Earth’s Impact Events Through Geologic Time: 
A List of Recommended Ages for Terrestrial Impact 
Structures and Deposits

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Abstract

This article presents a current (as of September 2019) list of recommended ages for proven terrestrial impact structures (n=200) and deposits (n=46) sourced from the primary literature. High-precision impact ages can be used to (1) reconstruct and quantify the impact flux in the inner Solar System and, in particular, the Earth–Moon system, thereby placing constraints on the delivery of extraterrestrial mass accreted on Earth through geologic time; (2) utilize impact ejecta as event markers in the stratigraphic record and to refine bio- and magnetostratigraphy; (3) test models and hypotheses of synchronous double or multiple impact events in the terrestrial record; (4) assess the potential link between large impacts, mass extinctions, and diversification events in the biosphere; and (5) constrain the duration of melt sheet crystallization in large impact basins and the lifetime of hydrothermal systems in cooling impact craters, which may have served as habitats for microbial life on the early Earth and, possibly, Mars. Key Words: Impact craters—Ejecta—Ages—Geochronology—Terrestrial—Cratering record. Astrobiology 20, 91–141.

1. Introduction

Impact cratering is a fundamental process in the Solar System, shaping asteroids, planets, and their satellites (e.g., Baldwin, 1971; Shoemaker, 1983; Melosh, 1989; Ryder, 1990; French, 1998, 2004; Canup and Asphaug, 2001; Kring and Cohen, 2002; Osinski and Pierazzo, 2012). Unlike the Moon, whose surface has been modified by numerous large and small impacts for more than 4 billion years (Ga, Gyr) (e.g., Stöffler et al., 2006), the Earth has retained a limited impact cratering record due to tectonic recycling of the crust, erosion, and the burial of impact craters underneath layers of sediment and lava (e.g., Grieve, 1987, 2001a, 2001b) (Fig. 1).

Before ~3.7 Ga before present, when most of the large lunar impact basins were created, impact rates in the Earth–Moon system were much higher than they are today (e.g., Turner et al., 1973; Tera et al., 1974; Ryder, 1990; Kring and Cohen, 2002; Grieve et al., 2006; Johnson and Melosh, 2012; Bottke and Norman, 2017). However, no traces of those Hadean (>4.0 Ga) and Eoarchean (4.0–3.6 Ga) impacts on the early Earth are currently known in the geologic record (e.g., Koeberl, 2006). Only 200 proven impact structures (counting fields of small impact craters produced during the same event as one) and 46 individual horizons of proximal and distal impact ejecta (again, counting layers with the same age at different localities as one) have thus far been recognized on our planet (Fig. 2). Those impact structures and deposits span a time from more than ~3.4 Ga, represented by Paleoarchean impact spherule layers in South Africa and Western Australia produced by large impacts (e.g., Glass and Simonson, 2012, 2013), to roughly 6 years ago when the Chelyabinsk airburst in Russia (February 15, 2013) shattered windows and its main stony meteorite mass produced an ~7 m-wide circular impact penetration hole in frozen Lake Chebarkul (e.g., Borovička et al., 2013; Popova et al., 2013).

The smallest geologic features on Earth’s surface produced by impact, usually only a few meters wide and commonly associated with surviving meteorite fragments, are (fields of) penetration funnels, pits, and small craters that form at relatively low, atmosphere-decelerated (ballistic) impact velocities (e.g., Melosh, 1989; Beauford, 2015). Some of the impact structures listed in this article belong to that type of low-energy impact feature (e.g., the crater-like pits produced...
during the fall of the Imilac pallasite in Chile, or the temporary Chalyabinsk ice-penetration hole, which we chose to include in the present listing). Hypervelocity impacts of larger meteoroids, at much higher incoming velocities, produce craters that show different morphologies with increasing size (e.g., Melosh, 1989; French, 1998). A textbook example of a well-preserved simple, bowl-shaped impact crater associated with its ejecta blanket is the 1.2 km-diameter Meteor Crater (aka Barringer Meteorite Crater) in Arizona (Shoemaker, 1960; Kring, 2017b) (Fig. 1). Earth’s impact craters larger than ~2 to 4 km in diameter are of complex morphology and structure, such as the ~3.8 km-diameter Steinheim Basin in Germany characterized by a pronounced central peak (uplift) and the ~25 km-diameter Nördlinger Ries with an ~10 km-wide inner ring of uplifted target rock and a well-preserved blanket of proximal impact ejecta surrounding the crater (e.g., Stöffler et al., 2002, 2013; Kring, 2005; Schmieder and Buchner, 2013). The 180 km-diameter Chicxulub crater on the Yucatán Peninsula in Mexico is a peak-ring basin similar in morphology and structure to the Schrödinger Basin on the Moon (Kring, 1995; Kring et al., 2016, 2017a; Morgan et al., 2016). The deeply eroded Vredefort impact structure in South Africa, probably ~250 to 300 km in original diameter, may represent the remnants of a terrestrial multiring basin (e.g., Melosh, 1989; Spudis, 1993; Therriault et al., 1997; French, 1998).
To assess the temporal distribution of impact events and calculate impact rates as an expression of the impact flux through time, different geochronologic techniques have been developed and applied. These include, first, crater counting and the calculation of isochrons based on the crater size–frequency distribution for the Moon, Mars, and other planetary bodies characterized by a crater production record (e.g., Hartmann and Neukum, 2001; this technique is not applicable to the geologically active Earth); second, stratigraphic age constraints (e.g., Koeberl et al., 2001; Lindström et al., 2005; Schmieder and Buchner, 2008); third, isotopic age determinations using the U–Pb, Ar–Ar (K–Ar), Rb–Sr, and (U–Th)/He geo-/thermochronometers and/or the 14C method with impact lithologies sampled in natural outcrop or drillings on Earth, in meteorites, or samples returned from space missions (e.g., Tera et al., 1974; Bottomley et al., 1990; Deutsch and Schärer, 1994; Jourdan et al., 2009, 2012); and, finally, methods other than those mentioned above. We here predominantly focus on the stratigraphic and isotopic methods. Due to improvements in U–Pb (e.g., chemical abrasion thermal ionization mass spectrometry [CA-TIMS]) (Schoene, 2014; Kenny et al., 2019a), secondary ion mass spectrometry (SIMS) (Kenny et al., 2019b), and 40Ar–39Ar geochronologic instrumentation and methods (e.g., Renne et al., 2010, 2011, 2013; Sprain et al., 2015; Schmieder et al., 2018a), the most precisely constrained “impact ages” today come with uncertainties on the thousands-of-years (ka, kyr) level.

This article provides a current (as of September 2019) summary of predominantly stratigraphic and isotopic recommended ages for proven impact structures and deposits on Earth. Structures and deposits of likely but, to some degree, uncertain impact origin (e.g., numerous oblong depressions near Rio Cuarto in Argentina; Schultz and Lianza,
1992; cf. Cione et al., 2002; Reimold et al., 2018; Cróstaa et al., 2019c; the recently reported Hiawatha “impact crater” in Greenland; Kjerr et al., 2018; and enigmatic glass deposits such as the Edeowie glass found in South Australia; Haines et al., 2001; glasses found near Dakhleh, Egypt; Osisinski et al., 2008; and the Pica glass found in the Atacama Desert of Chile; Roperch et al., 2017) are, therefore, not included. Likewise, the 1908 Tunguska airburst event in Russia, which seemingly did not produce any geologic feature other than uprooted trees, is not listed here (e.g., Kulik, 1940; Krinov, 1960). The present article does not intend to be the latest reference pertaining to the formation of simple and complex impact craters, their impact ejecta, and the physical aspects of the cratering process (e.g., Melosh, 1989; Melosh and Ivanov, 1999; Osisinski et al., 2011, 2012; Kenkmann et al., 2012), the petrology of impactites (rocks produced or modified by impact) (e.g., French, 1998; Stöffler and Grieve, 2007; Grieve and Therriault, 2012), or the verification of impact structures through the identification of macro- and microscopic shock-metamorphic features (e.g., shatter cones and shocked quartz and zircon grains) (French, 1998; French and Koeberl, 2010; Ferrière and Osisinski, 2012). For details about the more specific geologic features of terrestrial impact structures, we refer the reader to a number of review articles that summarize the impact cratering record of each continent on Earth, such as the works of Grieve (2006) for Canada in North America, Reimold et al. (2018) and Cróstaa et al. (2019b) for South America, Schmieder and Buchner (2013) for Europe, Reimold and Koeberl (2014) and Chabou (2019) for Africa and the Arab World, respectively, Masaitis (1999) and Reimold et al. (2008) for Russia and Asia, and Haines (2005) for Australia. [Somewhat surprisingly, there is currently no up-to-date review of the impact cratering record of the United States, and Walter H. Bucher’s (1936) early work on the country’s “cryptexplosion structures” probably remains the most recent systematic review of its kind; however, many impact structures in the United States were included in the more general listings of Freeberg (1969), Classen (1977), and Groller (1985), and a website project maintained by Beauford (2019) provides basic information and the relevant literature for almost all impact structures and crater fields recognized in the country.] Nor does this relatively short summary provide an in-depth explanation and discussion of the isotopic methods commonly used to determine impact ages, such as the U–Pb and Ar–Ar geochronometers. In this context, we recommend the comprehensive summaries on the U–Pb technique by, for example, Corfu (2013) and Schoene (2014), and on the Ar–Ar (and K–Ar) method by McDougall and Harrison (1999) and Kelley (2002). Previous U–Pb, Ar–Ar, and Rb–Sr geochronologic work on several terrestrial impact structures includes that of Bottomley et al. (1990) and Deutsch and Schärer (1994), from which much was learned regarding how different geochronometers behave with different types of impact crater materials analyzed. This summary builds upon that previous work, including critical evaluations of Earth’s impact crater ages that ensued (Jourdan et al., 2009, 2012; Jourdan, 2012). It should serve as a robust geochronologic database and a backbone for ongoing and future studies that make use of Earth’s impact crater ages for, for example, statistical calculations and cratering flux models (e.g., Mazrouei et al., 2019). Such studies have, in part, relied on a flawed representation of the terrestrial impact cratering record with partly inaccurate ages as input parameters (e.g., Telecka and Matyjasek, 2011; and the recently published Encyclopedic Atlas of Terrestrial Impact Craters of Flamenti et al., 2019 that lists numerous inaccurate impact ages), inevitably compromising the validity and significance of their conclusions (see also discussions in Miljkovic´, 2013, 2014; Schmieder et al., 2014c; Rampino and Caldeira, 2015; Meier and Holm-Alwmark, 2017). Finally, this work presents a referenced source for current best-estimate ages that can be listed in online impact databases, such as the Earth Impact Database (hosted at the University of New Brunswick, Fredericton, Canada), which has recently been complemented by the database Impact Earth maintained by Osisinski and Grieve (2019).

2. Data and Methods

Stratigraphic, isotopic, and additional age constraints are predominantly sourced from the primary literature, highlighting the work that led to the establishment of the (currently) preferred age for any particular impact event. Some ages are taken from summary articles (e.g., Grieve, 2006). Impact ages are grouped into three main categories: (1) stratigraphic age constraints; (2) isotopic ages, including U–Pb, Ar–Ar, K–Ar, Rb–Sr, (U–Th)/He, and 14C ages (while considering ages obtained using the high-temperature U–Pb and Ar–Ar geochronometers are usually preferred); and (3) age constraints other than the ones mentioned above.

2.1. Stratigraphic ages

The determination of relative stratigraphic ages, by superposition, can be applied to all impact structures on Earth and elsewhere, where the age of the host rock is to some degree constrained. Every impact structure has a target rock that the impacting body penetrated and, through simple geologic cross-cutting relationships, the youngest rock units affected by the impact provide a maximum (oldest possible) age for the impact. In turn, the oldest undisturbed rocks that fill the crater after its formation, commonly crater lake sediments in continental paleosettings, constrain the minimum (youngest possible) impact age. Some terrestrial impact crater ages are only very imprecisely constrained by the age of the impacted target rock as a maximum age (e.g., the <1800 million years [Ma, Myr] Île Rouleau impact structure, Québec, Canada) (Grieve, 2006). Sometimes, the stratigraphic age for an impact can only be bracketed within several hundred million years, as in the case of the 12 km-diameter Wells Creek impact structure in Tennessee (e.g., Wilson, 1953; Ford et al., 2012; Ford, 2015, and references therein). The crater must be younger than Mississippian (∼323 Ma) and older than Late Cretaceous (∼100 Ma) (see Cohen et al., 2013, for current stratigraphic age values), suggesting a “best-estimate” age of ∼211 ± 111 Ma and a relative error on the age of >100% (the commonly published age is 200 ± 100 Ma) (e.g., Grieve, 2001a). However, other stratigraphically constrained impact ages are remarkably precise, such as that of the ∼14 km-wide marine Lockne crater in Ordovician rocks of Central Sweden. There, the impact age is precisely constrained to be 455 Ma plus and minus a few hundred thousand years, because both the
youngest preimpact and oldest postimpact sediments lie in the late Sandbian (early Caradocian) lower Lagenochitina dalbyensis chitinozoan microfossil zone studied in great detail (Grahn et al., 1996; Grahn, 1997; Ormö et al., 2014). The stratigraphic method equally applies to impact ejecta layers.

2.2. Isotopic ages

Both the Wells Creek and Lockne impact craters described above have no or little recognized impact melt, respectively, that could potentially be used as material for radioisotopic analysis. However, a relatively large number of terrestrial impact structures have preserved impact melt-bearing rocks (e.g., Dence, 1971; von Engelhardt, 1984; Dressler and Reimold, 2001; Stöffler and Grieve, 2007; Osinski et al., 2018), such as the up to ~2.5 km-thick, differentiated crystalline melt sheet (the Sudbury Igneous Complex) overlain by ~1.5 km of melt-bearing impact breccia (the Onaping Formation) at the ~200 to 250 km-diameter Sudbury Basin in Ontario, Canada (e.g., Grieve, 2006; Davis, 2008; Roussell and Brown, 2009; Grieve et al., 2010); the up to ~1.2 km-thick melt sheet at the 100 km-diameter Manicouagan impact structure in Quebec, Canada (e.g., Floran et al., 1978; Grieve, 2006; Spray et al., 2010) (Fig. 3A); and the up to ~250 m-thick melt-bearing impact breccia (suevite) of the 25 km-diameter Nördlinger Ries crater in Germany (e.g., von Engelhardt et al., 1995; von Engelhardt, 1997; Stöffler et al., 2013) (Fig. 3B). The Ries impact also produced green glassy tektites (moldavites) (Fig. 3C), distal melt ejecta found ~200 to 500 km northeast of the crater (e.g., Stöffler et al., 2002; Trnka and Houzar, 2002). Because of the (partial to complete) resetting of geochronometers, for example, the U–Pb and K–Ar system, during high-temperature melting and degassing (diffusion) events such as major impacts (e.g., Jourdan et al., 2012), impact melt lithologies are in most cases suitable for geochronologic analysis using a variety of radioisotopic geochronometers.

2.2.1. U–Pb ages. One method used to determine impact ages is the uranium–lead (U–Pb) and coupled lead–lead (Pb–Pb) geochronometer (e.g., Nier, 1939; Wetherill, 1956, 1963; Tera and Wasserburg, 1972, 1974; and see Corfu, 2013 and Schoene, 2014 for reviews of its historical development and application). The U–Pb geochronometer is today used with several different technical setups. These include laser ablation inductively coupled plasma mass spectrometry.

**FIG. 3.** Impact crater materials commonly used for geochronologic analysis and two exemplary results. (A) Approximately 100 m-tall cliff of the impact melt sheet at the Manicouagan impact structure, Quebec, Canada (Baie Memory Entrance Island, photo taken by M. Schmieder in summer 2006). This type of impact melt rock is suitable for whole-rock Ar–Ar analysis and usually contains minerals (e.g., zircon) that can be analyzed using the U–Pb method. (B) Suevite, a polymict impact breccia with dark, elongated fäldle of impact glass from the Ries crater, Germany (Katzenstein Castle near Discingen, Baden-Württemberg). Impact glass is commonly used as sample material for Ar–Ar geochronology. (C) A green, glassy Ries tektite (moldavite) found in Besednice, Czech Republic. (D) Concordia (Wetherill) diagram showing U–Pb geochronologic results for zircon in impact melt rock from the Rochechouart impact structure in France (unpublished data). (E) Shocked zircon grain with LA-ICP-MS laser ablation pit created during U–Pb analysis in impact melt rock from the Charlevoix impact structure, Quebec, Canada (backscattered electron image) (Schmieder et al., 2019). (F) Argon–argon age diagram showing a well-defined plateau age, including relevant statistics for a Ries tektite sample similar to the one shown in (C) (from Schmieder et al., 2018a). LA-ICP-MS, laser ablation inductively coupled plasma mass spectrometry.
spectrometry (LA-ICP-MS), SIMS (SIMS and nanoSIMS), sensitive high-resolution ion microprobe (SHRIMP) analysis, and thermal ionization mass spectrometry after chemically abrading the mineral sample for better results (CA-TIMS). The latter, again, comes in different variations (isotope dilution, ID-TIMS; and total evaporation, TE-TIMS) (e.g., Davis, 2008). Each of these techniques has its advantage and disadvantage. While LA-ICP-MS and SIMS/SHRIMP are routinely and rapidly applied to thin-section or grain mount samples that can preserve the textural context of the sample, producing moderately precise U–Pb and Pb–Pb ages, CA-TIMS completely dissolves the mineral sample but produces much more precise ages with errors commonly in the range of a few thousands to tens of thousands of years (e.g., Schoene, 2014; Schaltegger et al., 2015). The U-bearing minerals most commonly used for the U–Pb geochronologic analysis of impact materials are either intensely shocked or melt-grown zircon crystals (Fig. 3D, E) (e.g., Davis, 2008; Crow et al., 2017; Kenny et al., 2019a, 2019b), baddeleyite (Krogh et al., 1984; Corfu and Lightfoot, 1996), monazite (e.g., Tohver et al., 2012; Erickson et al., 2017, 2019a, 2019b), and to a lesser degree titanite (Ames et al., 1998) and apatite, although recent results for terrestrial impact craters suggest the latter is a promising target mineral for future studies (McGregor et al., 2018, 2019). Uranium–lead results are typically visualized in a concordia diagram (Wetherill or Tera-Wassenburg plot) alongside their internal statistics (mean square weighted deviation [MSWD] and probability p as a measure of statistical fit) and can be corrected for a nonradiogenic (“common”) lead component. Zircon crystals from the less severely shocked, unmelted portion of the target rock of an impact structure commonly tend to yield older dates on or near concordia (the curve along which U–Pb ages from different U decay series are equal), reflecting the crystallization and/or metamorphic age(s) of the host rock (e.g., Schärer and Deutsch, 1990; Wielicki et al., 2012; Schmieder et al., 2015b). In contrast, intensely shocked and recrystallized zircon grains (so-called granular zircon, locally with μ-sized baddeleyite domains as a thermal decomposition product of zircon) (Wittmann et al., 2006; Timms et al., 2017) are chronometrically reset and commonly yield younger concordia ages, potentially reflecting the impact (Fig. 3D) (e.g., Hodych and Dunning, 1992; Krogh et al., 1993; Wielicki et al., 2012; Kenny et al., 2019b). If the isotopic system is affected by variable loss of Pb, a discordant array of dates may define a lower intercept with concordia from which the age of the impact can be derived (e.g., Kamo et al., 1996; Miintäri and Koivisto, 2001). However, episodic and/or modern postimpact Pb loss can cause significant disturbance of the U–Th–Pb system, and some zircon U–Pb ages obtained for impact events (e.g., the Ediacaran Acraman impact in South Australia) and their geologic significance are not straightforward to interpret (Schmieder et al., 2015b). A special type of zircon is typically U- and Th-rich metamict (internally radiation-damaged, pseudomorphous) zircon (e.g., Pidgeon et al., 1966; Meldrum et al., 1998; Nasdala et al., 2001), which is more susceptible to U–Pb chronometric resetting during impact events (and other thermostromorphic processes) than nonmetamict zircon (e.g., Schwarz et al., 2016a and unpublished data; Stockli et al., 2018; McGregor et al., 2019; Schmieder et al., 2019). The use of metamict (do-
Argon–argon results for impact structures can be disturbed by the effects of sample alteration causing the diffusive loss of radiogenic $^{40}$Ar and younger apparent ages (e.g., Schmieder et al., 2014a), and also the incorporation of inherited $^{36}$Ar* with inclusions of incompletely degassed older target rock material and/or excess argon from Ar-bearing fluids interacting with the sample, both causing older apparent ages (inherited and excess argon are summarized under the term “extraneous argon”) (e.g., Kelley, 2002). Such effects can be identified, quantified, and corrected for using the isochron approach (e.g., Roddick, 1978; Kuiper, 2002; Jourdan et al., 2008, 2011; Jourdan, 2012; Schmieder et al., 2015a). Statistically robust Ar–Ar results ideally form a “plateau” in the age spectrum (Fig. 3F), a sequence of individual degassing steps with increasing temperature that all overlap within a narrow error limit and include most (ideally at least 70%) of the $^{39}$Ar extracted from the sample (e.g., Jourdan, 2012). They are, moreover, characterized by their internal statistics expressed through MSWD and $p$ values for plateau sections and isochrons (and are typically reported with 2σ errors; that is, at the ∼95% confidence level, as is done in this work unless otherwise stated). Precise Ar–Ar ages have been obtained for a number of impacts on Earth, such as 66.05±0.031 Ma for glassy microtektites from the 180 km-diameter Chicxulub crater linked to the end-Cretaceous mass extinction (Renne et al., 2018). High-precision Ar–Ar results for the Chicxulub microtektites at the K/T boundary (more recently also known as the K/Pg boundary) were recently used to calibrate the timing and duration of the contemporaneous reverse magnetic chron C29r (Sprain, 2017; Sprain et al., 2008, 2011; Schmieder and Jourdan, 2013a). High-precision Ar–Ar results for the Chicxulub impact crater, Mexico, published by Roddick et al. (1992) using the K decay constants of Steiger and Jäger (1977) and the Fish Canyon sanidine (FCs) standard with a then-reported age of 27.84 Ma, becomes 66.05±0.18 Ma (2σ) after the recalculation of individual step ages, plateau sections and ages, and weighted mean (average) ages (n=3 plateau ages; MSWD=0.18; p=0.84) obtained from those results using Isoplot 4.15 (Ludwig, 2008) and the ArAR tool of Mercer and Hodges (2016). This recalculated age is within uncertainty indistinguishable from the more recent U–Pb age of 66.021±0.081 Ma for zircon crystals in ash layers around the K/T boundary in the Denver Basin (Clyde et al., 2016). It is also equivalent to Ar–Ar results of 66.038±0.049 Ma for glassy microtektites found at the K/T boundary in Beloc, Haiti (Renne et al., 2013; Sprain et al., 2015), an age of 66.051±0.031 Ma for similar microtektites at a K/T section exposed on Gorgonilla Island off the coast of Colombia (Renne et al., 2018), and an age of 66.052±0.043 Ma for tephra in the “Iridium Z coal” layer ∼1 cm above the iridium anomaly of the K/T boundary interval (Renne et al., 2013; Sprain et al., 2018). The ~24 km-diameter Boltysk impact structure in Ukraine, another end-Cretaceous impact structure (Kelley and Gurov, 2002), has a recalculated age of 65.80±0.67 Ma that is, within a somewhat larger error envelope, identical to the age of the Chicxulub impact (Jourdan, 2012). However, from the identification of distal Chicxulub ejecta in the basal lake sediments of the Boltysk crater, we know that this impact predates Chicxulub by a few thousand years (Jolley et al., 2010).

Likewise, through recalculation, the age of the ~35 km-diameter Manson impact structure, Iowa (decades ago still a contender for the K/T boundary impact site), also sees a notable shift from 74.1±0.1 Ma (Izett et al., 1998) to an older recommended age of 75.9±0.1 Ma (Table 1). The ~100 km-diameter Popigai impact structure in Russia, with a previously recommended Ar–Ar age of 35.7±0.2 Ma (Bottomley et al., 1997) has, after a reinterpretation of the original Ar–Ar results, a more conservative recalculated age of 36.63±0.92 Ma, which accounts for the spread of ~1 Myr between four plateau ages, not all of which overlap (n=4 plateau ages; MSWD=7.6; p=0.000) (see also Jourdan et al., 2009). From this recalculation, a time gap of at least ~0.5 Myr (and up to ~3 Myr) seems to occur between Popigai and the somewhat younger (34.86±0.32 Ma) ~40 to 45 km-diameter Chesapeake impact structure (a.k.a. Chesapeake Bay; final collapsed diameter ∼85 km) on the East coast of the United States (Assis Fernandes et al., 2019). This asteroid “one-two punch” is in agreement with the occurrence of two relatively closely spaced, but separate, distal ejecta layers in the Upper Eocene (Glass et al., 1985; Koeberl, 2009) (Table 2), known as the older clinopyroxene layer geochemically linked to the Popigai impact (Whitehead et al., 2000) and the younger North American (micro-)tektites linked to the Chesapeake impact (Deutsch and Koeberl, 2006).

In a few cases, recalculation of the original Ar–Ar results was omitted due to potentially unreliable standard ages used in the original geochronologic analysis. This, for example, applied to ages obtained using the B4M muscovite standard, which was commonly used in geochronology laboratories in the 1980s (e.g., for the Haughton impact structure, Canada) (Jessberger, 1988) and later (for the Ilyinets impact structure, Ukraine) (Pesonen et al., 2004). The B4M standard was recently shown to be quite heterogeneous in composition and age between finer- and coarser-grained domains of the...
| No | Impact structure | Country    | Latitude | Longitude | Diameter (m) | Type of target rock | Type of impactor | Stratigraphic age constraints | Radiometric age constraints | Other age constraints | Recommended age (Ma) | Recommended age reference* | Pre-recedition age (Ma) |
|----|------------------|------------|----------|-----------|--------------|---------------------|------------------|-------------------------------|--------------------------|----------------------|---------------------|---------------------------|---------------------------|
| 1  | Chelyabinsk     | Russia     | 45°58’N | 60°18’E  | 0.007        | Ice                 | LL-chondrite      | Recent                       | Fall February 15, 2013, main mass left 8 m-wide temporary hole in frozen Lake Chebarkul | 0.000006          | Boevička et al. (2013) |
| 2  | Caracas         | Peru       | 16°40’S | 69°02’W  | 0.0135       | Sedimentary        | H-chondrite       | Recent                       | Fall September 15, 2007 | 0.000012            | Tancrús et al. (2009)  |
| 3  | Stekhämlik     | Russia     | 53°40’N | 55°59’E  | 0.0094       | Sedimentary (soil, loam) | BIAB iron | Recent                        | Fall May 17, 1990 | 0.000029          | Potapov (1992)             |
| 4  | Sildjbo Ain (Field) | Russia   | 46°09’N | 134°39’E | 0.027       | Crystalline        | BAB iron          | Recent                       | Fall February 12, 1947 | 0.000072          | Krnov (1971)               |
| 5  | Imilac         | Chile      | 24°12’S | 68°48’W  | 0.015       | Crystalline (volcanic, soil) | Pallasitic | Recent                       | Found 1822 AD, fall produced ~15 m-wide impact pit, ~4 m deep | >0.0002          | Bushwald (1973); Ivyan (2006) |
| 6  | Sobolev        | Russia     | 46°17’N | 137°54’E | 0.053       | Sedimentary        | Iron             | Recent                       | Trees in crater          | 0.0003±0.00025        | Yarmolyuk (1951); Khryashev (1981) |
| 7  | Wabar          | Saudi Arabia | 21°30’N | 50°28’E  | 0.116       | Sedimentary (sand) | BIAB iron      | Historical                    | Luminescence dating, historical | ~0.0003          | Bursich (2003); Pascott et al. (2004) |
| 8  | Whitecourt      | Canada     | 54°00’N | 115°36’W | 0.036       | Sedimentary        | BIAB iron        | Quaternary (14C)             | Preservation of morphology | <0.0011          | Heid et al. (2008) |
| 9  | Dugzaragta      | Australia  | 27°45’S | 117°05’E | 0.021       | Crystalline        | Mesoosiderite    | Quaternary (10Be/26Al exposure age) | Thermoluminescence dating | ≤0.004           | Shoomaker and Shoomaker (1988); Sighiroti et al. (2015) |
| 10 | Kamil           | Egypt      | 22°01’N | 26°05’E  | 0.045       | Sedimentary        | Iron (ataxite)   | Quaternary (14C)             | ~0.00324                  | ~0.0035          | Pedersen et al. (1992) |
| 11 | Kaali (Kuuligirv (Field)) | Estonia  | 58°22’N | 22°40’E  | 0.11         | Sedimentary        | IAB iron         | Quaternary (14C)             | ~0.004                     | ~0.0047          | Romula and Cassidy (1973)  |
| 12 | Vaca Muerta     | Chile      | 25°45’S | 70°30’W  | 0.007       | Crystalline (volcanic) | Mesoosiderite | Quaternary (14C)             | Fall produces field of pitted crater largest ~7.16 m in diameter and 1.35 m deep in crater | ~0.005           | Preservation of ejecta blanket |
| 13 | Campo del Cielo (Field) | Argentina | 27°38’S | 61°42’W  | 0.115       | Sedimentary        | IAB iron         | Quaternary (14C)             | ~0.007                     | ~0.007           | Shoemaker and Shoomaker (1988); Haines (2005); Shoemaker et al. (2005) |
| 14 | Voevers         | Australia  | 22°58’S | 125°22’E | 0.08        | Sedimentary        | BAB iron         | Quaternary (14C)             | Preservation of ejecta blanket | ~0.0047          | Shoemaker and Shoomaker (1988); Haines (2005); Shoemaker et al. (2005) |
| 15 | Mozasko (Field) | Poland     | 52°29’N | 27°24’E  | 0.1         | Sedimentary        | IAB iron         | Quaternary (14C)             | Luminescence dating         | ~0.005           | Stankowski et al. (2007) |
| 16 | Hlumstsa (Field) | Estonia   | 57°57’N | 16°54’E  | 0.08        | Sedimentary        | Unknown          | Quaternary (14C)             | ~0.007                     | ~0.007           | Raadik et al. (2001); Losiak et al. (2009); Losiak (2019), personal communication |
| 17 | Macha (Field)   | Russia     | 60°05’N | 117°39’E | 0.3         | Sedimentary        | Iron             | Quaternary (14C)             | ~0.00375±0.00008          | ~0.0008          | Gurov et al. (1998); Gurov and Gurova (1998) |
| 18 | Haviland        | United States | 37°35’N | 99°10’W  | 0.015       | Sedimentary        | Pallasitic (diogenite) | Quaternary (14C)             | Cosmogenic nuclides (14C) | 0.020±0.002        | Honda et al. (2002) |
| 19 | Boxhole         | Australia  | 22°37’S | 135°12’E | 0.185       | Crystalline        | BIAB iron       | Quaternary (14C)             | 26Al/39Ar exposure age | 0.03±0.005       | Shoomaker et al. (1990) |
| 20 | Henbury         | Australia  | 24°35’S | 133°09’E | 0.157       | Sedimentary        | BIAB iron       | Quaternary (14C)             | Cosmogenic nuclides (14C) | 0.042±0.019        | Kohman and Goel (1963) |
| 21 | Armgard         | Algeria    | 26°05’S | 4°23’E   | 0.45        | Sedimentary        | Lower Devonian target rocks | Quaternary (14C)             | Lower Devonian target rocks (14C) | ≤0.17            | Lambert et al. (1980); Gibbons et al. (2008); Haines (2014) |
| 22 | Hickman         | Australia  | 23°02’S | 119°41’E | 0.26        | Mixed (banded iron formation, rhyolite) | Quaternary (14C) | Plumbage of local drainage system | Plumbage of local drainage system | ≤0.17            | Gibbons et al. (2008); Haines (2014) |
| 23 | Barringer (Meteor Crater) | United States | 35°02’N | 111°01’W | 1.186       | Sedimentary        | IAB iron | Early Triassic to Quaternary | 39Cl surface exposure; 26Al, 39Ar exposure | ~0.0567±0.0048  | Sutton et al. (1985); Marrero et al. (2010); Kring (2017b) and references therein; Barrow et al. (2019) |
| 24 | Odessa (Field)  | United States | 31°45’N | 102°29’W | 0.168       | Sedimentary        | IAB iron | Quaternary (14C)             | Optically stimulated luminescence | 0.0635±0.0045       | Holliday et al. (2005) |

(continued)
| No | Impact structure                      | Country   | Latitude | Longitude | Diameter (km) | Type of target rock | Type of impactor | Stratigraphic age constraints | Radiometric age constraints | Other age constraints | Recommended age (Ma) | Recommended age reference* | Precalculated age (Ma) |
|----|--------------------------------------|-----------|----------|-----------|---------------|--------------------|-----------------|-------------------------------|---------------------------|----------------------|----------------------|-----------------------------|-------------------------|
| 25 | Wolfe Creek (Kondinakal)              | Australia | 19°18'S | 127°46'E | 0.875         | Sedimentary        | BIAB iron        | Optical stimulated luminescence, ²⁶⁰⁹Be, ⁹⁷³⁰⁸Ne exposure | 0.120±0.009               | Shoemaker et al. (1990, 2005), Barlow et al. (2019) | 0.570±0.047 | | |
| 26 | Twaining (Pretoria Saltpan)           | South Africa | 25°24'S | 28°05'E | 1.13          | Crystalline       | Chondritic       | Glass fusion track                                  | 0.20±0.104                | Sooster et al. (1999), Reimold et al. (2007) | 0.25±0.05 | | |
| 27 | Kalkkop                              | South Africa | 32°43'S | 24°26'E | 0.64          | Sedimentary       | Chondritic?      | U-Th series dating of limestone                     | 0.576±0.047               | Jourdan et al. (2011), recalculated | 0.663±0.09 | | |
| 28 | Lunar                                | India     | 19°59'N | 76°31'E | 1.83          | Crystalline (basalt) | Carbonaceous chondrite? | Ar-Ar (impact melt rock) | 0.576±0.047               | Jourdan et al. (2011), recalculated | 0.663±0.09 | | |
| 29 | Montaraqui                           | Chile     | 23°56'S | 68°17'W | 0.46          | Crystalline (garnet, volcanics) | IAB? iron | (U-Th)/He (zircon and apatite from impact melt) | 0.815±0.011               | Rodetti et al. (2019) | 0.91±0.014 | | |
| 30 | Pantasma                              | Nicaragua | 13°12'N | 85°37'W | 14            | Crystalline (volcanic) | Chondritic | Ar-Ar (impact glass) | 1.13±0.10                     | Jourdan et al. (2012) | 1.4±0.1 | | |
| 31 | Zhamsunshin                           | Kazakhstan | 48°24'N | 60°58'E | 14            | Mixed              | Carbonaceous chondrite | Ar-Ar (impact glass) | 1.13±0.10 | Jourdan et al. (2012) | 1.4±0.1 | | |
| 32 | Bosumwei                              | Ghana     | 6°32'N | 1°25'W  | 10.5          | Crystalline | Chondrite? | Ar-Ar (I-vory Coast tektites) | 1.13±0.10 | Jourdan et al. (2012) | 1.4±0.1 | | |
| 33 | New Québec (Pinguichult)              | Canada    | 61°17'N | 73°40'W | 3.44          | Crystalline       | Chondrite (L? | Ar-Ar (impact melt rock) | 1.13±0.10 | Jourdan et al. (2012) | 1.4±0.1 | | |
| 34 | Tapanzene (Mădășna)                  | Slovenia  | 33°19'N | 4°02'E  | 1.75          | Sedimentary       | Eocene or younger | Preservation of crater morphology | 1.13±0.10 | Jourdan et al. (2012) | 1.4±0.1 | | |
| 35 | Tenoumer                              | Mauritania | 22°55'N | 10°24'W | 1.9           | Crystalline | | Ar-Ar (impact melt rock) | 1.13±0.10 | Jourdan et al. (2012) | 1.4±0.1 | | |
| 36 | Aouellou                              | Mauritania | 20°15'N | 12°41'W | 0.36          | Sedimentary       | | K-Ar (impact glass) | 3.1±0.3 | Jourdan et al. (2012) | 3.58±0.04 | | |
| 37 | Elgygytgyn                            | Russia    | 67°30'N | 172°05'E | 18            | Crystalline | | Ar-Arg (impact melt rock) | 3.8±0.3 | Jourdan et al. (2012) | 3.7±0.3 | | |
| 38 | Roter Kamme                           | Namibia   | 52°27'N | 16°18'E | 2.8           | Mixed              | | Ar-Arg (impact melt rock) | 3.8±0.3 | Jourdan et al. (2012) | 3.7±0.3 | | |
| 39 | Rigach                                | Kazakhstan | 48°30'N | 82°00'E | 7            | Mixed | sedimentary | Mocone or younger | 5±3 | Jourdan et al. (2012) | 5±3 | | |
| 40 | Khotken                              | Russia    | 54°54'N | 108°47'E | 12            | Sedimentary | Mocone to Piscine | Proven ando to Miocene | 5±3 | Jourdan et al. (2012) | 5±3 | | |
| 41 | Xiuyan                               | China     | 40°22'N | 123°27'E | 1.8           | Crystalline | | Ar-Arg (impact melt rock) | 3.8±0.3 | Jourdan et al. (2012) | 3.7±0.3 | | |
| 42 | Shunak                                | Kazakhstan | 47°12'N | 72°42'E | 2.8           | Crystalline (volcanic) | | Crater morphology | 12±5 | Jourdan et al. (2012) | 14.08±0.038 | | |
| 43 | Nördlinger Ries (Ries crater)         | Germany   | 48°53'N | 10°37'E | 24            | Mixed | No contamination | Mocone or younger | 14.08±0.038 | Jourdan et al. (2012) | 14.08±0.038 | | |
| 44 | Steinheimer Becken (Steinheim Basin)  | Germany   | 48°40'N | 10°04'E | 3.8 | Sedimentary | Pulssite? | Mocone crater lake sediments | Presumably synchronous with Ries impact | 14.08±0.038 | Jourdan et al. (2012) | 14.08±0.038 | | |
| 45 | Haughton                              | Canada    | 75°22'N | 89°41'W | 24            | Mixed | No contamination | Ar-Arg (impacts) | 23.4±1.0 | Jourdan et al. (2012) | 23.4±1.0 | | |
| 46 | Jebel Waag as Sina                   | Jordan    | 31°03'N | 36°48'E | 6            | Sedimentary | Middle Eocene | Tectonic history | 14.08±0.038 | Jourdan et al. (2012) | 14.08±0.038 | | |
| 47 | Karakul (Kara-Kul)                   | Tajikistan | 39°01'N | 73°27'E | 52            | Crystalline | | Tectonic history | 30±2±0.5 | Jourdan et al. (2012) | 30±2±0.5 | | |
| 48 | Logonok                              | Belarus   | 54°12'N | 27°48'E | 17            | Mixed | | Ar-Arg (impact glass) | 30±2±0.5 | Jourdan et al. (2012) | 30±2±0.5 | | |
| 49 | Beyenchime-Salatin                   | Russia    | 71°50'N | 123°30'E | 8            | Sedimentary | | | 33±33 | Jourdan et al. (2012) | 33±33 | | |
| 50 | Eagle Butte                          | Canada    | 49°42'N | 110°35'W | 10 | Sedimentary | Late Cretaceous or younger | Late Cretaceous | 6±5 | Jourdan et al. (2012) | 6±5 | | |
| 51 | Guev                                 | Russia    | 48°21'N | 40°14'E | 3            | Sedimentary | Younger than Late Cretaceous | Late Cretaceous | 6±5 | Jourdan et al. (2012) | 6±5 | | |
| 52 | Chesapeake Bay                       | United States | 37°15'N | 76°05'W | ~40 to 45 | Sedimentary | Chondritic (L?) | Ar-Arg (alkites and impact melt rock) | 3.84±0.32 | Jourdan et al. (2012) | 3.84±0.32 | | |
| 53 | Chukchich                            | Russia    | 75°42'N | 97°48'E | 6            | Mixed | Cretaceous or younger | Maastichnan or younger | 7±7 | Jourdan et al. (2012) | 7±7 | | |
| 54 | Maple Creek                          | Canada    | 49°48'N | 109°06'W | 6 | Sedimentary | | | 6±5 | Jourdan et al. (2012) | 6±5 | | |

(continued)
| No | Impact structure | Country       | Latitude | Longitude | Diameter (km) | Type of target rock | Type of impactors | Stratigraphic age constraints | Radiometric age constraints | Other age constraints | Recommended age (Ma) | Recommended age reference | Pre-reckalculated age (Ma) |
|----|------------------|---------------|----------|-----------|---------------|---------------------|-------------------|-----------------------------|---------------------------|-----------------------|------------------------|--------------------------|--------------------------|
| 55 | Popigai          | Russia        | 71°30'N  | 111°00'E | 100           | Mixed              | Chondrite (H or L?) | Ar-Ar (impact melt rock)   | 36.63±0.92                | Bottomley et al. (1997), recalculation, mean of 4 plateau ages | 35.7±0.2                |
| 56 | Wanapitei        | Canada        | 46°28'N  | 80°45'E  | 7.5           | Crystalline       | Chondrite (L or LL?) | Ar-Ar (impact melt rock)   | 37.7±1.2                  | Greve (2006) after Bottomley et al. (1979), recalculated | 37.2±1.2                |
| 57 | Mistasun         | Canada        | 55°53'N  | 63°18'W  | 28            | Crystalline       | No contamination?  | U-Pb (CA-TIMS, melt rock zircon) | 37.83±0.05                | Shoemaker and Shoemaker (1986) |                        |
| 58 | Connolly Basin   | Australia     | 23°32'S  | 124°45'E | 9             | Sedimentary      | Palaeogene         | ~66 to 23                  | Masaitis et al. (1989) | 120 Koeberl et al. (1992) | 0.78 Schmieder and Renne et al. (1992) |
| 59 | Logancha         | Russia        | 65°30'N  | 95°48'E  | 20            | Mixed            | Palaeogene         | ~66 to 23                  | Lambert et al. (1981) | 120 Koeberl et al. (1992) | 0.78 Schmieder and Renne et al. (1992) |
| 60 | Tin Tider (Tademot) | Algeria    | 27°36'N  | 5°07'E   | 6             | Sedimentary      | Comacia or younger | ~56 to 41                  | Vishnevsky (2007)   | 120 Koeberl et al. (1992) | 0.78 Schmieder and Renne et al. (1992) |
| 61 | Chuby (Shuyli)   | Kazakhstan    | 49°10'N  | 57°17'E  | 5.5           | Sedimentary      | Early to Middle Eocene | <100                      | Oliviera et al. (2017), Crista et al. (2019b) | 120 Koeberl et al. (1992) | 0.78 Schmieder and Renne et al. (1992) |
| 62 | Santa Mara       | Brazil        | 10°10'S  | 45°14'W  | 10            | Sedimentary      | Late Cretaceous    | 120 Koeberl et al. (1992) | 0.78 Schmieder and Renne et al. (1992) | 120 Koeberl et al. (1992) | 0.78 Schmieder and Renne et al. (1992) |
| 63 | Kamesnok         | Russia        | 48°20'N  | 10°15'E  | 25            | Sedimentary      | Ar-Ar (impact glass) | 50.37±0.40                | Jourdan et al. (2012) after Litte et al. (1994) | 50.5±1.6                |
| 64 | Montagnais       | Canada        | 42°53'N  | 64°13'W  | 45            | Sedimentary (shelf) | Ar-Ar (impact melt rock) | 51.1±1.6                  | Bottomley and York (1980), recalculated | 50.5±1.6                |
| 65 | Goat Paddock     | Australia     | 18°20'S  | 126°40'E | 5.1           | Sedimentary      | Early Eocene (palaeontol.) | ~56 to 48                  | Milk and Macdonald (2005) | 120 Koeberl et al. (1992) | 0.78 Schmieder and Renne et al. (1992) |
| 66 | Ragozinka        | Russia        | 58°18'N  | 62°0'E   | 9             | Mixed            | Thetanian, Early Eocene (Sanov Suite) | ~59 to 56                  | Vishnevsky (1999)   | 120 Koeberl et al. (1992) | 0.78 Schmieder and Renne et al. (1992) |
| 67 | Sierra Madure    | United States | 30°36'N  | 102°55'W | 13            | Sedimentary      | Albion (Georgetown Fm.) or younger | <13                      | Wylie and Gilby (1990), McMahon and Sorkhabi (1994) | 120 Koeberl et al. (1992) | 0.78 Schmieder and Renne et al. (1992) |
| 68 | Marquez          | United States | 31°17'N  | 96°18'W  | 13            | Sedimentary      | Around Palaeocene/Eocene transition | 58.3±3.1                  | Sharpnent and Gilby (1990), McMahon and Sorkhabi (1994) | 120 Koeberl et al. (1992) | 0.78 Schmieder and Renne et al. (1992) |
| 69 | BP structure     | Libya         | 21°19'N  | 24°20'E  | 2             | Sedimentary      | Early Cretaceous or younger (Nubian Sandstone) | ≤1 ≤20                     | Koebel et al. (2005b) | 120 Koeberl et al. (1992) | 0.78 Schmieder and Renne et al. (1992) |
| 70 | Oasis            | Libya         | 21°35'N  | 24°24'E  | 18            | Sedimentary      | Early Cretaceous or younger (Nubian Sandstone) | ≤1 ≤20                     | Koebel et al. (2005b) | 120 Koeberl et al. (1992) | 0.78 Schmieder and Renne et al. (1992) |
| 71 | Mount Toondina   | Australia     | 27°57'S  | 135°22'E | 4             | Sedimentary      | Aptian to Albian, Early Cretaceous, or younger (Boullag Shale) | <1 <25                     | Plescic et al. (1994) | 120 Koeberl et al. (1992) | 0.78 Schmieder and Renne et al. (1992) |
| 72 | Chacxuhb         | Mexico        | 21°20'N  | 89°30'W  | 180           | Mixed            | Carbonaceous chondrite? | 66.05±0.043                | Swisher et al. (1992), recalculated Renne et al. (2013, 2018), Sprant et al. (2015, 2018), Clyde et al. (2016) | 0.78 Schmieder and Renne et al. (1992) |
| 73 | Bolotsh          | Ukraine       | 48°45'N  | 32°10'E  | 24            | Crystalline      | Chondrite?         | Ar-Ar (impact melt rock)   | 65.80±0.67                | Kelly and Groen (2002), recalculated Jourdan (2012), Crista et al. (2019) | 70.3±2.2                |
| 74 | Cerro do Jaru    | Brazil        | 30°12'S  | 56°32'W  | 13.5          | Mixed            | Early Cretaceous (Serra Geral Fm.) or younger | ≤35                      | 70.7±2.2                  | 70.3±2.2                |
| 75 | Kara             | Russia        | 69°05'N  | 64°18'E  | 65            | Mixed            | Chondrite?         | Ar-Ar (impact melt rock)   | 65.5±0.1                  | 74.1±0.1                  | 70.3±2.2                |
| 76 | Mammon           | United States | 42°35'N  | 94°31'W  | 35            | Mixed            | Chondrite          | Ar-Ar (sulphide in melt breccia) | 77.85±0.78                | 70.3±2.2                |
| 77 | Lappajarvi       | Finland       | 63°09'N  | 23°42'E  | 23            | Mixed            | H-chondrite        | U-Pb (zircon in impact melt rock) | 77.85±0.78                | 70.3±2.2                |

(continued)
| No | Impact structure | Country     | Latitude | Longitude | Diameter (km) | Type of target rock | Type of impact | Stratigraphic age constraints | Radiometric age constraints | Other age constraints | Recommended age (Ma) | Recommended age reference                          | Pre-recalculation age (Ma) |
|----|------------------|-------------|----------|-----------|---------------|---------------------|----------------|-----------------------------|-----------------------------|-----------------------|----------------------|---------------------------------------------|--------------------------|
| 78 | Zeleny Gai       | Ukraine     | 48°42'N  | 32°30'E  | 3.5           | Crystalline        | Ar-He (impact melt rock) | (U-Th)/He (apatite and zircon) | ~85                        | ~83.5                 | 80±2.07             | Maastricht (1999)                                      |                          |
| 79 | Wetumpka         | United States | 32°31'N  | 86°11'W  | 6.5           | Mixed              | Chondrite?       | Close to Santonian/ Campanian boundary |                                  |                       | ~85                 | Schmieder et al. (2016a); Schmieder et al. (2016b)  |                          |
| 80 | Suvansevi North  | Finland     | 62°39'N  | 28°10'E  | 3.5           | Crystalline        | Ar-Ar (impact melt rock) |                                  |                       |                       | 89.8–83.6 Ma | Cox et al. (2019)                      |                          |
| 81 | Yallalie         | Australia   | 30°28'S  | 115°47'E | 15            | Sedimentary        | Coniacian, Late Cretaceous |                                  |                       |                       | <1.83               | Kiems et al. (1999)                                  |                          |
| 82 | Agoudal          | Morocco     | 31°59'N  | 5°31'W   | 1.3           | Sedimentary        | Early Jurassic (Kazoo dolomite) | (U-Th)/He (apatite and zircon) | ~94–90                      |                       | ~102–95             | Brandt et al. (2002)                                |                          |
| 83 | Kgagadi          | Botswana    | 22°29'S  | 27°35'E  | 3.5           | Crystalline        | Early Jurassic (Touremian or younger) | (U-Th)/He (apatite and zircon) | ~94–90                      |                       | ~110–114            | Sexl et al. (1990a)                                 |                          |
| 84 | Avak             | United States | 71°15'N  | 156°36'E | 12            | Sedimentary        | Turonian, Late Cretaceous (palynology) | (U-Th)/He (apatite and zircon) | ~145 to 94                    |                       | ~145 to 94          | Bernet and Fenton (2008)                           |                          |
| 85 | Upheaval Dome    | United States | 38°26'N  | 109°54'W | 10            | Sedimentary        | Early Jurassic (Toarcian) or younger | (U-Th)/He (apatite and zircon) | ~145 to 94                    |                       | ~145 to 94          | Bernet and Fenton (2008)                           |                          |
| 86 | Deep Bay         | Canada      | 56°24'N  | 102°59'W | 13            | Crystalline        | Early Cretaceous to Turonian | (U-Th)/He (apatite and zircon) | ~145 to 94                    |                       | ~145 to 94          | Bernet and Fenton (2008)                           |                          |
| 87 | Rotmistrovka     | Ukraine     | 49°00'N  | 32°00'E  | 2.7           | Crystalline        | Early Cretaceous to Turonian | (U-Th)/He (apatite and zircon) | ~145 to 94                    |                       | ~145 to 94          | Bernet and Fenton (2008)                           |                          |
| 88 | Vista Alegre      | Brazil      | 25°57'S  | 52°41'W  | 9.5           | Mixed              | Early Cretaceous (~134 Ma Serra Geral Fm.) or younger | (U-Th)/He (apatite and zircon) | ~145 to 94                    |                       | ~145 to 94          | Bernet and Fenton (2008)                           |                          |
| 89 | Mien             | Sweden      | 56°25'N  | 14°52'E  | 9             | Crystalline        | Stone?            | Ar-Ar (impact melt rock) | ~122.4±2.3                   |                       | ~122.4±2.3          | Boy et al. (1990), recalculated                    |                          |
| 90 | Vargulio         | Brazil      | 26°50'S  | 52°07'W  | 12            | Sedimentary        | Early Cretaceous (~134 Ma Serra Geral Fm.) or younger | (U-Th)/He (apatite and zircon) | ~122.4±2.3                   |                       | ~122.4±2.3          | Boy et al. (1990), recalculated                    |                          |
| 91 | Serra da Cangalha | Brazil     | 8°05'S   | 46°52'W  | 12            | Sedimentary        | Late Permian or younger | (U-Th)/He (apatite and zircon) | ~122.4±2.3                   |                       | ~122.4±2.3          | Boy et al. (1990), recalculated                    |                          |
| 92 | Tookoonooka      | Australia   | 27°00'S  | 143°00'E | 55            | Sedimentary        | Barremian/Aptian boundary | (U-Th)/He (apatite and zircon) | ~122.4±2.3                   |                       | ~122.4±2.3          | Boy et al. (1990), recalculated                    |                          |
| 93 | Dellen           | Sweden      | 61°55'N  | 16°39'E  | 19            | Crystalline        | Stone?            | Ar-Ar (impact melt rock) | ~122.4±2.3                   |                       | ~122.4±2.3          | Boy et al. (1990), recalculated                    |                          |
| 94 | Mjohanir         | Norway      | 73°48'N  | 29°40'E  | 20–40          | Sedimentary (sea floor) | Early Berriasian (Volgan/Ryazanian boundary) | (U-Th)/He (apatite and zircon) | ~143±2.12                    |                       | ~143±2.12          | Smelror et al. (2001)                               |                          |
| 95 | Monweng          | South Africa | 25°28'S  | 23°32'E  | 70            | Crystalline        | LL-chondrite      | (U-Th)/He (apatite and zircon) | ~143±2.12                    |                       | ~143±2.12          | Smelror et al. (2001)                               |                          |
| 96 | Des Plaines      | United States | 42°03'N  | 87°52'W  | 8             | Sedimentary        | Pennsylvanian     | (U-Th)/He (apatite and zircon) | ~143±2.12                    |                       | ~143±2.12          | Smelror et al. (2001)                               |                          |
| 97 | Kentland         | United States | 40°45'N  | 87°24'W  | 13            | Sedimentary        | Younger than Mississippian, older than Pennsylvanian | (U-Th)/He (apatite and zircon) | ~143±2.12                    |                       | ~143±2.12          | Smelror et al. (2001)                               |                          |
| 98 | Middlesboro      | United States | 36°37'N  | 83°44'W  | 6             | Sedimentary        | Early Pennsylvanian | (U-Th)/He (apatite and zircon) | ~143±2.12                    |                       | ~143±2.12          | Smelror et al. (2001)                               |                          |
| 99 | Riachulo         | Brazil      | 7°43'S   | 46°39'W  | 4.5           | Sedimentary        | Early Pennsylvanian | (U-Th)/He (apatite and zircon) | ~143±2.12                    |                       | ~143±2.12          | Smelror et al. (2001)                               |                          |

(continued)
| No   | Impact structure                        | Country         | Latitude | Longitude | Diameter (km) | Type of target rock | Type of impactor | Stratigraphic age constraints | Radiometric age constraints | Other age constraints | Recommended age (Ma) | Recommended reference          | Pre-recalcul. age (Ma) |
|------|----------------------------------------|-----------------|----------|-----------|---------------|---------------------|-------------------|-----------------------------|--------------------------|-------------------------|---------------------|--------------------------------|----------------------|
| 100  | Tavan Khor Ovoo (Tabun-Khan-Obo)       | Mongolia        | 44°06'N  | 109°36'E | 1.3           | Crystalline        | Late Triassic to Late Cretaceous | Maximum age based on morphologic expression, likely a few Myr old | 150±20                  | Masaitis (1999)         |                    |                                |                      |
| 101  | Vepriai                                | Lithuania       | 55°06'N  | 24°36'E  | 8             | Sedimentary        | Middle Devonian to Late Jurassic, likely Middle Jurassic | ~250 (Masaitis 1999) | 160±5                   | Masaitis et al. (1980); Masaitis (1999) |                       |
| 102  | Decaturville                           | United States   | 39°54'N  | 92°43'W  | 6             | Mixed             | Younger than Pennsylvanian | ~350 (Masaitis 1980); Masaitis (1999); Gurov et al. (2002) | 165±6                   | Masaitis (1999); Gurov et al. (2002) |                       |
| 103  | Zapadnyaya (Bablyiska)                 | Ukraine         | 49°44'N  | 29°00'E  | 3.2           | Crystalline        | K-Ar (impact melt rock) | ~100 (Masaitis 1999) | 169±7                   | Gurov et al. (2009)  |                       |
| 104  | Obolon'                                | Ukraine         | 49°30'N  | 32°35'E  | 20            | Sedimentary        | Iron?  | Early Triassic to Middle Jurassic (Bathonian) | K-Ar (impact melt rock) | ~360 | Masaitis (1999) |                      |                                |                      |
| 105  | Mishina Gora                           | Russia          | 58°40'N  | 28°00'E  | 2.5           | Mixed             | Latest Devonian or younger | ~360 (Masaitis 1999) | 150±10                  | Masaitis (1999); Gurov et al. (2002) |                       |
| 106  | Serpent Mount                          | United States   | 39°02'N  | 83°24'W  | 8             | Sedimentary        | Tourmaisian, Early Mississippian (Cuyahoga Fm.) or younger | ~360 (Masaitis 1999) | 150±10                  | Masaitis (1999); Gurov et al. (2002) |                       |
| 107  | Viewfield                              | Canada          | 49°35'N  | 103°04'W | 2.5           | Sedimentary        | Younger than Mississippian, likely older than Triassic-Jurassic | ~150 (Masaitis 1999) | 150±10                  | Masaitis (1999); Gurov et al. (2002) |                       |
| 108  | São Miguel do Tapuio                   | Brazil          | 5°38'S   | 41°23'E  | 20            | Sedimentary        | Late Devonian or younger (Cabezas Fm.) | ~360 (Masaitis 1999) | 150±10                  | Masaitis (1999); Gurov et al. (2002) |                       |
| 109  | Aorounga                               | Chad            | 19°06'N  | 19°15'E  | 16            | Sedimentary        | Late Devonian (?) or younger | ~360 (Masaitis 1999) | 150±10                  | Masaitis (1999); Gurov et al. (2002) |                       |
| 110  | Gwesi-Fada                            | Chad            | 17°25'N  | 21°45'E  | 22            | Sedimentary        | Late Devonian (?) or younger | ~360 (Masaitis 1999) | 150±10                  | Masaitis (1999); Gurov et al. (2002) |                       |
| 111  | Piccaninnny                            | Australia       | 17°32'S  | 128°25'E | 7             | Sedimentary        | Frasnian (Late Devonian) or younger | ~360 (Masaitis 1999) | 150±10                  | Masaitis (1999); Gurov et al. (2002) |                       |
| 112  | Puchezh-Katunki                        | Russia          | 57°00'N  | 43°35'E  | 80            | Mixed             | Early Triassic to Middle Jurassic | ~200 (Masaitis 1999) | 150±10                  | Masaitis (1999); Gurov et al. (2002) |                       |
| 113  | Gow Lake                               | Canada          | 56°27'N  | 104°29'W | 5             | Crystalline        | Iron?  | Ar-Ar (impact melt rock) | ~150 (Masaitis 1999) | 150±10                  | Masaitis (1999); Gurov et al. (2002) |                       |
| 114  | Cloud Creek                            | United States   | 43°07'N  | 106°45'W | 7             | Sedimentary        | Late Triassic (Norian?) to Middle Jurassic (Bathonian?) | ~200 (Masaitis 1999) | 150±10                  | Masaitis (1999); Gurov et al. (2002) |                       |
| 115  | Quarktiz                               | Algeria         | 29°00'N  | 7°33'W   | 3.5           | Sedimentary        | Visean, Carboniferous to Paleogene | ~200 (Masaitis 1999) | 150±10                  | Masaitis (1999); Gurov et al. (2002) |                       |
| 116  | Rochecourant                           | France          | 45°50'N  | 0°56'E   | 23-40         | Crystalline        | Chondrite? Iron? Stony-iron? | ~200 (Masaitis 1999) | 150±10                  | Masaitis (1999); Gurov et al. (2002) |                       |
| 117  | Red Wing Creek                         | United States   | 47°36'N  | 103°33'W | 9             | Sedimentary        | Perm-Triassic (Sparingly Fm.) to Bathonian, Middle Jurassic (Piper Fm.) | ~200 (Masaitis 1999) | 150±10                  | Masaitis (1999); Gurov et al. (2002) |                       |
| 118  | Wells Creek                            | United States   | 36°23'N  | 87°40'W  | 12            | Sedimentary        | ~200 (Masaitis 1999) | ~200 (Masaitis 1999) | 150±10                  | Masaitis (1999); Gurov et al. (2002) |                       |
| 119  | Manicouagan                            | Canada          | 51°23'N  | 68°42'W  | 100           | Mixed             | No contamination? | ~200 (Masaitis 1999) | ~200 (Masaitis 1999) | ~200 (Masaitis 1999) | Masaitis (1999); Gurov et al. (2002) |                       |
| 120  | Lake Saint Martin                      | Canada          | 51°47'N  | 98°32'W  | 40            | Mixed             | Devonian to Middle Jurassic | ~200 (Masaitis 1999) | ~200 (Masaitis 1999) | ~200 (Masaitis 1999) | Masaitis (1999); Gurov et al. (2002) |                       |
| 121  | Lappsum                                | Finland         | 60°08'20''N 20°07'30''E | 9             | Mixed             | Middle Ordovician (Caradocian) or younger | ~200 (Masaitis 1999) | ~200 (Masaitis 1999) | ~200 (Masaitis 1999) | Masaitis (1999); Gurov et al. (2002) |                       |
| No  | Impact structure          | Country         | Latitude | Longitude | Diameter (km) | Type of target rock | Type of impactor | Stratigraphic age constraints | Radiometric age constraints | Other age constraints | Recommended age reference | Recommended age (Ma) | Pre-recalculation age (Ma) |
|-----|--------------------------|-----------------|----------|-----------|---------------|---------------------|------------------|-----------------------------|--------------------------|------------------------|---------------------------|------------------------|--------------------------|
| 122 | Paukkala                  | Finland         | 62°12'N  | 29°23'E  | 10            | Mixed              | Younger than Mesoproterozoic | Ar-Ar (recrystallized feldspar glass and impact melt breccia) |                         | 23.1±0.22              | Schmieder et al. (2010a); Schwartz et al. (2015) | 23.1±0.22              |                         |
| 123 | Saqqr                    | Saudi Arabia    | 29°35'N  | 38°42'E  | 34            | Sedimentary        | Early Devonian (Jafu Fm.) to Late Cretaceous |                    |                         | 7.0–410                  | Neville et al. (2014); Kenkmann et al. (2015)  | 7.0–410                  |                         |
| 124 | Glover Bluff              | United States   | 43°58’N  | 89°32’W  | 8             | Sedimentary        | Early Ordovician or younger | ~9 Ma (U-Th)/He zircon age; Older paleomagnetic age | ~260 to 2,307; ~97; | 845                      | Road (1983);           |                         |                         |
| 125 | Karikkoselkä             | Finland         | 62°13’N  | 25°14’E  | 1.5           | Crystalline        | Younger than Late Devonian, older than Middle–Albian | Ar-Ar (SHRM, SIMS, monazite and zircon), Ar-Ar (var. lithologies) | 9–11 Ma (U-Th)/He zircon age; Older paleomagnetic age |                         |                         |                         |                         |
| 126 | Stem River                | Canada          | 59°31’N  | 117°37’W | 25            | Mixed              | Early Devonian to Late Triassic | U-Pb (SHRM, LA-ICP-MS, SIMS, monazite and zircon) | ~383 to 108; 132±1.37 | 254.7±2.57; 259±5.7; 251±5.2±9.9 | Tovber et al. (2012); Erickson et al. (2017); Hauser et al. (2019) | 254.7±2.57; 259±5.7; 251±5.2±9.9 |                         |
| 127 | Araguaninha              | Brazil          | 16°46’S  | 52°59’W  | 40            | Mixed              | Early Carboniferous to Middle Jurassic | Ar-Ar minimum age (impact melt rock) | ~383 to 165                | 359–163                  | Macdonald et al. (2005) | 359–163                  |                         |
| 128 | Glikson                  | Australia       | 23°59’S  | 121°34’E | 19            | Sedimentary        | Palaeozoic          |                             | <508±5                   |                         | Masaitis (1999)          |                         |                         |
| 129 | Kursk                    | Russia          | 51°40’N  | 36°00’E  | 6             | Sedimentary        | Early Carboniferous to Middle Jurassic | Ar-Ar minimum age (impact melt rock) | ~383 to 165                | 359–163                  | Macdonald et al. (2005) | 359–163                  |                         |
| 130 | Gosses Bluff (Tbarala)   | Australia       | 23°50’S  | 132°19’E | 22            | Sedimentary        | Early Carboniferous to Middle Jurassic | Ar-Ar minimum age (impact melt rock) | ~383 to 165                | 359–163                  | Macdonald et al. (2005) | 359–163                  |                         |
| 131 | Douglas (Sheep Mountain) (Field) | Wyoming, United States | 42°40’N  | 105°28’W | 0.15          | Sedimentary        | Early Permian (Uppermost Casper Fm.) | Early Permian (Uppermost Casper Fm.) | ~280                |                         | Kasting and Hannon (1996); Kenkmann et al. (2018) | 286±2.6±2.6             |                         |
| 132 | Ternovka (Terny)         | Ukraine         | 48°01’N  | E33°05’E | 16–19         | Mixed              | Chondrite?         | K-Ar (feldspar and mica) | 230±10                   |                         | Valet et al. (1981)       | 230±10                   |                         |
| 133 | West Clearwater Lake     | Canada          | 56°13’N  | 74°30’W  | 36            | Mixed              | No contamination   | Ar-Ar (impact melt rock) | 286±2.6±2.6             |                         | Bottomly et al. (1990); Schmieder et al. (2015a) | 286±2.6±2.6             |                         |
| 134 | Luara                    | Democratic      | 10°10’S  | 27°55’E  | 17            | Sedimentary        | Late Neoproterozoic or younger | Ar-Ar (impact melt rock) | 286±2.6±2.6             |                         | Master et al. (2001); Passy et al. (2011) | 286±2.6±2.6             |                         |
| 135 | Elbow                    | Canada          | 50°59’N  | 106°43’W | 8             | Sedimentary        | Middle Devonian to pre-Jurassic | Ar-Ar (impact melt rock) | 286±2.6±2.6             |                         | Master et al. (2001); Passy et al. (2011) | 286±2.6±2.6             |                         |
| 136 | Saarjärvi                 | Finland         | 65°17’N  | 28°25’E  | 1.5           | Crystalline        | Early Carboniferous to Late Permian | Fission track | 393–201                  |                         | Grieve (2006)            |                         |                         |
| 137 | Dobcle                   | Latvia          | 56°35’N  | 23°15’E  | 4.5           | Sedimentary        | Early Carboniferous to Late Permian | ~600–520                | 401–201                  |                         | Grieve (2006)            |                         |                         |
| 138 | West Hawk Lake           | Canada          | 49°46’N  | 95°11’W  | 2.44          | Crystalline        | Early Carboniferous to Late Permian | Ar-Ar (impact melt rock) | 351±207                  |                         | Masaitis (1999)          |                         |                         |
| 139 | Sjöjan                   | Sweden          | 61°02’N  | 14°52’E  | 52            | Mixed              | Younger than ~2.22 Ga | Ar-Ar (impact melt rock) | ~380±9.2±4.6            |                         | Jourdan and Retzlaff (2012) | 380±9.2±4.6             |                         |
| 140 | Flynn Creek              | United States   | 36°17’N  | 85°40’W  | 3.8           | Sedimentary        | Late Devonian (conodonts) | Ar-Ar (impact melt rock) | ~382±Ma                 |                         | Schieber and Over (2005) | 382±Ma                  |                         |
| 141 | Kaluga                   | Russia          | 54°30’N  | 36°15’W  | 15            | Mixed              | Middle Devonian | Ar-Ar (impact melt rock) | ~394 to 383            |                         | Masaitis (1999, 2002)   |                         |                         |
| 142 | Nicholson Lake           | Canada          | 62°40’N  | 102°41’W | 12.5          | Mixed              | Early Carboniferous to Late Permian | Ar-Ar (impact melt rock) | 357±5.5                  |                         | McGregor et al. (2018) |                         |                         |
| 143 | Crovod Creek             | United States   | 37°50’N  | 91°23’W  | 7             | Sedimentary        | Early Ordovician to pre-Pennsylvanian | Ar-Ar (impact melt rock) | 485–323                  |                         | Snyder and Gerdemann (1965) | 485–323                  |                         |
| 144 | Lac Couture              | Canada          | 60°08’N  | 75°20’W  | 8             | Crystalline        | Early Ordovician to pre-Pennsylvanian | Ar-Ar (impact melt rock) | 429±25                   |                         | Bottemy et al. (1990); recalculated Lepaulaud et al. (2019) | 429±25                  |                         |
| 145 | Tunnunik (Prince Albert) | Canada          | 72°27’N  | 113°54’W | 25            | Sedimentary        | Katian or younger (Neville Fm.) | Ar-Ar (impact melt rock) | 453±430                  |                         | Whitehead et al. (2003); Schmieder et al. (2019) | 453±430                  |                         |

(continued)
| No. | Impact structure | Country       | Latitude | Longitude | Diameter (km) | Type of target rock | Type of impacta | Stratigraphic age constraints | Radioisotopic age constraints | Other age constraints | Recommended age (Ma) | Recommended age referencea | Pre-reCalculation age (Ma) |
|-----|------------------|---------------|----------|-----------|---------------|---------------------|-----------------|-------------------------------|-------------------------------|--------------------------|----------------------|-----------------------------|-----------------------------|
| 147 | Ilynuts          | Ukraine       | 49°08'N  | 29°11'E  | 8.5          | Mixed             | Iron?           | Ar-Ar (impact melt breccia)  | ~445±20                      | Pesonen et al. (2004)   |                     |                             |                             |
| 148 | Glasford         | United States | 40°36'N  | 89°47'W  | 4            | Sedimentary       |                 | Ar-Ar (impact melt rock)    | 450±2                         | Bottomley et al. (1990), recalculated | 445 ± 2                          |                             |
| 149 | Pilot            | Canada        | 60°17'N  | 111°01'W | 6            | Crystalline       |                 | Ar-Ar (impact melt rock)    | ~450                         | Sharpton et al. (1997); Grieve (2006) |                             |                             |
| 150 | Slate Islands    | Canada        | 48°40'N  | 87°00'W  | 30           | Mixed             |                 | Ar-Ar (impact melt rock)    | ~450                         | Miheen (1994)            |                             |                             |
| 151 | Calvin           | United States | 41°50'N  | 85°57'W  | 8.5          | Sedimentary       | Crystalline      | 458–444                      | ~453–445                      | McGregor et al. (2019) |                             |                             |
| 152 | La Moineerie     | Canada        | 45°26'N  | 66°37'W  | 8            | Crystalline       |                 | U-Pb (LA-ICP-MS on apatite) | 543±3                        | Mckay et al. (1996)       |                             |                             |
| 153 | Brent            | Canada        | 46°05'N  | 78°29'W  | 3.8          | Crystalline       | Chondrite (L. or LL?) | 458–453                      | ~458                         | Milstein (1994)          |                             |                             |
| 154 | Kärdeja          | Estonia       | 58°59'N  | 22°40'E  | 4            | Mixed             | Transition A. curvata/| 455±1                         |                             | Grahm et al. (1996)       |                             |                             |
| 155 | Lockne           | Sweden        | 63°00'N  | 14°48'E  | 7.5–14       | Mixed             | Lower L. dalbyensis zone (= late Sandbian), likely slightly older than Lockne | 455±1                         |                             | Grahm et al. (1996); Grahm (1997); Ormo et al. (2014) |                             |                             |
| 156 | Mälängen         | Sweden        | 62°55'N  | 14°33.84'E | 0.7        | Mixed             | Lower L. dalbyensis zone (= late Sandbian), likely slightly younger than Kärdeja | 455±1                         |                             | Grahm et al. (1996)       |                             |                             |
| 157 | Tvären           | Sweden        | 58°46'N  | 17°25'E  | 2            | Mixed             | Contemporaneous with Lockne | 458                          |                             | Ormo et al. (2014); Ormo et al. (2014) |                             |                             |
| 158 | East Clearwater Lake | Canada      | 56°05'N  | 74°07'W  | 26           | Crystalline       | Chondrite (L. or LL?) | 458                          |                             | Ormo et al. (1994); Grahm et al. (1996) |                             |                             |
| 159 | Hummeld          | Sweden        | 57°22'04"N | 16°14.56'E | 1.2       | Mixed             | Chondrite        | 465±1                         |                             | Bottomley et al. (1990); Schneider et al. (2015a) |                             |                             |
| 160 | Granby           | Sweden        | 58°25'N  | 14°56'E  | 3            | Sedimentary       | Upper C. regnelli zone (= early Darriwilian) | 466±1                        |                             | Awramark et al. (2015), after Grahm et al. (1996) |                             |                             |
| 161 | Decovna          | United States | 43°19'N  | 91°46'WW | 5.5          | Sedimentary       | Early–Middle Darriwilian (Middle Ordovician) | 467±2                        |                             | Bergstrom et al. (2018); French et al. (2018) |                             |                             |
| 162 | Ames              | United States | 36°15'N  | 98°10'W  | 16           | Mixed             | Early–Middle Darriwilian (Middle Ordovician) | 468±1                        |                             | Koebel et al. (2001) |                             |                             |
| 163 | Rock Elm         | United States | 44°43'N  | 92°14'W  | 6            | Sedimentary       | Early to Middle Ordovician (Fossil to Darriwilian) | 472±2                        |                             | Conda (1985); French et al. (2004) |                             |                             |
| 164 | Lawn Hill         | Australia     | 18°40'S  | 138°39'E | 18           | Mixed             | Early to Middle Ordovician | 476±2                        |                             | Darlington et al. (2016), recalculated |                             |                             |
| 165 | Ramgath          | India         | 25°20'N  | 76°37'E  | 10           | Sedimentary       | Neoproterozoic to Middle Jurassic (Callovian) | ~750 to 1655                  |                             | Ray et al. (2003); Kenkmann et al. (2019) |                             |                             |

(continued)
| No | Carwell | Location | Other age constraints |
|----|---------|----------|-----------------------|
| 166 | Carswell | Canada 58°27'N 109°30'W 39 Mixed | Ar-Ar (adularia in impact melt rock) |
| 167 | Newport | United States 48°58'N 101°58'W 3 Sedimentary | Late Cambrian to Early Ordovician (Deadwood, Fm.) |
| 168 | Mizarai | Lithuania 54°00'N 23°54'E 5 Mixed | Early Ordovician to Early to Middle Cambrian |
| 169 | Ritland | Norway 59°14'N 6°26'E 2.7 Mixed | Early Cambrian |
| 170 | Neugrand | Estonia 59°20'N 23°33'E 20 Crystalline | Neoprotorezoic to Cambrian; Nonmagmatic iron? |
| 171 | Gardnos | Norway 60°39'N 9°00'E 5 Crystalline | Neoprotorezoic to Cambrian; Chondrite? |
| 172 | Holford | Canada 44°28'N 76°38'W 2.35 Crystalline | Latest Protorezoic to Early Paleozoic; Distal ejecta in Ediacaran Bushveld. |
| 173 | Acraman | Australia 32°01'S 155°27'E 40-90 Crystalline (dacite) | U-Pb (zircon in melt breccia) |
| 174 | Saiikjarvi | Finland 61°24'N 22°24'E 6 Crystalline | Same iron? Iron? Chondrite? Ashochondrite |
| 175 | Strangways | Australia 15°12'S 133°35'E 25 Mixed | U-Pb (zircon from impact melt rock) |
| 176 | Beaverhead | United States 44°36'N 113°00'W 60 Mixed | Ar-Ar (impact melt rock) |
| 177 | Janisjarvi | Russia 61°58'N 30°55'E 14 Crystalline | Ar-Ar (impact melt rock) |
| 178 | Goyder | Australia 13°29'S 135°02'E 3 Sedimentary | Mesoproterozoic or younger; Paleoproterozoic (Penicosti Sandstone) or younger; younger than Yampi Orogeny; older than Ediacaran (Marinoan glaciation) |
| 179 | Spider | Australia 16°44'S 126°05'E 13 Sedimentary | Paleoproterozoic or younger; Mesoproterozoic or younger |
| 180 | Île Rouleau | Canada 50°41'N 73°53'W 4 Sedimentary | Paleoproterozoic or younger; Mesoproterozoic or younger |
| 181 | Santa Fe | United States 35°45'N 105°56'W 6-13 Crystalline | U-Pb (zircon) |
| 182 | Matt Wilson | Australia 15°30'S 131°11'E 7.5 Sedimentary | Mesoproterozoic (Jasper Gorge Sandstone) or younger |
| 183 | Shoemaker (Lake Teague) | Australia 25°52'S 120°53'E 30 Mixed | Mesoproterozoic (Teague Granite) or younger; Paleoproterozoic or younger |
| 184 | Sumunnen | Finland 62°39'N 25°22'5'CE 2.6 Crystalline | Mesoproterozoic to Early Cambrian; Paleoproterozoic to Early Cambrian; Neoprotorezoic to Neoprotorezoic |
| 185 | Clewiston | Australia 18°10'S 137°56'E 15 Sedimentary | Minimum K-Ar alteration age (illite) |
| 186 | Foehn | Australia 16°40'S 136°47'E 6 Sedimentary | K-Ar alteration age (illite) |
| 187 | Iso-Naakkima | Finland 62°11'57"N 27°07'59"E 3 Sedimentary | K-Ar alteration age (illite) |
| 188 | Kametuk | Ukraine 47°46'N 32°21'E 1.2 Crystalline | Paleoproterozoic to Lake Miozero Protorezoic (Dalgalantia Superserie) -- Bjögian, Middle Janiasic |
| 189 | Woodleigh | Australia 26°05'S 114°43'E 60 Mixed | Paleoproterozoic to Lake Miozero Protorezoic (Dalgalantia Superserie) -- Bjögian, Middle Janiasic |

**Table 1. (Continued)**
| No  | Impact structure | Country   | Latitude  | Longitude | Diameter (km) | Type of target rock | Type of impactor | Stratigraphic age constraints | Radiometric age constraints | Other age constraints | Recommended age (Ma) | Recommended age reference  | Pre-reconstruction age (Ma) |
|-----|------------------|-----------|-----------|-----------|---------------|--------------------|------------------|-----------------------------|-----------------------------|------------------------|------------------------|-----------------------------|-----------------------------|
| 190 | Kelly West       | Australia | 19°56'S   | 133°57'E  | 10            | Crystalline       | Proterozoic, likely Neoproterozoic | Paleozoic to later Neoproterozoic | Ar-Ar (impact melt breccia) | ~1640 to 550          | ~1700 to 541           | Haines (2005)                |                             |
| 191 | Amelia Creek     | Australia | 20°51'S   | 134°53'E  | 20            | Mixed             |                  | Paleozoic to later Neoproterozoic | Ar-Ar (impact melt breccia) | 1151±10                | Haines (2005)             |                             |
| 192 | Keurusselkä     | Finland   | 62°08'N   | 24°36'E   | 30            | Crystalline       |                  | Paleozoic to later Neoproterozoic ? | ~1870 to 541           | 1849.53±0.21         | Krogh et al. (1984); Davis (2008) |                             |
| 193 | Liverpool        | Australia | 12°24'S   | 134°03'E  | 1.6           | Sedimentary       |                  | Paleozoic to later Neoproterozoic ? | ~1870 to 541           | 2023±4                 | Kamo et al. (1996)       |                             |
| 194 | Söderfjärden     | Finland   | 63°00'N   | 21°35'E   | 6.6           | Crystalline       |                  | Ar-Ar (melt breccia) | ~1880 to 640            | Schmieder et al. (2014b) | Schmieder et al. (2016b); Schwarz et al. (2016a) |                             |
| 195 | Suvasvesi South  | Finland   | 62°24'N   | 28°12'E   | 3.8           | Crystalline       |                  | Ar-Ar (impact melt breccia) | ~710 to 1880            | 1849.53±0.21         | Krogh et al. (1984); Davis (2008) |                             |
| 196 | Presqu‘ile       | Canada    | 49°43'N   | 78°48'W   | 24            | Crystalline       |            | Neoarchean or younger | <27.29                  | Higgins and Tait (1990)  |                             |                             |
| 197 | Sudbury          | Canada    | 46°36'N   | 81°11'W   | 200           | Crystalline       |                  | U-Pb (CA-TIMS, melt-grown zircon in felsic norite) | 1849.53±0.21         | 2023±4                 | Kamo et al. (1996)       |                             |
| 198 | Vredefort        | South Africa | 27°07'S  | 27°30'E   | 250           | Crystalline       |                  | U-Pb (CA-TIMS, melt-crystallized zircon) | ~2500 to 1700          | 2229±5               | Fletcher and McNaughton (2002); Erickson et al. (2019a, 2019b) |                             |
| 199 | Dhala            | India     | 25°18'N   | 78°08' E  | 11            | Mixed             |                  | Younger than Bundelhund Craton, older than Vindhyan Supergroup U-Pb (monazite and zircon in impact melt rock) | ~2500 to 1700          | 2229±5               | Fletcher and McNaughton (2002); Erickson et al. (2019a, 2019b) |                             |
| 200 | Yarrabubba       | Australia | 27°10'S   | 119°50' E | 30–70         | Crystalline       |                  |                  |                            |                            |                        |                             |                             |

Sorting by “numerical” age (not listed for stratigraphic maximum ages). A stratigraphic age of ≤573 Ma (Luizi) can alternatively be written as a numerical value of 287±287 Ma and is then listed before a seemingly younger age, such as 455±1 Ma (Lockne). In such cases, the more conservative stratigraphic maximum/minimum age notation is preferred over the numerical value.

1Type of target rock largely taken from the Earth Impact Database (as of 2018; now offline) and Osinski and Grieve (2019).
2Type of impactor taken from the Earth Impact Database (2018) and the literature, including Palme et al. (1978, 1979, 1981), Morgan et al. (1993), Evans et al. (1993), Schmidt and Pernicka (1994), Schmidt et al. (1997), Koeberl (1998), Maier et al. (2006), Tagle and Hecit (2006), Koeberl et al. (2007a), Tagle et al. (2009), Goderis et al. (2009, 2013), Koeberl (2014), Magna et al. (2017), Pati et al. (2017), Buchner et al. (2018), and Moust et al. (2019), and references in those articles.
3Recalculated ages calculated using the ASTAR tool of Mercer and Hodges (2016).
4Temporary impact penetration hole.
5Impact pit(s).
6Field of impact craters (higher energy) together with impact pits and/or funnels (lower energy). CA-TIMS = Chemical abrasion thermal ionization mass spectrometry; ID-TIMS = Isotope dilution thermal ionization mass spectrometry; LA-ICP-MS = Laser ablation inductively coupled plasma mass spectrometry; SHRIMP = Sensitive high-resolution ion microprobe; SIMS = Secondary ion mass spectrometry.
| Impact ejecta and deposits | Country | Latitude | Longitude | Diameter (km) | Type of impactor | Stratigraphic age constraints | Radioisotopic age constraints | Other age constraints | Recommended age reference | Recommended age (Ma) | Pre-recalculation age (Ma) |
|---------------------------|---------|----------|-----------|---------------|-----------------|---------------------------|-------------------------------|-----------------------|------------------------|------------------------|--------------------------|
| 1 Rio Cuarto (fresh)      | Argentina | Chondrite (H?) | Holocene | Ar-Ar (glass) | Source crater uncertain | ~0.004 to 0.010, 0.006 to 0.002 | Schulte et al. (2004, 2006) | 0.114 ± 0.026 | 0.07 ± 0.2 | 0.114 ± 0.026 | 0.114 ± 0.026 |
| 2 Rio Cuarto (old)        | Argentina | Chondrite (H?) | Pleistocene | Ar-Ar (glass) | Source crater uncertain | 0.115 ± 0.026, recalculated | Schulte et al. (2004, 2006), Bland et al. (2002) | 0.230 ± 0.030, recalculated | 0.445 ± 0.021 | 0.45 ± 0.021 |
| 3 Centinela del Mar       | Argentina | Chondrite | Pleistocene | Ar-Ar (glass) | Source crater uncertain | 0.232 ± 0.030, 0.449 ± 0.021 | Schulte et al. (2004, 2006), recalculated | 0.445 ± 0.021 | 0.45 ± 0.021 |
| 4 Belize impact glass     | Belize | Chondrite | Pleistocene | Ar-Ar (glass) | Source crater uncertain | 0.769 ± 0.016 | 0.445 ± 0.021 | 0.45 ± 0.021 |
| 5 Australasian Tektites  | Semiglobal | Chondrite? | Pleistocene | Ar-Ar (glass) | Source crater uncertain | 0.788 ± 0.028 | Schultz et al. (2004, 2006), recalculated | 0.816 ± 0.007 | - | - |
| 6 Darwin Glass | Australia | Pleistocene | Ar-Ar (glass) | Source crater uncertain | 0.828 ± 0.007 | Lo et al. (2002), recalculated | Jourdan (2012), after Koehler et al. (1997b) | 3.33 ± 0.10 | 5.33 ± 0.05 | 5.33 ± 0.05 |
| 7 Ivory Coast tektites    | Africa | Chondrite | Pleistocene | Ar-Ar (glass) | Source crater uncertain | 3.64 ± 0.007 | Jourdan et al. (2010), recalculated | 3.33 ± 0.10 | 5.33 ± 0.05 | 5.33 ± 0.05 |
| 8 Eocene or younger?      | | | | | | | | | | |
| 9 Bolivian Blanca         | Argentina | Pleistocene | Ar-Ar (glass) | Source crater uncertain | 3.64 ± 0.007 | Jourdan et al. (2010), recalculated | 3.33 ± 0.10 | 5.33 ± 0.05 | 5.33 ± 0.05 |
| 10 Chassigno              | Argentina | Pleistocene | Ar-Ar (glass) | Source crater uncertain | 3.64 ± 0.007 | Jourdan et al. (2010), recalculated | 3.33 ± 0.10 | 5.33 ± 0.05 | 5.33 ± 0.05 |
| 11 Atacamaite             | Chile | Pleistocene | Ar-Ar (glass) | Source crater uncertain | 3.64 ± 0.007 | Jourdan et al. (2010), recalculated | 3.33 ± 0.10 | 5.33 ± 0.05 | 5.33 ± 0.05 |
| 12 Torkelena                | Denmark | Pleistocene | Ar-Ar (glass) | Source crater uncertain | 3.64 ± 0.007 | Jourdan et al. (2010), recalculated | 3.33 ± 0.10 | 5.33 ± 0.05 | 5.33 ± 0.05 |
| 13 Central European Tektites | Czech Republic, Austria, Germany, Poland | Middle Miocene | Ar-Ar (glass) | Source crater uncertain | 3.64 ± 0.007 | Jourdan et al. (2010), recalculated | 3.33 ± 0.10 | 5.33 ± 0.05 | 5.33 ± 0.05 |
| 14 Uraguas                | Uruguay | Middle Miocene | Ar-Ar (glass) | Source crater uncertain | 3.64 ± 0.007 | Jourdan et al. (2010), recalculated | 3.33 ± 0.10 | 5.33 ± 0.05 | 5.33 ± 0.05 |
| 15 Libyan Desert Glass    | Egypt | Eocene | Ar-Ar (glass) | Source crater uncertain | 3.64 ± 0.007 | Jourdan et al. (2010), recalculated | 3.33 ± 0.10 | 5.33 ± 0.05 | 5.33 ± 0.05 |
| 16 North American Tektites | United States | Late Eocene | Ar-Ar (glass) | Source crater uncertain | 3.64 ± 0.007 | Jourdan et al. (2010), recalculated | 3.33 ± 0.10 | 5.33 ± 0.05 | 5.33 ± 0.05 |
| 17 Chondrites              | | | | | | | | | | |
| 18 K/T (K/Pg)              | Worldwide | Paleocene | Eocene boundary | Ar-Ar (glass) | Source crater uncertain | 3.64 ± 0.007 | Jourdan et al. (2010), recalculated | 3.33 ± 0.10 | 5.33 ± 0.05 | 5.33 ± 0.05 |
| 19 Paleogene boundary ejecta | Atlantic | Paleocene | Eocene boundary | Ar-Ar (glass) | Source crater uncertain | 3.64 ± 0.007 | Jourdan et al. (2010), recalculated | 3.33 ± 0.10 | 5.33 ± 0.05 | 5.33 ± 0.05 |
| 20 Nunavut (Disko)        | Greenland | Paleocene | Eocene boundary | Ar-Ar (glass) | Source crater uncertain | 3.64 ± 0.007 | Jourdan et al. (2010), recalculated | 3.33 ± 0.10 | 5.33 ± 0.05 | 5.33 ± 0.05 |
| 21 K/T (K/Pg) boundary ejecta Worldwide | Carbonaceous chondrite | Paleocene | Ar-Ar (glass) | Source crater uncertain | 3.64 ± 0.007 | Jourdan et al. (2010), recalculated | 3.33 ± 0.10 | 5.33 ± 0.05 | 5.33 ± 0.05 |
| 22 Tookooomoka ejecta horizon | Australia | Paleocene | Ar-Ar (glass) | Source crater uncertain | 3.64 ± 0.007 | Jourdan et al. (2010), recalculated | 3.33 ± 0.10 | 5.33 ± 0.05 | 5.33 ± 0.05 |
| 23 Eocene boundary ejecta | Australia | Paleocene | Ar-Ar (glass) | Source crater uncertain | 3.64 ± 0.007 | Jourdan et al. (2010), recalculated | 3.33 ± 0.10 | 5.33 ± 0.05 | 5.33 ± 0.05 |
| 24 Late Triassic boundary ejecta | United Kingdom | Paleocene | Ar-Ar (glass) | Source crater uncertain | 3.64 ± 0.007 | Jourdan et al. (2010), recalculated | 3.33 ± 0.10 | 5.33 ± 0.05 | 5.33 ± 0.05 |
| 25 Late Devonian boundary ejecta | China | Paleocene | Ar-Ar (glass) | Source crater uncertain | 3.64 ± 0.007 | Jourdan et al. (2010), recalculated | 3.33 ± 0.10 | 5.33 ± 0.05 | 5.33 ± 0.05 |
| 26 Senessee/Hony ejecta | Belgium | Paleocene | Ar-Ar (glass) | Source crater uncertain | 3.64 ± 0.007 | Jourdan et al. (2010), recalculated | 3.33 ± 0.10 | 5.33 ± 0.05 | 5.33 ± 0.05 |
| 27 Late Triassic boundary ejecta | United States | Paleocene | Ar-Ar (glass) | Source crater uncertain | 3.64 ± 0.007 | Jourdan et al. (2010), recalculated | 3.33 ± 0.10 | 5.33 ± 0.05 | 5.33 ± 0.05 |

(continued)
| Impact ejecta and deposits | Country | Latitude | Longitude | Diameter (km) | Type of impactor | Stratigraphic age constraints | Radioisotopic age constraints | Other age constraints | Recommended age (Ma) | Recommended age reference | Pre-recalculation age (Ma) |
|---------------------------|---------|----------|-----------|--------------|-----------------|----------------------------|----------------------------|------------------------|---------------------|-------------------------|---------------------------|
| 28 Hallen ejecta layer    | Sweden  |          |           |              |                 | Late Sandbian (Late Ordovician) | From Lockne–Målingen impact | Source crater unknown | ~ 455               | Starkell et al. (2000) |                          |
| 29 Osmussaar Breccia     | Estonia | 59°18'N  | 23°21'E   |              |                 | Middle Ordovician (Early Darriwilian) |                        | Source crater unknown | ~ 466               | Ahmavark et al. (2010) |                          |
| 30 Valkejokiik Breccia   | Sweden  | 68°22'N  | 19°14'E   |              |                 | Middle Cambrian | Source crater hidden underneath mountain |                        | ~ 521 to 514        | Örmo et al. (2017)    |                          |
| 31 Acreman-Bunyeroo horizon | Australia |          |           |              |                 | Chondrite | From Acreman impact |                        | ~ 655               | Schmidt et al. (2015b) |                          |
| 32 Boa Pada Member       | Scotland; United Kingdom |          |           |              |                 | Chondrite | Mesoproterozoic | Ar-Ar (authigenic K-feldspar) | Source crater hidden | 1177 ± 5            | Parnell et al. (2011)  |                          |
| 33 Lake Superior/ Michigan ejecta | United States |          |           |              |                 | Paleoproterozoic | From Sudbury impact |                        | 1849.53 ± 0.21 | Addison et al. (2005); Cannon et al. (2010) |                      |
| 34 Grønnesø | Greenland |          |           |              |                 | Carbonaceous chondrite | Paleoproterozoic | Source crater unknown | ~ 1990              | Glass and Simonson (2012, 2013); Huber et al. (2019) |                          |
| 35 Zaonega spherules     | Russia  |          |           |              |                 | Carbonaceous chondrite | Paleoproterozoic | Source crater unknown | ~ 2050 to 1975 | Glass and Simonson (2012, 2013); Huber et al. (2014) |                          |
| 36 Dales Gorge; Kuruman | Western Australia; South Africa |          |           |              |                 | Ordinary chondrite? Enstatite chondrite? Chondrite? | Paleoproterozoic | Source crater unknown | 2495 ± 16           | Simonson et al. (2009); Glass and Simonson (2012, 2013); Simonson et al. (2009); Hassler et al. (2011); Glass and Simonson (2012, 2013) |                          |
| 37 Bee Gorge; Parahurudoo; Rev 80; Wittenoom Jeeramale | Western Australia; South Africa |          |           |              |                 | Ordinary chondrite? Enstatite chondrite? | Novarocran | Source crater unknown | 2541 ± 18           | Glass and Simonson (2012, 2013); Simonson et al. (2009); Hassler et al. (2011); Glass and Simonson (2012, 2013) |                          |
| 38 Carawine; Monteville  | Western Australia; South Africa |          |           |              |                 | Ordinary chondrite? Enstatite chondrite? | Novarocran | Source crater unknown | 2629 ± 5            | Rasmussen et al. (2005); Simonson et al. (2009); Glass and Simonson (2012, 2013) |                          |
| 39 S5 (Barberton)        | South Africa |          |           |              |                 | Paleorachn | Source crater unknown | ~ 3234              | Lowe and Byeby (2010); Glass and Simonson (2012, 2013); Lowe et al. (2014); Lowe et al. (2003, 2014); Lowe et al. (2012, 2013); Lowe et al. (2012, 2013) |                          |
| 40 S4 (Barberton)        | South Africa |          |           |              |                 | Carbonaceous chondrite | Paleorachn | Source crater unknown | ~ 3234              | Lowe et al. (2003, 2014); Lowe et al. (2012, 2013); Lowe et al. (2012, 2013) |                          |
| 41 S3 (Barberton)        | South Africa |          |           |              |                 | Carbonaceous chondrite | Paleorachn | Source crater unknown | ~ 3243              | Lowe et al. (2003, 2014); Lowe et al. (2012, 2013); Lowe et al. (2012, 2013) |                          |
| 42 S2 (Barberton)        | South Africa |          |           |              |                 | Carbonaceous chondrite | Paleorachn | Source crater unknown | ~ 3260              | Lowe et al. (2003, 2014); Lowe et al. (2012, 2013); Lowe et al. (2012, 2013) |                          |
| 43 S6 (Barberton)        | South Africa |          |           |              |                 | Carbonaceous chondrite | Paleorachn | Source crater unknown | ~ 3330              | Lowe and Byeby (2010); Glass and Simonson (2012, 2013); Lowe et al. (2014) |                          |
| 44 S7 (Barberton)        | South Africa |          |           |              |                 | Carbonaceous chondrite | Paleorachn | Source crater unknown | 3416 ± 5           | Lowe et al. (1991); Lowe and Byeby (2010); Glass and Simonson (2012, 2013); Lowe et al. (2014) |                          |
| 45 Marble Bar            | Western Australia |          |           |              |                 | Paleorachn | Source crater unknown | ~ 3460              | Glass and Simonson (2012, 2013); Lowe et al. (2014); Glass and Simonson (2012, 2013); Lowe et al. (2014) |                          |
| 46 S1 (Barberton); Warrawoona | South Africa; Western Australia |          |           |              |                 | Paleorachn | Source crater unknown | 3470 ± 2           | Byefy et al. (2002); Lowe et al. (2003, 2014); Lowe et al. (2012, 2013) |                          |

*Type of impactor taken from Menec et al. (1990), Koeberl (1997), McDonald (2002), Kyte et al. (2003, 2011), Tagle and Hect (2006), Simonson et al. (2009), Godier et al. (2012, 2013, 2017), Glass and Simonson (2013), Koeberl (2014), Mougel et al. (2017), Folco et al. (2018), and references in those articles.

*Recalculated age calculated using the ArAr tool of Mercier and Hodges (2016).
muscovite and is, therefore, not recommended as a standard in modern Ar–Ar geochronology (Heri et al., 2014). Finally, some impact structures, predominantly those in Russia and Ukraine, have only K–Ar ages (e.g., Val’ter et al., 1981; Gurov et al., 2009). Because any possible disturbance of the isotopic system (e.g., alteration or contamination with older material as outlined above) cannot be identified and quantified, K–Ar age values should be treated as “ballpark” numbers until more robust Ar–Ar results are available.

2.3. Rb–Sr, (U–Th)/He, and 14C ages

The Rb–Sr method has been applied to impact melt lithologies and mineral separates from a number of terrestrial impact structures (e.g., Reimold et al., 1981; Deutsch et al., 1992). However, Rb–Sr ages are notoriously unreliable due to the high mobility of Rb and Sr and, consequently, the susceptibility of the Rb–Sr isotopic system to alteration (e.g., Jourdan et al., 2009; Nebel et al., 2011; Schmieder et al., 2015a). Today, all of the older Rb–Sr ages for terrestrial impact structures (e.g., Reimold et al., 1981) have been superseded by more robust U–Pb and/or Ar–Ar ages and, therefore, none of the original Rb–Sr results is recommended as best-estimate ages in this summary (Table 1).

The low-temperature (U–Th)/He geothermochronometer can monitor the cooling of impact lithologies to temperatures below approximately 200–180°C using zircon and ~110–40°C using the less He-retentive mineral apatite (e.g., Stockli et al., 2000; Farley and Stockli, 2002; Farley, 2002; Reiners et al., 2004; Reiners, 2005). While (U–Th)/He analyses of uplifted basement rocks at the large Manicouagan impact structure resulted in ages younger than the impact age due to slow cooling and postimpact He loss (van Soest et al., 2011; Biren et al., 2014), (U–Th)/He age determinations for other terrestrial impact structures and distal ejecta deposits yielded ages that are, within error, consistent with U–Pb and Ar–Ar ages (Young et al., 2013; Biren et al., 2019) and precise stratigraphic ages (Wartho et al., 2012). In the absence of more robust stratigraphic and isotopic age constraints, a (U–Th)/He age of 663 ± 90 ka currently represents the most reasonable estimate for the age of the ~350-m-diameter Monturaqui impact crater in the Chilenan Andes (Ukstins Peate et al., 2010).

Finally, the 14C (radiocarbon) method has occasionally been applied to charcoal and other types of organic material found at geologically young impact craters, such as the Xiuyan crater in China (>50 ka) (Liu et al., 2013) and the Kaali and Ilumetsa impact crater fields in Estonia (Losiak et al., 2016, 2017, 2019). Because of the short half-life of 14C of ~5730 years, the method fails to determine ages older than roughly 50,000 years (Hughen et al., 2004; Muscheler et al., 2014).

2.4. Other ages

Impact ages obtained via different methods, such as fission track analysis (on zircon, apatite, or glass) (e.g., Bigazzi and De Michele, 1996), cosmogenic nuclides and exposure ages (e.g., Marrero et al., 2010; Barrows et al., 2019), luminescence (e.g., Prescott et al., 2004), or paleomagnetic methods (e.g., Pesonen et al., 1999; Lepaulard et al., 2019), were selected as best-estimate ages, provided they agree with the local geologic constraints. Recent re-

views of fission track analysis and its application in the Earth sciences are provided by Malusà and Fitzgerald (2019) and articles therein. This technique, based on the identification of damage trails in crystals and glasses induced by the spontaneous fission of 238U in the sample and their density (e.g., Kohn et al., 2019), has been applied to impact lithologies ever since their discovery (e.g., Genty et al., 1967, 1969; Koebel et al., 1993; McHone and Sorkhabi, 1994; Weber et al., 2005). In the case of the 1.13 km-diameter Tswaing impact crater in South Africa, a fission track age of 220±104 ka for impact glass (Storzer et al., 1999) is preferred over a very poorly constrained stratigraphic age (<2.05 Ga) and Ar–Ar results that are disturbed toward more ancient apparent ages due to the presence of inherited 40Ar* sourced from the Paleoproterozoic granitic target rock (Jourdan et al., 2007). Sometimes, these geochronologic techniques provide the only age constraints for an impact structure other than the (maximum) stratigraphic age.

3. Result: A List of Recommended Ages for Terrestrial Impact Structures and Deposits

Significant work on the terrestrial impact structures has produced a large number of ages of different type and quality (e.g., for the Nördlinger Ries in Germany) (Buchner et al., 2010a, 2010b, 2013 and references therein; Schmieder et al., 2018a, 2018b). In such cases, the most precise and accurate ages obtained by using modern isotopic techniques, in line with geologic and stratigraphic constraints, were carefully chosen as the recommended best-estimate impact age. Stratigraphic constraints were calibrated using the latest International Chronostratigraphic Chart (ICS; updated, v2018/08) (Cohen et al., 2013). It is important to keep in mind that stratigraphic ages in the ICS may (slightly) change in the future as those ages are refined.

The recommended terrestrial impact ages (n=200) are listed in Table 1, and ages for impact deposits (distal and proximal ejecta; n=46) are listed in Table 2. Both tables are sorted by age, with the youngest impact structures and deposits on top and the oldest ones at the bottom. Twenty impact structures have either stratigraphic or isotopic ages with relative errors ±1% (e.g., Chixulub and the Ries); 36 have errors ±2%. All terrestrial impact ages are, in addition, plotted in histograms in Fig. 4. They can be used to:

1. reconstruct and quantify the impact (mass) flux in the inner Solar System and, in particular, the Earth–Moon system through geologic time, thereby assessing Earth’s impact rate (e.g., Grieve and Dence, 1979; Montanari et al., 1998; Grieve, 2001a, 2001b; Bland, 2005; Meier and Holm-Alwmark, 2017; Mazrouei et al., 2019);
2. utilize impact ejecta as event markers in the (bio-)stratigraphic record and to refine magnetostratigraphy, for example, around the K/T boundary (e.g., Sprain et al., 2015, 2018) and in the Neogene stratigraphic record (e.g., Schmieder et al., 2018a, 2018b);
3. test models of synchronous double or multiple impacts in the terrestrial record, such as that proposed for the apparent East and West Clearwater Lake impact
crater doublet in Québec, Canada (e.g., Dence et al., 1965; cf. Schmieder et al., 2015a), and the postulated Late Triassic terrestrial impact crater chain (e.g., Spray et al., 1998; cf. Schmieder et al., 2010b, 2014a);

(4) assess the potential link between large impacts and mass extinction and diversification events in the biosphere, exemplified most dramatically by the Chicxulub impact at the K/T boundary (e.g., Alvarez et al., 1980; Rampino, 1999; Grey et al., 2003; Schmitz et al., 2008; Schulte et al., 2010; Racki, 2012; DePalma et al., 2019);

and

(5) constrain the duration of melt sheet crystallization in large impact craters (e.g., Davis, 2008; Kenny et al., 2019a) and the lifetime of hydrothermal systems in cooling impact craters (e.g., Ames et al., 1998; Abramov and Kring, 2004, 2007; Schmieder and Jourdan, 2013a, 2013b; Pickersgill et al., 2019a; Kenny et al., 2019b), which may have served as potential habitats for microbial life on the early Earth and possibly also Mars (e.g., Kring, 2000; Rathbun and Squyres, 2002; Cockell et al., 2003; Osinski et al., 2013; Rummel et al., 2014).

4. Discussion

4.1. Considerations on the terrestrial impact flux from the age distribution

With a representative set of precise and accurate isotopic ages for terrestrial impacts, as well as stratigraphic ages within their generally larger envelope of uncertainty (Tables 1 and 2), one can examine and re-evaluate the potential temporal connection between impact events on Earth themselves and the overall terrestrial impact cratering record (e.g., Grieve and Dence, 1979; Grieve and Robertson, 1979; Grieve, 1987, 1991, 2001a, 2001b; Grieve and Pesonen, 1996).

As more impact structures are discovered and their ages determined and refined, a population of the Phanerzoic impact structures and deposits stands out: those with Ordovician ages. The Ordovician period spans the time between ~485 and ~443 Ma (Cohen et al., 2013). At present, 22 of the currently known 200 impact structures on Earth, that is, more than 10%, have proven or very likely Ordovician ages, creating a distinct age spike in the terrestrial impact cratering record. A representative histogram is shown in Fig. 4. Recent additions to the list of (very likely) Ordovician impacts, based on new U–Pb and Ar–Ar geochronologic results, include, for example, the 54 km-diameter Charlevoix impact structure (453–430 Ma via LA–ICP–MS U–Pb on zircon in impact melt rock) (Schmieder et al., 2019), the 50 km-diameter Carswell impact structure (Alwmark et al., 2017), and the 8 km-diameter Osmussaar Breccia in Estonia (Alwmark et al., 2010), all three located in Canada; as well as the 18 km-diameter Lawn Hill impact structure in Australia (Darlington et al., 2016). Those impact structures, six in the United States, nine in Canada, five in Sweden, and one in Estonia, Ukraine, and Australia, respectively, were produced over several million years (e.g., Grahn et al., 1996; Alwmark et al., 2010). In addition, a large number of fossil meteorites found in Ordovician limestone in Sweden (e.g., Schmitz et al., 1996, 2001) and the impact-produced Osmussaar Breccia in Estonia (Alwmark et al., 2010) testify to a period of enhanced bombardment of Earth by asteroids at that time. Analysis of the fossil meteorites and impact breccias suggests that most of the Ordovician impacts are linked to the collisional breakup of the L-chondrite parent asteroid in space some 470 Myr ago (e.g., Ar–Ar results of Bogard et al., 1976, 1995; Korochantseva et al., 2007;
Swindle et al., 2014), which then sent large masses of partially shock-melted stony meteorites into Earth-crossing orbits. Extraterrestrial chromite grains extracted from reburial deposits of the Lockne impact structure and the Osmussaar Breccia indicated an L-chondritic source (Alwmark and Schnitz, 2007; Alwmark et al., 2010). Geochemical analysis of impact melt rock from the East Clearwater Lake impact structure in Canada also suggested an ordinary (possibly L-) chondritic impactor (Palme et al., 1979; McDonald, 2002; Daly et al., 2018). However, the Ordovician bombardment of Earth was one of numerous but predominantly relatively small asteroids.

Apparent “clusters” of impacts, that is, two or more impact events with overlapping or nearly overlapping ages, also seem to occur in geologic times other than the Ordovician. For example, at least four impact structures, Popigai in Russia (Bottomley et al., 1997, Ar–Ar age recalculated), Chesapeake in the United States (Assis Fernandes et al., 2019), and Wanapitei (Bottomley et al., 1979, recalculated) and Mistastin in Canada (Sylvester et al., 2013), have isotopic ages that all fall in the time range between ~38 and ~35 Ma in the Late Eocene (Cohen et al., 2013). However, not all of their (recalculated) ages overlap (n = 4 impact crater ages; MSWD = 114; p = 0.000). From the age distribution (and the associated uncertainty) alone, the formation of four larger impact structures within a few million years may appear like the usual background production when considering the effective impact crater distribution and cratering rate (Wanapitei-sized impact craters are statistically produced every ~60,000 years; Mistastin-sized craters every ~600,000 years; Chesapeake-sized craters every ~4.5 Myr; and Popigai-sized impact craters every ~26 Myr) (e.g., Grieve and Shoemaker, 1994; French, 1998). However, a distinct ~2.5 Myr-long spike in extraterrestrial 3He in pelagic limestone (Farley et al., 1998), in combination with a strong enrichment in extraterrestrial chromite grains in Upper Eocene sediments of the Global Boundary Stratotype Section and Point (GSSP) for the Eocene–Oligocene at Massignano, Italy, (Schnitz et al., 2015; Boschi et al., 2017), argues for a Late Eocene asteroid (or comet) shower, thereby potentially producing a distinct impact cluster. One mechanism that can explain the formation of clusters in the terrestrial impact crater record is one or more impacts in space causing the breakup of large asteroids into families of asteroids, members of which can then be delivered to the Earth (e.g., Zappalà et al., 1998; Nesvorný et al., 2002, 2006; Farley et al., 2006; Bottke et al., 2007; Claeys and Goderis, 2007; Schmitz et al., 2008). Trace element analysis of impactites suggested that the Popigai and Wanapitei impact structures both had L-chondritic impactors (Masaitis and Raithlin, 1986; Tagle and Claeys, 2004, 2005; Tagle and Hecht, 2006; Tagle et al., 2006), although Kyte et al. (2011) argued that the Popigai-derived Upper Eocene clinoxyroxene sphalerite layer may be linked to the impact of an H-chondrite. The nature of the impactor that produced the Chesapeake crater is, at this point, still somewhat uncertain (McDonald et al., 2009; Goderis et al., 2010). The geochemical and oxygen isotopic analysis of extraterrestrial chromite grains found in Upper Eocene sediments at Massignano indicates an H-chondritic source for the Popigai impact and an L-chondritic source for the somewhat younger Chesapeake impact (Schmitz et al., 2015; Boschi et al., 2017).

In addition to seemingly clustered impacts, the recognition of an apparent periodic pattern in the timing of impact events has caused a debate that started in the mid-1980s and still continues today. Following Raup and Sepkoski (1984), who found that mass extinctions in the Phanerzoic seem to have a periodic pattern potentially caused by extraterrestrial forces (such as periodic comet showers), other researchers also recognized through time-series analysis that large impacts occurred in a similar repetitive pattern of predominantly ~26 and ~30 Myr intervals over the past ~250 Myr and may, therefore, be causally linked (e.g., Alvarez and Muller, 1984; Davis et al., 1984; Rampino and Stothers, 1984; Torbett and Smoluchowski, 1984; Muller, 1985; Rampino and Haggerty, 1996; Rampino and Caldeira, 2015, 2017). However, one should keep in mind that those periodicity models were based on the impact crater ages available in the 1980s and 90s, and since then, other workers have called the proposed periodicity into question (e.g., Grieve et al., 1988; Heisler and Tremaine, 1989; Baks, 1990; Weissman, 1990; Yabushita, 1996; MacLeod, 1998; Montanari et al., 1998; Bailey-Jones, 2011), some of them noting that the apparent periodicity may, in part, be an artificial effect due to the rounding of imprecise impact ages to integer values, often in multiples of 5 or 10 Ma (e.g., Jetsu and Pelt, 2000; Grieve and Kring, 2007). More recently, Meier and Holm-Alwmark (2017) demonstrated that the apparent periodic pattern in Earth’s impact events, at least those filtered for reasonably precise and accurate age constraints (compare Baks, 1990), may be related to clusters of impacts with similar ages that seem to be the main carriers of the periodic signal. Based on refined statistics, they argued that there is currently no evidence for periodicity in the terrestrial impact record when up-to-date impact crater ages are used as input parameters. Ages presented in Tables 1 and 2 of this work aim to help resolve such issues and debates.

In the context of seemingly periodic impacts and extinction events (Raup and Sepkoski, 1984) and the “kill curve” of Raup (1990), we also refer to the role of impacts in Earth’s biosphere (Section 4.4).

Precise and accurate impact ages, moreover, help constrain the preserved terrestrial crater size–frequency distribution and, by inference, estimate the impact cratering rate in the Earth–Moon system in the past. Figure 5 shows the cumulative number of Earth’s impact structures of variable size with reasonably well-constrained ages (~10 Ma error) for the entire Earth, including very small impact craters (and pits) ~7 to 500 m in diameter (which are usually not plotted because they are preferentially removed from Earth’s record by erosion; e.g., Grieve and Dence, 1979; Hughes, 2000). Because the terrestrial impact record is incomplete for several reasons outlined earlier (e.g., Johnson and Bowling, 2014; Hergen and Kenkmann, 2015) (Fig. 1), the lunar impact record and its crater size–frequency distribution are commonly used as a proxy for the impact crater production rate on Earth (e.g., Neukum and Ivanov, 1994; Neukum et al., 2001; Werner et al., 2002; Ivanov et al., 2003). Additional constraints come from the size–frequency distribution of near-Earth asteroids (e.g., Shoemaker et al., 1979; Durda et al., 1998; Morbidelli, 1999; Bottke et al., 2000; Werner et al., 2002; Stuart and Binzel, 2004; Michel and Morbidelli, 2007; Le Feuvre and Wieczorek, 2011; Johnson
and Bowling, 2014; Wheeler and Mathias, 2019), the population of Earth-crossing comets, the Sun’s position in the galactic plane (e.g., Shoemaker, 1998a, 1998b; Ye, 2018), as well as the distribution of extraterrestrial ³He (Farley, 1995, 1998, 2001), platinum-group metals (Peucker-Ehrenbrink, 2001), and fossil meteorites and extraterrestrial chromite grains (e.g., Schmitz et al., 1996, 2001, 2015; Heck et al., 2004; Alwmark and Schmitz, 2009; Schmitz, 2013) in marine sediments. While some authors proposed that the impact flux in the Earth–Moon system has continuously declined over the past 3 Gyr (Minton and Malhotra, 2010), others suggested that the impact flux has remained more or less stable over the last 2 Gyr (e.g., Neukum and Ivanov, 1994; Hörz, 2000; Hughes, 2000). Part of this debate is whether the Earth has seen a significant increase of impacts, particularly those producing craters >20 km in diameter, over the last few hundred Myr—perhaps by a factor of two or three (e.g., Grieve, 1984; McEwen et al., 1997; Shoemaker, 1998a, 1998b; Hughes, 2000; Bland, 2005; cf. Grier et al., 2001). More recently, Mazrouei et al. (2019) suggested that the terrestrial impact flux experienced an increase by a factor of 2.6 some 290 Myr ago. It is beyond the scope of this geochronology-focused article to assess Earth’s effective impact cratering rate, but while Bland (2005) provides a useful summary and discussion, the list of recommended impact ages (Tables 1 and 2) may help place additional constraints on the Proterozoic (2.5 Ga to ~541 Ma) and Phanerozoic (~541 Ma until present) terrestrial impact crater production.

4.2. Impact-delivered extraterrestrial mass accreted on Earth over time

While the distribution of impact ages in the geologic time line suggests that the Earth was hit by asteroids (and/or comets) more frequently during, for example, the Ordovician compared with other periods of time, it is important to note that this temporal distribution is biased by various factors. First, the terrestrial impact cratering record is, with currently 200 impact structures recognized on Earth, very limited and, therefore, not representative of a planetary production record (e.g., Grieve and Dence, 1979; Johnson and Bowling, 2014). Because the majority of impactors hit the seafloor (particularly during geologic times with supercontinents) and the oceanic crust has been tectonically recycled in multiple Wilson cycles over ~2 Gyr (e.g., Scotese, 2001), most impact structures have been removed from Earth’s surface (e.g., Johnson and Bowling, 2014; Hergarten and Kenkmann, 2015). With the exception of the ~20 to 40 km-diameter Jurassic–Cretaceous Mjølnir impact structure off the coast of Norway (Dypvik et al., 1996), the ~45 km-diameter Eocene Montagnais impact structure on the Scotian Shelf of eastern Canada (Jansa et al., 1989), and evidence for the Pleistocene submarine Eltanin impact (Gersonde et al., 1997), no impact structures are currently known on the present-day seafloor. Second, some countries (e.g., the United States, Canada, Australia, and many European countries) have a longer tradition in impact crater research compared with others (e.g., China), which may cause an apparent preponderance of impacts in those countries and their respective geologic settings. Australia and Finland, for example, have a relatively high density of preserved Precambrian impact structures because much of their landmass consists of Archean and Proterozoic rocks that can preserve this old cratering record (Fig. 2). Third, impact ages can be more precisely determined stratigraphically in well-characterized sedimentary target settings similar to that at the Lockne crater, Sweden, than in others (e.g., Île Rouleau, Canada), an effect that probably contributes to the impact age spike in the Ordovician. Lastly, the impact age distribution shown in Fig. 4 does not take into account the actual magnitude of the impact events that occurred over time, which can be expressed by the mass of projectile material delivered to Earth during impact and the corresponding impact energy (half of the projectile mass times the impact velocity squared) (e.g., French, 1998).

An alternative and perhaps more informative way of representing the impact flux through geologic time is plotting the accreted impactor mass versus time (Fig. 6). By using equations modified after the work of Abramov et al. (2012) and well-established impact crater scaling laws (e.g., Grieve et al., 1981; Lakomy, 1990; Melosh, 1989), along with
reasonable constraints on the type of impactors (e.g., Tagle and Hecht, 2006; Goderis et al., 2012; Koeberl, 2014), their bulk density (e.g., Consolmagno and Britt, 1998; Consolmagno et al., 2008; Macke, 2010; Macke et al., 2011), different types of target rock (e.g., Abramov et al., 2012), and variable impact velocities (e.g., between 10 and 20 km$^{-1}$), the absolute and relative mass flux can be calculated. However, because many of the input parameters are associated with significant uncertainties, these calculations can only provide approximate first-order estimates. For this purpose, we calculated the mass of the three largest impacting bodies based on transient crater diameter values in the literature (125 km for Vredefort, 110 km for Sudbury, and 100 km for Chicxulub) (Stöffler et al., 1994; Kring, 1995, 2005; Therriault et al., 1997; Grieve and Therriault, 2000). Moreover, such calculations do not take into account the mass accreted from potentially large impacts on Earth that created the Archean spherule layers because the size and type of those projectiles are not well constrained. (One could potentially use the thickness of an ejecta layer as a gauge for the corresponding impactor size, but distal ejecta layers become thinner with distance from their source crater and postimpact sedimentary reworking commonly modifies the thickness of fallout deposits; e.g., McGetchin et al., 1973; Simonson et al., 2000; Byerly et al., 2002; Johnson and Melosh, 2012; Johnson et al., 2016.) Therefore, estimates of the total accreted projectile mass based on the impact crater record alone are minimum estimates.

Doing the relative mass flux calculations for the partially preserved terrestrial impact crater record ($n = 200$) with the above caveat in mind (and not taking into account the [large] impacts that produced the terrestrial impact ejecta deposits), a few things become immediately apparent (Fig. 6): The giant Vredefort impact alone delivered >40% of the total projectile mass accreted among all 200 known crater-forming impacts over the last >2 Gyr, and the three largest impact structures on Earth—Vredefort, Sudbury, and Chicxulub—were created by projectiles that together make up >90% of that total impactor mass. The end-Cretaceous Chicxulub impact concentrates >70% of all extraterrestrial mass in the Phanerozoic impact crater record ($n = 172$). In contrast, other relatively large impacts (e.g., Acraman and Manicouagan) in the Ediacaran and Phanerozoic only contributed a small percentage of the total impactor mass. For example, the Ordovician impacts, creating a large group of medium-sized and smaller impactors with proven and likely Ordovician ages (Fig. 4) (Section 4.1), only delivered ~0.3% of the total impactor mass (Fig. 6) because those projectiles were, although numerous, relatively small. Seeingly sizeable impact events such as the Ries–Steinheim double impact ~14.8 Myr ago (Stöffler et al., 2002; Schmieder et al., 2018a, 2018b) and the three largest Pleistocene impacts (Bosumtwi, Zhamanshin, and Pantasma, not including the enigmatic impact that created the large Australasian tektite strewn field) (e.g., Hartung and Koeberl, 1994; Cavosie, 2018; Rochette et al., 2019), all producing impact craters >10 km in diameter, delivered asteroid masses that are statistically insignificant (~0.01% or less). Such calculations put the production rate, relative abundance, and effective significance of large- versus medium-sized
and small impacts through geologic time (e.g., Grieve and Dence, 1979; Grieve, 2001a, 2001b; Meier and Holmlund Alwmark, 2017; Rampino and Caldeira, 2017; Mazrouei et al., 2019) into a different perspective.

However, one should also keep in mind that the above relative impactor mass distribution is only relevant to the partially preserved impact crater record observable today \((n = 200)\) and, therefore, draws a distorted image of the true impact crater production over time. Assuming Chicxulub-sized (\(~180\) km diameter) impacts occur approximately every \((100–150\) Myr (Grieve and Shoemaker, 1994; Neukum and Ivanov, 1994; French, 1998), the production record for the past \(~2\) Gyr, at a more or less constant impact rate, would contain \(~20\) Chicxulub- or Sudbury-sized impacts (producing \(~150\) to \(200\) km-diameter craters), \(~77\) Popigai-sized impacts (\(~100\) km), \(~450\) Siljan-sized impacts (\(~50\) km), and \(~5780\) Ries-sized impacts (\(~20\) km). Those \(>6000\) impacts producing craters \(>20\) km in diameter would have delivered several hundred million megatons of impactor material to Earth, only \(~6\)% of which would have been concentrated in the Vredefort projectile (Chicxulub \(~3\)%). The same calculations adjusted for an impact rate \(~2\) to \(3\) times lower before \(\sim 0.3\) Ga (e.g., Shoemaker, 1998b; Mazrouei et al., 2019) yield roughly \(2300\) impacts producing craters \(>20\) km in diameter over \(~2\) Gyr (Vredefort \(~10\%\); Chicxulub \(~5\%) of accreted impactor mass). The above calculations, depending on the cratering rate chosen, suggest that today’s partial preservation record \((n = 200)\) represents only some \(15–25\)% of the impact craters produced over the past \(~2\) Gyr. These estimates are broadly consistent with those of Johnson and Bowling (2014).

4.3. Geochronologic evidence for double and multiple impact events on Earth

There has been an ongoing debate about the geologic and geochronologic evidence for double and multiple impact events on Earth (Spray et al., 1998; Miljković et al., 2013, 2014; Schmieder et al., 2014a, 2014c, 2015a, 2016b). Classic examples of pairs of closely spaced impact craters are the \(~25\) km Nordlinger Ries and \(~3.8\) km Steinheim Basin in Germany (Stöffler et al., 2002) and the two Clearwater Lakes in Québec, Canada (e.g., Dence et al., 1965; Schmieder et al., 2015a) (Fig. 7). While the age of the Nordlinger Ries is precisely constrained (tektite Ar–Ar age of \(14.808 \pm 0.038\) Ma) (Schmieder et al., 2018a, 2018b), the

![FIG. 7. The two clearwater Lakes in Québec, Canada. The western structure, West Clearwater Lake, is \(~36\) km in diameter and has a ring of islands where impact melt-bearing rocks occur. The eastern structure, East Clearwater Lake \(~26\) km in diameter, has a more subtle appearance. Both impact structures were considered to represent a 290 million year-old impact crater doublet (Dence et al., 1965; Reimold et al., 1981) until recently. New Ar–Ar geochronologic results, however, demonstrate that the eastern crater formed during the Middle Ordovician \(~465\) Ma), a time of intense asteroid bombardment of Earth, whereas the western crater formed in the Early Permian \(~286\) Ma) and is therefore \(~180\) Myr younger (Schmieder et al., 2015a). Landsat OLI/TIRS satellite image taken on June 13, 2013, when the western lake was still partly frozen (Source: GloVis, USGS). Scene width \(~120\) km. OLI, Operational Land Imager; TIRS, Thermal Infrared Sensor.](image-url)
age of the Steinheim Basin is still somewhat enigmatic. However, the two impact craters are thought to be genetically linked because of their proximity, the similar age of their Middle Miocene crater lake sediments (Heizmann and Hesse, 1995), and their geometric alignment with the Central European tekite strewn field to the northeast (Stöffler et al., 2002). Clearly, a representative isotopic age for Steinheim would help assess that situation with more confidence; unfortunately, previous Ar–Ar results for impact-melted sandstone and (U–Th)/He results for zircon crystals from the central uplift of the complex Steinheim impact crater failed to produce geologically meaningful results (Buchner et al., 2010a).

In Canada, the larger, ~36 km-diameter West Clearwater Lake impact structure has a ring of islands where impact melt-bearing rocks occur. East Clearwater Lake, 26 km in diameter, has a more subtle appearance and impact melt rock is only known from drillings (e.g., Simonds et al., 1978; Reimold et al., 1981; Grieve, 2006). For almost 50 years, these two impact structures had been considered a textbook example of an impact crater doublet created simultaneously by the impact of a binary asteroid (Dence et al., 1965) in the early Permian some 290 Myr ago (Reimold et al., 1981). However, repeated Ar–Ar analysis (Bottomley et al., 1990; Schmieder et al., 2015a), alongside other lines of geological evidence (e.g., Scott et al., 1997), eventually made a convincing case against the double impact scenario. While the larger western crater was indeed produced in the Permian at 286.2 ± 2.6 Ma (Schmieder et al., 2015a), the eastern crater is almost 180 Myr older and, with an age around 465 Ma (Bottomley et al., 1990; Schmieder et al., 2015a; Biren et al., 2016), is part of the prominent Ordovician impact crater population preserved on our planet (Fig. 4 and Table 1).

Two closely spaced impact structures similar in spatial arrangement to the Clearwater Lakes in Canada are the Suvasvesi North and South impact structures in Finland, both ~4 km in diameter and ~6 km apart from center to center (e.g., Pesonen et al., 1996b; Lehtinen et al., 2002). Not surprisingly, the two impact structures had previously been considered a possible crater doublet created by the impact of a binary asteroid (Werner et al., 2001). However, more recent Ar–Ar and U–Pb (zircon) geochronologic results for impact melt rock samples from both structures suggest Suvasvesi South is considerably older (≥720 Ma, i.e., Proterozoic) than the Suvasvesi North structure (~85 Ma, Cretaceous). Similar to the two Clearwater Lake impact structures, Suvasvesi North and South seem to constitute a “false” impact crater doublet (Schmieder et al., 2014c, 2016b; Schwarz et al., 2016a). In contrast, the 14 km-diameter Lockne and 0.7 km-diameter Målingan impact structures in Sweden may represent a true crater doublet (Ormø et al., 2014) within the framework of multiple impacts during the Ordovician (see also Section 4.1). A review and geochronologic assessment of these and other proposed terrestrial impact crater doublets (e.g., Gusev and Kamensk in Russia; Movshovic et al. 1991; Melosh and Stansberry, 1991; Bottke and Melosh, 1996; Masaitis, 1999) are provided by Schmieder et al. (2014c).

While the Ordovician period can be regarded as a time of intense impact flux, there is currently no evidence for synchronous multiple impact events resulting in the formation of larger-scale impact crater chains on Earth. Although such a scenario had been proposed for at least five impact structures with overlapping ages (Manicouagan and Lake Saint Martin in Canada, Red Wing Creek in the United States, Rochechouart in France, and Obolon in Ukraine) in the Late Triassic some 214 Myr ago (Spray et al., 1998), more recent Ar–Ar age determinations on the Lake Saint Martin (227.8±0.9 Ma) (Schmieder et al., 2014a) and Rochechouart (206.92±0.32 Ma) (Cohen et al., 2017; cf. Schmieder et al., 2010b) impacts and refined stratigraphic age constraints for Obolon (<185 Ma) (Schmieder and Buchner, 2008) demonstrated that all of those craters have very different ages and are thus unrelated. We conclude that the Late Triassic Earth did not see a multiple impact event similar to the impact of several large fragments of comet Shoemaker-Levy 9 on Jupiter as observed by the Hubble Space Telescope in July 1994 (Crawford et al., 1994). While there are geologically old impact crater chains on the Moon and other planetary bodies that formed after the impact of tidally disrupted “rubble pile” asteroids or comets (e.g., Wichman and Wood, 1995; Schenk et al., 1996; Richardson et al., 1998), no such chain is known to exist on Earth and their formation over shorter periods of geologic time is considered very unlikely (Bottke et al., 1997).

4.4. The role of impacts and impact ages in Earth’s biosphere

With the advent of the “New Catastrophism” in the wake of the impact mass extinction hypothesis, according to which Earth’s Mesozoic life—most prominently the dinosaurs—was wiped out due to the impact of a large asteroid that was also the source of a global iridium anomaly (Alvarez et al., 1979, 1980; Ganapathy, 1980; Hsu, 1980; Kyte et al., 1980; Smit and Hertogen, 1980), larger meteorite impacts have been discussed as potential triggers for most, if not all, of the “big five” biological extinction events in the geologic past (e.g., Raup and Sepkoski, 1984; Raup, 1990, 1992; Hodicky and Dunning, 1992; Sepkoski, 1996; Hallam and Wignall, 1997; Rampino et al., 1997; Toon et al., 1997; Rampino, 1999; Pálfy, 2004; Reimold et al., 2005, 2008; Kelley, 2007; Racki, 2012; and see also Section 4.1 on impact periodicity). The concept of impact-driven mass extinctions led to the concept of an impact kill curve (Raup, 1990, 1992) that correlates extinction magnitude or species exterminated with impact crater size. Chicxulub, it was postulated, was particularly devastating because of its large size. That then begged the question: What was the threshold of an extinction level event? It was subsequently recognized that there may be a family of kill curves that reflect extant ambient and biological conditions at the time of impact (Kring, 2002). Yet, the question remained: What is the threshold size of event or events needed to cause extinction? The community has probed that question in two ways. First, an effort has been made to locate evidence of shock metamorphism at mass extinction horizons, which has generated contradictory results (e.g., Retallack et al., 1998 for the end-Permian; and Bice et al., 1992; Patzer et al., 2004; Kring et al., 2017a for the Late Triassic). The second approach has been to locate ejecta from other large impact events and determine if they are correlated with extinctions (e.g., Grey et al., 2003; Pálfy, 2004; Clutson et al., 2018).
The Late Devonian Frasnian/Famennian transition, associated with an extinction event, has an age (~372 Ma) (Percival et al., 2018; cf. Kaufmann, 2006) that is similar to a previously published age of 377±2 Ma for the ≥52 km-diameter Siljan impact structure in Sweden, Europe’s largest impact structure (Reimold et al., 2005). However, current Ar–Ar results suggest that the Siljan impact occurred at either ~400 or ~380 Ma (Jourdan and Reimold, 2012). Therefore, a causal link with the Frasnian/Famennian boundary event appears implausible (Racki, 2012). Likewise, there is currently no convincing evidence of global-scale impacts at the end-Permian at ~252 Ma (e.g., Retallack et al., 1998; Reimold and Koeberl, 2000; Renne et al., 2004; Wignall et al., 2004), which marks the biggest of all life crises on Earth during which more than 95% of marine species and 70% of terrestrial vertebrates went extinct (e.g., Erwin et al., 2002). The event that created the Permo-Triassic ~40 km-diameter Araguainha impact structure in Brazil, South America’s largest impact structure with a U–Pb age of 254.7±2.5 Ma (Töhrer et al., 2012), may have had continent-scale effects (Töhrer et al., 2013, 2018), but was likely too small to cause a global biological trauma (e.g., Walkden and Parker, 2008). A more recent set of geochronologic results, moreover, suggests that the Araguainha impact may be somewhat older (259±5 Ma) (Erickson et al., 2017). Instead, the end-Permian extinction event may have been caused by volcanic activity in large igneous provinces, such as the Emeishan and Siberian Traps in the final stages of the Permian (e.g., Shen et al., 2011; Burgess et al., 2017; Ernst and Youbi, 2017) and potentially other compounding environmental factors.

It appears, however, that there may be a small, but measurable, extinction event that is correlated with the Manicouagan impact event around ~215 Ma (Onoue et al., 2016), which would have produced regional to global environmental consequences (Durda and Kring, 2004; Kring, 2017a) and may be linked to a positive platinum group element anomaly in Upper Triassic deep-sea sediments (Sato et al., 2017). The door on those events has just opened; many more details should be forthcoming now that relevant outcrops have been located for more detailed study. Evidence for impact coinciding with the end-Triassic at ~201 Ma is somewhat dubious (e.g., Olsen et al., 2002; Simms, 2003, 2007; Tanner et al., 2004; Hesselbo et al., 2007; Kring et al., 2007; Schmieder et al., 2010b; Smith, 2011; Lindström et al., 2015), although earlier reports of putative shocked quartz grains at the Triassic/Jurassic boundary in Austria (Badjukov et al., 1987) and Italy (Bice et al., 1992) and an iridium anomaly (Olsen et al., 2002) certainly leave room for new research. The Latest Triassic (Rhaetian) ~40 km-diameter Rochechouart impact structure in France previously had an age that overlapped with the Triassic/Jurassic boundary (Schmieder et al., 2010a), but new Ar–Ar results suggest that the impact occurred some ~5 Myr before the transition (Cohen et al., 2017). Similar to widespread volcanism during the end-Permian, the Central Atlantic Magmatic Province (CAMP) may be a driving force of extensive seismicity, emission of gases, and extinction at the end of the Triassic (e.g., Marzoli et al., 1999; Lindström et al., 2015; Davies et al., 2017).

Thus far, the only convincing case for impact as the trigger of a mass extinction and severe, global-scale paleoenvironmental effects remains the giant Chicxulub impact on the Yucatán Peninsula in Mexico, which has been stratigraphically, (micro)‐paleontologically, geochemically, and in terms of precise U–Pb and Ar–Ar ages linked with the Cretaceous/Paleogene boundary at ~66.05 Ma (e.g., Hildebrand et al., 1991; Kring and Boynton, 1991; Toon et al., 1997; Smít, 1999; Kring, 2007; Schulte et al., 2010; Renne et al., 2013, 2018; DePalma et al., 2019). Some of the hazardous paleoenvironmental effects caused by the Chicxulub impact (see Kring, 2007 for a summary) include a roughly Richter magnitude 10.5 earthquake that, in turn, triggered a large-scale tsunami and, in paleolakes and lagoons, forceful seiches (e.g., Smít and Romein, 1985; Bourgeois et al. 1988; DePalma et al., 2019); the global distribution of airborne distal impact ejecta (e.g., Smít, 1999; Claeyis et al., 2002); shock-heating of the atmosphere and widespread wildfires caused by the fallout of hot ejecta (e.g., Wolbach et al., 1985; Melosh et al., 1990; Kring and Durda, 2002; Durda and Kring, 2004; Robertson et al., 2013; Belcher et al., 2015); an almost instantaneous phase of “impact winter” caused by atmospheric dust blocking the sunlight (e.g., Vellekoop et al., 2014, 2016; Brugger et al., 2017), followed by a superimposed, slower greenhouse effect in response to the voluminous release of atmospherically active gases (e.g., water vapor, CO₂, and SO₂) from the carbonate- and sulfate-dominated target rock (Kring et al., 1996; Pope et al., 1997; Pierazzo et al., 1998; Kring, 2007); and the acidification of ocean water and leaching of soil due to acid rain (e.g., Prinn and Fegley, 1987; Retallack et al., 1987; D’Hondt et al., 1994; Retallack, 1996). At the time of impact, the contemporaneous Deccan trap volcanism in India had already been active (Renne et al., 2015; Richards et al., 2015).

It is worth noting that large impacts, capable of causing widespread havoc and mass extinctions, do not only have detrimental effects on the biosphere. While the end-Ordovician extinction (~443 Ma) was most likely related to climatic effects and glaciation (e.g., Wang et al., 2019), some researchers have argued that frequent impacts during the mid-Ordovician (~470 to 458 Ma) may have, in fact, boosted biodiversity (Schmitz et al., 2008). A similar biodiversity effect among fossil plankton was also proposed for the Acanram impact in the Ediacaran (Grey et al., 2003), a time when more highly organized organisms emerged (e.g., Knoll et al., 2006); stratigraphic and isotopic age constraints for the Acanram impact are, however, relatively imprecise (Schmieder et al., 2015b). Recently, Erickson et al. (2019a, 2019b) suggested the ~2.23 Ga Yarrabubba impact in Western Australia, which potentially affected a Paleoproterozoic “Snowball Earth,” may have been a trigger mechanism for the release of large amounts of water vapor into the atmosphere (Kring, 2003), thereby creating a warming effect that may have helped Earth escape its icehouse state (see also Koeberl et al., 2007b; Koeberl and Ivanov, 2019).

4.5. High-precision impact geochronology and its relevance to exo- and astrobiology

Could life have first flourished on Earth beneath the floor of an impact crater? This question (the Impact-Origin of Life Hypothesis) (Kring, 2000, 2019) has not been answered
quite yet, but an integral part of it—a temporal component studied in detail using high-precision geochronologic techniques—is a core aspect of this work. As formulated in previous studies suggesting that the origin of life may lie in impact crater settings (e.g., Kring 2000, 2003, 2019; Cockell and Lee, 2002; Ryder, 2002; Osinski, 2003, 2011; Cockell, 2006), cooling impact craters that hosted hydrothermal systems are thought to have served as a habitat for microbial life on the early Earth and, possibly, Mars (e.g., Abramov and Mojzsis, 2009; Osinski et al., 2013, 2017; Rummel et al., 2014; Grimm and Marchi, 2018; Bowling and Marchi, 2018).

A number of geo-biological paleoenvironmental settings have been proposed as potential loci for the origin and evolution of microbial life on the Hadean–Archean Earth more than 3.8 Ga ago (e.g., Nisbet and Sleep, 2001); a recent review is provided by Westall et al. (2018). These settings include, among others, sulfide-rich hydrothermal vents (e.g., Baross and Hoffman, 1985; Russell and Hall, 1997; Russell and Arndt, 2005; Martin et al., 2008) and hydrothermal-sedimentary crustal settings, in which prebiotic molecules may have been initially produced, stabilized, and complexified as a starting material for organic life (e.g., Westall et al., 2018). Impact craters and basins on the early Earth, hosting extensive postimpact hydrothermal systems, would have provided a very similar promising setting (e.g., Abramov and Kring, 2004). The largest asteroid impacts on the Hadean and Archean Earth more than 3.7 Ga ago would have created at least ~40 basins ~1000 km in diameter and several of order 5000 km-diameter (Grieve, 1980; Kring and Cohen, 2002; Kring, 2003; Grieve et al., 2006) and would have, at the same time, delivered prebiotically relevant elements, such as structurally bound water, carbon, nitrogen, phosphorous, and sulfur (e.g., Kring and Cohen, 2002; Pasek and Lauretta, 2008; Svetsov and Shuvalov, 2015; Barnes et al., 2016) (compare Section 4.2 and Fig. 6). However, smaller impact craters some tens of km across would have been much more abundant and saturated Earth’s surface (e.g., Abramov and Mojzsis, 2009). While the largest of those impact events likely vaporized surface water (Sleep et al., 1989; Zahnle and Sleep, 2006) and produced large amounts of impact melt (e.g., Grieve and Cintala, 1992; Grieve et al., 2006), making surface conditions untenable for life, numerical models suggest the subsurface was still habitable (Abramov and Kring, 2004, 2005, 2007; Abramov and Mojzsis, 2009; Grimm and Marchi, 2018). Basin-sized and smaller impacts would have produced subsurface hydrothermal systems conducive for prebiotic chemical reactions that could have led to the early evolution of microbes (e.g., Kring, 2000, 2003; Ryder, 2002; Bowling and Marchi, 2018). The volumes of impact-generated habitable zones for mesophilic, thermophilic, and hyperthermophilic microbial life forms in the subsurface of the Hadean–Archean Earth (i.e., inside impact craters and the fractured crust below) were significant (of order ~10³ km³) (Abramov and Mojzsis, 2009). As with the flux of impactor mass over time (see Section 4.2), the largest impact structures would have provided the most voluminous hydrothermally altered and habitable zones. The volume of rock that sustained habitable temperatures (≤110°C) over hundreds of thousands of years attained up to ~40,000 km³ in larger impact structures ~200 km across (Abramov and Kring, 2004). The colonization of the central domains of such impact craters may have occurred some ~20,000 years after the impact (Abramov and Kring, 2004; Abramov and Mojzsis, 2009). This estimate is consistent with the relatively rapid recovery of life at ground zero inside the Chicxulub crater after ~30,000 years (Lowery et al., 2018).

Although large impacts were much more abundant during the Hadean and Archean before ca. 3.7 Ga (e.g., Turner et al., 1973; Tera et al., 1974; Ryder, 1990; Kring and Cohen, 2002; Bottke and Norman, 2017), impact craters and their hydrothermally altered rocks and minerals accessible on Earth today (e.g., Allen et al., 1982; Osinski et al., 2001, 2013; Zürcher and Kring, 2004; Naumov, 2005; Kring et al., 2017b) are valuable analog sites for the type of impact-produced, wet, and warm habitat described above. Putative fossils of microbial life found in hydrothermally altered impact glass, for example, at the early Cretaceous, 19 km-diameter Dellen impact structure in Sweden (Lindgren et al., 2010) and the Miocene Ries crater in Germany (Sapers et al., 2014, 2015), as well as sulfur isotopic signatures indicating microbial reduction of target rock sulfate at the Miocene, ~24 km-diameter Haughton impact structure, Canada (Parnell et al., 2010), and the latest Triassic, ~40 km-diameter Rochechouart impact structure, France (Simpson et al., 2017), may be evidence for the colonization of impact-crater-hosted habitable zones by thermophilic microbes. Figure 8 shows a variety of impactites typically found in terrestrial impact structures, including lithologies enriched in biologically relevant elements (such as carbon and sulfur) and hydrothermally altered rocks that may represent analogues for the setting in impact-crater-hosted microbial habitats (e.g., Kring, 2000, 2003; Ryder, 2002; Cockell et al., 2003; Cockell, 2006).

In addition to habitable volumes and substrates, two key factors in hot fluid systems as biological habitats are their temperature and lifetime. Geochronologic studies and numerical modeling suggest that the largest terrestrial impact craters, such as Sudbury and Chicxulub, may have sustained initially hot (>300°C) hydrothermal systems for more than 2 Myr (e.g., Ames et al., 1998; Abramov and Kring, 2004, 2007; Zürcher and Kring, 2004), whereas medium-sized impact craters around 20–30 km in diameter were generally thought to cool down more rapidly, perhaps over a few thousands or tens of thousands of years (e.g., Pohl et al., 1977; Osinski et al., 2001). Recent high-precision U–Pb and Ar–Ar results for the 23 km-diameter Lappajärvi impact crater in Finland, however, suggest those initial estimates may have been too conservative. An older zircon U–Pb age of ~77.85 Ma, recording lead diffusion at ~900°C (Kenny et al., 2019b), in combination with significantly younger Ar–Ar results of ~76 to 75 Ma for impact melt rock and K-feldspar that record argon diffusion at ~400 to 200°C over several hundred thousand years (Schmieder and Jourdan, 2013a), indicates that even the comparatively small Lappajärvi crater cooled down from initially hot, impact melt-producing temperatures (>200°C) (Bischoff and Stöfﬂer, 1984) to hotter-than-habitable conditions over a period of at least 1.3 Myr (Kenny et al., 2019b). This demonstrates that modern isotopic techniques have the capacity to resolve various stages of an impact event as a protracted geologic process rather than an instantaneous event. It is becoming more apparent that the most precise and accurate impact ages are obtained by using high-temperature geochronometers and/
FIG. 8. Impact lithologies with biologically relevant elements and/or evidence of hydrothermal alteration as potential analogues for impact crater-hosted microbial habitats. (A) Impact melt breccia rich in carbon (enriched in dark interstitial material) from the ~5 km-diameter Gardnos impact structure, Norway. (B) Impact glass from the Nördlinger Ries, Germany, with vesicular domain of silica glass (lechatelierite) and whiskers (trichites) of pyroxene; this type of glass has been linked with possible evidence of fossil microbial life (e.g., Lindgren et al., 2010; Sapers et al., 2014, 2015). (C) Hydrothermally altered impact melt rock with larger vesicle lined by secondary clay minerals from the ~80 km Puchezh-Katunki impact structure, Russia. (A–C) Optical images, plane-polarized light. (D) Altered and locally corroded K-feldspar overgrown by clay minerals in shock-recrystallized and hydrothermally altered granite from the Lappajärvi impact structure, Finland. Unaltered K-feldspar (darker gray) from this sample was used for high-precision Ar–Ar geochronology (Schmieder and Jourdan, 2013a). Secondary electron image. (E) Clay alteration domain (gray, with irregular cracks) and secondary barite (Ba-sulfate) in altered impact melt rock from the ~90 km-diameter Acraman impact structure, South Australia (Williams, 1994; Schmieder et al., 2015b). (F) Small pyrite (Fe-sulfide) frambooids in zeolite (light gray: analcime; darker gray: Na-dachiardite) in hydrothermally altered reworked suevitic breccia from the 180 km-diameter Chicxulub impact crater (Kring et al., 2017b). (E, F) Backscattered electron images.
or, if available, rapidly cooled (distal) impact melt lithologies that landed (far) outside their hot and slowly cooling source crater (Schmieder et al., 2018a; Kenny et al., 2019b). More importantly, the slow cooling of the Lappajärvi crater resolved by combined high-resolution U–Pb and Ar–Ar geochronology makes medium-sized impact craters (*~20 to 30 km in diameter), which are orders of magnitude more common over geologic time than Sudbury- or Chicxulub-sized craters (e.g., French, 1998), an important type of habitat for thermophilic and hyperthermophilic microbes on the early Earth (Kring, 2000, 2003; Cockell et al., 2003; Cockell, 2006). A scheme of a slow-cooling complex impact crater, such as Lappajärvi, is shown in Fig. 9. Slowly cooling impact crater-hosted hydrothermal systems similar in volume and lifetime to that at Lappajärvi are, therefore, also relevant to astro- and exobiology. In analogy to Earth, medium-sized impact craters on early (Noachian) Mars may have been an important extraterrestrial habitat, as well (e.g., Newsom, 1980; Newsom et al., 1986, 2001; Rathbun and Squyres, 2002; Abramov and Kring, 2005; Schwenzer and Kring, 2009; Osinski et al., 2013; Rummel et al., 2014; Abramov and Mojzsis, 2016).

5. Conclusions

This work presents a comprehensive collection of revised ages for terrestrial impact structures and deposits. Impact geochronology and the use of the U–Pb and Ar–Ar techniques and other methods have significantly refined the timeline for a number of impact events on Earth, whose ages can be correlated with other impacts and geologic events in Earth history, and which can be used to assess the impact (mass) flux on Earth through geologic time. Based on the latest geochronologic results, synchronous double impacts on Earth seem to be rare, and evidence for a large-scale multiple impact event on our planet is currently missing. However, the Ordovician marks a time period of intense bombardment over several million years, supported by a growing number of Ordovician U–Pb, Ar–Ar, and stratigraphic impact ages. Only the Chicxulub impact at the K/T boundary 66.05 Myr ago has been firmly linked to a mass extinction event, in part, based on high-precision U–Pb and Ar–Ar results. The latter can also be used to determine the lifetime of hydrothermal systems in cooling impact craters, as recently done for the slowly cooled Lappajärvi impact crater in Finland as an analog site for impact crater-hosted habitats for microbial life on the early Earth and, possibly, Mars.

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**Abbreviations Used**

- CA-TIMS = chemical abrasion thermal ionization mass spectrometry
- ICS = International Chronostratigraphic Chart
- LA-ICP-MS = laser ablation inductively coupled plasma mass spectrometry
- MSWD = mean square weighted deviation
- SHRIMP = sensitive high-resolution ion microprobe
- SIMS = secondary ion mass spectrometry