DATING THE CHARLEVOIX IMPACT STRUCTURE (QUEBEC, CANADA) – A TOUGH NUT TO CRACK IN $^{40}Ar/^{39}Ar$ GEOCHRONOLOGY.

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Introduction and Background: The ~54 km Charlevoix impact structure (Québec, Canada; center at 58°27' N, 109°30' W; Fig. 1), set in ~0.9 Ga crystalline rocks (mainly charnockitic and granitic gneisses, migmatites, anorthosites, and dike intrusions) of the Grenville Province of the Canadian Shield and overlying Middle Ordovician sedimentary rocks (sandstones and limestones) of the St. Lawrence platform, counts among the 15 largest impact structures currently known on Earth [1-4]. Impactites comprise pseudotachylitic breccia dikes in the shocked crater basement, as well as autochthonous and allochthonous impact melt rocks of variable appearance and textures (e.g., spinifex-textured and nodular types from Sainte-Marie-de-Charlevoix and fluidal-vesicular melt rocks near Sainte-Irénée) and some suevite-like impactites; the original breccia infill of the impact structure is almost completely eroded [5]. Although the Charlevoix impact structure has been studied for decades, no conclusive data have been obtained to answer the two principal questions (1) when (exactly) did the impact occur and (2) what is the nature of the Charlevoix impactor [6]. The stratigraphic age of the Charlevoix impact structure is bracketed by the Grenvillian age of the crystalline target rocks and the overlying Cambro-Ordovician sedimentary cover (e.g., Middle Ordovician limestones with well-developed shatter cones at Cap-aux-Oies) as a maximum impact age (~460-450 Ma [7]). The SE part (~40%) of the Charlevoix impact structure is overthrusted by the northern Appalachian front along the Logan's Line, and unshocked lower Paleozoic rocks (e.g., at the Île aux Coudres in the St. Lawrence River) juxtapose the shocked units in the NW (Fig. 1). Orogenic tectonism and heating in the southern Québec Appalachians is thought to have occurred during the Taconian and Acadian orogenies between ~463 and ~377 Ma [8;9], which therefore defines a minimum age for the Charlevoix impact. The St. Lawrence normal fault that runs through the Charlevoix impact structure (Fig. 1), reactivated in the mid-Mesozoic, also constrains a pre mid-Mesozoic minimum impact age [3]. Earlier K/Ar dating of impact melt rocks [5] yielded a Devonian age of ~356-321 Ma [10] (recalculated after [11]). More recently, an Ordovician impact age of ~470-460 Ma was suggested based on $^{40}Ar/^{39}Ar$ laser spot dating of impact melt rocks and pseudotachylitic breccias [10]. In addition to these data, we here report the first $^{40}Ar/^{39}Ar$ step-heating dating results for the Charlevoix impact structure.

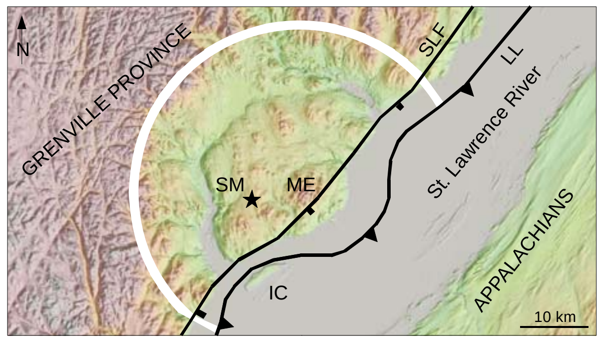

Fig. 1: Digital elevation model of the Charlevoix impact structure (white circle) with major geologic-tectonic units and faults; LL: Logan's Line thrust; SLF: St. Lawrence normal fault; SM: Ste-Marie-de-Charlevoix (impact melt rock); ME: Mont des Éboulements (central uplift); IC: Île aux Coudres; Canadian Digital Elevation Data (CDED).

Samples and Dating: Whole-rock chips (130 mg) of a virtually unaltered, spinifex-textured, and medium-grained crystalline impact melt rock from Ste-Marie-de-Charlevoix, predominantly made up of Fe-augite, K-feldspar, plagioclase, quartz, and accessories (see also [5;10]), were chosen for $^{40}Ar/^{39}Ar$ dating; the total K content was 3.6 wt%. $^{40}Ar/^{39}Ar$ dating was done at the University of Heidelberg, using the 328.5 ± 1.1 Ma (1σ) BMus/2 standard [12] and the K decay constant by [11] (see [12] for further technical details).

Dating Results and Interpretation: $^{40}Ar/^{39}Ar$ step-heating analysis yielded a fairly flat, 'plateau-like' age spectrum (Fig. 2A) – though not a plateau *sensu stricto*. The spectrum yielded younger apparent ages in the first two low-temperature steps (~185 to ~283 Ma; ~3% of the total ^{39}Ar released), intermediate steps 3-11 with ages of ~379-360 Ma (~90% of ^{39}Ar released), and older apparent ages in the high-temperature (>1200°C) steps 12-15 (~470-400 Ma; ~7% of ^{39}Ar released). The ages of steps 8-11 (~36% of ^{39}Ar)

overlap within 2σ and yielded a mean age of 362 ± 4 Ma (2σ; MSWD=0.40; p=0.94), close to the total gas age of 369 ± 4 Ma (2σ; Fig. 2A). Inverse isochron plots revealed two individual arrays of heating steps, one 'younger' ~360 Ma isochron (steps 8-11; MSWD=0.41) with an initial $^{40}Ar/^{36}Ar$ intercept at 330 ± 66 and one 'older' ~414 Ma isochron (steps 12-15; MSWD=0.91) with an $^{40}Ar/^{36}Ar$ intercept at 306 ± 19 (Fig. 2B); both initial $^{40}Ar/^{36}Ar$ ratios are atmospheric within uncertainty and yielded no obvious excess argon component (e.g., [13;14]). The step-shaped age spectrum, together with a complex Ca/K ($^{37}Ar/^{39}Ar$) distribution and degassing behavior (not shown) are in agreement with the mixture of Ca- and K-bearing phases in the Ste-Marie melt rock (pyroxene, plagioclase, K-feldspar, and possibly some mesostasis) and might be a result of argon recoil redistribution upon irradiation (e.g., [13]); emphasized degassing of ^{36}Ar in the high-temperature steps (1200-1500°C) suggests quartz as the main degassing phase.

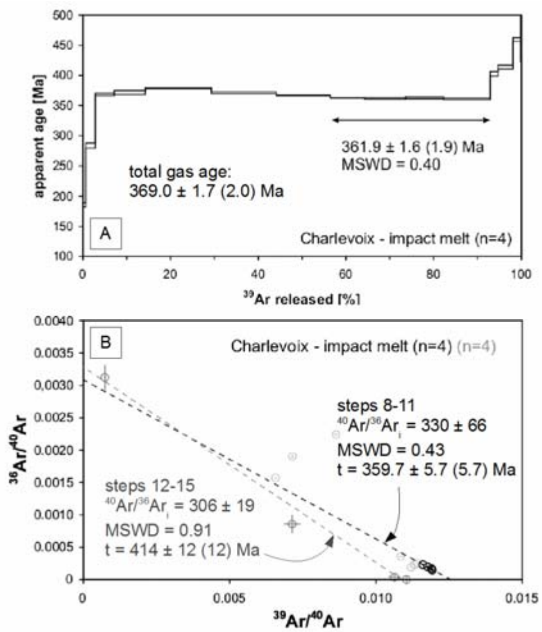

Fig. 2: $^{40}Ar/^{39}Ar$ age spectrum (A) and inverse isochron plot (B) for the Charlevoix impact melt rock (Ste-Marie-de-Charlevoix). Errors and boxes are at the 1σ level; errors in parentheses include error of the age standard.

Discussion and Conclusions: Although the 'plateau-like' age spectrum (Fig. 2A) and the isochron defined by steps 8-11 (Fig. 2B) indicate a Late Devonian cooling age around ~370-360 Ma for the Charlevoix impact melt rock (similar to the dating results by [5]), this new $^{40}Ar/^{39}Ar$ age value needs to be discussed with care with respect to the geologic-tectonic field relationships. As the Charlevoix impact structure is partially buried beneath tectonic units of the northernmost Appalachians that were emplaced during the Taconian to Acadian orogeny at ~466-377 Ma [8;9], it can be ruled out that the even younger Late Devonian rock age coincides with the Charlevoix impact event. Instead, dating of the impact melt rock is probably in analogy to $^{40}Ar/^{39}Ar$ dating of impact melt rocks from the Gardnos impact structure (Norway), which was affected by Caledonian orogenic activity and, thus, yielded an anomalous young apparent impact age of ~385 Ma [15] incompatible with field geology; a more robust U/Pb age of ~546 Ma was recently obtained for the Gardnos impact [16]. Our data suggest that, despite the primary optical appearance of the impact melt rocks in thin section, late Acadian tectonism in the Charlevoix area was most likely responsible for at least partial thermal resetting of the impact melt lithologies. In turn, the high-temperature heating steps 12-15 (~470-400 Ma; Middle Ordovician to Early Devonian [7]; Fig. 2A) and the corresponding older individual isochron (~414 Ma; Fig. 2B) might offer an Early Devonian minimum age for the impact, which is in consistence with the age peaks obtained by [10]. Clearly, further dating work needs to be done in order to more reliably distinguish the different syn- and post-impact thermometamorphic events at the Charlevoix impact site.

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