The Geological Society of America
Special Paper 557

Impact-crater ages and micrometeorite paleofluxes compared: Evidence for the importance of ordinary chondrites in the flux of meteorites and asteroids to Earth over the past 500 million years

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ABSTRACT

Although the ~200 impact craters known on Earth represent only a small fraction of the craters originally formed, the available data suggest an excess of craters by one order of magnitude, in number, in the interval ca. 470–440 Ma during the Ordovician. Most of these "excess" craters may be related to the breakup of the L-chondrite parent body (LCPB) in the asteroid belt at 465.8 ± 0.3 Ma. This is the only obvious peak in the crater-age record that can currently be attributed to an asteroid breakup and shower event. Spatial crater densities in regions with high potential for crater preservation (e.g., Canada and Scandinavia) support a one order-of-magnitude increase in the flux of large (>0.1 km) impactors following the LCPB breakup. A similar pattern as seen in the cratering record is emerging in studies of the flux of micrometeoritic chrome spinel through the Phanerozoic, with so far only one major spike in the flux, and associated with the LCPB breakup. Similarly, the record of K-Ar and (U-Th)/He gas retention ages of recently fallen meteorites only locates one major breakup, the LCPB event, during the Phanerozoic. On the other hand, astronomical backtracking studies of the

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Schmitz, B., Schmieder, M., Liao, S., Martin, E., and Terfelt, F., 2022, Impact-crater ages and micrometeorite paleofluxes compared: Evidence for the importance of ordinary chondrites in the flux of meteorites and asteroids to Earth over the past 500 million years, *in* Koeberl, C., Claeys, P., and Montanari, A., eds., From the Guajira Desert to the Apennines, and from Mediterranean Microplates to the Mexican Killer Asteroid: Honoring the Career of Walter Alvarez: Geological Society of America Special Paper 557, https://doi.org/10.1130/2022.2557(18).

orbits of asteroid family members indicate ~70 major family-forming breakups within the past ~540 m.y., which apparently have not left any clear imprint in Earth's geological record. The chrome-spinel grains recovered in our studies dominantly represent large micrometeorites (>300 µm) and as such are also representative of the flux of larger meteorites to Earth. An observed, nearly constant flux of ordinary chondritic chrome-spinel grains throughout the Phanerozoic, except after the LCPB event, indicates that the present situation—with a clear dominance of ordinary chondritic matter in the large (>500 µm) micrometeorite and macroscopic meteorite fractions—has prevailed at least for the last 500 m.y. This is also supported by generally high ratios in our samples of chrome-spinel grains from ordinary chondrites compared to other types of spinel-bearing meteorites. The chrome-spinel data together with the abundance of fossil meteorites (1–21 cm in diameter) on the Ordovician seafloor also sets an upper limit at one order of magnitude on the increase in flux of large (>0.1-km-diameter) L-chondritic projectiles to Earth following the LCPB. Such an increase would not stand out in the global cratering record if ordinary chondritic impactors had only represented a small fraction of all Phanerozoic impactors. We argue that the origin of impactors delivered to Earth during the past 500 m.y. has mirrored the flux of large micrometeorites and meteorites, with ordinary chondrites being an important or, most likely, the dominant (in numbers) component throughout.

INTRODUCTION

In the 1960s it was discovered that whereas most meteorites falling on Earth today have K-Ar gas retention ages going back to the early solar system, the ordinary chondrites of the L type appear to have undergone a collision that reset their K-Ar isotopic clock at ca. 500 Ma (Kirsten et al., 1963; Anders, 1964; Hintenberger et al., 1964; Keil, 1964; Heymann, 1967; for recent updates, see Bogard, 1995, 2011; Swindle et al., 2014). No one hypothesized at the time that a signal of this event also could be apparent in Earth's geological record, but the signal "announced itself" when quarry workers started to find abundant fossil meteorites in marine Ordovician limestone in southern Sweden (Schmitz et al., 1997). It soon turned out that the fossil meteorites (~1–21 cm large) are diagenetically altered L chondrites that are much more common on the Ordovician seafloor than would be expected given the recent flux of meteorites (Schmitz et al., 2001). To date, more than 130 fossil meteorites have been found in the quarry, and of the ca. 100 meteorites that have been analyzed so far, all except for one appear to be L chondrites (e.g., Schmitz, 2013; Schmitz et al., 2016). The precise level in Ordovician sedimentary strata that corresponds to the time of the breakup of the L-chondrite parent body (LCPB) has recently been located using bulk-rock extraterrestrial ^{3}He and ^{187}Os/^{186}Os analyses as well as detailed studies of the distribution of sediment-dispersed, L-chondritic chromite grains (Schmitz et al., 2019a). This information, together with U-Pb data for zircon grains from three ash layers in the same sediment section and fossil-meteorite ^{21}Ne cosmic-ray exposure ages through the section, give an absolute age of 465.8 ± 0.3 Ma for the breakup (Liao et al., 2020). This is similar to ages established by the most sophisticated Ar-Ar measurements of recent L chondrites, 470 ± 6 Ma (Korochantseva et al., 2007) and 475 ± 6 Ma (Weirich et al., 2012). There is also a range of relatively young (U-Th)/He ages in support of these dates (Wasson and Wang, 1991). That the breakup of the LCPB was a major event in the late solar system is evident also from the fact that even today, about a third of all meteorites falling on Earth are L chondrites (~22,900 out of ~65,600 registered meteorites in total; Meteoritical Bulletin Database, 2021), with most of them showing shock features or young Ar-Ar ages (Heymann, 1967; Swindle et al., 2014). The ca. 466 Ma disruption of the LCPB is the largest documented asteroid breakup event of the past 3 g.y. based on studies of recently fallen meteorites. However, astronomical studies that backtrack the orbits of members of asteroid families to their parent-body source indicate that ~70 major breakups have taken place in the asteroid belt during the last 0.5 g.y. alone (Nesvorný et al., 2015; Reiners and Turchyn, 2018). Based on model calculations of the thermal history of the LCPB, its size has been estimated at ~150 km (Bennett and McSween, 1996). The enormous amounts of dust released to the inner solar system in the LCPB breakup appear to have blocked some sunlight from reaching Earth, which led to cooling and the development of ice-age conditions (Schmitz et al., 2019a). For a few million years after the breakup, the amounts of fine-grained extraterrestrial dust in the Earth's atmosphere were orders of magnitude higher than normal, which shielded the Earth from some sunlight and lowered temperatures on the ground. Additionally, iron released from the ablation of meteorites and dust in the atmosphere could have fertilized the oceans and caused drawdown of atmospheric CO_2, leading to further cooling (Reiners and Turchyn, 2018). Following the LCPB event, the flux of larger (>0.1 km) bodies to Earth most likely also increased, and there is evidence in Earth's cratering record of a one order-of-magnitude enhanced number of impact craters in the ~30 m.y. after the breakup event compared to other time periods of the Paleozoic Era (Fig. 1; see also, fig. 8 in Schmitz et al., 2001; Korochantseva et al., 2007; Schmieder et al., 2015, 2019; Schmieder and Kring, 2020). During the past few years, the following structures have been added to the list of impact structures that formed in the ~30 m.y. after the LCPB breakup: Lawn Hill in Australia (Darlington et al., 2016), Decorah in Iowa, USA (Bergström et al., 2018, 2020; French et al., 2018), Glasford in Illinois, USA (Monson et al., 2019), and Charlevoix (Schmieder et al., 2019) and La Moinerie (McGregor et al., 2019) in Canada.

In the present paper we critically evaluate the evidence from impact-crater ages for an asteroid shower following the LCPB. We also compare the crater-age record with our reconstructions of the fluxes of extraterrestrial relict chrome-spinel grains to Earth through the Phanerozoic (Schmitz, 2013; Terfelt and Schmitz, 2021). The chrome-spinel grains dominantly represent large (>300 µm) micrometeorites (Schmitz et al., 2019a, see also Prasad et al., 2015) but only provide a record of the types of micrometeorites that contain common, large (>32 µm) chrome-spinel grains. This includes the ordinary and R chondrites and many types of achondrites, including the HED, Lunar, and Martian meteorites (for details, see Heck et al., 2017). The flux variations of such micrometeorites, based on sediment-dispersed chrome spinel, have been shown to also reflect the variations in the flux of corresponding larger, centimeter- to decimeter-sized meteorites (Schmitz et al., 2019a). This is also consistent with the fact that in the recent flux, ordinary chondrites dominate both the micrometeorite >500 µm- and macroscopic meteorite-size fractions (Cordier and Folco, 2014). The argument here is that asteroid showers related to breakup events should be accompanied by increases in the flux of material also in the meteorite to the interplanetary dust-size fraction. Statistically robust estimates for the flux of the chrome-spinel–bearing types of micrometeorites have been established for 15 Phanerozoic time windows (Terfelt and Schmitz, 2021, and references therein). Micrometeorite flux data exist now, e.g., for the Middle Cambrian; mid-Ordovician before and after the LCPB breakup; Late Silurian; Late Devonian; Middle Jurassic; Early, middle, and Late Cretaceous; and the Paleocene (e.g., Heck et al., 2017; Martin et al., 2018, 2019, this volume; Schmitz et al., 2017, 2019a, 2019b; Boschi et al., 2020). These data provide new perspectives on the more general question of from where in space most large, crater-forming impactors originated over the past 500 m.y. We note that the delivery model for the extraterrestrial flux to Earth is rather complex and is quite different for dust and micrometeorites than for large bodies such as meteorites and asteroids. For the large bodies, there is a chain of events that includes: collisional breakup, semi-major axis drift induced by Yarkovsky effects, thin resonance influence of the eccentricity up to Mars crossing status and, finally, hurling into an Earth-crossing orbit by a strong resonance (Farinella et al., 2001). For small particles, the solar radiation pressure is believed to be the principal transport force (Burns et al., 1979; Kortenkamp et al., 2001). Micrometeoroids (ca. 10 µm to 2 mm large) are affected by the Poynting-Robertson drag, which causes these fragments to coil into the inner solar system and the Sun (Burns et al., 1979; Schmitz et al., 2019b).

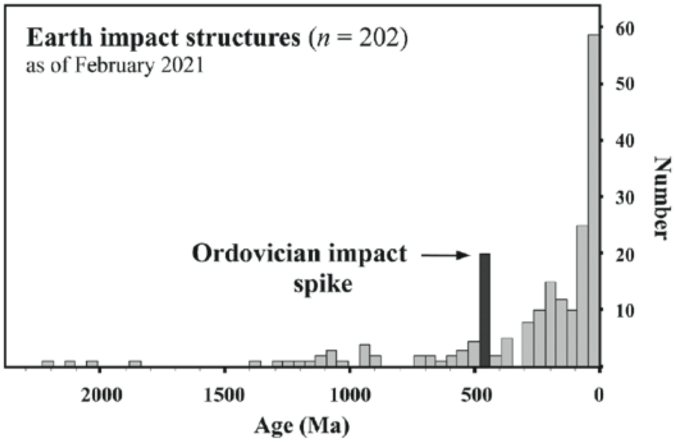

Figure 1. Histogram shows the age distribution of terrestrial impact structures (modified from Schmieder et al., 2019). Note the distinct Ordovician impact spike at ca. 470–450 Ma. The diagram does not distinguish between larger and smaller impacts. Crater ages were taken from Schmieder and Kring (2020). The ages of two additional, recently confirmed impact structures, Hiawatha in Greenland (Garde et al., 2020; Gustafsson, 2020) and the Jeokjung-Chogye Basin in South Korea (Lim et al., 2021), were added.

In the 1980s and 1990s, the prevailing idea was that many of Earth's impact craters, in particular the largest, were formed by comets from the outer parts of the solar system (e.g., Shoemaker, 1983, 1998; Farley et al., 1998). For only a very small fraction of the ~200 known impact craters has it been possible to determine with confidence the impactor type (Goderis et al., 2012, and references therein), but with recent developments in, e.g., chromium isotope and fossil (micro)meteorite approaches, large craters previously believed to have formed from comet impacts rather appear to have formed from ordinary chondritic impactors. For example, the largest crater of the Cenozoic Era, the 100-km-diameter Popigai crater that formed at ca. 36 Ma, and the 80-km-diameter Morokweng crater that formed at ca. 146 Ma, i.e., shortly before the Jurassic–Cretaceous boundary, have both been confidently attributed to ordinary chondritic impactors (Maier et al., 2006; Kyte et al., 2011; Boschi et al., 2017; Kenny et al., 2021). Present models and ideas of the origin of meteorites rely on studies of the recent asteroid belt and the meteorites that have fallen on Earth during the past ~100 k.y. Because meteorite falls are rare and meteorites weather and decay rapidly on Earth's surface, it is challenging to reconstruct the meteorite flux through deep time. With the recent development, however, of methods to recover relict extraterrestrial chrome-spinel grains from hundred-kilogram-sized samples of ancient sea-floor sediments, the first insights have now been gained into variations in the flux of different types of micrometeorites and meteorites through the Phanerozoic Eon (Schmitz et al., 2003; Schmitz, 2013, Martin et al., this volume; Terfelt and Schmitz, 2021). Here we will discuss the possible implications of this new, deep-time perspective and its relation to the cratering record and our general understanding of the flux of meteorites and large impactors to Earth. The ordinary chondrites presently make up ca. 85% of the flux of meteorites to Earth, but there is no consensus or robust understanding about why these meteorites so strongly dominate the flux (Meibom and Clark, 1999; DeMeo and Carry, 2014). Here we argue that this dominance has prevailed throughout the Phanerozoic, and we base this on: (1) Earth's cratering record (Schmieder and Kring, 2020, and references therein), (2) fossil meteorite abundance on the mid-Ordovician seafloor (Schmitz et al., 2001, 2016, this study), (3) our reconstructions of the micrometeorite flux in deep time (Schmitz, 2013; Terfelt and Schmitz, 2021), (4) K-Ar and (U-Th)/He gas retention ages of recently fallen meteorites (e.g., Bogard, 1995, 2011), and (5) the record of extraterrestrial ^{3}He anomalies in Earth's sedimentary record (e.g., Farley et al., 2012).

Ordovician Impact Craters, Spatial Distributions, and Projectile Types

The Ordovician Craters

Following a major asteroid breakup in the asteroid belt, the larger (e.g., >0.1 km) bodies released have to first drift into an orbital resonance before being redirected into an Earth-crossing orbit (Gladman et al., 1997; Zappalà et al., 1998). Therefore, one would expect that asteroids from the LCPB breakup typically hit Earth ~2–30 m.y. after the breakup. At least 20 terrestrial impact structures have proven or likely Ordovician stratigraphic and/or isotopic ages, most of which appear to postdate the LCPB breakup by up to 30 m.y. These impact structures are, in the United States: Rock Elm, Ames, Decorah, Calvin, and Glasford, and on the Canadian Shield: East Clearwater Lake, Brent, La Moinerie, Slate Islands, Pilot, Charlevoix, and Tunnunik; in Baltoscandia: Kärdla (Estonia), Granby, Hummeln, Tvären, Lockne, and Målingen (Sweden), on the Ukrainian Shield: Ilyinets; and in Australia: Lawn Hill (see Table 1 for references for these craters). The relatively large, ~50-km-diameter Carswell impact structure, Canada, with an Early Ordovician ^{40}Ar-^{39}Ar age of 481.5 ± 0.8 Ma, seemingly predates the LCPB breakup event by a few million years (Alwmark et al., 2017). Likewise, the Newporte (USA) and Mizarai (Lithuania) impact structures both have stratigraphic ages that span the Late Cambrian and Early Ordovician (Koeberl and Reimold, 1995; Masaitis, 1999; Abels et al., 2002). The Crooked Creek, Glover Bluff (USA), and Lumparn (Finland) impact structures have Ordovician stratigraphic maximum ages but may be younger (Snyder and Gerdemann, 1965; Merrill, 1980; Read, 1983; Bottomley et al., 1990; Abels, 2003); the Lac Couture impact structure (Canada) has an Ordovician to Early Devonian ^{40}Ar-^{39}Ar age (Bottomley et al., 1990; Grieve, 2006). A recent summary of terrestrial impact-crater ages, including Earth's Ordovician crater population, is presented by Schmieder and Kring (2020).

Some stratigraphically constrained impact ages are remarkably precise, such as that of the ~14-km-diameter marine Lockne impact structure of central Sweden. Because the youngest pre-impact and oldest post-impact sediments both lie in the late Sandbian (early Caradocian; Cohen et al., 2013) lower *Lagenochitina dalbyensis* chitinozoan microfossil zone, which has been studied micropaleontologically in detail (Grahn et al., 1996; Grahn, 1997; Ormö et al., 2014), the impact age can be constrained to ca. 455 Ma plus/minus ~1 m.y. The crater-filling, post-impact deposits of the so-called Winneshiek Shale that occurs within the ~5.5-km-diameter Decorah impact structure in Iowa, USA, suggests a Middle Ordovician (Darriwilian) age of ca. 464–467 Ma for the deposition of the shale and, by inference, the slightly older impact (Bergström et al., 2018, 2020). This age, obtained through high-precision chemostratigraphic ($\delta^{13}C_{org}$) correlation, is within uncertainty identical to the ages of a number of impact structures and fossil L chondrites found in Sweden (e.g., Schmitz et al., 2001).

Uranium-lead ages were obtained via laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) for shocked zircon in impact melt rock from the ≥54-km-diameter Charlevoix impact structure in Canada (Schmieder et al., 2019). The recently obtained U-Pb zircon age of 450 ± 20 Ma spans into the Silurian; however, because of concordant U-Pb laser spot results around ca. 450 Ma for zircon, the partial overthrusting of the Charlevoix impact structure along the (Ordovician) Taconian front of the Appalachian nappes in the southern domain of the impact structure, and taking into account previous ^{40}Ar-^{39}Ar geochronologic results (Whitehead et al., 2003; Kelley, 2006), Schmieder et al. (2019) tend to favor a Late Ordovician age for the Charlevoix impact, which has a stratigraphic maximum age of ca. 454 Ma based on the occurrence of shatter-coned limestone. Using a different U-bearing target mineral, LA-ICP-MS analysis of shocked and age-reset apatite grains by McGregor et al. (2019) yielded an Ordovician isotopic age of 453 ± 5 Ma for the La Moinerie impact structure, which is also located in Canada.

Several older ^{40}Ar-^{39}Ar ages, such as the results of Bottomley et al. (1990) for a number of Canadian impact structures, have been recalculated (Schmieder and Kring, 2020) using the revised K decay constants and standard (neutron fluence monitor) ages of Renne et al. (2010, 2011) and the ArAR tool of Mercer and Hodges (2016), so that the resultant ages are directly comparable to modern U–Pb ages. For example, the age of 445 ± 2 Ma of Bottomley et al. (1990) for the Pilot impact structure, Canada, which was calculated using an age of 1071 ± 7 Ma for the Hb3 gr (hornblende from the Lone Grove granite pluton, Texas, USA) dating standard and the K decay constants of Steiger and Jäger (1977; $\lambda_\varepsilon = 0.581 \pm 0.00581 \times 10^{-10}$ a^{-1}; $\lambda_\beta = 4.962 \pm 0.04962 \times 10^{-10}$ a^{-1}) becomes 450 ± 2 Ma after recalculation (revised Hb3 gr age: 1081 ± 1.2 Ma; revised K decay constants: $\lambda_\varepsilon = 0.5757 \pm 0.0016 \times 10^{-10}$ a^{-1}; $\lambda_\beta = 4.9548 \pm 0.0134 \times 10^{-10}$ a^{-1}; Renne et al., 2011, see also Schwarz et al., 2011; Mercer and Hodges, 2016). Errors on U-Pb and ^{40}Ar-^{39}Ar impact ages are, unless otherwise noted, given at the 2σ (~95% confidence) level (neglecting the uncertainties of the decay constants).

In addition to the proven impact structures listed above, a number of possible and likely impact structures have been

TABLE 1. SUMMARY OF CONFIRMED TERRESTRIAL IMPACT STRUCTURES OF ORDOVICIAN POST–L-CHONDRITE PARENT BODY AGE

Impact structure	Country	Latitude	Longitude	Diameter (km)	Stratigraphic age constraints	Radioisotopic age constraints	Recommended age (Ma)	Age reference
Ames	Oklahoma, USA	N 36°15′	W 98°10′	16	Early–Middle Ordovician (Floian–Darriwilian)	N.D.*	ca. 478–458	Koeberl et al. (2001)
Brent	Ontario, Canada	N 46°05′	W 78°29′	3.8	Early Caradoc (=Sandbian), conodont and chitinozoan biostratigraphy	U-Pb on zircon and apatite	458–453 452.8 ± 2.7	Grahn and Ormö (1995) McGregor et al. (2020)
Calvin	Michigan, USA	N 41°50′	W 85°57′	8.5	Late Ordovician	N.D.	458–443	Milstein (1994)
Charlevoix	Québec, Canada	N 47°32′	W 70°18′	54	Late Ordovician or younger	U-Pb (LA-ICP-MS on zircon in impact melt rock)	ca. 454–430	Schmieder et al. (2019)
Decorah	Iowa, USA	N 43°19′	W 91°46′	5.5	Middle Ordovician (Darriwilian Dw1–Dw2 interval) early post-impact Winneshiek Shale	N.D.	ca. 467–464	French et al. (2018) Bergström et al. (2018)
East Clearwater Lake	Québec, Canada	N 56°05′	W 74°07′	22	N.D.	Ar-Ar (impact melt rock)	470–460	Bottomley et al. (1990) Schmieder et al. (2015)
Glasford	Illinois, USA	N 40°36′	W 89°47′	4	Late Ordovician (Sandbian)	N.D.	ca. 455 ± 2	Buschbach and Ryan (1963) Monson et al. (2019)
Granby	Sweden	N 58°25′	E 14°56′	3	Lower *C. regnelli* zone (=lower Darriwilian) (chitinozoans)	N.D.	ca. 466	Grahn et al. (1996) Alwmark and Schmitz (2009)
Hummeln	Sweden	N 57°22′	E 16°15′	1.2	Upper *C. regnelli* zone (=lower Darriwilian) (chitinozoans)	N.D.	ca. 465	Grahn et al. (1996) Alwmark et al. (2015)
Ilyinets	Ukraine	N 49°08′	E 29°11′	4.5	N.D.	Ar-Ar (impact melt breccia)	445 ± 10	Pesonen et al. (2004)
Kärdla	Estonia	N 58°59′	E 22°40′	4	Transition *A. curvata* / *L. dalbyensis* zone (=late Sandbian), likely slightly older than Lockne	N.D.	455 ± 1	Grahn et al. (1996)
Lac Couture	Québec, Canada	N 60°08′	W 75°20′	8	N.D.	Ar-Ar (impact melt rock)	429 ± 25	Bottomley et al. (1990), recalculated
La Moinerie	Québec, Canada	N 57°26′	W 66°37′	8	Ordovician, pre-Silurian	U-Pb (LA-ICP-MS on apatite)	453 ± 5	Grieve (2006) McGregor et al. (2019)
Lawn Hill	Queensland, Australia	S 18°40′	E 138°39′	18	N.D.	Ar-Ar (impact melt breccia)	476 ± 8	Darlington et al. (2016), recalculated
Lockne	Sweden	N 63°00′	E 14°48′	7.5 (~14)	Lower *L. dalbyensis* zone (=late Sandbian), likely slightly younger than Kärdla	N.D.	455 ± 1	Grahn et al. (1996) Grahn (1997) Ormö et al. (2014)
Målingen	Sweden	N 62°55′	E 14°34′	0.7	Lower *L. dalbyensis* zone (=late Sandbian), contemporary with Lockne	N.D.	455 ± 1	Ormö et al. (2014)
Pilot	Northwest Territories, Canada	N 60°17′	W 111°01′	6	N.D.	Ar-Ar (impact melt rock)	450 ± 2	Bottomley et al. (1990), recalculated
Rock Elm	Wisconsin, USA	N 44°43′	W 92°14′	6	Early–Middle Ordovician	N.D.	ca. 485–458	Cordua (1985) French (2004)
Slate Islands	Ontario, Canada	N 48°40′	W 87°00′	30	N.D.	Ar-Ar (impact melt rock)	ca. 450	Sharpton et al. (1997) Grieve (2006)
Tunnunik (Prince Albert)	Northwest Territories, Canada	N 72°27′	W 113°54′	25	N.D.	N.D.	ca. 450–430[†]	Lepaulard et al. (2019)
Tvären	Sweden	N 58°46′	E 17°25′	2	*L. stentor* zone (=early Sandbian)	N.D.	ca. 458	Ormö (1994) Grahn et al. (1996)

Note: Modified after Schmieder et al. (2015) and Schmieder and Kring (2020). Stratigraphic ages were taken from Cohen et al. (2013, updated). LA-ICP-MS—laser ablation–inductively coupled plasma–mass spectrometry.

*N.D.—no data

[†] Paleomagnetic age.

proposed (see Schmieder et al., 2015). These are the Bouscaren, Dycus, Howell, Ingalls, Jeptha Knob, Peerless, and Versailles structures in the United States and the Banat Baqar and Jalamid structures in Saudi Arabia (see table 3 in Schmieder et al., 2015, for references; and Maione, 2015). However, geologic evidence for an impact origin of these enigmatic structures is, at this point, still unconvincing. We stress that our impact crater reconstructions here are entirely based on the confirmed Ordovician impact cratering record, which clearly separates proven from potential terrestrial impact sites. A list summarizing all confirmed terrestrial impact structures of proven and likely Ordovician age is provided in Table 1. Candidate impact structures with (likely) Ordovician ages are listed in Tables S1–S2 of the Supplemental Material[1].

Projectile Types for Ordovician Craters

There are substantial difficulties involved in determining the types of crater-forming projectiles mainly because projectiles are typically vaporized on impact or melted and admixed with the crater bedrock (see, e.g., Koeberl, 1998, 2002, 2014; Tagle and Hecht, 2006; Schmitz et al., 2011). Only for a few of Earth's craters has the projectile type been determined with confidence. For only two of the Ordovician craters, the Lockne and the Clearwater East craters, there is a robust understanding of the type of impacting projectile. In iridium-rich resurge deposits of the Lockne crater in central Sweden, extreme amounts of L-chondritic chromite have been found, which very likely reflects relict minerals from the impactor (Alwmark and Schmitz, 2007). The chromite content in the >63 μm fraction is 75 grains per kg, which is the same amount that one finds in ~4000 kg of "normal" condensed marine limestone of the same age as the Lockne crater. Tagle et al. (2008) challenged the idea of an L-chondritic projectile based on Ir/Cr ratios and platinum group element (PGE) patterns in the Lockne crater resurge deposits, as well as a reinterpretation of the chemical signature of the chromite grains. They argued instead that the projectile was a non-magmatic iron meteorite. Schmitz et al. (2011) showed that even when the PGE concentrations in diagenetically altered fossil (undisputable) L chondrites are as high as in recent meteorites, their Ir/Cr and PGE patterns cannot be used for a correct assignment of meteorite type. Different PGE data processing approaches regularly used in the literature lead to highly variable results, as was also shown for the Lockne resurge deposits. Schmitz et al. (2011) also showed that both the elemental and oxygen-isotopic composition of the abundant chromite grains from the resurge deposit clearly supported an L-chondritic origin. The chromite grains from the Lockne crater also differed from such grains found in fossil meteorites or dispersed in mid-Ordovician sediments in the absence of noble gases formed from exposure to cosmic rays or implanted by the solar wind. This can best be reconciled with an origin within a larger asteroid body at depths of more than 2 m to which cosmic rays cannot penetrate (i.e., a shielding effect). The discussion around the PGE patterns of the Loftarstone (i.e., the relatively fine-grained, impact-produced resurge arenite associated with the Lockne impact structure; Lindström and Sturkell, 1992) and Ordovician fossil meteorites conclusively highlighted the potential pitfalls in relying on PGE patterns for projectile determination (Schmitz et al., 2011). Farley (2009) raised similar concerns about the use of PGE patterns in impact suevite from the late Eocene Popigai crater for determination of the type of ordinary chondritic projectile. Koeberl and Reimold (2003) had similar concerns regarding the PGE patterns of impact breccias of the 146 Ma Morokweng impact structure.

Chromium isotope studies of siderophile-rich impact meltrock from the 26-km-large Clearwater East crater in Québec provide strong evidence for an ordinary chondritic impactor (Koeberl et al., 2007). Based instead on PGE patterns, Schmidt (1997) suggested a carbonaceous chondritic impactor, but the study may have underestimated the significance of the irregular distribution of PGEs in the melt rocks, the variability of the ratios, and the contribution of the crater bedrock. McDonald (2002), in a more comprehensive study of the PGE ratios, found the closest similarity with L chondrites, whereas Koeberl et al. (2007) argued that the PGE ratios can be reconciled with both an H- and L-chondritic impactor.

There are more ambiguous claims about the impactor type for other Ordovician craters as well. For the 3.8-km-large Brent crater in Ontario, different studies using siderophile element signatures have led to different conclusions. Palme et al. (1981) found Ni/Cr and PGE ratios consistent with an L- or LL-chondritic impactor, whereas Goderis et al. (2010) suggested a non-magmatic iron meteoritic impactor. By similar reasoning around siderophile element data, both the Lockne and the Rochechouart craters have been attributed to iron meteorite projectiles (Tagle et al., 2008; Janssens et al., 1977), which is at odds with more robust chromite data for Lockne (Schmitz et al., 2011, see above) and chromium isotopes showing an ordinary chondritic impactor for Rochechouart (Koeberl et al., 2007). As summarized by Gurov et al. (1998), there have been claims that the 8.5-km-large Ilyinets crater in Ukraine was formed by an iron meteorite or a stony meteorite projectile, but siderophile element enrichments in the impact melt lithologies studied are very minor, and the type of projectile is still unresolved.

The Flux of 0.1–1 km Projectiles from Spatial Crater Densities

Most of the Ordovician craters are found in two restricted areas: Baltoscandia and eastern U.S.–Canada. Particularly in Baltoscandia, the spatial density of impact craters is extremely high, with the average distance between them being less than 400 km (Fig. 2). However, four of the craters are small, between 1.2 km

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[1] Supplemental Material. Supplemental text and Tables S1 and S2. Please visit https://doi.org/10.1130/SPE.S.19072379 to access the supplemental material, and contact editing@geosociety.org with any questions.

and 4 km in diameter, and the fifth, Lockne, is ~14 km wide, with a flat outer and a deeper inner crater ~7.5 km in diameter (for the present purpose we count the Lockne-Målingen doublet that was formed by the impact of a binary asteroid as one crater, see Ormö et al., 2014). Of the ca. 20 Phanerozoic impact craters known in Baltoscandia five formed within the ca. 10 m.y. time period following the LCPB event, i.e., 25% of the craters formed during 2% of the eon. Of the altogether 56 craters known in the U.S. and Canada, 13 are dated to the Middle–Late Ordovician, i.e., 23% of the craters formed during ca. 6% of the time. The spatial density of these craters is particularly high around the Great Lakes, where six craters are found with an average distance between them of ~670 km. Three craters are found in Québec at an average distance of ~510 km. The stable cratonic setting in all of the aforementioned regions during the Phanerozoic suggests that tectonic activity (shortening and extension, e.g., as observed at Charlevoix) has not notably altered the original distances between the impact structures.

The many craters in North America and Baltoscandia reflect their formation on continental crust, where the potential for crater preservation is higher, and that the craters were covered and protected from erosion by marine sediments that deposited in shallow intracratonic seas during high sea levels. Some of the buried craters are very small, such as Tvären (2 km) and Hummeln (1.2 km) in Sweden, which would not have been found were it not for the ambitious crater searches by Nordic Earth scientists (see Dypvik et al., 2008). We note that sea levels were high with marine sediments forming on the cratons from at least the Early Cambrian to the Early Devonian, i.e., during a period of ~130 m.y., as well as later during intervals of the Mesozoic. Still, only the ~30 m.y. period after the LCPB has registered an excess of impact craters.

Figure 2. Maps show the distribution of Ordovician impact structures (indicated by stars) formed in Baltoscandia and North America within ~30 m.y. after the breakup of the L-chondrite parent body. Note that several of the Baltoscandian structures are small, between 1 and 4 km in diameter. The scale is the same in the two maps. For details, see Table 1.

One way of estimating the number of impactors that formed large craters after the LCPB would be to assume that the three-crater-dense areas seen in Figure 2, i.e., Baltoscandia, the Great Lakes region, and Québec, contain a basically complete record of at least the larger than ~20-km-sized craters that formed. Such large craters have greater preservation potential than smaller craters, and the likelihood is high that all or almost all have been found in these regions (Johnson and Bowling, 2014; Hergarten and Kenkmann, 2015). That the record for smaller craters in the three regions of concern is incomplete is obvious from the difference in the size population among the regions, with craters in North America generally being larger than those in Baltoscandia. In the area around the Great Lakes, four relatively small craters (3.8–6 km in diameter) have been found, and one of them quite recently (Decorah). In these areas, blankets of early Paleozoic sediment provide a crater preservation potential that is similar to the Baltoscandian situation.

Estimates of the flux of large impactors to Earth assume, on average, one impactor forming a crater ~20 km in diameter, or larger, per 0.3 m.y. (see, e.g., French, 1998; Schmieder and Kring, 2020, and references therein). Thus, if the impactor flux was normal during the ~30 m.y. after the LCPB, ~100 craters >20 km would have formed during this time if the entire Earth had been land. Of the known 20 Middle–Late Ordovician craters, six are larger than 16 km: Ames (16 km), Tunnunik (25 km), Charlevoix (54 km), Slate Islands (30 km), Clearwater Lake East (22 km), and Lawn Hill (18 km). Three of them occur at an average distance of ca. 1100 km from each other in eastern Canada. Extrapolating to the entire Earth yields that ~420 large craters would have formed after the LCPB. This crude exercise would imply a factor of ~4 increase in the flux of larger than 1 km impactors, but this is evidently an estimate with considerable statistical uncertainty. The only robust insight that can be gained is that the total flux of impactors creating craters larger than ~20 km most likely did not increase by more than one order of magnitude after the LCPB.

There are some additional complexities that need to be considered for a balanced picture. Firstly, it is crucial which size interval of the impactor flux is being considered. The size of the LCPB before the breakup, i.e., ~150 km in diameter, places an upper limit of the size of the fragments that could have hit Earth. We do not know the size distribution of the fragments that were ejected in the collision, but there is no evidence in the geological record from the ~30 m.y. following the LCPB of any biotic crisis similar to the Cretaceous–Paleogene (K-Pg) boundary event (Alvarez et al., 1980). Taking this at face value suggests that there was no observable flux increase to Earth after the LCPB breakup of impactors the size of the K-Pg event, i.e., with a diameter of ~10 km, although an impact of such a large object in the ocean with only minor global environmental effects cannot be entirely ruled out. It is likely that the increase in flux for crater-forming bodies in the size range e.g., 0.1–0.3 km in diameter, was significantly higher than for bodies >1 km. There is support for this in the compilation of Ordovician craters of which the majority are small to medium-sized in the range of ~1–8 km in diameter. Although smaller- to medium-sized impacts were numerous during the Ordovician, the impactor mass accreted by the Earth was comparatively small, i.e., only a fraction of the mass delivered by the K-Pg Chicxulub impactor in a single event (see also discussion by Schmieder and Kring, 2020).

A second aspect to be considered is the level of background impactor flux during the Paleozoic. It has recently been proposed that the impactor flux to the Earth-Moon system was higher by a factor of 2.6 for the past 290 m.y. compared to the geologic time before (Mazrouei et al., 2019a, 2019b; but see comment by Hergarten et al., 2019). Taking this proposal at face value implies that there would have been not 100 as estimated above, but ~40 craters >20 km in a 30 m.y. period in the background flux during the early Phanerozoic. The 420 craters estimated from the spatial distribution of the three large, Middle–Late Ordovician craters in eastern Canada would then, rather, represent a factor of 10 (and not 4) increase in the flux.

A crucial circumstance to consider is also the number of L-chondritic impactors in the background flux. If these made up, e.g., 1% of the background flux, then the excess craters represent a factor of 400 increase in the flux of L-chondritic bodies, assuming the background impactor flux in the early Paleozoic was the same as it is today. With a factor 2.6 reduced background flux compared to that of today, the excess craters would represent a factor 1000 increase in the flux of L-chondritic impactors. With the same setting regarding the total flux, but if the L-chondritic impactors made up ~33% (similar to their proportions among recent meteorite falls) of the background flux, the flux increase of L-chondritic impactors >1 km would be a factor of ~10–25. Clearly the latter values appear much more realistic.

In conclusion, we argue that the crater record suggests that the total flux of large impactors, e.g., ~0.1–1 km in diameter, after the LCPB did not increase significantly more than one order of magnitude. But there is most likely a trend with the flux increase (in numbers of objects, not necessarily in mass) being higher the smaller the size fraction of the impactors considered. The apparent preponderance of smaller impactors may be explained by the impact-disruption of the LCPB (Schmitz et al., 1997, 2001, 2003) and the formation of weakly coherent (and often melt-bearing) impact breccias in space, smaller fragments of which were eventually sent into Earth-crossing orbits (e.g., Kring and Boslough, 2014). Ordinary chondrites must have made up a major fraction of the impactor population in the background flux; otherwise, the ca. one order-of-magnitude increase in the total flux of asteroids to Earth after the LCPB breakup as seen in the crater ages of Figure 1 would represent an unrealistically high increase in flux of L-chondritic bodies.

Fossil Meteorites from Mid-Ordovician Seafloor Sediment

The idea that Earth experienced an asteroid shower following the breakup of the LCPB was first proposed based on the discovery of abundant fossil L-chondritic meteorites in mid-Ordovician limestone (Schmitz et al., 1997, 2001). Since 1993, a search program has been pursued with the workers and owners of the Thorsberg Quarry at Kinnekulle in southern Sweden in which all fossil meteorites (~1–21 cm in diameter) encountered during quarrying of the marine limestone are recovered and analyzed (for a review, see Schmitz, 2013, and also Schmitz et al., 2016). Based on the finds of the first 40 fossil meteorites, Schmitz et al. (2001) showed that the meteorite flux following the LCPB breakup was *at least* a factor of 69–173 higher than the recent flux. The range in the estimate reflects the uncertainty in the recent flux estimates, i.e., 5.7–14.3 kg of meteoritic material in the mass range 10^1–10^3 g per 10^6 km^2 per year, based on skywatch networks in Canada and meteorite search projects in the Nullarbor Desert in Australia (Halliday et al., 1989; Bevan et al., 1998; Bland, 2001; Drouard et al., 2019; Evatt et al., 2020). The quarrying of the Ordovician seafloor has proceeded at about the same rate the past two decades, and ~4–6 meteorites are found per year, which confirms the high spatial density of meteorites on the Ordovician seafloor and supports the paleoflux estimates by Schmitz et al. (2001). By February 2021, a total of ~130 fossil meteorites had been found, of which ~100 have been analyzed for chrome-spinel composition and classified so far. All except one of these are ordinary chondrites, and almost certainly they are L chondrites based on more detailed oxygen isotope and chondrule-size studies of a representative set of fossil meteorites (Bridges et al., 2007; Greenwood et al., 2007; Heck et al., 2010). Furthermore, the dramatic increase in the flux of micrometeorites with a confirmed L-chondritic composition simultaneously with the deposition of the fossil meteorites supports an L-chondritic origin of the many larger fossil meteorites (Schmitz et al., 2019a). One of the fossil meteorites found, however, represents a new type of achondritic meteorite not known from the global collections of recently fallen meteorites (Schmitz et al., 2016).

Although we know that the area of the Thorsberg Quarry where the fossil meteorites were found represents less than 30,000 m^2, detailed meteorite paleoflux calculations like the one performed by Schmitz et al. (2001) are difficult to work out for a number of reasons: (1) not all meteorites are recovered or reported, (2) the different limestone beds are quarried to different extents and in various ways at different times, (3) the precise position (at centimeter-resolution) of a meteorite in the strata is not always possible to determine, and (4) pairing of meteorite fragments is not possible (see Schmitz et al., 2001). The steady recovery rate in the quarry of fossil meteorites in the past decades and several large (10–20 cm in diameter) meteorites found in different limestone beds also in more recent years tend to support the conclusions in Schmitz et al. (2001) (Fig. 3). The number of >10-cm-sized meteorites compared to the number of smaller meteorites recovered supports a declining rate in flux increase when larger fraction size is considered. This provides additional support for a maximum one order-of-magnitude increase in the flux of even larger L-chondritic objects, e.g., in the 0.1–1 km-size interval.

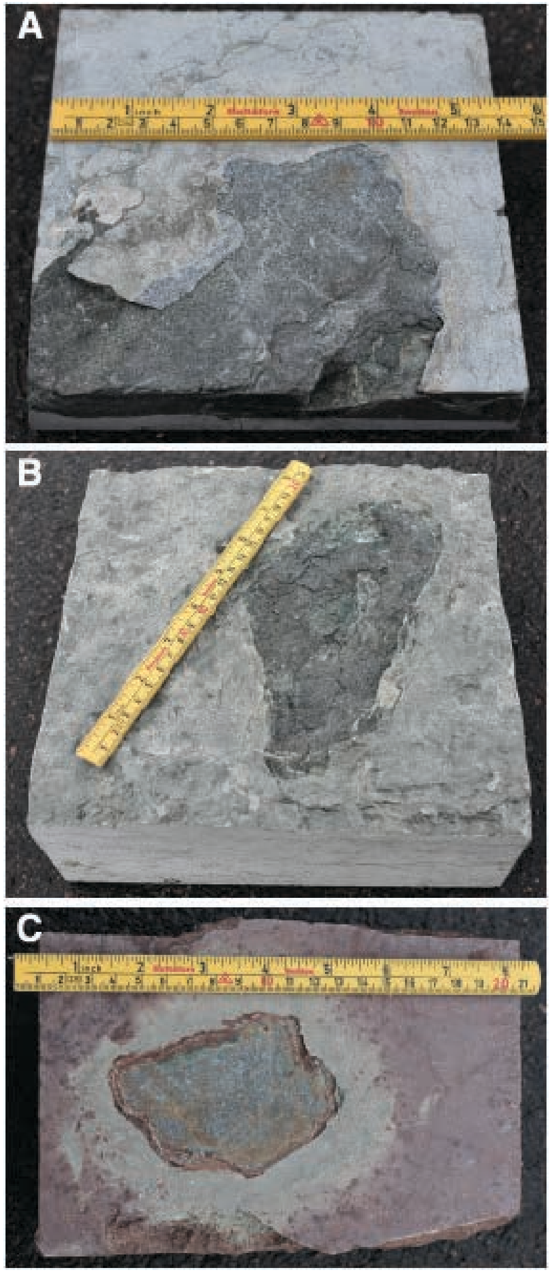

Figure 3. Three examples are shown of large fossil ordinary chondrites found in the Thorsberg Quarry in southern Sweden from 2017 to 2020. (A) Only a part of this meteorite probably from the Gråkarten bed was recovered. The meteorite is 11 × >9 × >2.5 cm large and was found in 2020. (B) Fossil meteorite, 17 × 8 × ? cm large, found in the Botten bed in 2019. (C) Fossil meteorite, 9 × 7 × ? cm, found in the Sextummen bed in 2017. The ordinary chondritic origin of the meteorites was confirmed by chemical analyses of their chromite grains. See Schmitz (2013) for details on the Thorsberg Quarry stratigraphy.

Micrometeorite Fluxes through the Phanerozoic

The LCPB breakup has not only left a strong signal in the form of macroscopic fossil meteorites but also as extremely abundant ~30–250-µm-sized chromite grains from L-chondritic micrometeorites dispersed in the sediments that formed after the breakup (Schmitz, 2013; Schmitz et al., 2019a). We know that the chromite grains originate from micrometeorites because they typically contain high concentrations of solar wind-implanted Ne and He (Heck et al., 2008; Meier et al., 2010). Solar wind ions only penetrate the outermost 100 nm; hence, the chromite grains must, at some time, have shared surface with the enclosing silicate micrometeoroid. Our records of the distribution of L-chondritic chromite in Ordovician sediments indicate a clear two orders-of-magnitude increase in the flux of micrometeorites to Earth during at least 2 m.y. after the LCPB breakup (Fig. 4; Table 2). In Ordovician limestone that formed before the breakup, we find a few meteoritic chromite grains (>63 µm) per hundred kilograms of rock, whereas in limestone that formed after the breakup there is between one and 10 L-chondritic grains per kilogram of sediment (Schmitz et al., 2019a).

To place the post-LCPB chrome-spinel enrichments in a larger perspective, we built the Astrogeobiology Laboratory in 2013 and have routinely dissolved 100 kg-sized samples of condensed limestone from different time periods in acids there to recover extraterrestrial spinel grains. We now have data for the flux of extraterrestrial chrome spinel to Earth from a total of 8484 kg of dissolved sediment that represents 15 "time windows"

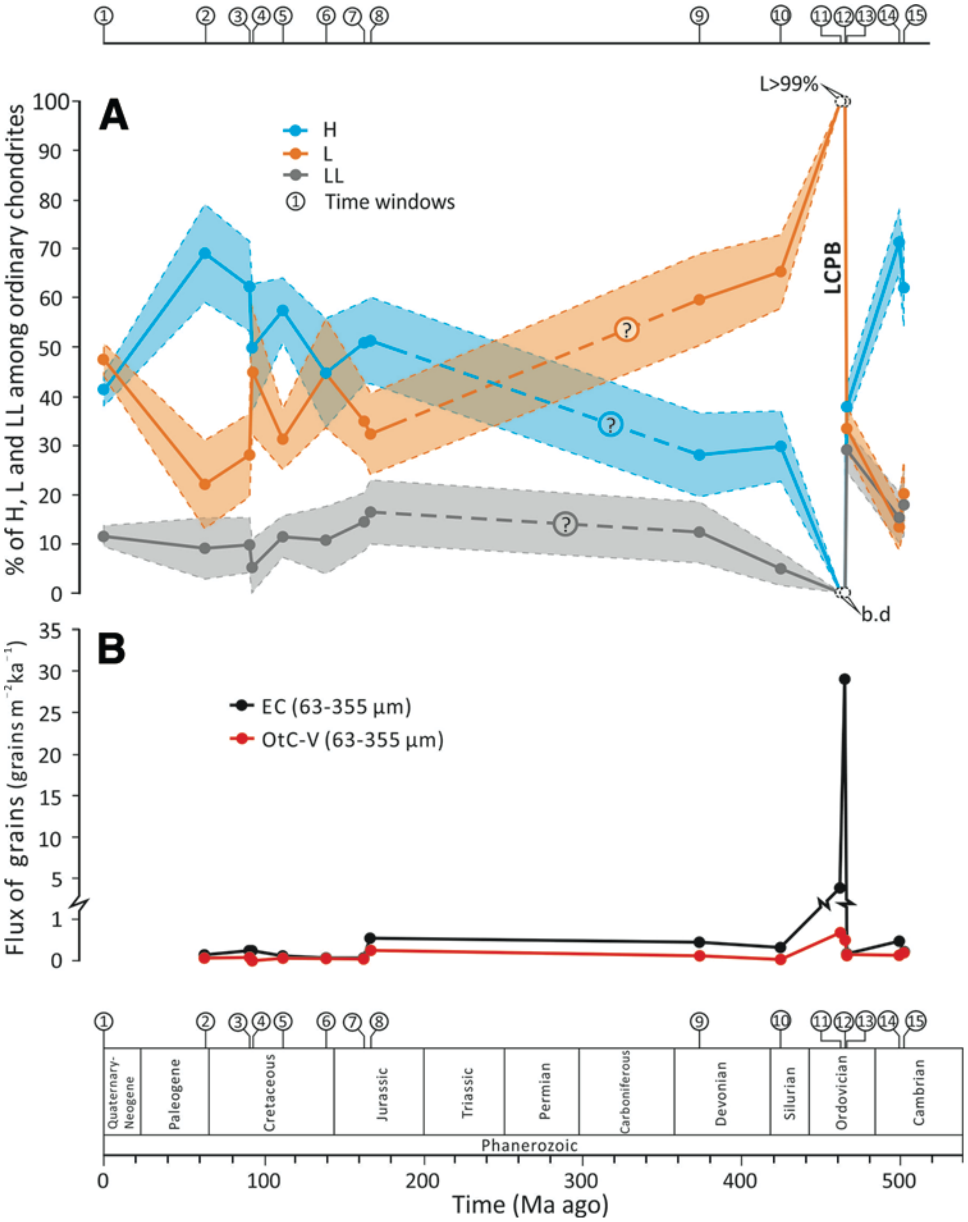

Figure 4. (A) Percentages of H, L, and LL chondrites among ordinary chondrites during 15 Phanerozoic time windows studied and today (based on data in Table 2 and from Terfelt and Schmitz, 2021). Both the small (32–63 µm) and the large (>63 µm) fractions of equilibrated, ordinary chondritic grains were included after 10% overlap correction for TiO_2 values. Colored shadow regions indicate 1σ uncertainties evaluated through binomial probability. Dashed bold lines and question marks represent extrapolated percentages. Numbers of time windows can be found in Table 2. The two synchronous, pre-LCPB time windows (ca. 467–466 Ma) were merged into a single one (no. 13). (B) Extraterrestrial flux data from the same 15 Phanerozoic time windows based on the >63 µm fraction. EC—equilibrated, ordinary chondritic chromite grains. OtC-V—other chrome-spinel grains with, e.g., V_2O_3 content >0.45 wt%. The OtC-V grains mainly originate from meteorites other than the equilibrated ordinary chondrites. See Terfelt and Schmitz (2021) for details. The two synchronous, pre-LCPB time windows are presented separately here but almost overlap, and therefore they are also labeled as a single one (no. 13). LCPB–L-chondrite parent body.

TABLE 2. OVERVIEW OF TIME WINDOWS STUDIED AND THEIR EXTRATERRESTRIAL CHROME-SPINEL GRAIN CONTENT

Time window[ref.]	Ma	kg of rock	EC^{32}	$OtC\text{-}V^{32}$	$EC/OtC\text{-}V^{32}$	EC^{63}	$OtC\text{-}V^{63}$	$EC/OtC\text{-}V^{63}$	EC^{32} m^{-2} ka^{-1}	EC^{63} m^{-2} ka^{-1}
2. Early Paleocene[1]	ca. 66–61	843	74[a]	39[a]	1.9	12	5	2.4	1.3	0.15
3. Late Cretaceous[2,5]	ca. 92–91	944	108	45	2.4	5	3	(1.7)	2.9	0.25[b]
4. Late Cretaceous[2]	ca. 94–92	432	50	4	12.5	9	0	>9.0	2.9	0.25[b]
5. Early Cretaceous[3]	ca. 117–103	689	217	73	3.0	10	5	2.0	2.7	0.12
6. Early Cretaceous[4]	ca. 145–133	1652	79	25	3.0	2	2	(1.0)	3.0	(0.08)
7. Middle Jurassic[5]	ca. 166–164	214	n/a	n/a	n/a	142	35	4.1	n/a	0.17
8. Middle Jurassic[5]	ca. 168–166	609	66[c]	9[c]	7.3	44	20	2.2	4.7[c]	0.54
9. Late Devonian[6]	ca. 374–372	898	n/a	n/a	n/a	46	12	3.8	n/a	0.45
10. Late Silurian[7]	ca. 426–424	321	154	13	11.9	10	1	10.0	4.8	0.31
11. Middle Ordovician[8]	ca. 463–462	51	n/a	n/a	n/a	23	4	5.8	n/a	3.8
12. Middle Ordovician[7]	ca. 466–465[d]	102	>7000	n/a	n/a	474	8[e]	59[e]	>429	29
13. Middle Ordovician[4,9]	ca. 467–466[f]	285	189	n/a	n/a	26	20	1.3	1.2	0.16
13. Middle Ordovician[10]	ca. 467–466[f]	791	228	49	4.7	15	14	1.1	2.4	0.16
14. Late Cambrian[5]	ca. 500–499	341	159[g]	44[g]	3.6	41	11	3.7	2.9	0.48
15. Late Cambrian[5]	ca. 503–502	312	129	42	3.1	18	15	1.2	1.7	0.23
Grand total	ca. 503–61	8484	>8453	343	n/a	877	155	n/a	n/a	n/a

Notes: Modified from Terfelt and Schmitz (2021). Numbering of time windows are the same as in Figure 4. EC—equilibrated ordinary chondritic chromite grains. OtC-V—other chrome-spinel grains with, e.g., V_2O_3 content >0.45 wt%. These grains originate from meteorites other than the equilibrated ordinary chondrites. See Terfelt and Schmitz (2021) for details. EC^{32} and $OtC\text{-}V^{32}$—EC and OtC-V grains 32-63 µm large. EC^{63} and $OtC\text{-}V^{63}$—EC and OtC-V grains 63-355 µm large. Values in parentheses are based on only a few grains. [a]From 633 kg. [b]Flux based on the 14 grains from both sample sets in the Late Cretaceous. [c]From 106 kg. [d]Post-LCPB. [e]All OtC-V grains likely from unequilibrated ordinary chondrites. [f]Pre-LCPB. [g]From 217 kg. References: [1]Boschi et al. (2020), [2]Martin et al. (2019), [3]Pangaea Data Archiving PDI-24476, [4]Schmitz et al. (2017), [5]Terfelt and Schmitz (2021), [6]Schmitz et al. (2019b), [7]Martin et al. (2018), [8]Alwmark and Schmitz (2009), [9]Heck et al. (2017), [10]Schmitz et al. (2019a).

during the Phanerozoic (Terfelt and Schmitz, 2021) (Fig. 4; Table 2). Admittedly, there are major time intervals that we have not yet studied, but for the period between 170 Ma in the Middle Jurassic and 60 Ma in the Paleocene, our coverage is sufficient for locating any potential breakup events that significantly changed the meteorite flux to Earth. There is also relatively good coverage from 503 Ma in the Middle Cambrian to 372 Ma at the end of the Devonian, which represents a 130 m.y. interval. Although our coverage is incomplete, we argue that the available data indicate that the flux of ordinary chondritic micrometeorites to Earth may have been more-or-less constant throughout the Phanerozoic (Fig. 4; Table 2). The only significant exception observed to date is after the LCPB breakup, when the flux increased by two orders of magnitude for about 2 m.y. For all other time periods we have studied, e.g., the Cambrian; Late Silurian; Late Devonian; Middle Jurassic; Early, middle, and Late Cretaceous; and the Paleocene, the flux of ordinary chondritic grains to the seafloor has been in the range of 0.1–0.3 grains per m^2 ka^{-1} (Table 2; Terfelt and Schmitz, 2021). For all time periods studied, the ordinary chondrites dominate over other types of chrome-spinel–bearing micrometeorites, although at times achondritic micrometeorites were more common than they are today (Heck et al., 2017).

In our reconstructions of the micrometeorite flux, each of the windows represented by a single point in Figure 4 represents the average of several large samples collected over stratigraphic intervals spanning up to 12 m.y. (Table 2, and references therein). Each sample is typically 100 kg in mass, and all stratigraphic levels studied—with two exceptions—yielded none or at the most 2–3 extraterrestrial grains >63 µm per sample. The two exceptions are the Ordovician post-LCPB samples that typically, per 100 kg of rock, give 200–500 L-chondritic grains >63 µm, and a decimeter-thick bed associated with the major faunal crisis at the Frasnian–Famennian boundary, which yielded 10 extraterrestrial chromite grains >63 µm per 100 kg rock. The latter grains represent a mixture of H-, L-, and LL-chondritic grains in the same ratios as in the background flux and may be related to an enhanced micrometeorite flux during postulated extreme minima in Earth-orbit eccentricity cycles (Schmitz et al., 2019b). If any of the other ca. 100-kg-sized samples studied by us had formed in the distal tail of an enhanced micrometeorite flux similar to that after the LCPB, we would have identified this tail already if the flux were only a factor of two to three higher than in the normal background flux. A resolvable signature of the tail from the excess LCPB micrometeorite flux is manifested by a factor of ~10 increase in the flux for at least 3–4 m.y. after the LCPB breakup (Fig. 4; Table 2). Our data for the time between 60 Ma and 170 Ma do not indicate any meteorite flux increases larger than a factor of two in any of the time windows or individual samples studied. The absence of evidence even of flux "tails" in any of the samples strongly argues against any major enhancements in the flux of ordinary chondritic grains during the time interval, like there was after the LCPB event. We conclude that our micrometeorite reconstructions are consistent with the insight from the terrestrial crater-age distribution, i.e., that the ordinary chondrites have dominated the flux in the meteorite–asteroid size range to Earth throughout the Phanerozoic. The flux increases in different size fractions, micrometeorites, meteorites, and asteroids in the Middle to Late Ordovician most likely reflect the same event: the breakup of the LCPB.

K-Ar Gas Retention Ages of Modern Meteorites

The consistency we see between the distribution of Phanerozoic crater ages and the micrometeorite flux, with only one profound flux peak (following the LCPB event), is also apparent in compilations of the K-Ar gas retention ages of the different types of meteorites falling on Earth today (Fig. 5). The K-Ar isotopic system measures the time when a body last experienced severe shock or thermal heating. Extensive studies have been performed of the K-Ar (or Ar-Ar) ages of most of the common types of meteorites falling on Earth today (e.g., Keil et al., 1994; Bogard, 1995, 2011; Swindle et al., 2014). All of the studied meteorite types, except the H and L ordinary chondrites, appear to dominantly have K-Ar ages going back to the first billion years of solar system history. The H and L chondrites show an enigmatic bimodal pattern with gas retention ages either >3.4 Ga or <1.5 Ga (and mostly <1 Ga) (Fig. 5; Swindle et al., 2014). The many young ages indicate that major collisions involving ordinary chondrites were much more common in the latest ca. 1 g.y. than in the ca. 2 g.y. before that. The L chondrites show a much more focused pattern, with the majority of the L chondrites originating from one major collisional event at ca. 470 Ma. The H chondrites appear to originate from several smaller breakup events or impacts on the H-chondrite parent body through the past ca. 500 m.y. We note that the distribution of K-Ar ages of the H and L chondrites falling on Earth today appears to be reflected in the flux of micrometeorites to Earth through the past 500 m.y. (cf. Fig. 4). The L-chondritic micrometeorites show one single flux peak that is two orders-of-magnitude large shortly after the LCPB breakup. The flux variations of H-chondritic micrometeorites through the Phanerozoic can be reconciled with a complex history of several smaller shock events on the H-chondrite parent body (Wittmann et al., 2010), which each time lead to an increase in the flux of a factor of two to three, i.e., nothing comparable in size to the flux increase seen for the L chondrites after the LCPB breakup.

The ^{3}He Record of Family-Forming Breakup Events

One more clue comes from reconstructions of the distribution of extraterrestrial ^{3}He in sedimentary sections. This approach has the advantage that sample sizes for ^{3}He analyses are less than 1 g as compared to 100 kg for the chrome-spinel approach. Ken Farley and co-workers have carefully scanned sediment sections representing the past 100 m.y. for positive anomalies in extraterrestrial ^{3}He (Farley et al., 1998; Mukhopadhyay et al., 2001; Farley, 2009; Farley et al., 2006, 2012). Five such distinct anomalies have been discovered, with three in the Late Cretaceous and two in Cenozoic strata. These anomalies are characterized by small, typically a factor of four to five, increases in the amount of ^{3}He from micron-sized interplanetary dust particles in the sediment. The ^{3}He was implanted by the solar wind while the dust particles traveled through space. The Phanerozoic sedimentary record that is older than 100 Ma has not been scanned systematically for extraterrestrial ^{3}He, but two anomalies are known. One such anomaly was recently registered in terminal Permian sediments, but again the observed increase is not more than a factor of three to four (Onoue et al., 2019). The seventh known Phanerozoic ^{3}He anomaly registers the breakup of the LCPB in the mid-Ordovician, but this anomaly is much more dramatic than the six other anomalies. The amount of extraterrestrial ^{3}He increases by two orders of magnitude over a few decimeters of sediment section and is accompanied by a similar large increase in (>32 µm-sized) L-chondritic chromite grains (Schmitz et al., 2019a).

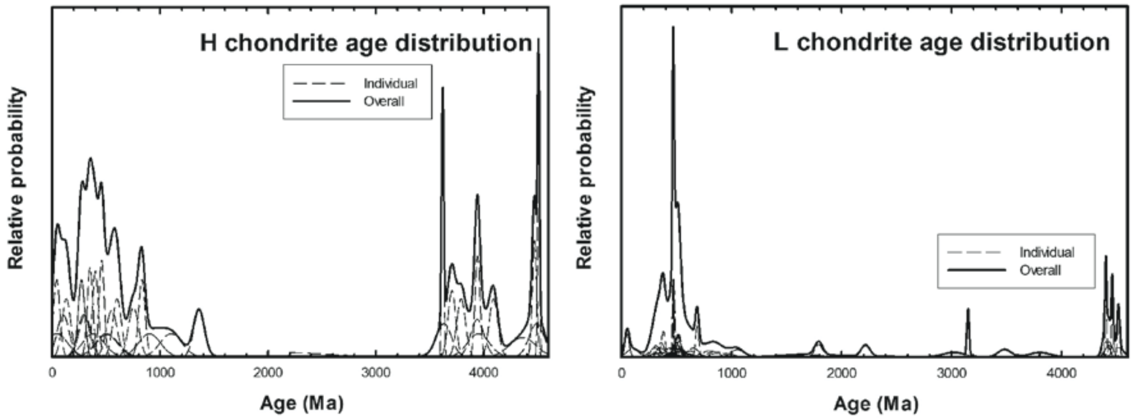

Figure 5. K-Ar ages of recent H and L chondrites are plotted (from Swindle et al., 2014). The plots show individual probability distribution for ages of individual meteorites (dashed line) and a combined probability distribution (solid line) for all of the data. The diagrams take into account the uncertainties in the individual data points in a graphical way by giving each data point equal area; see further Swindle et al. (2014) and Schmitz (2013).

We have studied sediment sections recording three of the <100-m.y.-old ^{3}He anomalies for extraterrestrial spinels. In late Miocene sediments recording a ~5-fold enrichment in ^{3}He deposited during a 1.6 m.y. time period (Farley et al., 2006; Montanari et al., 2017), we found no extraterrestrial spinel grains at all (Boschi et al., 2019). The absence of extraterrestrial spinels is expected because the anomaly is thought to reflect the breakup of the >150 km asteroid that created the Veritas asteroid family at ca. 8.3 ± 0.5 Ma. The Veritas asteroids are of the spectral C type, i.e., they likely correspond to carbonaceous chondrites that do not contain substantial amounts of chrome-spinel grains in the size fraction (>32 µm) that we study. The late Miocene ^{3}He-rich strata have also been searched for impact ejecta but without success (Montanari et al., 2017). In the late Eocene, a ~4-fold enrichment in ^{3}He is registered in sedimentary strata that formed during a 2 m.y. period during which two large impact craters also formed (Popigai and Chesapeake Bay) (Farley et al., 1998; Farley, 2009). There is no obvious enrichment in extraterrestrial chromite grains over this extended ^{3}He anomaly, but at a level 20 cm above the Popigai ejecta bed, which corresponds to the time of the Chesapeake Bay impact event (Glass, 2019), we find a decimeter-thick interval with abundant (17 grains in 100 kg rock), unusually well-preserved H-chondritic chromite grains (>63 µm) (Schmitz et al., 2015; Boschi et al., 2017). One possibility is that these grains represent regolith from the Chesapeake Bay projectile that was distributed globally following the impact. Also, considering the identification of an ordinary chondritic component by chromium isotopes in the Popigai impact ejecta (Kyte et al., 2011), it is possible that the late Eocene ^{3}He anomaly is related to a collisional event involving one or two ordinary chondritic asteroids (Schmitz et al., 2015; Boschi et al., 2017).

In Late Cretaceous condensed sediments in the Bottaccione section in Italy, three ^{3}He anomalies have been discovered: the "K3" anomaly in the Turonian, "K2" in the Santonian, and "K1" in the Campanian (Farley et al., 2012). The K3 and K1 anomalies represent ~4-fold enrichments in ^{3}He with durations of ca. 2 m.y., whereas the tiny K2 anomaly only represents a ~2-fold enrichment over a few 100 k.y. We have searched the sediments that formed in the Turonian just before and during the K3 anomaly for extraterrestrial spinel grains. The results may indicate a weak, factor of two, increase in H-chondritic chromite grains associated with the ^{3}He anomaly that possibly reflects a small cratering event in the asteroid belt involving the H-chondrite parent body (Martin et al., 2019; Boschi et al., 2020).

From the ^{3}He record we can conclude that at least during the past 100 m.y., Earth experienced nothing comparable in magnitude to the increase in dust flux seen after the LCPB event. The ^{3}He proxy, contrary to the chrome-spinel proxy, would give a signal for dust from all types of breakup events, i.e., from both carbonaceous and ordinary chondritic bodies. However, during the past 100 m.y., none of the many asteroid family-forming events known based on astronomical data (Nesvorný et al., 2015; Reiners and Turchyn, 2018) resulted in a dust-flux peak of the LCPB-breakup magnitude (see also the next section). The late Miocene Veritas breakup is estimated to have involved a body as large as the LCPB based on family member backtracking but only resulted in a factor of five increase in the flux of the most fine-grained dust to Earth. There is no evidence of any asteroid craters or impact ejecta related to this event (Farley et al., 2006).

Degassing of noble gas signals can be a problem in sediments as old as those from the Ordovician (Patterson et al., 1998). The ^{3}He concentrations in sediments that formed before the LCPB are very low, on average ~0.05×10^{-12} cm^3 STP g^{-1}, and increase to values around 5×10^{-12} cm^3 STP g^{-1} over the first meter of strata that formed after the LCPB (with peak values of 12.8×10^{-12} cm^3 STP g^{-1}, i.e., a factor of 250 enrichment) (Schmitz et al., 2019a). Although this ^{3}He record may be distorted by degassing, the coincident two orders-of-magnitude increase in L-chondritic chromite grains >32 µm provides independent support for the magnitude of the inferred ^{3}He enhancement. The ^{3}He signal reflects the most fine-grained, micron-sized fraction of the extraterrestrial flux to Earth, whereas the chromite grains represent micrometeorites typically in the 300–2000 µm size range. It is very likely that the flux increase for the most fine-grained dust was significantly higher than the increase for larger micrometeorites. From our studies of spinels across the much younger and less diagenetically altered late Eocene and Turonian ^{3}He anomalies, it appears that the increase in the flux of ^{3}He-rich fine dust is a factor of 5–10 higher than the corresponding increase in flux of extraterrestrial chromite grains >32 µm (Martin et al., 2019). This means that the partly degassed, factor of 100–250 enrichment of ^{3}He observed over the onset of the LCPB could even reflect a three orders-of-magnitude increase in the flux of the most fine-grained dust.

Where Are the Signatures of the Other Breakup Events?

Family-Forming Breakups as Seen in Astronomical Data

The fact that we only see one major peak in the flux of chrome-spinel–rich micrometeorites to Earth during the Phanerozoic and that this peak coincides in time with the only resolvable peak in the asteroid flux to Earth poses the question: Why are there no similar signatures either in the impact cratering or the micrometeorite record of any of the ~70 major family-forming breakup events proposed to have happened in the asteroid belt in the past ~0.5 g.y. based on astronomical data (Fig. 6; Terfelt and Schmitz, 2021)? Assigning absolute dates to breakup events based on orbital elements of asteroid family members is a complex endeavor, and age estimates for specific events have considerable uncertainties (see e.g., Nesvorný et al., 2015; Spoto et al., 2015; Paolicchi et al., 2019). There is general agreement, however, that many breakup events have occurred during the Phanerozoic. A compilation of such events is given in Reiners and Turchyn (2018) with ages calculated based on asteroid family data in Nesvorný et al. (2015). Of the ~70 families listed, 27 of them have more than ~500 members, and 16 of those have more than ~1000 members (Fig. 6). Fifteen of the families with more than ~500 members have spectral properties indicating that they are made

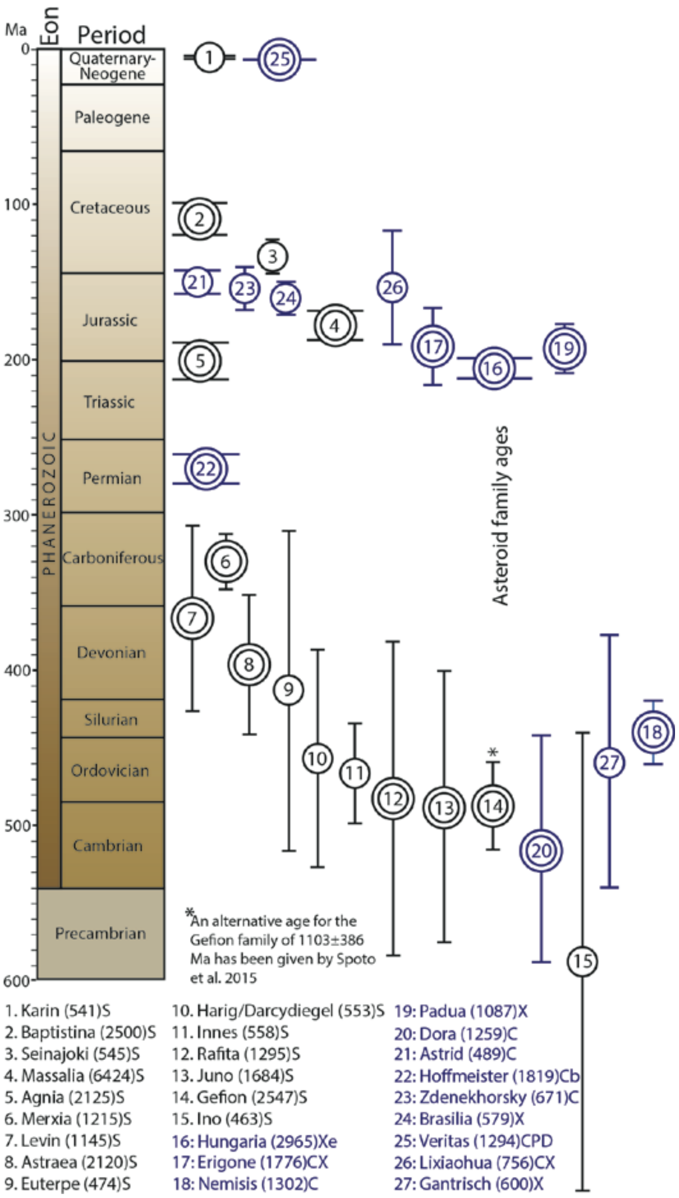

Figure 6. The timings of the 27 largest family-forming events in the asteroid belt during the Phanerozoic are plotted. Families colored black denote S- or V-type asteroids. Families colored blue denote asteroid family types other than S- or V-type. The S- and V-type asteroids contain large chrome spinel of the type searched for in Earth's Phanerozoic sedimentary strata (Fig. 4; Terfelt and Schmitz, 2021). All types of asteroid breakups are expected to have sent larger bodies to Earth that left an imprint in Earth's cratering record (Fig. 1). Despite the many large, Phanerozoic family-forming breakup events, Earth's records of impact craters (Fig. 1), micrometeorite fluxes (Fig. 4) and K-Ar gas retention ages of recently fallen meteorites (Fig. 5) only show a clear signal of one breakup: the L-chondrite parent body event at 466 Ma. In the figure, the largest families (>1000 members) are highlighted with double circles. In the legend, the number of family members is within brackets followed by the family taxonomic type. The ages with uncertainties and taxonomic types of the asteroid families follow Reiners and Turchyn (2018), as do the number of family members except for Seinajoki, where we follow Spoto et al. (2015).

up of material rich in the types of large chrome-spinel grains on which we base our reconstructions of the Phanerozoic micrometeorite flux (Fig. 6). Mainly the spectral S- and V-type asteroids contain large chrome-spinel grains (Terfelt and Schmitz, 2021). It could still be that we have simply been unlucky and missed the signatures of the breakups of any of the 15 major chrome-spinel–rich asteroids other than the LCPB. However, if we consider that none of the altogether 27 Phanerozoic major (>500 members) asteroid family-forming events (including chrome-spinel–poor asteroids) other than the LCPB event left a resolvable signal in the cratering record, this raises the possibility that only the LCPB event led to a major (orders-of-magnitude) increase in the flux of micrometeorites to Earth during the Phanerozoic. The general relation between Phanerozoic asteroid breakup events and meteorite fluxes based on chrome spinel is further discussed in Terfelt and Schmitz (2021).

The Baptistina and Flora Family-Forming Events

By backtracking the orbits of asteroids among the members of the Baptistina asteroid family in the inner main belt, Bottke et al. (2007) estimated that the ~170 km parent body of the Baptistina family broke up at 160 Ma, with an uncertainty range between 190 Ma and 140 Ma (see also Claeys and Goderis, 2007). Masiero et al. (2012) suggested a revised breakup age of 190 ± 30 Ma based on astronomical data. This is one of the youngest major asteroid family-forming events, and it resulted in a family of 2500 members. Reiners and Turchyn (2018) estimated an age of 110 Ma for the event based on the family compilation of Nesvorný et al. (2015). This is similar to an age of ca. 100 Ma as estimated by Paolicchi et al. (2019). Based on detailed spectral studies, Reddy et al. (2014) showed that the Baptistina family members have an LL-chondritic composition. A major part of the age interval from 100 Ma to 210 Ma, suggested by different authors for the Baptistina breakup, has now been covered by us using the chrome-spinel approach. We have good coverage from 91 Ma to 168 Ma, with small gaps at 94–103 Ma, 117–133 Ma, and 145–164 Ma. In none of the first samples after any of these 9–19-m.y.-long gaps is there any indication of an LL-chondritic contribution to the micrometeorite flux higher than the ~10% that the LL chondrites comprise of the total ordinary chondritic flux today (Meteoritical Bulletin Database, 2021 [May]) as well as in the Late Devonian and the Late Silurian (Martin et al., 2018; Schmitz et al., 2019b). If the Baptistina breakup occurred in any of these gaps we would have seen the "tail" of an enhanced LL-chondritic flux in the samples studied. Could the Baptistina breakup have occurred between 170 Ma and 220 Ma, the period during which Masiero et al. (2012) date the breakup and a period for which we have no data? Even today, the L chondrites, 466 m.y. after the LCPB breakup event, make up a third of the meteorite flux to Earth. Martin et al. (2018) showed that in the Late Silurian, 40 m.y. after the LCPB, there was still a recognizable, ca. factor two or three, imprint of the LCPB event on the micrometeorite flux. In our sample from the Jurassic, which is 166–168 m.y. old, the LL-chondritic contribution is only 10% of the total ordinary chondritic contribution, just like through most of the Phanerozoic. The absence of a weak but significant "tail" enhancement of LL-chondritic chromite also in the 166–168-m.y.-old sample makes it unlikely that there was a major increase in the LL-chondritic flux in the period 170–220 Ma. The large Morokweng impact structure formed from an LL-chondritic impactor at ca. 146 Ma (Maier et al., 2006; Kenny et al., 2021), but there is no indication in the cratering record of any peak in the flux of asteroids at any time in the period 100–220 Ma like that after the LCPB event (Fig. 1). Why has the breakup of the 150-km-large LCPB left such a strong impact on the micrometeorite and asteroid influx to Earth, and the much younger 170-km-sized Baptistina breakup apparently left no similar clear and recognizable signature?

Just as there is no obvious signal of the proposed 170-km-sized Baptistina breakup in Earth's cratering or sedimentary chrome-spinel record, there is neither any indication of such a signal in the K-Ar ages of recently fallen LL chondrites. Admittedly, the LL chondrites seem to record a different collisional history (i.e., a significantly higher degree of solid-state brecciation versus a lower degree of impact melting when compared to the H and L chondrites; Bischoff et al., 2018; Schmieder and Kring, 2018) and arguably, fewer LL chondrites have been analyzed for their K-Ar ages than H and L chondrites, but most K-Ar ages for the LL chondrites go back to the early solar system (Swindle et al., 2014). There are a few LL chondrites that experienced impact resetting in the last 1000 m.y., but there is nothing in the data indicating a major reset age in the 100–300 Ma interval. The LL chondrites making up ~10% of the ordinary chondrites falling on Earth today appear to have played a similar minor role throughout most of the Phanerozoic (Fig. 4). Only in one time slice studied by us, in the mid-Ordovician shortly before the breakup of the LCPB, were they more abundant, making up as much as a third of the micrometeorites reaching Earth (Heck et al., 2017). Previously, we argued that this higher abundance of the LL chondrites may reflect the late tail of the flux following the breakup of the Flora asteroid family with a dynamical age of 950 +200/–170 Ma, which is a likely source of the LL chondrites (Dykhuis et al., 2014; Heck et al., 2017). However, our new data for the Cambrian period show the same low (~10%) LL contribution to the flux as that of the recent flux, which rules out our previous explanation for the high, pre-LCPB flux of LL chondrites (Terfelt and Schmitz, 2021). With 14,000 members, the Flora family is one of the largest families in the asteroid belt, and spectral data for members of the family yield an LL-chondritic signature (Vernazza et al., 2008; Nesvorný et al., 2007). The family is also positioned close to the $\nu6$ secular resonance, which is known to produce Earth-crossing objects with high Earth-impact probabilities (Gladman et al., 1997; Nesvorný et al., 2007). One would expect that the flux of LL chondrites from the Flora breakup would have been high in the Cambrian, but there is no such signal. We do not understand the reason for the higher number of LL chondrites in the mid-Ordovician, pre-LCPB interval. In the same sediments, we find unusually high numbers of chrome-spinel grains (>63 µm) from achondritic micrometeorites (Heck et al., 2017), a signature that we do not generally see in any of the samples from other time slices studied. We know that both the high LL-chondritic and the achondritic contributions are not artifacts of, e.g., diagenesis, since the result can be reproduced between sections in Russia and Sweden, which are sites on the same paleocontinent 1100 km apart (Schmitz et al., 2019a). One possibility is that we have recorded a unique disturbance of the asteroid belt that led to unusual meteorite fluxes and also to the breakup of the LCPB, but more data are required before any conclusions can be drawn.

CONCLUSIONS

We have compared data from the Phanerozoic geological record on the flux to Earth of extraterrestrial matter in different size fractions, from the most fine-grained dust to kilometer-sized bodies. We show that there is only one clear peak in the flux of larger bodies to Earth in the distribution of the ages of known impact structures on Earth. There appears to be an excess by one order of magnitude of craters, by number, in the interval ca. 470–440 Ma in the Middle–Late Ordovician. Most of these "excess" craters are likely related to the breakup of the LCPB in the asteroid belt at 465.8 ± 0.3 Ma. The Middle–Late Ordovician craters are mostly small, in the range of 1–8 km in diameter, which is indicative of a shower of relatively small (<1 km in diameter) asteroids following the LCPB event. The peak in Ordovician craters is matched by a two orders-of-magnitude peak in the flux of L-chondritic micrometeorites to Earth as well as a major increase in the flux of the most fine-grained extraterrestrial dust as shown by the ^{3}He distribution in Ordovician sedimentary strata. In correspondence, the K-Ar measurements of recently fallen meteorites only provide evidence of one major breakup event during the Phanerozoic, the breakup of the LCPB at ca. 470 Ma. In the asteroid belt, ~70 family-forming breakup events have been dated to the Phanerozoic by backtracking the orbits of family members. None of these breakup events can be related to an increase in the flux of extraterrestrial matter in different size fractions at a magnitude similar to that after the LCPB. If ordinary chondritic asteroids had represented only a small fraction of all crater-forming bodies that hit Earth during the Phanerozoic, then a one order-of-magnitude increase in the flux of L-chondritic asteroids after the LCPB would not have stood out in the cratering record. Apparently, ordinary chondrites most likely dominated the flux of meteorites and large bodies to Earth during the entire Phanerozoic. Throughout this period, only a small region of orbital space delivered most of the meteorites and larger bodies that reached Earth.

ACKNOWLEDGMENTS

We are grateful to Walter Alvarez for encouragement, inspiration, and support over the years relating to our chrome-spinel project. We thank Steven Goderis and an anonymous reviewer for many helpful comments that improved the paper. This study was supported by grants to B. Schmitz from the European Research Council (ASTROGEOBIOSPHERE, 213000), the Knut and Alice Wallenberg Foundation, and the Swedish Research Council. Support to S. Liao was provided through the National Natural Science Foundation of China (42073060) and the pre-research phase of the Project on Civil Aerospace Technologies (D020202 and D020302) funded by the Chinese National Space Agency.

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Manuscript Accepted by the Society 4 October 2021
Manuscript Published Online 2 March 2022

Printed in the USA