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(U-Th)/He zircon dating of Chesapeake Bay distal impact ejecta from ODP site 1073

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Abstract

Single crystal (U-Th)/He dating has been undertaken on 21 detrital zircon grains extracted from a core sample from Ocean Drilling Project (ODP) site 1073, which is located ~390 km northeast of the center of the Chesapeake Bay impact structure. Optical and electron imaging in combination with energy dispersive X-ray microanalysis (EDS) of zircon grains from this late Eocene sediment show clear evidence of shock metamorphism in some zircon grains, which suggests that these shocked zircon crystals are distal ejecta from the formation of the ~40 km diameter Chesapeake Bay impact structure. (U-Th/He) dates for zircon crystals from this sediment range from 33.49 ± 0.94 to 305.1 ± 8.6 Ma (2σ), implying crystal-to-crystal variability in the degree of impact-related resetting of (U-Th)/He systematics and a range of different possible sources. The two youngest zircon grains yield an inverse-variance weighted mean (U-Th)/He age of 33.99 ± 0.71 Ma (2σ uncertainties n = 2; Mean Square Weighted Deviation (MSWD) = 2.6; Probability (P) = 11 %), which is interpreted to be the (U-Th)/He age of formation of the Chesapeake Bay impact structure. This age is in agreement with K/Ar, $^{40}Ar/^{39}Ar$, and fission track dates for tektites from the North American strewn field, which have been interpreted as associated with the Chesapeake Bay impact event.

1. Introduction

The largest well-preserved impact structure in the United States of America lies hidden beneath part of Chesapeake Bay (Fig. 1), near the southwestern tip of the Delmarva Peninsula in Virginia (Horton et al., 2009). Seismic profiles and gravity data were used to locate the Chesapeake Bay structure, and its impact origin was later confirmed by the presence of shocked quartz and feldspar grains observed within various drill core samples (e.g., Poag et al., 1992, 1994; Koeberl et al., 1996; Harris et al., 2004; Horton and Izett, 2005; Horton et al., 2009). The impact structure represents a complex crater that is roughly centered on the town of Cape Charles and exhibits an 85 km-diameter outer damage zone of collapsed and mobilized sediments and a 40 km-diameter central crater (Fig. 1; Collins and Wünnemann, 2005; Horton and Izett, 2005). The Chesapeake Bay impact structure is thought to be the source crater for the North American tektite (NAT) strewn field (Fig. 2; e.g., Horton and Izett, 2005; Deutsch and Koeberl, 2006; Koeberl, 2009), including tektites and ejecta material found preserved both onshore and offshore.

Previous attempts to determine the age of impact structures, such as the Chesapeake Bay crater, have mainly focused on the use of $^{40}Ar/^{39}Ar$ or U/Pb geochronometers (e.g., Jourdan et al., 2012 and references therein). Recently, (U-Th)/He thermochronology of apatite, titanite, and zircon has proven to be another valuable isotopic system for this purpose (e.g., Ukstins Peate et al., 2010; van Soest et al., 2011; Wartho et al., 2012; Young et al., 2013a, b; Biren et al. 2014; 2016; Wielicki et al., 2014). In order to augment previous attempts to date the Chesapeake Bay event using a variety of isotopic and fission-track chronometers, we have used the (U-Th)/He method to date 21 individual zircon grains in an unconsolidated sediment from ODP site 1073 hole A, located ~390 km north-east of the Chesapeake Bay impact structure (Fig. 2). This section of core contains ejecta products presumably related to the Chesapeake Bay structure, and thus might be expected to offer an opportunity to determine (U-Th)/He closure dates for zircon crystals that may have had their helium isotopic systematics disturbed or reset at the time of the impact event.

Zircon crystals ejected from the Chesapeake Bay impact crater and distally deposited on the sea floor would have the advantage of being cooled very rapidly, in contrast to zircon grains sourced from proximal impactites within a hot and slowly cooling crater. This is especially important considering the relatively low He closure temperature of zircon (~200 °C; Reiners et al., 2004). $^{40}Ar/^{39}Ar$ or U/Pb geochronometers have recently been used to examine different settings (slow crater cooling and hydrothermal resetting/alteration vs. rapid ejecta cooling) in relation to hydrothermally-reset vs. impact-formation ages, respectively (Schmieder et al., 2018; Kenny et al., 2019).

1.1 Geological context

The Chesapeake Bay impact structure was formed on the continental margin of Virginia in a shallow-marine sequence of 200-500 m of seawater, 600-1000 m of Cretaceous to Eocene unconsolidated sediments, and underlying Proterozoic to Paleozoic crystalline rocks (Kamo et al., 2002; Collins and Wünnemann, 2005; Horton and Izett, 2005). The Chesapeake Bay impact structure is also associated with distal ejecta found onshore in Georgia (the tektite deposits are termed georgiaites), Texas (bediasites), Massachusetts (Martha's Vineyard), and Barbados, and offshore in the Caribbean Sea (Deep Sea Drilling Project (DSDP) site 149), the Gulf of Mexico

(DSDP site 94), and the continental shelf of the NW Atlantic (DSDP site 612; ODP sites 903 and 1073; Fig. 2; e.g., Glass and Liu, 2001; Glass, 2002; Simonson and Glass, 2004).

1.2 Previous age determinations for the Chesapeake Bay impact structure

The age of the Chesapeake Bay impact structure has been inferred indirectly from K/Ar, fission track, and $^{40}Ar/^{39}Ar$ dates of NAT ranging from 32.5 ± 2.0 to 35.9 ± 4.8 Ma (2σ; Table 1; e.g., Fernandes et al. 2019). In addition, TIMS U-Pb dating of 24 intensely shocked zircon crystals from the NA microtektite layer from DSDP/ODP sites 612, 903 and 904 and Bath Cliff in Barbados produced upper and lower intercept U-Pb Concordia ages of 400 ± 32 Ma and ~35.4 Ma, respectively (Kamo et al., 2002).

1.3 Sample Description

A ~30 cm^3 core sample of upper Eocene unconsolidated glauconite-bearing sediment (Fig. 3) was obtained from ODP site 1073, hole A, core 72X (depth range of core 72X = 654.1 - 663.6 meters below sea floor), section 4, interval 83-94 cm, obtained during ODP Leg 174A expedition (Austin et al., 1998), from the International Ocean Drilling Project (IODP) Bremen Core Repository in Germany. The upper Eocene interval of the 1073 drill hole A mainly consists of clay-rich nannofossil chalk and diatom-rich nannofossil clay that is strongly bioturbated (Austin et al., 1998). Unmelted impact ejecta (> 125 μm) are confined to an interval between 61-120 cm in core 72-4, with numerous white (opaque) grains of shock metamorphosed quartz and K-feldspar with planar deformation features. Coesite and reidite are also present in this interval, but no microtektites or clinopyroxene-bearing spherules have been identified (Liu et al., 2006). Dark green glauconite clays, sand and pellets are present below, above, and throughout the ejecta layer, but form an abundance maximum associated with the ejecta layer (Liu and Glass, 2001).

2. Analytical Methods

The unconsolidated sediment sample was disaggregated and cleaned with deionized water in an ultrasonic bath and then wet-sieved. The heavy minerals were separated using standard gravimetric and magnetic techniques. A Leica MZ16 binocular microscope was used to select and accurately measure the dimensions of twenty-one zircon grains for dating using the (U-Th)/He method (Table 2). Individual zircon crystals were photographed and measured on at least 2 difference crystal faces, and loaded into individual 0.7 mm OD x 1.0 mm long Nb tubes prior to isotopic analysis

(U-Th)/He analyses were undertaken in the Group 18 Laboratories at Arizona State University. An Australian Scientific Inc. *Alphachron Mk II* helium extraction and analytical system was employed for the helium isotopic analyses. On this system, an infrared (980 nm) diode laser is used to heat Nb-encapsulated samples *in vacuo*. Evolved gases were purified using hot and cold SAES NP10 getters prior to spiking with ^{3}He for isotope dilution analysis using a Balzers QMS 200 quadrupole mass spectrometer. Blank Nb tubes and crystals of Fish Canyon zircon were also analyzed in order to establish system blanks and monitor system performance. The average ^{4}He blank was 0.049 femtomole for all procedures. ^{4}He abundances for the unknowns were between 200-30000 times the blank for the zircon analyses. The concentration of the ^{4}He aliquot pipetted from the ^{4}He standard tanks is known to within 1.18% (1 σ), which for most analyses, contributes the largest uncertainty to this part of the analytical process.

After helium extraction and analysis, the encapsulated zircon crystals were removed from the Alphachron vacuum system, spiked with a solution of ^{230}Th and ^{235}U in 50% HNO_3, and dissolved in separate solutions of HF, HNO_3 and HCl acids using Parr digestion vessels at elevated temperatures. U and Th isotopic ratios were measured by isotope dilution on a Thermo Scientific *iCapQ* inductively coupled plasma source mass spectrometer (ICP-MS). Additional details of the (U-Th)/He analytical procedures can be found in van Soest et al. (2011). (U-Th)/He dates were calculated iteratively from blank-corrected ^{4}He, ^{232}Th, and ^{238}U concentrations. Raw calculated dates were corrected for α-ejection based on optical measurements of the crystals prior to analysis, following the protocols recommended by Farley et al. (1996). All (U-Th)/He dates and inverse-variance mean ages are quoted in Table 2 with 2σ uncertainties.

Eight undated and unpolished zircon grains and grain fragments were mounted on sticky carbon tape and photographed using a Leica MZ16 binocular microscope using the same procedures as the dated grains. The grains were then carbon coated and examined using secondary electron (SE) and backscattered electron (BSE) imaging and energy dispersive X-ray spectrometry (EDS) with a JEOL JXA-8530F electron microprobe located at the John M. Cowley Center for High Resolution Electron Microscopy, ASU. Operating conditions were 10 kV accelerating voltage and a 250 pA beam current. A low beam current was required to minimize charging effects during the imaging session, during which spot analyses by EDS were performed under the same conditions using a silicon drift diode (SDD) detector to confirm the elemental compositions of the observed minerals and decompression melt phases, using acquisition times of 25 seconds. Reported compositions utilize a ZAF matrix correction with oxygen calculated by stoichiometry, and measurements were calibrated using an instrument-specific mineral standard database.

These grains and grain fragments were not dated with the (U-Th)/He method because they were too small or broken, plus the carbon coating required for SE/BSE/EDS analysis would have caused a carbon contamination problem during the measurement of helium in the quadrupole mass spectrometer, which is a common issue for noble gas mass spectrometer analyses. However, the optical, SE, BSE, and EDS characteristics of this sub-set of zircon grains are considered to be representative of the dated population of 21 zircon grains.

3. Results

Optical photomicrographs of the eight youngest (U-Th)/He dated zircon grains reveals the presence of: (1) clear euhedral zircon crystals (Figs. 4A-B, and 4F); (2) rounded slightly cloudy translucent zircon grains (Figs. 4C-E, G); and (3) one milky white opaque rounded zircon grain (Fig. 4H).

The presence of zircon is supported by EDS spectra from the eight undated unpolished zircon grains/fragments that all show pronounced and resolvable X-ray peaks for Zr (Lα) and Si (Kα) and by quantitative analyses of six grains which yield average weight (wt.) % values for ZrO_2 of 69.2 ± 6.2, SiO_2 of 28.6 ± 4.0, and analytical totals of 97.9 ± 7.2 (2σ). Five of the eight undated zircon grains/fragments are optically clear and euhedral, and these zircon grains/fragments show no evidence of shock metamorphism in the SEM images (e.g., Figs. 5A.1-5A.2 and B.1-B.2). Multiple linear features were observed in two undated zircon grains (Figs. 5C.2-C.3 and 5D.2-D.3) and are interpreted as planar deformation features. The optical photomicrographs of these two zircon grains indicate cloudy regions (Fig. 5C.1) or a totally translucent crystal (Fig. 5D.1) that correlate with the presence of planar deformation features, observed in Figs. 5C.2-C.3 and 5D.2-D.3; such features are commonly observed in shock metamorphosed zircon grains (e.g., Kamo et al., 1996; Wittmann et al., 2006; Schmieder et al., 2015). One partially-rounded, opaque undated zircon grain (Fig. 5E.1) shows evidence of partial decomposition, marked by the transformation of zircon to a micron-scale dendritic intergrowth of baddeleyite (ZrO_2) and silica (SiO_2, with an EDS analysis yielding a wt. % ZrO_2/SiO_2 ratio of ~31 in the bright BSE regions of intergrowth, Figs. 5E.2-E.3). The baddeleyite + silica assemblage mainly occurs along the rims of the zircon grain and along cracks.

As shown in Table 2 and Fig. 6A, the twenty-one individual (U-Th)/He zircon analyses yield dates ranging from 33.49 ± 0.94 to 305.1 ± 8.6 Ma. Six of the 21 dates are younger than 70 Ma, and the three youngest dates are 36.7 ± 1.0 Ma, 34.6 ± 1.1 Ma, and 33.49 ± 0.94 Ma.

4. Discussion

Based on our microscope observations and information gleaned from the electron probe analyses, we conclude that the zircon population sampled in ODP 1073 hole A shows various degrees of shock deformation (Fig. 5). Evidence for shock metamorphism includes planar deformation features (Figs. 5C.2-C.3 and 5D.2-D.3), granular texture, and decomposition from zircon to a dendritic assemblage of baddeleyite and silica (Figs. 5E.2-E.3). The zircon to baddeleyite + silica decomposition process is estimated to occur at extreme shock conditions (Wittmann et al., 2006; 2009a, b; Schmieder et al., 2015; Timms et al, 2017). Shock metamorphism commonly results in cloudy or opaque zircon grains, as observed by Bohor et al. (1993) and Corfu et al. (2003), which is also observed in our optical photomicrographs (Figs. 5C.1, 5D.1 and 5E.1) and has been confirmed by SEM observations of these grains (Figs. 5C.2-C.3, 5D.2-D.3 and 5E.2-E.3).

Our ODP sample is comprised a mix of unshocked, weakly-shocked, and intensely-shocked (including granular texture) zircon grains. The shocked zircon grains likely represent distal ejecta from the Chesapeake Bay impact structure due to the excavation/ejection process, whereas the unshocked zircon crystals may be derived from (1) unshocked Chesapeake Bay target rocks, (2) different sources unrelated to the impact, or (3) may represent contamination by drilling mud (Andrews et al., 2016). ODP drilling procedures include the use of a sepiolite drilling mud (Sea Mud™), which is produced by mixing material quarried from the Amargosa Basin of Nevada with seawater to form a gel that is able to carry heavier particles out of the drill hole. Drill cores can become contaminated with the drilling fluids due to the elevated water pressure or via fracturing of the core during drilling. Intrusion of drilling mud is likely to be greater in drill core sample lithologies that are unlithified, porous, or heavily fractured. U/Pb TIMS and Secondary Ionization Mass Spectrometer (SIMS) dating of the Sea Mud™ zircon grains has yielded ages ranging from 1.89 to 2889 Ma (Andrews et al., 2016), but no (U-Th)/He data exist for Sea Mud™ zircon grains and we thus cannot comparatively evaluate the possibility of contamination in our drill core sample. However, the broad distribution of (U-Th)/He zircon dates from this sample, with a distinctive, young cluster of dates (Fig. 6A), is similar to that found in (U-Th)/He datasets for rocks collected from other impact structures (e.g., Ukstins Peate et al., 2010; van Soest et al., 2011; Wartho et al., 2012; Young et al., 2013a, b; Biren et al., 2014; 2016), i.e., many dates distributed over a wide age range, with a number of comparatively tightly clustered young dates (Fig. 6A). We interpret this distribution to be indicative of (1) variable resetting of pre-impact zircon crystals in the target rocks (i.e., ~260-240 Ma Alleghanian granites, pegmatites and metamorphic basement rocks; e.g., Gibson et al., 2009; Horton et al., 2009); and (2) (U-Th)/He zircon cooling dates from different sources.

Two of the three youngest zircon crystals are optically distinctive from some of the other (U-Th)/He dated zircon crystals (Fig. 4). Zircon 1073 Z13 (33.49 ± 0.94 Ma; Fig. 4H) has an opaque milky white appearance, and is similar to the undated opaque zircon (Fig. 5E.1) that is partially decomposed to baddeleyite and silica (Figs. 5E.2-E.3). Zircon 1073 Z21 (34.6 ± 1.1 Ma; Fig. 4G) is translucent and partly cloudy and is similar in appearance to the undated cloudy and translucent zircon grains/fragments that preserve planar deformation features (Figs. 5C.1-C.3 and 5D.1-D.3). However, Zircon crystal 1073 Z06 (36.7 ± 1.0 Ma; Fig. 4F) is clear and euhedral, and is similar in appearance to (1) two of the older dated zircon grains (1073 Z04 and Z20; Figs. 4A-B), and (2) two of the clear euhedral undated zircon grains (Figs. 5A.1-B.2) that preserve no evidence of shock metamorphism (Figs. 5A.2 and 5B.2). Due to these observations, the zircon 1037 Z06 with a (U-Th)/He date of 36.7 ± 1.0 Ma, is excluded from our inverse variance weighted mean age.

We suggest that the two youngest zircon grains may have been shock-metamorphosed during the formation of the Chesapeake Bay impact event, ejected from the target area, and deposited at ODP site 1073 hole A, which is presently ~390 km NE of the impact structure (Fig. 2). Thus, the inverse-variance weighted mean age of 33.99 ± 0.71 Ma (n = 2; MSWD = 2.6; P = 11 %; Fig. 6B) represents our best estimate of the (U-Th)/He age of the Chesapeake Bay impact event.

Owing to the fast He diffusion parameters in zircon (Reiners et al., 2004) it is advantageous to undertake (U-Th)/He studies on ejected heavy minerals found within tektite and microtektite layers in distal marine deposits. These shock-metamorphosed distal zircon grains would have undergone virtually instantaneous cooling via interaction with the air and seawater, thereby yielding a reliable impact formation age. In contrast, geochronological analyses of proximal and crater-filling impactite samples may suffer from the effects of prolonged post-impact cooling and/or hydrothermal resetting/alteration, thus potentially yielding ages that are younger than the impact formation event (e.g., Schmieder et al., 2018; Kenny et al., 2019). $^{40}Ar/^{39}Ar$ studies indicate that medium sized (~23 km diameter) impact craters can host relatively long-lived hydrothermal systems (> 1 Ma; Schmieder and Jourdan, 2013).

Our inverse variance-weighted mean (U-Th)/He age of 33.99 ± 0.71 Ma for Chesapeake Bay is in agreement or slightly younger than previous ages obtained from analyses of NA tektites by fission track, K/Ar, and $^{40}Ar/^{39}Ar$ dating methods (Fig. 7; Reynolds, 1960; Zähringer, 1963; Fleischer and Price, 1964; Gentner et al. 1969; Garlick et al., 1971; Storzer and Wagner, 1971; Glass et al., 1973; Bottomley et al., 1979; Storzer and Wagner, 1977; Bottomley, 1982; Glass et al, 1986, Obradovich et al., 1989; Glass et al., 1995; Albin and Wampler, 1996; Horton and Izett, 2005; Fernandes et al., 2019), and U/Pb TIMS zircon single crystal analyses (Fig. 7; Kamo et al., 2002). This (U-Th)/He zircon age suggests that Chesapeake Bay is a late Eocene impact event (Koeberl, 2009), and it also overlaps within 2σ errors with the 33.91 ± 0.05 Ma age of the Eocene-Oligocene boundary (Fig. 7; Brown et al., 2009). However, the more precise inverse isochron $^{40}Ar/^{39}Ar$ age of 34.86 ± 0.32 Ma (Fernandes et al., 2019), obtained from NA tektites and Chesapeake Bay impact melt lithologies, does not overlap with the Eocene-Oligocene boundary (Fig. 7), which suggests that there is no connection between the Chesapeake impact structure and the Eocene-Oligocene extinction event. This is confirmed by the observation that the NA microtektite layer is located metres below the global stratigraphic Eocene/Oligocene boundary in the Massignano section, Italy (Koeberl, 2009).

Conclusions

(U-Th)/He dating of zircon crystals from a distal ejecta sample from ODP drill hole 1073A yields a range of dates from 33.49 ± 0.94 to 305.1 ± 8.6 Ma. The two youngest zircon grains, which show evidence of shock metamorphism, yield a weighted mean date of 33.99 ± 0.71 Ma. This date is consistent with previous geochronological results (Fig. 7), and is interpreted as the shock-induced zircon (U-Th)/He resetting age of the Chesapeake Bay impact event. Our results provide evidence that it is possible to obtain impact crater formation ages via (U-Th)/He dating of carefully characterized distal ejecta samples.

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References

Albin E. F., and Wampler J. M. 1996. New potassium-argon ages for georgiaites and the Upper Eocene Dry Branch Formation (Twiggs Clay Member): Inferences about tektite stratigraphic occurrence (abstract). 27th Lunar and Planetary Science Conference, p. 5-6.

Andrews G. D. M., Schmitt A. K., Busby C. J., Brown S. R., Blum P., and Harvey J. C. 2016. Age and compositional data of zircon from sepiolite drilling mud to identify contamination of ocean drilling samples. Geochemistry, Geophysics, Geosystems 10.1002/2016GC006397

Austin J. A., Christie-Blick N., Malone M.J., and Shipboard Scientific Party. 1998. Proceedings of the Ocean Drilling Program initial reports volume 174A, College Station, Texas.

Biren M. B., van Soest M. C., Wartho J-A., and Spray J. G. 2014. Dating the cooling of exhumed central uplifts of impact structures by the (U-Th)/He method: A case study at Manicouagan. Chemical Geology 377:56-71.

Biren M. B., van Soest M. C., Wartho J-A., Hodges K. V., and Spray J. G. 2016. Diachroneity of the Clearwater West and Clearwater East impact structures indicated by the (U-Th)/He dating method. Earth and Planetary Science Letters 453:56-66.

Böhlke, J. K., de Laeter, J. R., de Bièvre, P., Hidaka, H., Peiser, H. S., Rosman, K. J. R., and Taylor, P. D. P. 2005. Isotopic compositions of the elements, 2001. Journal of Physical and Chemical Reference Data 34:57-67.

Bohor B. F., Betterton W. J., and Krogh T. E. 1993. Impact-shocked zircons: Discovery of shock-induced textures reflecting increasing degrees of shock metamorphism. Earth and Planetary Science Letters 199:419-424.

Bottomley R. J. 1982. ^{40}Ar-^{39}Ar dating of melt rock from impact craters. Ph.D. thesis, University of Toronto, Canada.

Bottomley R. J., York D., and Grieve R. A. F. 1979. Possible source craters for the North American tektites – a geochronological investigation (abstract). Transactions of American Geophysical Union EOS 60:309.

Brown R.E., Koeberl C., Montanari A., and Bice D.M. 2009. Evidence for a change in Milankovitch forcing caused by extraterrestrial events at Massignano, Italy, Eocene-Oligocene Boundary GSSP In The late Eocene Earth: Hothouse, Icehouse, and Impacts, edited by Koeberl, C., and Montanari, A. Geological Society of America Special Paper 452:119-137.

Collins G. S., and Wünnemann K. 2005. How big was the Chesapeake Bay impact? Insight from numerical modeling. Geology 33:925–928.

Corfu F., Hanchar J. M., Hoskin P. W. O., and Kinny P. 2003. Atlas of zircon textures. Reviews in Mineralogy and Geochemistry 51:469-500.

Deutsch A., and Koeberl C. 2006. Establishing the link between the Chesapeake Bay impact structure and the North American tektite strewn field: The Sr-Nd isotopic evidence. Meteoritics and Planetary Science 41:689–703.

Farley K. A., Wolf R., and Silver L. 1996. The effects of long alpha-stopping distances on (U-Th)/He ages. Geochimica et Cosmochimica Acta 60:4223-4229.

Fernandes, V., Hopp, J., Schwarz, W.H., Fritz, J.P., Trieloff, M., Povenmire, H. 2019. ^{40}Ar-^{39}Ar step heating ages of North American tektites and of impact melt rock samples from the Chesapeake Bay impact structure. Geochimica et Cosmochimica Acta (in press).

Fleischer R. L, and Price P. B. 1964. Fission track evidence for the simultaneous origin of tektites and other natural glasses. Geochimica et Cosmochimica Acta 28:755-760.

Garlick G. D., Naeser C. W., and O'Neil J. R. 1971. A Cuban tektite. Geochimica et Cosmochimica Acta 35:731-734.

Gentner W., Storzer D., and Wagner G.A. 1969. New fission track ages of tektites and related glasses. Geochimica et Cosmochimica Acta 33:1075-1081.

Gibson R. L., Townsend G. N., Horton J. W., and Reimold W. U. 2009. Pre-impact tectonothermal evolution of the crystalline basement-derived rocks in the ICDP-USGS Eyreville-B core, Chesapeake Bay impact structure. In The ICDP-USGS Deep Drilling Project in the Chesapeake Bay impact structure: Results from the Eyreville core holes, edited by Gohn G. S., Koeberl C., Miller K. G., and Reimold W. U. Geological Society of America Special Papers 458:235-254.

Glass B. P. 2002. Upper Eocene impact ejecta/spherule layers in marine sediments. Chemie der Erde Geochemistry 62:173–96.

Glass, B.P. and Wu, J., 1993. Coesite and shocked quartz discovered in the, Australasian and North American, microtektite layers. Geology, 21:435-438.

Glass B. P., and Liu S. 2001. Discovery of high-pressure $ZrSiO_4$ polymorph in naturally occurring shock-metamorphosed zircons. Geology 29:371-373.

Glass B. P., Baker R. N., Storzer D., and Wagner G.A. 1973. North American microtektites from the Caribbean Sea and their fission track age. Earth and Planetary Science Letters 19:184-192.

Glass B. P., Hall C. M., and York D. 1986. $^{40}Ar/^{39}Ar$ laser-probe dating of North American tektite fragments from Barbados and the age of the Eocene-Oligocene boundary. Chemical Geology: Isotope Geoscience Section 59:181–86.

Glass B. P., Koeberl C., Blum J. D., Senftle F., Izett G. A., Evans B. J., Thorpe A. N., Povenmire H., and Strange R. L. 1995. A Muong Nong-type Georgia tektite. Geochimica et Cosmochimica Acta 59: 4071–82.

Gohn G. S., Koeberl C., Miller K. G., Reimold W. U., Browning J. V., Cockell C. S., Horton Jr. J. W., and Kenkmann, T. 2008. Deep drilling into the Chesapeake Bay impact structure. Science 320:1740-1745.

Harris R. S., Roden M. S., Schroeder P. A., Holland S. M., Duncan M. S., and Albin E. F. 2004. Upper Eocene impact horizon in east-central Georgia. Geology 32:717-720.

Horton, J. W., Jr., and Izett G. A. 2005. Crystalline-rock ejecta and shocked minerals of the Chesapeake Bay impact structure: The USGS-NASA Langley corehole, Hampton, Virginia, with supplement constraints on the age of the impact. In Studies of the Chesapeake Bay impact structure, edited by Horton Jr. J. W., Powars D. S., and Gohn G. S. U.S. Geological Survey, Reston, Virginia. pp. E1–E29.

Horton, J. W., Jr., Kunk, M. J., Belkin, H. E., Aleinikoff, J. N., Jackson, J. C., and Chou, I-M. 2009. Evolution of crystalline target rocks and impactites in the Chesapeake Bay impact structure, ICDP-USGS Eyreville B core. In The ICDP-USGS Deep Drilling Project in the Chesapeake Bay Impact Structure: Results from the Eyreville Core Holes, edited by Gohn, G. S., Koeberl, C., Miller, K. G., and Reimold, W. U. Geological Society of America Special Paper 458:277-316.

Hourigan J. K., Reiners P. W., and Brandon M. T. 2005. U-Th zonation-dependent alpha-ejection in (U-Th)/He chronometry. Geochimica et Cosmochimica Acta 69:3349-3365.

Jourdan F., Reimold W. U., and Deutsch A. 2012. Dating terrestrial impact structures. Elements 8:49-53.

Kamo S. L., Reimold W. U., Krogh, T. E., and Colliston W. P. 1996. A 2.023 Ga age for the Vredefort impact event and a first report of shock metamorphosed zircons in pseudotachylitic breccias and granophyre. Earth and Planetary Science Letters 144:369-387.

Kamo S. L., Krogh T. E., Glass B. P., and Liu S. 2002. U-Pb study of shocked zircons from the North American microtektite layer (abstract). 33rd Lunar and Planetary Science Conference, abstract #1643.

Kenny, G.G., Schmieder, M., Whitehouse, M.J., Nemchin, A.A., Morales, L.F., Buchner, E., Bellucci, J.J. and Snape, J.F., 2019. A new U-Pb age for shock-recrystallised zircon from the Lappajärvi impact crater, Finland, and implications for the accurate dating of impact events. Geochimica et Cosmochimica Acta, 245:479-494.

Koeberl C. 2009. Late Eocene impact craters and impactoclastic layers – An overview. In The late Eocene Earth: Hothouse, Icehouse, and Impacts, edited by Koeberl, C., and Montanari, A. Geological Society of America Special Paper 452:17-26.

Koeberl C., Poag C. W., Reimold W. U., and Brandt D. 1996. Impact origin of the Chesapeake Bay structure and the source of the North American tektites. Science 271:1263-1266.

Liu S., and Glass B. P. 2001. Upper Eocene impact ejecta/spherule layers in marine sediments: New sites. 32nd Lunar and Planetary Science Conference, abstract #2027.

Liu S., Papanastassiou D. A., Ngo H. H., and Glass B. P. 2006. Sr and Nd analyses of upper Eocene spherules and their implications for target rocks. Meteoritics and Planetary Science 41:705-714.

Mercer C. M., and Hodges K. V. 2016. ArAR – A software tool to promote the robust comparison of K-Ar and ^{40}Ar/^{39}Ar dates published using different decay, isotopic, and monitor-age parameters. Chemical Geology 440:148-163.

Obradovich J., Snee L. W., and Izett G. A. 1989. Is there more than one glassy impact layer in the Late Eocene? (abstract). Geological Society of America Abstracts with Program 21:134.

Poag C. W., Powars D. S., Poppe L. J., Mixon R. B., Edwards L. E., Folger D. W., and Bruce S. 1992. Deep Sea Drilling Project Site 612 bolide event: New evidence of a late Eocene impact-wave deposit and a possible impact site, US east coast. Geology 20:771-774.

Poag C. W., Powars D. S., Poppe L. J., and Mixon R. B. 1994. Meteroid mayhem in Ole Virginny: Source of the North American tektite strewn field. Geology 22:691-694.

Reiners, P.W., Spell, T.L., Nicolescu, S. and Zanetti, K.A., 2004. Zircon (U-Th)/He thermochronometry: He diffusion and comparisons with ^{40}Ar/^{39}Ar dating. Geochimica et Cosmochimica Acta 68:1857-1887.

Renne, P.R., Balco, G., Ludwig, K.R., Mundil, R. and Min, K. 2011. Response to the comment by WH Schwarz et al. on “Joint determination of ^{40}K decay constants and ^{40}Ar∗/^{40}K for the Fish Canyon sanidine standard, and improved accuracy for ^{40}Ar/^{39}Ar geochronology” by PR Renne et al.(2010). Geochimica et Cosmochimica Acta 75:5097-5100.

Reynolds J. H. 1960. Rare gases in tektites. Geochimica et Cosmochimica Acta 20:101-114.

Simonson B. M., and Glass B. P. 2004. Spherule layers – records of ancient impacts. Annual Review of Earth and Planetary Sciences 32:329-361.

Schmieder, M. and Jourdan, F., 2013. The Lappajärvi impact structure (Finland): Age, duration of crater cooling, and implications for early life. Geochimica et Cosmochimica Acta 112:321-339.

Schmieder, M., Tohver, E., Jourdan, F., Denyszyn, S.W. and Haines, P.W. 2015. Zircons from the Acraman impact melt rock (South Australia): Shock metamorphism, U–Pb and $^{40}Ar/^{39}Ar$ systematics, and implications for the isotopic dating of impact events. Geochimica et Cosmochimica Acta 161:71-100.

Schmieder, M., Kennedy, T., Jourdan, F., Buchner, E. and Reimold, W.U., 2018. A high-precision $^{40}Ar/^{39}Ar$ age for the Nördlinger Ries impact crater, Germany, and implications for the accurate dating of terrestrial impact events. Geochimica et Cosmochimica Acta 220:146-157.

Storzer D., and Wagner G. A. 1971. Fission track ages of North American tektites. Earth and Planetary Science Letters 10:435-440.

Storzer D., and Wagner G. A. 1977. Fission track dating of meteorite impacts. Meteoritics 12:368-369.

Timms, N.E., Erickson, T.M., Pearce, M.A., Cavosie, A.J., Schmieder, M., Tohver, E., Reddy, S.M., Zanetti, M.R., Nemchin, A.A. and Wittmann, A. 2017. A pressure-temperature phase diagram for zircon at extreme conditions. Earth-Science Reviews, 165:185-202.

Ukstins Peate I., van Soest M. C., Wartho J-A., Cabrol, N. A., Grin E., Piatek J., and Chong G. 2010. A novel application of (U-Th)/He geochronology to constrain the age of small, young meteorite impact craters: A case study of the Monturaqui crater, Chile (abstract). 41st Lunar and Planetary Science Conference, abstract #2161.

van Soest M. C., Hodges K. V., Wartho J-A., Biren M. B., Monteleone B. D., Ramezani J., Spray J. G., and Thompson L. M. 2011. (U-Th)/He dating of terrestrial impact structures: The Manicouagan example. Geochemistry, Geophysics, Geosystems 10.1029/2010GC003465

Wartho J-A., van Soest M. C., King Jr. D. T., and Petruny L. W. 2012. An (U-Th)/He age for the shallow-marine Wetumpka impact structure, Alabama, USA. Meteoritics and Planetary Science 47:1243-1255.

Wielicki M. M., Harrison T. M., and Stockli D. 2014. Dating terrestrial impact structures: U-Pb depth profiles and (U-Th)/He ages of zircon. Geophysical Research Letters 41:4168-4175.

Wittmann A., Kenkmann T., Schmitt R. T., and Stöffler D. 2006. Shock-metamorphosed zircon in terrestrial impact craters. Meteoritics and Planetary Science 41:433-454.

Wittmann A., Reimold W. U., Schmitt R. T., Hecht L., and Kenkmann T. 2009a. The record of ground zero in the Chesapeake Bay impact crater – suevites and related rocks. In The ICDP-USGS Deep Drilling Project in the Chesapeake Bay impact structure: Results from the Eyreville core holes, edited by Gohn G. S., Koeberl C., Miller K. G., and Reimold W. U. Geological Society of America Special Paper 458:349-376.

Wittmann A., Schmitt R. T., Hecht L., Kring D. A., Reimold W. U., and Povenmire H. 2009b. Petrology of impact melt rocks from the Chesapeake Bay crater, USA. In The ICDP-USGS Deep Drilling Project in the Chesapeake Bay impact structure: Results from the Eyreville core holes, edited by Gohn G. S., Koeberl C., Miller K. G., and Reimold W. U. Geological Society of America Special Paper 458:377-396.

Young K. E., van Soest M. C., Hodges K. V., and Watson E.B. 2013a. Impact thermochronology and the age of the Haughton impact structure, Canada. Geophysical Research Letters 40:3836-3840.

Young K. E., Hodges, K. V., van Soest M. C., Wartho J-A., Mercer C. M., Osinski G. R., and Marion C. L. 2013b. Geochronology and thermochronology of the Mistastin Lake impact structure, Labrador, Canada (abstract). 2013 American Geophysical Union Fall Conference, abstract #P34C-02.

Zähringer J. 1963. K-Ar measurements of tektites. Radioactive Dating, Proceedings of the symposium on radioactive dating held by the International Atomic Energy Agency in co-operation with the Joint Commission on Applied Radioactivity in Athens, 19-23 November 1962. International Atomic Energy Agency, Vienna p. 289-299.

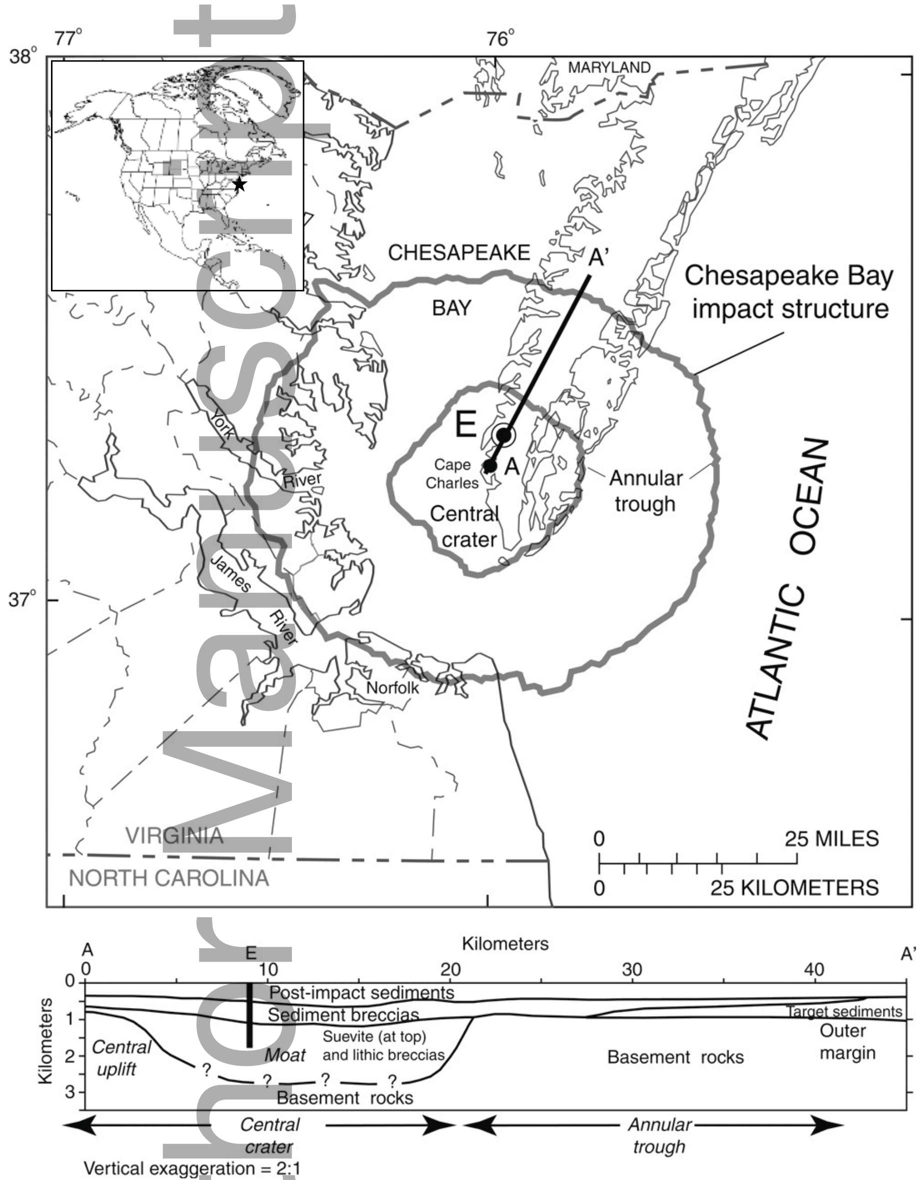

Fig. 1. Map and generalized cross-section (A-A') of the Chesapeake Bay impact structure, showing the location of the Eyreville drill site (E; map modified from Gohn et al., 2008). Inset map shows the location (black star) of the Chesapeake Bay impact crater in North America.

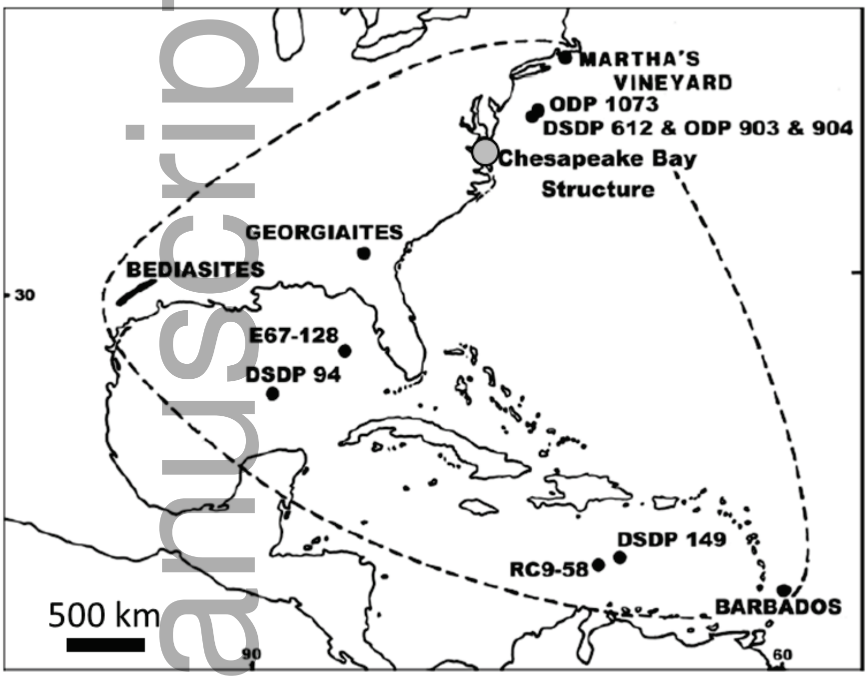

Fig. 2. Map of the North American tektite strewn field (modified map from Glass, 2002), showing onshore tektite locations in Texas (bediasites), Georgia (georgiaites), Massachusetts (Martha's Vineyard), and Barbados. Offshore tektite and microtektite locations include the Caribbean Sea (DSDP 149 and Core RC9-58), Gulf of Mexico (DSDP 94 and Core E67-128), and continental shelf in the north-west Atlantic Ocean (DSDP 612 and ODP site 904). Unmelted ejecta has been found at all the offshore core sites except for Core E67-128 (Glass and Wu, 1993; Glass and Liu 2001). The (U-Th)/He dated zircons in this study were sampled from ODP site 1073 hole A.

Fig. 3. ~30 cm^3 unconsolidated glauconite-bearing late Eocene sediment obtained from ODP site 1073, hole A, core 72, section 4, interval 83-94 cm.

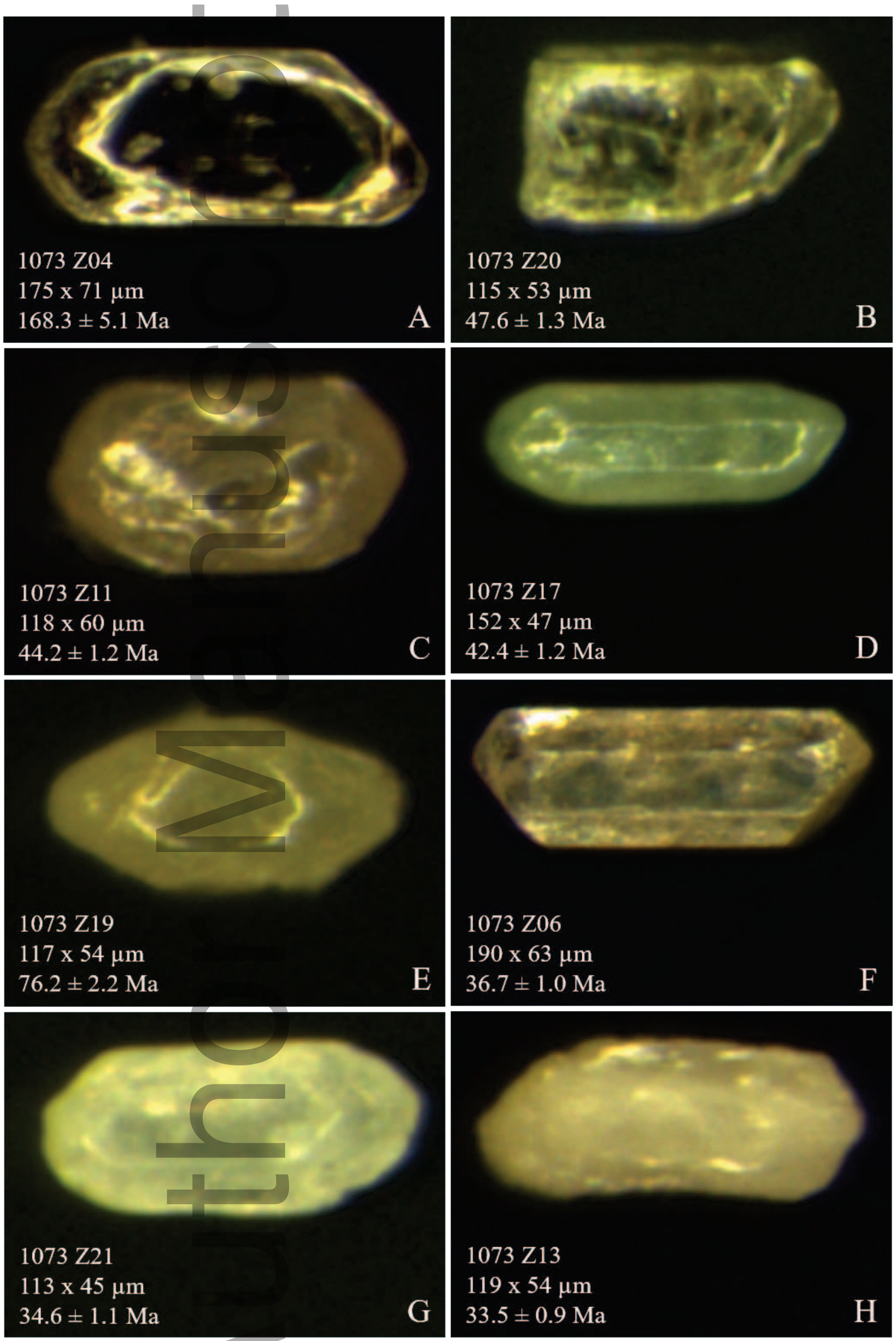
1073 Z04
175 x 71 µm
168.3 ± 5.1 Ma
A
1073 Z20
115 x 53 µm
47.6 ± 1.3 Ma
B
1073 Z11
118 x 60 µm
44.2 ± 1.2 Ma
C
1073 Z17
152 x 47 µm
42.4 ± 1.2 Ma
D
1073 Z19
117 x 54 µm
76.2 ± 2.2 Ma
E
1073 Z06
190 x 63 µm
36.7 ± 1.0 Ma
F
1073 Z21
113 x 45 µm
34.6 ± 1.1 Ma
G
1073 Z13
119 x 54 µm
33.5 ± 0.9 Ma
H

Fig. 4. Binocular light microscope photomicrographs of the eight youngest zircon crystals dated using the (U-Th)/He technique, showing the (U-Th)/He ages (2σ uncertainties), and lengths and average widths of the crystals: (A) 1073 Z04 – a clear euhedral zircon crystal. (B) 1073 Z20 – a transparent subhedral zircon that is missing one crystal termination. (C) 1073 Z11 – a subhedral, slightly rounded, semi-translucent zircon crystal. (D) 1073 Z17 – a light-colored translucent zircon. (E) 1073 Z19 – a semi-translucent subhedral zircon. (F) 1073 Z06 – a translucent euhedral zircon. (G) 1073 Z21 – a white-colored translucent zircon crystal that has the appearance of an uncooked grain of rice. (H) 1073 Z13 – a white semi-opaque zircon crystal that has the appearance of a cooked grain of rice.

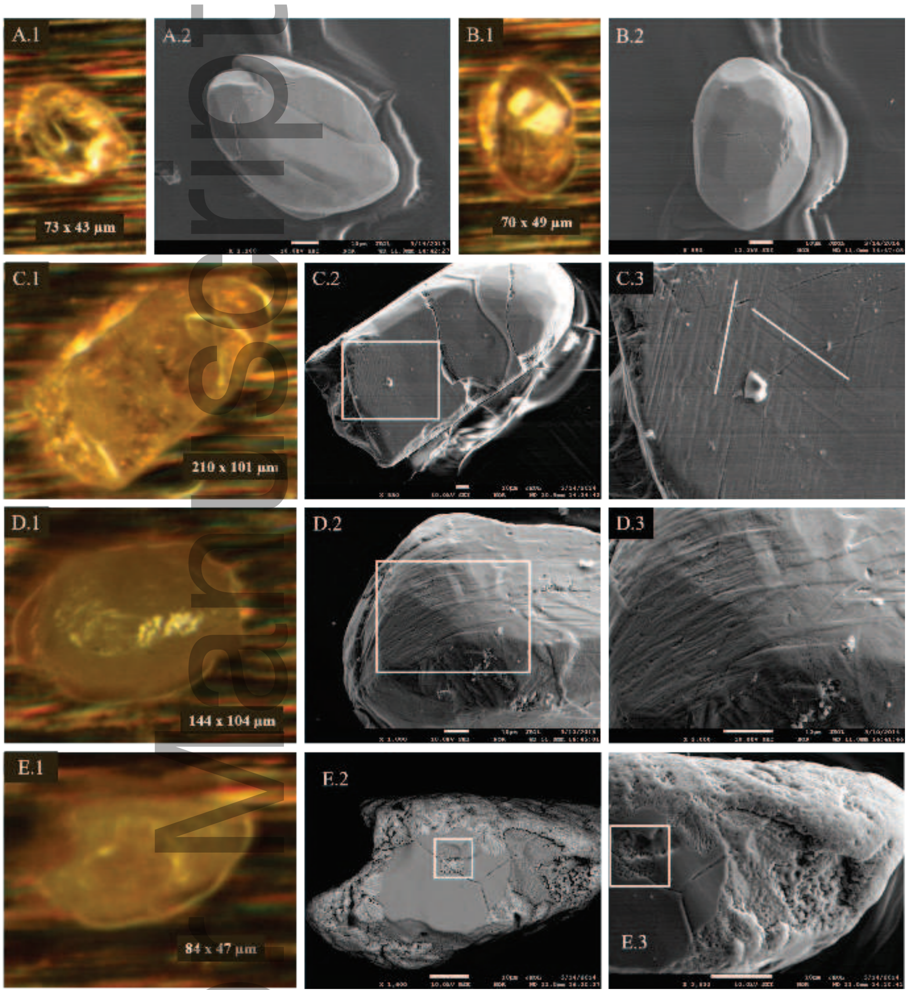

Fig. 5. Binocular light microscope photomicrographs and secondary electron (SE) and back-scattered electron (BSE) images of undated zircon grains and grain fragments from Late-Eocene unconsolidated sediment from ODP Site 1073, hole A. Light microscope (A.1 and B.1) and SE images (A.2 and B.2) of two unshocked zircons. Light microscope (C.1 and D.1) and SE images (C.2-C.3 and D.2-D.3) of two zircon grains with multiple linear/planar features, interpreted to be planar deformation features. The white boxes in 5C.2 and 5D.2 show the magnified areas in 5C.3 and 5D.3, respectively. The white lines in Fig. 5C.3 highlight the two sets of planar deformation features. Light microscope (5E.1) and BSE (5E.2) and SE (5E.3) images of a zircon grain that shows a granular texture, and dendritic textures caused by partial decomposition of zircon to baddeleyite and silica (confirmed by EDS analyses on these phases). For ease of comparison, the white boxes in the BSE (5E.2) and SE (5E.3) photomicrographs indicate the same region in this zircon grain. The white scale bars in the SE and BSE photomicrographs are all 10 µm. The horizontal streaks in the SE images 5B.2, 5C.2 and 5C.3) were caused by sample surface charging effects.

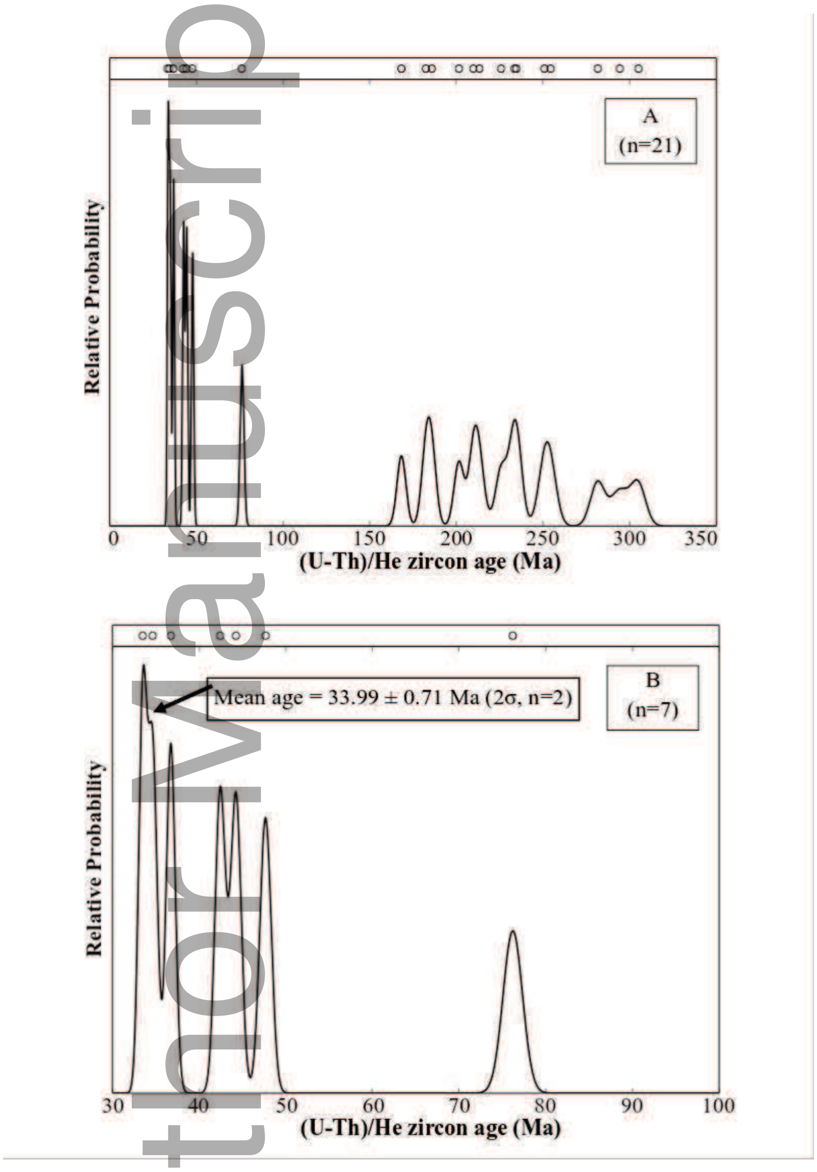

Fig. 6. Probability density plots of (U-Th)/He zircon ages ranging from (A) 33.49 ± 0.94 to 305.1 ± 8.6 Ma (2σ) for all 21 zircon grains, and (B) the 7 youngest zircon grain ages. The individual (U-Th)/He ages are shown as white circles in the upper portions of the plots.

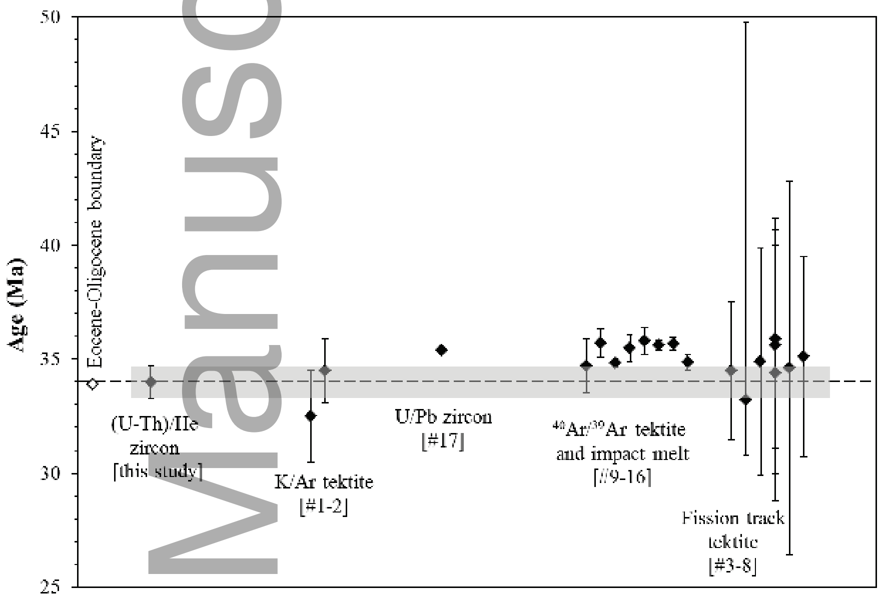

Fig. 7. Plot of previous geochronological ages (fission track, K/Ar, $^{40}Ar/^{39}Ar$, and U/Pb; black diamonds) compared with our new (U-Th)/He age for the Chesapeake Bay and NAT strewn field (2σ uncertainties). The numbers (#) refer to references quoted in Table 1. The dashed line and grey box indicate our 33.99 ± 0.71 Ma inverse-variance weighted mean (U-Th)/He age and 2σ uncertainty envelope, respectively. The white diamond shows the Eocene-Oligocene boundary age of 33.91 ± 0.05 Ma (Brown et al., 2009; 2σ errors are smaller than the symbol size).

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Table 1. Previous geochronological ages for the Chesapeake Bay impact structure and associated NAT deposits. ¶

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