THE MANICOUAGAN IMPACT MELT SHEET: IDENTIFICATION OF PROTOLITHS, AND DEGREE OF INITIAL MIXING AND HETEROGENEITY. C. D. O'Connell-Cooper[1], A. P. Dickin[2] and J. G. Spray[1], [1]Planetary & Space Science Centre, University New Brunswick, 2 Bailey Drive, Fredericton, NB E3B 5A3, Canada, O.Connell-Cooper@unb.ca, [2]Geography & Earth Sciences, McMaster University, Hamilton, ON L8S 4K1, Canada.

Introduction: The Manicouagan impact structure, a ~85-km [1], 214±0.5 Ma [2] complex crater located in Quebec, Canada (51° 23° N, 68° 42° W), is the 2nd largest of Canada's confirmed 30 impact structures [3]. First identified as a potential impact structure in the early 1960s [4], later exploration drilling at Manicouagan has revealed local developments of impact melt that are substantially thicker than the previously documented average of ~300 m [1, 5]. The bulk of the melt sheet is undifferentiated quartz monzodiorite (U-IMS)[1], with minimal chemical variation and an average thickness of ~250 m [5]. In contrast, geochemical and petrographical evidence reveals that a thicker section (D-IMS) (~1045 m) of impact melt has undergone fractional crystallization [5], and can be divided into three layers based on chemical, mineralogical and textural variations: evolving from monzodiorite to quartz monzodiorite and rare quartz monzonite [5]. The mineralogy comprises plagioclase > orthoclase > clinopyroxene > orthopyroxene, with ubiquitous amphibole and biotite, and rare olivine (Fig. 1).

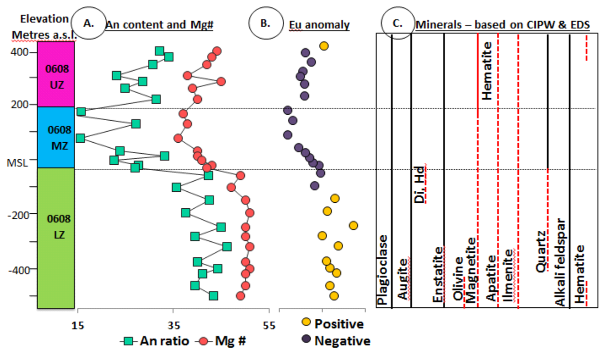

Fig. 1. Magmatic fractionation indicators. A. An content and Mg# versus elevation (m a.s.l.). **B.** Eu/Eu* versus elevation. **C**. Mineral assemblage, based on CIPW calculations and EDS analysis.

The whole-rock geochemical profile displays previously unidentified systemic heterogeneities [5], resulting from magmatic differentiation within the thicker sections of melt (D-IMS), in an otherwise relatively homogenous melt sheet. In contrast, the isotopic profile of the Manicouagan impact melt sheet shows considerable homogeneity, both laterally and vertically [7, 8].

Isotope chemistry: Country rocks in the Manicouagan area comprise Proterozoic gneisses and meta-igneous suites (Lelukuau and Tshenukutish Terranes, within the Manicouagan Imbricate Zone (MIZ)), and Archean quartzo-feldspathic gneisses (Gagnon Terrane). Isotope analysis highlights the relationship between the protolith and the impact melt sheet, and gives further insight into the evolution of the differentiated impact melt.

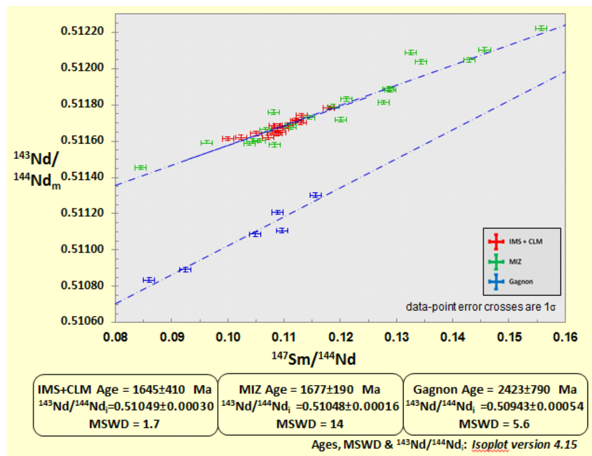

Fig. 2. $^{143}Nd/^{144}Nd_m$ versus $^{147}Sm/^{144}Nd$ showing individual analyses for the IMS (i.e., U-IMS and D-IMS) + CLM units, and underlying MIZ and Gagnon basement rocks. Error: Average reproducibility $^{143}Nd/^{144}Nd$ = 0.00001 (1σ).

Sm-Nd: Nd isotopic ratios for the melt sheet cluster close to those of the MIZ, indicating that shock melting at Manicouagan primarily occurred within MIZ target lithologies, rather than the Archean Gagnon [7, 8].

Averages for the combined IMS+CLM unit and the MIZ show a strong similarity (Fig. 2), indicating a high degree of homogeneity between the two units. It is clear that the original melt volume comprised primarily MIZ target, with little input from the Archean Gagnon country rock. The similarity of Nd isotopic ratios in the U-IMS and D-IMS indicates a common source for both ($^{143}Nd/^{144}Nd_m$ ave. : U-IMS 0.511659 ± 0.000028; D-IMS 0.511646 ± 0.000031).

$^{143}Nd/^{144}Nd_i$[2] for the gneiss-dominated target rocks within the MIZ, show a degree of homogeneity

[1] U-IMS = undifferentiated impact melt sheet; D-IMS = differentiated impact melt sheet (which is subdivided into three units: *0608 UZ, 0608 MZ* and *0608 LZ);* IMS – impact melt sheet (both U-IMS and D-IMS); CLM = clast-laden melt; MIZ = Manicouagan Imbricate Zone

[2] derived using Isoplot, version 4.15 [6]

($^{143}Nd/^{144}Nd_i$ aves.: anorthosite 0.51048 ± 0.00055, MSWD 10.5; charnockites 0.51051 ± 0.00042, MSWD 12; mesocratic gneisses 0.51058 ± 0.00054, MSWD 5.7). Thus, the source terrain at Manicouagan was itself relatively isotopically homogeneous – this resulted in a melt from which it is not easy to resolve distinct target rock components on the basis of isotopic ratios (other than local anorthositic contamination).

Slight variation in Nd ratios for the three units within the D-IMS (*0608 UZ*, *MZ* & *LZ* - Fig. 1)) is unsystematic, which may reflect an inherited heterogeneity, due to incomplete mixing of the initial melt, rather than the effect of later differentiation within the D-IMS.

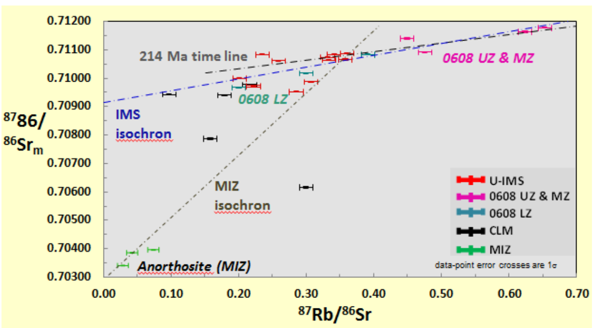

Fig. 3. $^{87}Sr/^{86}Sr_m$ versus $^{87}Rb/^{86}Sr$ - U-IMS, D-IMS (*0608 UZ, MZ, LZ*), CLM melt units, and underlying Proterozoic MIZ basement rocks. Error: Average reproducibility $^{87}Sr/^{86}Sr$ 0.00002 (1σ)

Rb-Sr: Plotting $^{87}Rb/^{86}Sr$ versus $^{87}Sr/^{86}Sr_m$, it can be seen that samples from both the U-IMS and D-IMS lie close to the MIZ-derived (ie. country rock) isochron (Fig. 3). Melt samples, particularly those from the D-IMS, also lie along an isochron defined by the time of impact (t= 214 Ma) – this is interpreted to reflect Rb/Sr fractionation due to magmatic differentiation of the melt sheet, coupled with Rb decay within both the U-IMS and D-IMS since 214 Ma.

Although the Manicouagan IMS is relatively homogeneous, local variations can be attributed to the assimilation of anorthositic basement, which dominates the central uplift region (Fig. 3). Average $^{87}Sr/^{86}Sr_m$ for two CLM units lie closer in value to those of the anorthositic samples than other MIZ samples, reflecting the anorthosite-dominant clast content of the melts in these units (ave. $^{87}Sr/^{86}Sr_m$: CLM 0.708135 ± 0.001662; MIZ anorthosites 0.704480 ± 0.001102).

Pb-Pb analysis: The Pb isotope signature for the IMS and CLM units is homogeneous both laterally (across the melt sheet) and vertically (with depth). Pb ratio values for the IMS, CLM and MIZ overlap, whilst the Gagnon plots in a distinct cluster. Analysis indicates the presence of a hydrothermal system, which has affected the isotopic signature of the U-IMS, but has not affected the D-IMS, even in its upper 200 metres.

Conclusion: The Rb-Sr, Pb-Pb and Sm-Nd isotope chemistry of the impact-generated melt sheet and target rocks reveal that the melt body, though locally subsequently differentiated via fractional crystallization, was isotopically homogenized during its formation following its derivation primarily from charnockites and mesocratic gneisses. Isotopic signatures of the target rocks indicate that the protolith for the melt was the Paleoproterozoic Manicouagan Imbricate Zone. The underlying Archean Gagnon Terrane was not involved in melt production, or its subsequent modification via assimilation, despite impact melt resting on Archean lithologies in the southwest sector of the melt sheet.

Sr, Nd and Pb ratios in impact melt from the western edge of the island fit the general trend for the IMS, and are similar those found within melt at the centre of the structure, indicating that the melt was homogenized on a large scale. It also indicates that the periphery of the melt sheet cooled quickly enough that it did not have time to assimilate the underlying basement, which is closer, in terms of T_{DM} [7] to the Gagnon than the MIZ. Local heterogeneity at the base of the thicker (up to 1.4 km thick) melt sections near the centre of the structure, is attributed to assimilation of the centrally uplifted anorthosite by superheated melt, which locally modified the original isotopic signature.

However, the Sr isotopic profile of the D-IMS shows more variation than the Nd profile (which is consistent across the melt sheet), reflecting Rb/Sr fractionation but limited Sm/Nd mobility. This provides further evidence that differentiation has resulted from fractionation processes within the thicker melt sections (D-IMS), rather than inherited initial heterogeneities.

References: [1] Spray J. G. and Thompson L. M. (2008) *Meteoritics. & Planet. Sci., 43*, 2049-2057. [2] Hodych and Dunning (1992) Geology, 20, 51-54. *JGR, 90*, 1151–1154. [3] Earth Impact Database (Accessed: 11 January 2016) http:/www.unb.ca/passc/ImpactDatabase/ [4] Beals C. S. et al. (1956) *J. Royal Astr. Soc. Canada, 50*, 203-211. [5] O'Connell-Cooper and Spray, *JGR, 116*, B06204, [6] Ludwig, K., http://www.bgc.org/isoplot_etc/isoplot.html. [7] Thomson et al., (2011) *Precam. Res., 191*, 184-193, [8] O'Connell-Cooper et al. (2012) *EPSL, 335-336*, 48-58.