THE AGE OF THE LAKE SAINT MARTIN IMPACT STRUCTURE (MANITOBA, CANADA).

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Introduction and Geologic Background: The $\geq$40 km diameter Lake Saint Martin impact structure in the Interlake Region of southern Manitoba [1-3] is one of the largest impact structures in North America. Target rocks comprise Precambrian (~2.4 Ga) granite of the Superior Province of the Canadian Shield overlain by ~200-400 m of Ordovician to Devonian sedimentary rocks that build up the northeastern flank of the Paleozoic intracratonic Williston Basin. Shocked and partially molten basement granite is exposed in the central uplift of the impact structure. The annular crater moat is filled with a sequence of impactites including carbonate-dominated and granitic lithic impact breccias, impact melt rocks, and suevitic breccias (aka the 'St. Martin Series' [1]). Surficial outcrop of impactites is generally scarce, and most of the crater-filling and subcrater lithologies are known from drill core studies. The St. Martin impact structure is partially filled by post-impact Middle Jurassic intra-crater red beds and evaporites and largely covered with up to ~30 m of Pleistocene glacial drift [1-3].

Previous Age Determinations: Previous dating of impact melt lithologies from St. Martin yielded rather imprecise K/Ar apparent ages of 200 ± 25 and 250 ± 25 Ma [1] and a Rb/Sr age of 219 ± 32 Ma [4], which is currently accepted as the 'official' impact age in the *Earth Impact Database*. However, these techniques are known to yield spurious results warranting additional geochronological studies [5]. Recent ^{40}Ar/^{39}Ar dating of intensely and moderately altered impact melt rock resulted in disturbed age spectra yielding minimum (alteration) ages of ~209 Ma [6] and ~225 Ma [7], respectively. Dating attempts using the (U-Th)/He technique on apatite and zircon separated from melt rocks yielded scattered ages with two age peaks around ~214 Ma and ~234 Ma [8], each associated with a weak statistical robustness. Apatite and zircon fission track dating gave an apparent age of 208 ± 14 Ma [9]. However, (U-Th)/He and fission track ages have likely been compromised by an Eocene thermal event in the greater Lake St. Martin region and partial resetting of these low-temperature geochronometers [8,9]. A Sr and S isotopic study of the post-impact evaporites favoured a significantly older, Devonian-Carboniferous, age for the St. Martin impact [10]. In summary, despite several attempts using different dating techniques and sample material, the age of the Lake St. Martin impact remains poorly constrained.

New ^{40}Ar/^{39}Ar Dating: ^{40}Ar/^{39}Ar step-heating experiments were done using a MAP215-50 mass spectrometer coupled with a NewWave Nd-YAG IR (1064 nm) laser at the Western Australian Argon Isotope Facility, Curtin University. We carried out analyses on several single-grain (~500-800 μm in size) aliquots of (1) two particles of shock-molten and recrystallized K-feldspar extracted from a fluidal-vesicular impact melt rock recovered from the eastern sector of the impact crater moat; (2) three recrystallized K-feldspar grains from shocked, partially molten, and uplifted Precambrian basement granite collected at the central uplift; and (3) one whole-rock chip of optically reasonably fresh, fine-grained crystalline impact melt rock. Note that the melt rock was leached in 5N HF for 2 minutes to tentatively remove surficial alteration phases. ^{40}Ar/^{39}Ar ages were calculated using the Fish Canyon sanidine standard and the potassium decay constants of Renne et al. [11].

^{40}Ar/^{39}Ar Results and Interpretation:

Melt rock K-feldspar: The K-feldspar melt particles yielded one plateau age of 226.7 ± 2.4 Ma (2σ; MSWD = 0.78; P = 0.66; 84% of ^{39}Ar released; Fig. 1A) for sample LSM-1A. This sample did not develop a proper isochron due to a poor spreading factor [5] and clustering near the radiogenic axis given by all but one step data. The second K-feldspar particle LSM-1B separated from the melt rock yielded a disturbed age spectrum.

Granite K-feldspar: Three K-feldspar melt particles handpicked from the central uplift granite yielded two concordant plateau ages of 227.0 ± 1.2 Ma (2σ; MSWD = 1.00; P = 0.46; 84% of ^{39}Ar) for sample LSM-2A (Fig. 1B) and 228.1 ± 1.4 Ma (2σ; MSWD = 1.40; P = 0.18; 73% of ^{39}Ar) for sample LSM-2B. The inverse isochron for LSM-2A yielded a coeval age of 228.5 ± 2.4 Ma (2σ; MSWD = 0.78; P = 0.71; ^{40}Ar/^{36}Ar intercept = 288 ± 15; spreading factor S = 34%) whereas data points for LSM-02B cluster near the radiogenic axis and fail to provide an isochron. A third granite K-feldspar particle, LSM-02C, produced a disturbed and tilde-shaped age spectrum. Individual steps in the high-temperature extraction range gave older apparent ages of up to ~260 Ma, suggesting partial inheritance of ^{40}Ar* from an incompletely degassed Precambrian precursor K-feldspar in sample LSM-02C.

Melt rock sample: The impact melt rock chip LSM-3 yielded no plateau in a disturbed, tilde-shaped age spectrum, with younger step ages (~180-200 Ma) in the low- and high-temperature extraction range and older apparent ages of ~220-230 Ma in the mid-temperature steps (Fig. 1C). This tilde-shape age spectrum is similar to some of the previous age spectra obtained on impact melt rocks from St. Martin [7] and some other spectra from terrestrial impact structures in which hump- and tilde shapes have been attributed to alteration effects [12,13]. We note that the optically less altered melt rocks from this study and [7] provide minimum ages closer to the well-defined K-feldspar ages presented here (Fig. 1A-B), compared to heavily altered, reddish, melt rock [6].
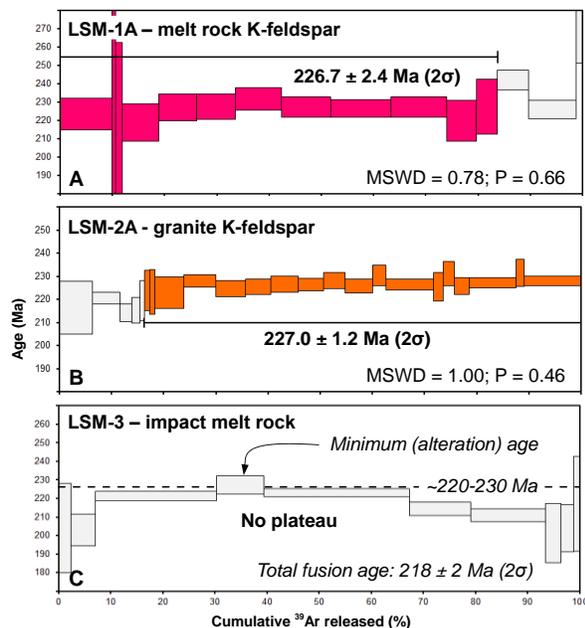
Fig. 1: Selected ^{40}Ar/^{39}Ar age spectra obtained on K-feldspar and melt rock from the Lake St. Martin impact structure.

Conclusions: A combination of the three fully concordant plateau ages obtained for monomineralic recrystallized K-feldspar melt particles separated from impact melt rock (LSM-1A) and the selectively molten central uplift granite (LSM-2A+B) yields a weighted mean of **227.4 ± 0.8 Ma** [± 1.2 Ma full external error] (2σ; MSWD = 0.89; P = 0.41), which represents the most precise and accurate age currently available for the large St. Martin impact. This age is supported by approximative, minimum ages of ~220-230 Ma for the impact melt rock sample LSM-3 and results from [7].

The Middle/Late Triassic (Ladinian/Carnian) boundary (reported as ~228.7 Ma in [14]) is characterized by a minor extinction event among marine reptiles (9 families) at this stage transition [15].

Furthermore, the basaltic flood volcanism in the Wrangellia large igneous province in western Canada (the locally up to ~6,000 m thick Karmutsen Formation basalts mainly exposed on Vancouver Island) [16] U/Pb-dated at 227 ± 3 Ma [17] was apparently coeval with the St. Martin impact within uncertainties. However, a possible connection between the St. Martin impact and the proposed Ladinian/Carnian biologic crisis and/or flood volcanism currently remains purely speculative (see also general considerations in [18]). Lastly, our new age implies that the Lake St. Martin structure becomes the last addition to a list of impacts that have been demonstrated to be unrelated to a proposed ~214 Ma Late Triassic multiple impact event [19], where several impacts were previously dismissed as being coeval [7,20,21].

The relative error on the new impact age is ± 0.5% including all sources of uncertainties, which makes Lake St. Martin one of the most precisely dated terrestrial impact structures, and further analyses are ongoing to achieve increased robustness and refinement of the age. The three concordant plateau ages obtained in this study suggest that this age is robust [5] and, thus, warn us to exercise caution on the use of low-temperature geochronometers, such as (U-Th)/He for impact research, at least with our current level of understanding of this technique; none of the previous (U-Th)/He age peaks (~214 and ~234 Ma [8]) have reliably indentified the age of the Lake St. Martin impact within error, and the unambiguous applicability of this technique remains to be thoroughly tested.

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