PROFILE OF THE DIFFERENTIATED MANICOUAGAN IMPACT MELT SHEET – GEOCHEMISTRY, MINERALOGY, PETROGROGRAPHY AND ISOTOPE ANALYSIS.

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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]. The bulk of the melt sheet is undifferentiated quartz monzodiorite (U-IMS), with minimal chemical variation and an average thickness of ~250 m [4]. In contrast, geochemical and petrographical evidence reveals that a thicker section (D-IMS) (~1045 m) of impact melt has undergone fractional crystallization [4], and can be divided into three layers based on chemical, mineralogical and textural variations: evolving from monzodiorite to quartz monzodiorite and rare quartz monzonite. Geochemical, isotope, mineralogical and petrogrographical analysis has clearly established the presence of magmatic differentiation within the thicker sections of the Manicouagan impact melt sheet [4-7]. The evidence below characterizes the melt sheet – (1) an effective initial homogenization of a melt volume, which (2) evolved through a process of crystal fractionation and (3) with some limited (later) localized assimilation at the base of the melt sheet.

The initial melt sheet – homogenized on a large scale: The isotopic profile (Sm-Nd, Rb-Sr, and Pb-Pb) of Manicouagan's impact melt sheet is similar with depth and across the ~55 km diameter of the melt body. Isotopic evidence (Sm-Nd and Rb-Sr) indicates that the impact melt sheet (IMS) at Manicouagan is derived from Proterozoic MIZ target lithologies (particularly mesocratic and charnockitic gneisses) (Fig. 1) [6-8]. The Pb isotope signature for the IMS and CLM units is also homogeneous, without any indication of inherited heterogeneities, and overlaps with that of the MIZ. The similarity between Rb-Sr, Nd-Sm and Pb-Pb ratios for impact melt from the western edge of the island (overlying Gagnon basement) and the IMS from the centre of the island indicates that the initial melt was turbulently mixed and largely homogenized. A slight variation seen in Nd ratios for the *0608** core is unsystematic, and may reflect an inherited heterogeneity, due to incomplete mixing of the initial melt, rather than the effect of later differentiation within the D-IMS.

[*Note - core names shown in italics. 7 core were investigated. Cores discussed here: *0608*=D-IMS core; *0501*, *0511*=U-IMS core].

The initial melt sheet – thick enough to facilitate fractional crystallization: Early work on impact melts concluded that terrestrial impact melts could not facilitate traditional igneous processes such as fractional crystallization, due to insufficient volume. *Jaupert and Tait* [1995] [9] estimate the critical thickness for fractionation to occur to be >1000 m, with melt sheets thinner than 1 km crystallizing too rapidly to facilitate differentiation due to fractionation. However, drill core evidence indicates that the basement topography underlying the Manicouagan IMS is not uniform [1], allowing an accumulation of melt thickness (1.4 km of impact melt, in the central region) that exceeds this lower limit, and facilitated magmatic evolution of the melt.

Magmatic evolution of the melt sheet: The Manicouagan (macroscopic clast-poor to clast-free) impact melt sheet is divided into two units [4-7], the undifferentiated U-IMS (average 250 metres; max. 500 metres within the *0501* drill-core) and the differentiated D-IMS (1045 metres, in the *0608* drill-core).

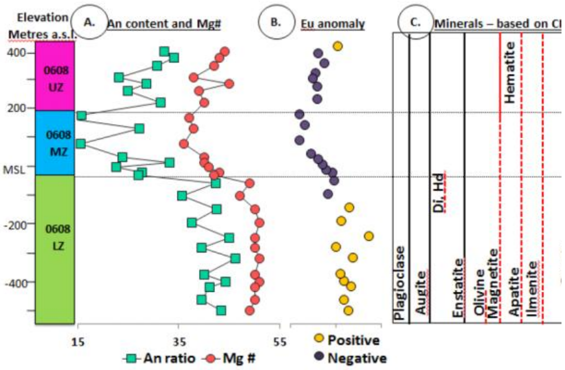
Whilst the U-IMS shows little to no change with increasing depth down-core or laterally across the melt sheet, the D-IMS shows systemic change with depth in the 1045 m of impact melt contained in the *0608* core. Magmatic evolution is supported by the presence of magmatic trends in the *0608* core:

(1) Mg# increases with increasing depth, from the *0608 UZ* (ave: Mg # 42 ± 3) to the *LZ* (ave: Mg # 50 ± 1);

(2) An content increases down core, from the UZ (ave: $An_{29 \pm 4}$) to the LZ (ave: $An_{41 \pm 3}$);

(3) The presence of a weakly developed mineral sequence in the *0608* core, resulting in an evolution of the melt from monzodiorite (at base) to quartz monzodiorite, and rare quartz monzonite (at top);

- *UZ & MZ*: ab > or > an > qz > opx > cpx
- *LZ*: ab > an > or > opx > cpx > qz ± ol
- *CLM*: ab>an> or > opx > cpx > ± ol ± qz



(4) The presence of a tentative mineral sequence in the *0501* core (500 metres melt) indicates that melt thickness is a critical factor for magmatic evolution.

(5) A progressive change in the Eu/Eu* pattern, from negative (at the top of the core) to positive (at the base of the core). This pattern, often seen in layered igneous complexes, in which early rocks show a positive anomaly and late-stage rocks a negative anomaly, indicates fractionation of plagioclase within the D-IMS.

(6) Rb/Sr fractionation due to magmatic differentiation, seen when ^{87}Rb/^{86}Sr is plotted against ^{87}Sr/^{86}Sr$_m$. The *0608 LZ* samples cluster near the U-IMS samples, but the *0608 UZ* and *MZ* samples are spread out, along the upper length of two isochrons, defined by the IMS dataset and the age of impact, respectively. This variation is interpreted as Rb/Sr fractionation during magmatic fractionation of the differentiated *0608* drill core.

(7) Similarility between strontium ratios for the *0608 LZ* and the U-IMS, indicating that the more mafic *0608 LZ* is closer in composition to the original bulk composition of the melted volume, as represented today by the undifferentiated U-IMS.

(8) The anomalous *MZ*, the most felsic unit, contains the highest abundances of incompatible elements, including REE, suggesting that the *MZ* was the last material to crystallize, and may be analogous to the Sandwich Horizon of the Skaergaard Intrusion.

(9) Magmatic trend reversals (Mg#, An content, Eu/Eu*) seen in the clast laden melt (CLM), at the base of the *0608* core, may represent poorly developed reverse fractionation trends, similar to the marginal reversal, seen in many mafic-ultramafic intrusions.

Post-formation modification of the melt sheet: The isotopic similarity between the melt sheet overlying Archean Gagnon basement on the western side of the structure to that overlying Proterozoic MIZ basement in the centre of the structure shows that the melt did not assimilate underlying basement in the west, suggesting that thermal energy dissipated too rapidly in shallower melt sections (post-erosional thickness <100 m) to allow continuing evolution of the melt sheet through incorporation of new basement material [6, 7].

Anorthosite assimilation (revealed in ^{87}Sr/^{86}Sr$_m$ ratios) occurred within the clast-laden melts at the base of the thicker melt sections near the centre of the structure (*0511* CLM; *0608* CLM). The *0511* core is underlain by elevated anorthositic basement as part of the central uplift, so it is likely that ^{87}Sr/^{86}Sr variation reflects secondary local assimilation by the hot melt, rather than incomplete mixing of initial melt. This also indicates that uplift was largely accomplished prior to the start of melt sheet solidification (i.e., was geologically rapid).

Conclusion: Taken as a whole, evidence supports the theory that magmatic differentiation through fractional crystallization resulted in the evolution of the thicker sections of the Manicouagan impact melt sheet. This study concludes that fractional crystallization is the main cause of the variation seen within the D-IMS. Fractional crystallization only occurs within the thickest sections of melt, whilst the thinner sections (c. 200-300 m contains very poorly developed evolution trends, indicates that the thickness of melt in the D-IMS region was a critical factor in facilitating fractional processes.

Implications: (1) As differentiation at Manicougan was not identified until these recent studies [2-4?], Manicouagan (regarded as the type example for a medium sized crater) has been used to conclude that mid-szed craters do not accumulate sufficient melt to facilitate typical igneous evolution processes. Therefore, the identification of magmatic trends and evolution at Manicouagan has important implications for our understanding of crater formation, and melt accumulation, particularly within other mid-sized.

(2) The variations in thickness in melt identified at Manicouagan (from an average of c. 250 m in the U-IMS, up to a maximum of 1045 m in the D-IMS) was facilitated by the presence of a variable basement topography. This implies that other impact structures may also have thicker melt accumulations than can be identified through field work, or that have been identified through laboratory analysis of surficial samples.

(3) Lunar impact melts are dated using the premise that impact melts are homogeneous mixtures of pre-existing lithologies, without change or evolution from the initial impact melt body, so that samples with distinctly different profiles are assigned to different impact events [10]. If an impact event the size of Manicouagan can allow an accumulation of melt sufficient to allow differentiation, then the assigning of lunar samples to different impact events based on varying mineralogical and chemical composition may need to reevaluated, as such samples may represent a suite for fractionated rocks from a single event, rather than samples from separate events.

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