Earth and Planetary Science Letters 453 (2016) 56–66

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Diachroneity of the Clearwater West and Clearwater East impact structures indicated by the (U–Th)/He dating method

M.B. Biren[a,*], M.C. van Soest[a], J.-A. Wartho[a,b], K.V. Hodges[a], J.G. Spray[c]

[a] Group 18 Laboratories, School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287, USA
[b] GEOMAR Helmholtz Centre for Ocean Research Kiel, Wischhofstr. 1-3, D-24148 Kiel, Germany
[c] Planetary and Space Science Centre, University of New Brunswick, 2 Bailey Drive, Fredericton, New Brunswick E3B 5A3, Canada

ARTICLE INFO

Article history:
Received 21 March 2016
Received in revised form 27 July 2016
Accepted 27 July 2016
Available online 23 August 2016
Editor: A. Yin

Keywords:
thermochronology
impact cratering
helium diffusion
shock metamorphism

ABSTRACT

The (U–Th)/He method has been applied to constrain the formation ages of the Clearwater West and East impact structures of Quebec, Canada. Zircons were separated from impact melt samples derived from a surface exposure at Clearwater West (32 km diameter), and from a drill core at Clearwater East (26 km diameter). The (U–Th)/He results indicate ages of 280 ± 27 Ma (2σ, $n = 7$) for Clearwater West, and 450 ± 56 Ma (2σ, $n = 8$) for Clearwater East. Our (U–Th)/He date for Clearwater West supports the findings of previous Rb–Sr (266 ± 15 Ma; 2σ) and $^{40}Ar/^{39}Ar$ (280 ± 4 Ma and 283.8 ± 2.2 Ma, 2σ) impact melt studies. Our (U–Th)/He date for Clearwater East also overlaps with previously published $^{40}Ar/^{39}Ar$ dating results, which yielded U-shaped spectra, with 'maximum' and 'best-estimate' dates of $\sim$ 460–470 Ma. Our results support the contention, previously based solely on $^{40}Ar/^{39}Ar$ data, that the Clearwater West and East impact structures do not comprise an impact doublet that formed coevally from a binary asteroid pair.

1. Introduction

Impact crater doublets have been observed on the Moon, Venus, and Mars (Bottke and Melosh, 1996), and impacts of binary asteroids are widely accepted as the most plausible formation mechanism for crater doublets (e.g., Bottke and Melosh, 1996). Binary asteroids consist of two bodies that orbit one another and share a common center-of-mass (Melosh and Stansberry, 1991), and they may comprise $\sim$15–16% of the Near Earth Asteroid (NEA) population. Six potential crater doublets have been proposed on Earth (Melosh and Stansberry, 1991; Miljković et al., 2013). One of these terrestrial impact doublets, the adjacent Clearwater East and West impact craters in Quebec, Canada (Fig. 1), have long been thought to have formed by coeval impacts at $\sim$280–290 Ma (Dence et al., 1965; Palme et al., 1978; Reimold et al., 1981; Melosh and Stansberry, 1991; Miljković et al., 2013). However, geochronological data from the eastern crater imply that its age is much older ($\sim$460–470 Ma; Bottomley et al., 1990; Schmieder et al., 2015) than that of the western crater ($\sim$270–310 Ma; Wanless et al., 1965; Reimold et al., 1981; Bottomley et al., 1990; Schmieder et al., 2015). In an effort to further explore the two competing models, we obtained (U–Th)/He thermochronologic data from zircons found in impactites associated with the two craters.

Although the (U–Th)/He technique is not yet as widely applied to dating impact structures as the U–Pb, Rb–Sr, K–Ar, or $^{40}Ar/^{39}Ar$ methods, it is proving to be a viable technique, both when neoblastic U–Th phases like zircon form from impact melts and, especially, when impact heating was sufficiently limited so that the resetting of higher-temperature chronometers was incomplete (e.g., van Soest et al., 2011; Wartho et al., 2012).

The (U–Th)/He isotope system was the first dating method to be used as a geochronometer in the early 1900s. It is based on the α decay of ^{238}U, ^{235}U, ^{232}Th, ^{147}Sm (and their intermediate daughter isotopes) to ^{4}He. Early results associated with this geochronometer were perceived as "nonsensical", due to ^{4}He daughter concentrations reflecting both production and diffusive loss, but these initial drawbacks were later understood to be scientifically tractable when the method was used as a thermochronometer that could determine low-temperature thermal histories recorded in Earth's upper crust (Farley, 2002 and references therein).

The primary analytical issue affecting the reliability of (U–Th)/He dates is α-ejection, which occurs when radiogenic α-particles (^{4}He nuclei) are propelled out of the crystal structure due to the energy released by decay (Farley et al., 1996; Hourigan et al., 2005). This causes the outermost margins of the crystal to be depleted in ^{4}He and may result in anomalously young

* Corresponding author.
E-mail address: marc.biren@asu.edu (M.B. Biren).

http://dx.doi.org/10.1016/j.epsl.2016.07.053

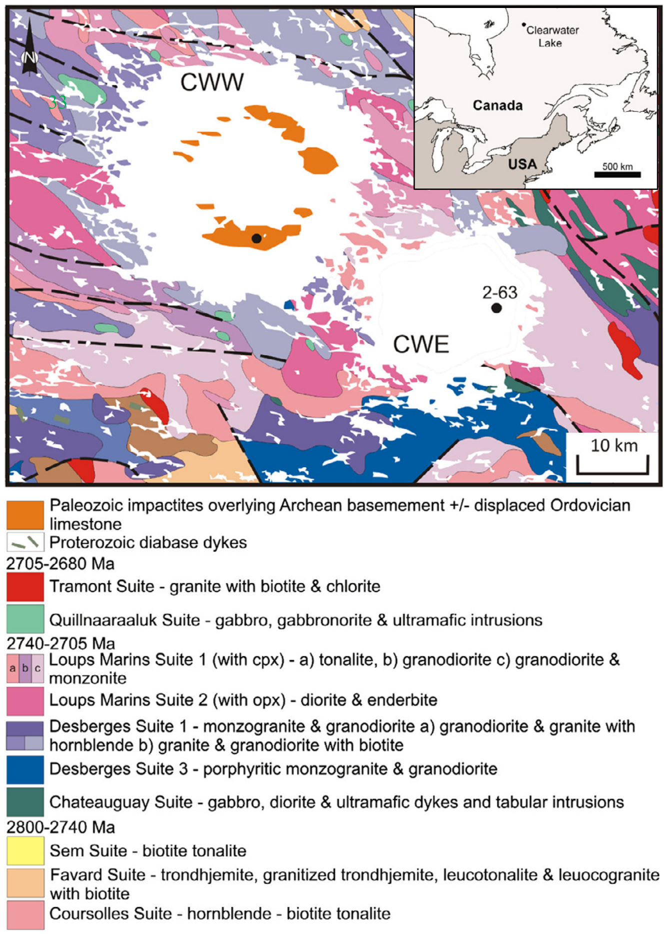

Fig. 1. Simplified geological map for the Clearwater West (CWW) and East (CWE) impact structures. Geology modified after Simard et al. (2004), with additional compilation by L.M. Thompson. The black circles indicate impact melt sample locations from Clearwater West (Atkinson Island), and drill hole #2–63 from Clearwater East. cpx = clinopyroxene, and opx = orthopyroxene.

dates. Methods for calculating and applying α-ejection corrections can result in accurate dates with total 2σ analytical errors typically in the range of 6–10%, but sometimes larger errors (up to 30%) are obtained (Hourigan et al., 2005). Properly corrected (U–Th)/He dates are consistent with results obtained using other geochronological systems (e.g., U–Pb and $^{40}Ar/^{39}Ar$) on rapidly cooled samples (e.g., Farley, 2002). (U–Th)/He dating has been successfully deployed on a wide variety of minerals (e.g., zircon, apatite, monazite, titanite, garnet, magnetite, hematite, and merrillite) over a wide range of ages (e.g., ka to Ga; Min et al., 2013 and references therein). This thermochronological method offers a reliable and powerful tool for constraining the thermal histories of the upper crust of the Earth and Mars (e.g., Farley, 2002; Min et al., 2013), as well as the shock metamorphism history of meteorites (e.g., Min et al., 2013 and references therein). Here we apply the technique to date a renowned pair of impact craters on Earth.

2. Geologic background

The ∼32 km diameter Clearwater West impact structure is located approximately 110 km east of Hudson Bay (56°13′N; 74°30′W) in northern Quebec, Canada, where it lies adjacent to the smaller ∼26 km diameter Clearwater East impact structure (56°05′N and 74°07′W). Approximately 30 km separates the centers of the two craters (Fig. 1, Dence et al., 1977; Bottke and Melosh, 1996). The Clearwater East and West structures are now fully and partially submerged, respectively, by Clearwater Lake/Lac à l'Eau Claire.

The Clearwater East and West structures were first linked to probable meteorite impacts by Beals et al. (1956), and their impact origin was later confirmed by petrographic, geochemical and structural studies (McIntyre, 1962; Dence et al., 1965; Grieve, 1978; Simonds et al., 1978). Both structures are classified as complex craters with central uplifts (Dence et al., 1977; Grieve, 1978; Simonds et al., 1978).

The target rocks for both impact structures are predominantly late Archean (∼2694–2711 Ma) granitic gneisses, and metamorphosed granodiorite, diorite, and tonalite, with subordinate occurrences of more mafic lithologies, all belonging to the Superior Province of the Canadian Shield (Rosa and Martin, 2010 and references therein). Metamorphic assemblages in these Archean rocks indicate amphibolite to granulite facies conditions. Various down-faulted blocks of limestone reflect the impact-induced disruption of the Ordovician (∼485–443 Ma) sedimentary cover at Clearwater West (Reimold et al., 1981; Rosa and Martin, 2010). Rock outcrops in the Clearwater West crater are primarily limited to the prominent 16–20 km diameter island ring and the central cluster of four small islands where basement rocks are exposed, while the Clearwater East structure is almost completely submerged.

Three distinct impact-related rock types are observed on the central ring of islands of Clearwater West. The basal unit is a 20 m thick red, friable impact-melt-bearing breccia consisting of moderately shocked (12–15 GPa) Archean basement, overlain by an 18 m-thick red, well-jointed, fine-grained, clast-rich impact melt unit, and an 85 m-thick coarser-grained, poorly-jointed, clast-poor impact melt sheet (Reimold et al., 1981; Rosa and Martin, 2010). Overall, the melt rocks exposed on the islands have a minimum combined thickness of ∼120 m (Simonds et al., 1978). Much of what is known about both structures comes from the study of numerous drill cores obtained by the Dominion Observatory of Canada (Ottawa) during the early 1960s. Impactites known from Clearwater East (drill hole 2–63) include an impact breccia enclosed in a crystalline melt matrix that grades from a dark–green fine-grained layer starting at ∼245 m depth, into a gray-colored highly-vesicular coarser-grained section, before transitioning into a darker, non-vesicular coarse-grained phase where drilling was stopped at a depth of ∼300 m (grain size of the melt matrix at this depth suggests drilling was stopped near the middle of the breccia lens, Dence et al., 1965).

3. Previous geochronological dating of Clearwater East and West

The Clearwater impact craters have been dated previously using a variety of geochronological techniques (Wanless et al., 1965; Reimold et al., 1981; Bottomley et al., 1990; Schmieder et al., 2015), although most work has focused on the better-exposed Clearwater West structure. For the sake of clarity, we only refer to K–Ar, $^{40}Ar/^{39}Ar$ and Rb–Sr ages using the decay constants of Steiger and Jäger (1977) in the text. However, recalculated K–Ar, $^{40}Ar/^{39}Ar$ and Rb–Sr ages using more recent decay constants (e.g., Renne et al., 2011 and references therein; Rotenburg et al., 2012) are shown in Table 1.

3.1. Clearwater West

K–Ar whole rock dating of Clearwater West impactites yielded dates of 291 ± 30 and 306 ± 30 (2σ; Wanless et al., 1965; recalculated using the decay constants of Steiger and Jäger, 1977). Impact melt glasses yielded very young fission track dates of ∼34 Ma (Fleischer et al., 1969), but Rb–Sr whole-rock analyses of impact melt rocks indicated a 266 ± 15 Ma age (2σ; Wooden & Simonds, pers. comm., in Reimold et al., 1981). A $^{40}Ar/^{39}Ar$ study of a