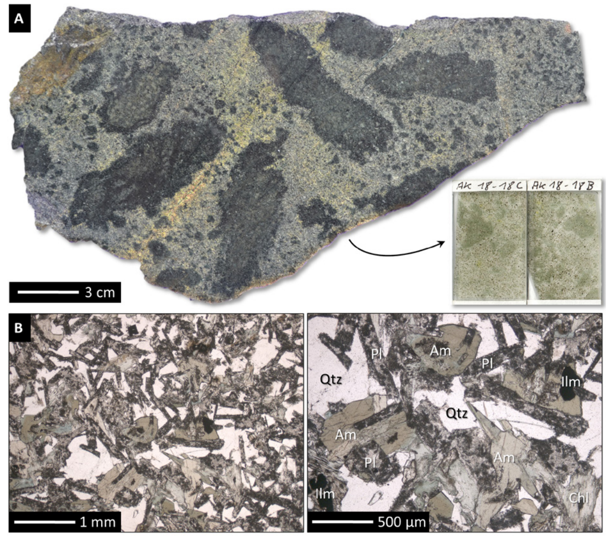

Fig. 1: Photographs of the sample material; **A:** polished slab of the inclusion-bearing quartz diorite from the Rathbun Offset Dike; **B:** thin sections of the same specimen, under transmitted light and plane polars.

Analytical details: Wave length-dispersive electron microprobe analyses were performed on polished thin sections using a JEOL JXA 8800L superprobe at the Institute of Geography and Geology, University of Würzburg, Germany. Operating conditions were 15 kV acceleration voltage, 20 nA beam current, 1 µm beam diameter, 20–40 s counting time for peaks, and 10–20 s counting time for the background. Analyses were calibrated against mineral standards and synthetic oxides.

Temperatures were obtained using the single-phase amphibole thermometers of [6] and the recently developed Ti-in-amphibole thermometer of [7]; pressures were calculated following [6], [8], and [9]. Not included in this study are the various linear Al-in-hornblende barometers (e.g., [10]) because these are neither suited for low-pressure amphiboles nor do they control for the potential effects of temperature or oxygen fugacity on crystal site occupancy. All of the above listed geothermobarometers are suited for calc-alkaline intermediate igneous rocks and require saturation in SiO_2, CaO, Na_2O, K_2O, TiO_2, and, most importantly, saturation in Al_2O_3, because undersaturation in those elements would result in an underestimation of the actual pressure and temperature. These preconditions are considered to be fulfilled by the observation that the analyzed amphibole occurs in textural equilibrium with biotite, feldspar, quartz, and Fe-Ti oxides.

Results: Representative mineral chemical analyses for amphibole from the Rathbun Offset Dike are presented in Table 1. The composition of the amphibole conforms to that of a typical magnesio hornblende.

Temperature. Temperatures calculated according to [6] are 718 ± 32°C on average (± one standard deviation; n = 74). Similar values, 681 ± 92°C, were obtained using the Ti-in-amphibole thermometer of [7]. These temperatures are above the H_2O-saturated granite solidus of ca. 650°C, which is one of the prerequisites for the application of most of the amphibole barometers listed above. Moreover, the high temperature obtained on the hornblende is consistent with textural evidence of a primary igneous origin. The temperature of 600–750°C also far exceeds the peak-metamorphic conditions previously established for the sample location (≤ 350°C), and it precludes that significant subsolidus re-equilibration had taken place.

Pressure. Using the above calculated temperatures in concert with the barometers of [6], [8] and [9] gives an average pressure of 0.86 ± 0.23, 1.3 ± 0.3, and 1.9 ± 0.4 kbar, respectively; the standard deviation of each is within the claimed uncertainty of the barometers used. Note that these values are only slightly above the lower stability limit (~0.8 kbar) of magmatic amphibole (e.g., [9]). According to the general equation P=ρgh, a crystallization pressure of 0.8–2.3 kbar equates to an emplacement depth (h) of 3,300–5,000 m by assuming an average density (ρ) of 2,600 kg/m^3 for the overburden (the pre-impact sedimentary target rocks). In case of a magmastatic instead of a lithostatic pressure, and using the average density of an andesitic hydrous impact melt of 2,530 kg/m^3 [11], the same pressure would have been reached at the bottom of a 3,400 to 5,200 m-thick melt column (i.e., impact melt sheet).

Interpretation & conclusions: The petrographic and mineral chemical evidence presented in this study not only demonstrates that primary and relatively pristine Al-Na-Ti-rich hornblende exists within certain areas and lithologies of the Sudbury Impact Structure, but that it is possible to derive internally quite consistent conditions of crystallization (*P,T*) for these amphibole-bearing impact melt rocks by using conventional geothermobarometry. Al-rich hornblende within one of the impact melt dikes at Sudbury implies crystallization at relatively great depth, some 3–5 km below paleosurface. This depth corresponds surprisingly well to the combined average true thickness of the Main Mass of the Sudbury Igneous Complex (2.5 km) plus the overlying crater fill deposits (1.5 km) [2]. Consequently, it is suggested that the Rathbun Offset Dike was emplaced vertically from above, i.e., at the bottom of an initially much more extensive, but now deeply eroded, impact melt sheet. Support for this hypothesis comes from the presence of so-called footwall-type Cu-PGE mineralization associated with the Rathbun Offset Dike [3], which, by definition, is confined to the basement of the Sudbury Impact Structure, and is typically found beneath the thickest parts of the impact melt sheet, most likely within former topographic depressions on the undulating crater floor [12].

Acknowledgments: Thanks is due to Inventus Mining Corp. for logistic support and access to their property; S. Höhn for calibration of the microprobe; J. VanderWal and H.E. Frimmel for insightful discussions. Financial support was provided by the German Research Foundation DFG [grant FR 2183/12-1]

References: [1] Kovaleva et al. (2018) *S. Afr. J. Geol.,* 121, 383–402. [2] Therriault et al. (2002) *Econ. Geol.,* 97, 1521–1540. [3] Kawohl et al. (2020) *Econ. Geol., 115*, 505–525. [4] Wichman & Schultz (1993) *Meteoritics,* 28, 222–231. [5] Huber et al. (2020) *MAPS*, 55, 2320–2337. [6] Ridolfi & Renzulli (2012) *Contrib. Mineral. Petrol.,* 163, 877–895. [7] Liao et al. (2021) *Am. Mineral.,* 106, 180–191. [8] Anderson & Smith (1995) *Am. Mineral.,* 80, 549–559. [9] Mutch et al. (2016) *Contrib. Mineral. Petrol.,* 171, 1–27. [10] Hammarstrom & Zen (1986) *Am. Mineral.*, 71, 1297–1313. [11] Warren et al. (1996) *Geol. Soc. Am. Spec. Pap.,* 307, 105–124. [12] Dreuse et al. (2010) *Terra Nova*, 22, 463–469.

Tab. 1: Representative electron microprobe data for primary (igneous) hornblende from the Rathbun Offset Dike, Sudbury Impact Structure, Canada; all analyses are given in weight%; mean and standard deviation were calculated for 74 analyses.

	Hbl1	Hbl2	Hbl3	Mean		1Std.
SiO_2	52.55	49.30	48.10	49.28	±	1.60
TiO_2	0.65	1.21	1.36	1.01	±	0.40
Al_2O_3	3.39	7.02	7.20	6.05	±	1.16
FeO	16.72	13.93	15.28	14.31	±	1.03
MgO	13.72	14.19	13.37	14.27	±	0.79
CaO	11.61	11.05	11.10	11.02	±	0.22
MnO	0.29	0.25	0.15	0.23	±	0.06
Na_2O	0.84	1.03	1.19	1.01	±	0.18
K_2O	0.17	0.50	0.73	0.48	±	0.15
Σ	98.95	98.55	98.47	97.69	±	0.56