(U-Th)/He DATING OF SINGLE ZIRCON AND APATITE CRYSTALS – A NEW TOOL FOR DATING TERRESTRIAL IMPACT STRUCTURES.

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Introduction: On a geological timescale, impact cratering events are instantaneous, thus in principle, precise geochronological dating should be possible. However, studies indicate that about 90% of the target rocks affected by an impact event preserve pre-shock ages, because shock and post-shock events are insufficient to completely reset most isotopic dating systems, such as U-Pb, Rb-Sr, and ^{40}Ar-^{39}Ar (e.g., [1-2]). As a result, dating of whole rock samples or even pure mineral fractions often gives ambiguous ages [3].

Our approach has been to utilize the low-temperature (U-Th)/He geochronological technique on single apatite and zircon crystals to date impact events, as this geochronometer has a better chance of being completely reset during the formation of impact craters, as is outlined below.

Computer modelling: (U-Th)/He dating of apatites has already been proven as an important technique in determining shock metamorphism ages in meteorites [4-6]. The low He closure temperatures of 105°C and 230°C for apatite and zircon, respectively (calculated using the He diffusion parameters of Farley [7] and Reiners et al. [8], assuming a 100 µm crystal diameter and cooling rates of 1000°C/Ma), and fast He diffusion properties in these minerals result in rapid resetting of this geochronometer.

For example, computer modelling of He diffusion rates from 100 µm diameter apatite and zircon crystals indicates that 100 % of the radiogenic ^{4}He would be lost in very short durations of 0.1 and 30 seconds, respectively, during an initial impact heating event of 1227°C (e.g., calculated for Popigai, a 100 km diameter impact structure [9]), and 30 seconds and 5.9 days, respectively, for a 600°C initial heating event (e.g., calculated for Ries, a 24 km diameter impact crater [10]). These short heating durations are within the bounds of either the initial impact heating event, or a post-impact-hydrothermal overprinting event that are estimated to last thousands of years [e.g., 11-12], and suggest that (U-Th)/He analysis of these minerals could be a suitable technique for dating terrestrial impact events.

Impact structures dated: Individual euhedral zircon and apatite crystals from three impact structures (Manicouagan, Lake Saint Martin, and Bosumtwi) have been analysed using the single crystal (U-Th)/He dating technique. Details of the craters, previously determined ages, and our new (U-Th)/He zircon and apatite ages are shown in Table 1. In addition, we will present (U-Th)/He results for samples from two other impact structures – a crater suevite sample from the ca. 15 Ma, 23 km diameter Ries impact crater in Germany [13], and two samples (a basal suevite and impact melt breccia) from the Palaeozoic, 54 km diameter Charlevoix impact structure in Canada [14].

(U-Th)/He dating results and discussion: The new (U-Th)/He zircon and apatite ages are outlined in Table 1. The unweighted mean (U-Th)/He zircon ages agree, within error, with previously determined U-Pb, Rb-Sr, ^{40}Ar-^{39}Ar and fission track ages for each impact structure. The (U-Th)/He apatite ages show more complex results, as discussed below.

Details of the (U-Th)/He zircon and apatite ages obtained from each individual impact crater include:

Manicouagan: The (U-Th)/He mean zircon age of 213.6 ± 4.6 Ma is within error of the most precise U-Pb age of 215.56 ± 0.05 Ma [15-16], which was determined on zircons from the same sample. The (U-Th)/He apatite ages range from 205.9 ± 6.5 to 162.0 ± 5.3 Ma (2σ) and are all younger than the mean zircon age, and hence show evidence of later resetting, possibly due to a 137-177 Ma thermal event [17].

Lake Saint Martin: For this 40 km diameter impact crater the (U-Th)/He mean zircon age of 235.2 ± 6.2 Ma and the oldest (U-Th)/He mean apatite age cluster of 231.5 ± 7.2 Ma define a more tightly constrained age compared to the previously obtained K-Ar, Rb-Sr and apatite fission track ages of 225 ± 40, 219 ± 32, and 208 ± 14 Ma [18-20]. The younger cluster of apatite ages 177.2 ± 1.4 Ma (n=2) appears to be a distinct population, but this needs to be confirmed by further analyses.

Bosumtwi: (U-Th)/He analyses of zircon grains from Bosumtwi yield a mean age of 0.921 ± 0.034 Ma, which is slightly younger than the previously determined $^{40}Ar/^{39}Ar$ tektite age of 1.1 ± 0.1 Ma [21], but is within error of fission track impact glass age of 1.03 ± 0.22 Ma [21]. The (U-Th)/He zircon mean age of 0.921 ± 0.034 Ma may indicate a hydrothermal cooling age through the zircon He closure temperature of ca. 230°C, rather than an initial impact age.

Conclusions: From (U-Th)/He analyses of individual zircon crystals of three impact craters (Manicouagan, Lake Saint Martin, and Bosumtwi), we have demonstrated the ability of the (U-Th)/He geochronometer to accurately date melt rock and suevite material from variably sized impact structures (i.e., 100, 40, and 10.5 km in diameter).

(U-Th)/He apatite ages show more complexity than the (U-Th)/He zircon ages, demonstrating that when closure temperatures for the resetting of a geochronometer are very low, the system becomes highly susceptible to disturbance by later thermal events unrelated to the impact. However, in certain well constrained cases this could be utilized to constrain post impact cooling rates of the impact material.

The results presented here show that when geochronometers (e.g., U-Pb and ^{40}Ar-^{39}Ar) that usually yield very precise results, are either not isotopically reset, or not completely reset due to an impact event, the (U-Th)/He method provides a suitable alternative that can yield accurate and fairly precise ages. Hence, the technique has great potential to date smaller terrestrial impact structures, where thermal/shock effects are less marked.

In addition to zircon and apatite, other mineral phases such as monazite, titanite, xenotime, and magnetite (and other iron oxide phases), with He closure temperatures in the range of 200 to 270˚C, are routinely utilized for the (U-Th)/He dating method. This provides a wide spectrum of mineral phases that can be targeted for use in the dating of a wide variety of impact materials.

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Table 1	**Manicouagan**	**Lake Saint Martin**	**Bosumtwi**
Diameter (km)	100	40	10.5
Target rocks	Grenville metamorphics and Ordovician carbonates	Precambrian granites and Paleozoic sediments	2.1-2.2 Ga metasediments and metavolcanics
Examples of previously determined ages (Ma, 2σ)	214 ± 5, Rb-Sr MI [22] 214 ± 1, U-Pb zircon [23] 215.56 ± 0.05, U-Pb zircon [14-15]	225 ± 40, K-Ar WR [18] 219 ± 32, Rb-Sr MI [19] 208 ± 14, apatite FT [20]	1.1 ± 0.10, ^{40}Ar-^{39}Ar tektite [21] 1.03 ± 0.22, FT glass [21]
New material dated	Melt sheet (zircon and apatite)	Melt rock (zircon and apatite)	Suevite (350-380 m), outside crater (zircon)
(U-Th)/He zircon ages (Ma, 2 SE)	Mean = 213.6 ± 4.6 (n=9)	Mean = 235.2 ± 6.2 (n=4)	Mean = 0.921 ± 0.034 (n=8)
(U-Th)/He apatite ages (Ma, 2 SE)	Individual grain range = 205.9 ± 6.5 to 162.0 ± 5.3 (n=5, 2σ)	Mean = 231.5 ± 7.2 (n=5) Mean = 177.2 ± 1.4 (n=2)	-

Abbreviations. MI = mineral isochron, WR = whole rock, FT = fission track, SE = standard error.