Multiphase U-Pb Geochronology and Shock Analysis of apatite, titanite and zircon from the La Moinerie impact structure, Canada. M. McGregor[1,2], C. R. M. McFarlane[2] and J. G. Spray[1,2], [1]Planetary and Space Science Centre, [2]Department of Earth Sciences, University of New Brunswick, Fredericton, NB E3B 5A3, Canada mmcgrego@unb.ca

Introduction: Impact structures provide important insight into solar system evolution. Determining their ages helps understand projectile flux and influences on planetary environments through geologic time. However, dating impact structures can be challenging. In the absence of coherent impact melt sheets (i.e., in smaller <15 km-diameter craters on Earth; 75% of known terrestrial craters [1]) only underlying variably shocked and melt-bearing suevitic crater fill deposits may be available. As a result, and due to other processes, including erosion and post-impact tectonothermal overprinting, the chronologic record of impact on Earth remains poorly constrained. While the nature of impactites makes precise and accurate impact geochronology challenging, obtaining quality ages and understanding the mechanisms responsible for isotopic heterogeneities (e.g., due to partial resetting) is critical for improving our understanding on how shock metamorphism and melting affect isotope systematics.

Here, we deploy in situ LA-ICP-MS U-Pb geochronology on apatite, titanite and zircon to explore impact and protolith ages for the La Moinerie impact structure. We demonstrate the importance of linking petrographic context to isotopic resetting, and the viability of a multiphase approach to resolving the impact ages of shocked and variably melted lithologies.

Geologic background: The La Moinerie impact structure is a small (~8 km apparent diameter), presumably complex crater situated in northern Quebec, Canada (N 57° 26', W 66° 37'). Previous studies of La Moinerie are limited to an abstract confirming its impact origin [2], and ^{40}Ar-^{39}Ar dating of impact melt-bearing rocks, which provided a broad age estimate of 400 ± 50 Ma [3]. The structure is located within the Core Zone of the Southeast Churchill Province (SECP), which is composed of reworked Archean crustal blocks and Paleoproterozoic meta-intrusive suites ranging in age from 2.78 – 1.74 Ga [2]. Locally, the target rocks consist of the De Pas Batholith granitoids [4] and a thin veneer of Ordovician limestone. De Pas magmatism predates and overlaps with 1.84 – 1.78 Ga metamorphic overprinting [4]. A ~10 km-diameter gravity low of 5 mGal coincides with the impact structure. A ~4 km-diameter incomplete ring of islands central to the lake surround a ~1-2 km-diameter, minor gravity high, which together may define the remains of a central uplift [2].

Results and Discussion:

Shock Microstructures: Back-scattered electron (BSE) microscopy and Raman spectroscopy reveal shock microstructures and polymorphs in apatite, titanite and zircon from within suevites, clast-laden impact melts and polymictic breccias. Several types of microstructure were observed, which record variable degrees of shock deformation. Zircons contain open planar microstructures and exhibit variable extents of thermal dissociation and granularization, analogous to those identified at other terrestrial impact craters [5]. Raman spectroscopy reveals the preservation of the high temperature *t*-ZrO_2 (tetragonal) polymorph, the first known natural occurrence of this polymorph. Stable at temperatures 1200 – 2850 °C [5], its preservation suggests rapid quenching of superheated impact melt from temperatures ≥1200°C. Observed shock features in apatite include single to multiple sets of open (dark in BSE) planar microstructures (2 sets) coexisting with, or without, linear arrays of vesicles (1-2 sets) (Fig. 1a), intra-grain neoblastic apatite (e.g., Fig. 1b) and the presence of neocrystalline (i.e., impact melt-grown) apatite (Fig. 1c). Titanite records a similar array of shock features, including both planar microstructures and linear to sub-linear arrays of vesicles infilled by a lower (dark in BSE) density phase (Fig. 1d).

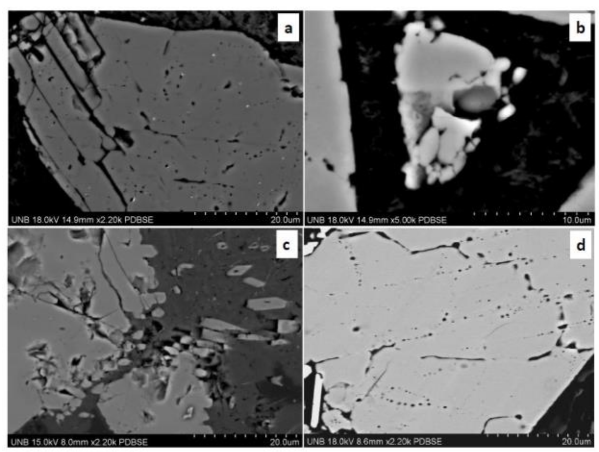

Fig 1. Shock features in apatite; **a)** planar microstructures; **b)** neoblastic apatite and **c)** impact-recrystallized apatite; and **d)** planar microstructures in titanite.

U-Pb Geochronology: In situ U-Pb geochronology was performed using a 193 nm Excimer laser coupled to a quadrupole ICP-MS. A total of 97 apatites, 82 titanites and 66 zircons from 7 thin sections were selected for dating. On a semi total U-Pb diagram, apatite and titanite record $^{238}U/^{206}Pb$ ratios populating a region between an older Proterozoic array with a lower intercept of ~1714 Ma (apatite: 1708 ± 11 Ma (MSWD = 1.3) (Fig. 2); titanite: 1719 ± 13 Ma (MSWD = 0.67)) and a younger Paleozoic isochron with a lower intercept age of 452.6 ± 5.1 Ma (MSWD = 0.94) for apatite (Fig. 2), and 444 ± 15 Ma (MSWD = 2.2) for titanite. Isotopic resetting in apatite and titanite is strongly controlled by their proximity to what would have been impact melt. Pre-impact basement ages are retained in apatite and titanite mineral clasts associated with the clastic matrix, while impact ages (i.e., complete isotopic resetting) are recorded by mineral clasts juxtaposed with impact melt (Fig. 2). While partial Pb-loss is recorded in apatite and titanite grains with planar microstructures, there is no strong correlation between shock level and impact induced resetting.

Zircons give anomalously younger impact ages and older basement ages compared to apatite and titanite. Crystalline zircons define an upper intercept concordia age of 1774 ± 16 Ma (MSWD = 2.7). A lower intercept age of 410.1 ± 8.9 Ma (MSWD = 1.9) was obtained by anchoring the upper intercept at 1774 Ma and regressing a line through a concordant $^{206}Pb/^{238}U$ age of 429.1 ± 4.7 Ma obtained from granular zircon. In comparison, a regression through the upper intercept and analysis with metamict textures define an isochron with a younger, meaningless lower intercept age of 325.1 ± 6.1 Ma. Both calculated ages are anomalously young compared to co-existing apatite and titanite, which we attribute to modern (post-impact) Pb-loss in zircon caused by chemical weathering during post-impact erosion and glaciation. We interpret post-impact Pb-loss to have been facilitated by zircon lattice damage during pre-impact metamictization, as well as impact-induced granularization.

Based on the crystalline structure (Raman spectroscopy), lowest errors, and resistance to modern Pb-loss, apatite provides the more robust age. We conclude, using the apatite age of 452.6 ± 5.1 Ma (Fig. 2), that the La Moinerie impact event occurred during the Late Ordovician (Sandian-Katian boundary). This result is in agreement with La Moinerie's stratigraphic setting (i.e., limestone deposition occurring pre-impact), and refines the previous Ar-Ar age of 400 ± 50 Ma [3]. We note that the age for La Moinerie (452.6 ± 5.1 Ma) is coincident with several other terrestrial impact structures, including Clearwater East, Hummeln, Kärdla, Lockne, Mälingen and Tvären [1]. This age places the La Moinerie impact event during the increased bombardment flux associated with the L-chondrite parent body breakup initiated at ~466 Ma [6].

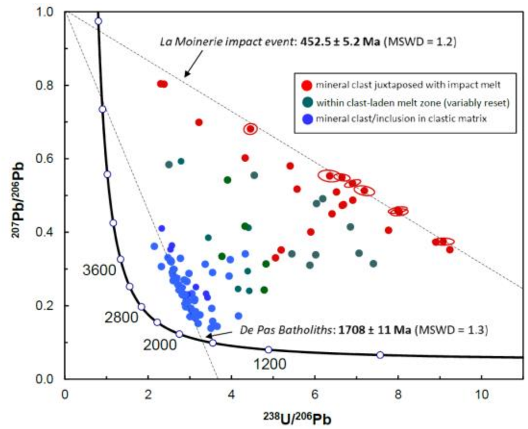

Fig. 2. All apatite U-Pb data plotted on an inverse concordia diagram. The youngest isochron, with a lower intercept age of 452.5 ± 5.2 Ma, is defined by grains directly juxtaposed with impact melt. The second, older array is defined by grains within clastic matrices and gives a lower intercept age of 1708 ± 11 Ma corresponding to the De Pas Batholith basement rocks. Green points correspond to variably reset apatite within clast-laden melt zones.

Conclusions: U-Pb dating of apatite and titanite provide the first higher precision age for the La Moinerie impact event. The age obtained from apatite (i.e., the lower intercept age of 452.5 ± 5.2 Ma; Fig. 2), indicates that the La Moinerie impact occurred during the Late Ordovician, coincident with the increased micrometeorite and asteroid flux associated with the L-chondrite parent body breakup [6]. Our results validate the use of relic apatite and titanite within variably reset melt-bearing breccias for U-Pb dating. We emphasize the importance of understanding petrographic context, and caution that heavily damaged zircons may experience significant post-impact Pb loss, giving anomalously young ages. A multiphase dating approach is recommended for resolving impact ages. We provide data on new shock microstructures in apatite and titanite (Fig. 1), document the first known natural occurrence of *t*-ZrO_2 within thermally dissociated zircons, and provide P-T estimates associated with the La Moinerie impact.

References:

[1] Earth Impact Database (2019) http://www.passc.net/EarthImpactDatabase/. Accessed 01 January 2019. [2] Gold D.P and Tanner J.G. (1978) *Geol. Soc. Ann. Meet.* 10, 44. [3] Bottomley et al. (1990) *Proc. Lunar. Plant. Sci. Conf.* 20, 421–431. [4] James D.T and Dunning G.R. (2000) *Precam. Res.* 103, 31-54. [5] Timms et al. (2017) *Earth. Sci. Rev.* 165, 185-202. [6] Martin E. et al. (2018). *Meteor. Planet. Sci.* 53, 1-17.