AN EXAMINATION OF NOBLE GAS GEOCHRONOLOGY AND THERMOCHRONOLOGY IN THE CONTEXT OF DATING IMPACT EVENTS.

K. E. Young[1], C. M. Mercer[1], M. C. van Soest[1], K. V. Hodges[1], J-A Wartho[1], and M.B. Biren[1], [1]School of Earth and Space Exploration, Arizona State University, ISTB4 Bldg 75, 781 E Terrace Rd, Tempe, Arizona, 85287-6004. Contact: Kelsey.E.Young@asu.edu

Introduction: The significance of bolide impact in earth system development – especially its apparent influence on biological evolution – motivates the continued development of more accurate and more precise methods to determine the ages of terrestrial impact events. Unfortunately, because we live on a tectonically active planet with both a hydrosphere and a biosphere, Earth's surface is continually reworked and only a small number of impact craters are available to study. Of these 184 structures [1] an even smaller number have been accurately dated [2]. This is due to the fact that many impact sites are not in target areas that are amenable to using stratigraphic constraints on impact timing, or because commonly applied isotopic chronometers do not yield straightforward dating results. An important research goal of the Noble Gas, Geochronology, and Geochemistry Laboratories (NG^{3}L) at Arizona State University is to expand the arsenal of isotopic techniques used for impact dating in order to to enable more precise dating of terrestrial and extraterrestrial impactites. Here we review two new methods we have been evaluating: (U-Th)/He thermochronology of the phases zircon, titanite, andapatite; and laser ablation ^{40}Ar/^{39}Ar microanalysis. These techniques have applications both in dating terrestrial impact craters as well as extraterrestrial samples.

Impact Dating as a Thermochronologic Problem: While stratigraphic dating (constraining the age of an impact event based on determining the ages of surrounding units or crater infill) can give a rough idea of when a crater formed (e.g. [3]), isotopic dating is much more precise. The method used often depends on the phases found at the structure of interest. Historically, U-Pb, Rb-Sr, K-Ar and ^{40}Ar/^{39}Ar methods have been the most common isotopic methods applied to the dating of impact events [2]. The U-Pb and ^{40}Ar/^{39}Ar techniques have been shown to be especially effective for the precise and accurate dating of minerals that crystallize from impact melt sheets. However, these methods can often provide inaccurate crater ages due to analysis contamination by pre-impact minerals or lithic clasts, or by incomplete resetting of pre-impact materials.

The possible reasons for these difficulties were explored by [4]. Using published experimental data for Pb, Ar, and He diffusion in minerals, they explored the likelihood that a variety of chronometric systems would be reset during the brief but intense thermal events related to bolide impact. They found that it is very unlikely for most U-Pb chronometers to be sensibly reset by an impact event. Many of the commonly used ^{40}Ar/^{39}Ar chronometers (i.e., muscovite, biotite, feldspar, etc.) would not be reset in smaller impacts because the duration and magnitude of the thermal event is so small. However, it seems likely that chronometers based on the production of ^{4}He by U, Th, and (to a lesser extent) Sm decay may be quite readily reset. This observation has motivated our interest in exploring the practical value of (U-Th)/He thermochronoloy in impact studies.

(U-Th)/He Thermochronology: (U-Th)/He thermochronology capitalizes on the production of abundant alpha particles (^{4}He) as a consequence of U, Th, and Sm decay. The method is typically applied to the minerals zircon, titanite, or apatite in orogenic belts to evaluate the time of bedrock cooling below 200-70˚C. Reheating by bolide impact can reset these chronometers very effectively, but the spatial variability of heating in impact target regions and the brevity of an impact heating event typically mean that analyzed samples from target regions include crystals that range from essentially unreset (which yields regional cooling ages of the target rocks), through various degrees of partial resetting, to young and fully reset ages. If an impact event is sufficiently energetic to produce extensive melting and the growth of neoblastic zircon, titanite, or apatite, (U-Th)/He analysis of those phases can be expected to yield accurate impact melt crystallization ages. In other cases, minimum ages from the unreset to reset spectra are reasonably interpreted as impact ages [4].

The NG^{3}L group is applying (U-Th)/He thermochronology to a wide variety of impact structures [4, 5, 6, 7] One such structure that has been examined is the Manicouagan crater in Quebec, Canada [5, 7]. This structure contains an extensive melt sheet that has been crosscut by a central uplift that exposes a Precambrian target. Accessory minerals from both the melt sheet and the uplift were dated, including neoblastic minerals that formed directly out of the melt itself. Zircons, apatites, and titanites were analyzed. The zircon population yielded an age of 213.2 $\pm$ 2.3 Ma (2 standard errors, n=9, [5]), which is consistent with the U-Pb neoblastic zircon age of the structure [8]. Titanite (U-Th)/He systematics for samples from the central uplift were complex and suggestive of some form of postimpact He loss (most likely enhanced by shock damage to the crystal structure), but a weighted mean titanite age of 208.9 ± 5.1 (2σ) is also within error of the U-Pb age [5, 8].

Laser Ablation $^{40}Ar/^{39}Ar$ Thermochronology: Other research in our laboratories addresses the challenges associated with conventional $^{40}Ar/^{39}Ar$ dating of impact melt products that are contaminated by pre-impact materials. $^{40}Ar/^{39}Ar$ thermochronology is based on the decay of ^{40}K to ^{40}Ar. Applications of this technique to impactites that have yielded data that are complex and hard to interpret have usually been compromised by the need to date relatively large aliquots of material that often contain unavoidable clasts or mineral crystals from the target rock with isotopic systematics not fully reset by the impact event. Mechanical mixtures of melt and partially reset or unreset clasts yield hybrid $^{40}Ar/^{39}Ar$ ages that can be geologically meaningless. We have been attempting to minimize such effects by increasing the spatial resolution of analysis using a laser microprobe. Our approach is to employ a focused ArF (193 nm) laser to ablate melt components in a polished impactite sample while avoiding clasts where possible. In a separate presentation at this meeting, [9] discuss the results of applying this *in situ* $^{40}Ar/^{39}Ar$ approach to samples from the Apollo 17 archive. Here we describe results for samples from the Mistastin impact structure in northern Canada.

When applied to six thick sections from a broadly distributed array of Mistastin impactites, the $^{40}Ar/^{39}Ar$ laser microprobe technique yielded a remarkably consistent result. Eighty-nine dates for material excavated from 200 μm diameter x 40 μm deep ablation pits in melt domains yielded a single major mode indicative of an impact age of 36.6 $\pm$ 2.0 Ma (2σ). The cumulative kernel density estimator [10] for these data indicates a slight skew toward older dates (Figure 1). We interpret this as indicative of the presence of some undetected clast material in some of the ablation pits.

While it is impossible to avoid clasts that do not express themselves on sample surfaces, the high spatial resolution of this method provides greatly improved textural awareness.

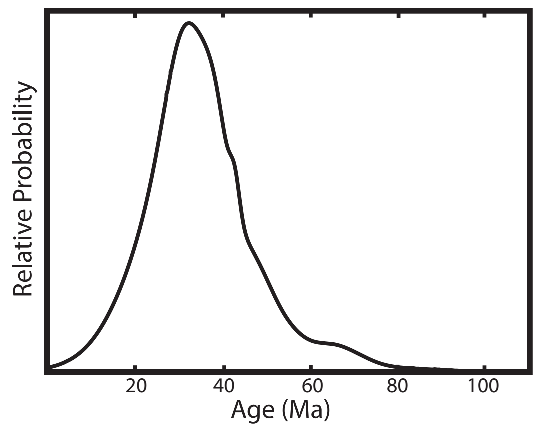

Figure 1. Kernel density plot of our $^{40}Ar/^{39}Ar$ results for the Mistastin impact structure (n=89).

Conclusions: Emerging techniques such as (U-Th)/He thermochronology and *in situ* laser ablation $^{40}Ar/^{39}Ar$ geochronology show great promise. The NG^{3}L group at Arizona State University has now dated several structures using these techniques (i.e., Haughton, Mistastin, Manicouagan, Wetumpka, Bosumtwi, Lake Saint Martin, Monturaqui, Ries, Clearwater West, Charlevoix, etc.). We are also examining the application of these techniques to dating extraterrestrial samples. We look forward to further studies and invite expressions of interest from our planetary science collegues regarding opportunities for collaboration.

References: [1] Earth Impact Database, accessed Jan 2014. [2] Jourdan, F. et al. (2012) *Elements, 8,* 49-53. [3] Frisch, T. and Thorsteinsson, R. (1978) *J. Arctic Inst. North Am., 31*, 108-124. [4] Young, K. E. et al. (2013) *GRL, 40*, 3836-3840. [5] van Soest, M. C. et al. (2011) *Geochem. Geophys. Geosyst., 12*. [6] Wartho, J-A. et al. (2011) *LPS LXXIII*, #1524. [7] Biren, M. B. et al. (2014), submitted to *Chem. Geo.* [8] Hodych, J. P. and Dunning, F. R. (1992) *Geology, 20*, 51-54. [9] Mercer, C. M. et al. (2014) Submitted to *LPS LXXVI.* [10] Vermeesch, P. (2012) *Chem. Geo., 312-313*, 190-194.