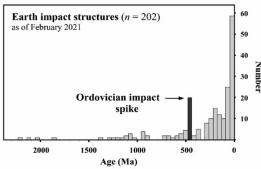
IMPACT-CRATER AGES AND MICROMETEORITE PALEOFLUXES COMPARED: EVIDENCE FOR THE IMPORTANCE OF ORDINARY CHONDRITES IN THE FLUX OF METEORITES AND ASTEROIDS TO EARTH DURING THE PAST 500 MILLION YEARS. B. Schmitz<sup>1</sup>, M. Schmieder<sup>2</sup>, S. Liao<sup>3</sup>, E. Martin<sup>1</sup>, and F. Terfelt<sup>1</sup>. <sup>1</sup>Astrogeobiology Laboratory, Department of Physics, Lund University, Lund, Sweden (birger.schmitz@nuclear.lu.se), <sup>2</sup>HNU Neu-Ulm University of Applied Sciences, Neu-Ulm, Germany, <sup>3</sup>Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing, China.

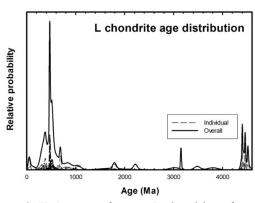
**Introduction:** Although the ~200 impact craters known on Earth represent only a small fraction of the craters originally formed, the available data suggest an excess by one order-of-magnitude of craters, by number, in the interval ~470-440 Ma in the Ordovician [1, 2]. It is a matter of debate whether the Ordovician "excess" craters reflect a preservation bias [3], or are related to the breakup of the L-chondrite parent body (LCPB) in the asteroid belt 465.8 ±0.3 Ma [2, 4]. Here we summarize five independent lines of empirical evidence providing support for the latter view.



**Figure 1.** Histogram showing the age distribution of terrestrial impact structures. Note the distinct Ordovician impact spike around 470 to 450 Ma, see further [1, 2, 5].

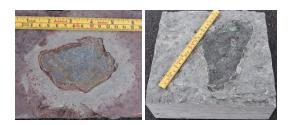
Crater densities: Most of the Ordovician craters are found in eastern North America and Baltoscandia, regions with enhanced preservation potential for impact craters. However, this fact can also be used to establish minimum crater spatial densities for the largest craters with the highest preservation potential [1]. Extrapolations of such observed densities on a global scale are consistent with a one order-of-magnitude increase in the flux of large impactors following the LCPB breakup.

K-Ar ages of recent meteorites: The record of K-Ar gas retention ages of many different types of recently fallen meteorites only document one major breakup in the asteroid belt during the Phanerozoic, the LCPB event [6, 7]. Among the meteorites falling on Earth today about a third originate from this event. It would be remarkable if the conspicuous peak in L-chondritic K-Ar ages at ~470 Ma was not matched by a corresponding enhanced flux of L chondrites to Earth shortly after the breakup.



**Figure 2**. K-Ar ages of recent L chondrites, from [7]. 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, see [7] for details.

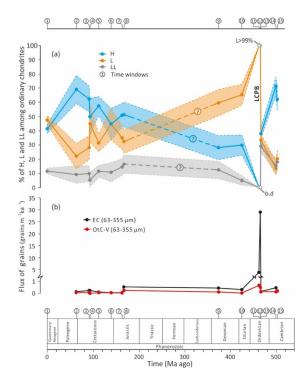
Fossil meteorites: More than 130 fossil meteorites (1-21 cm large) have now been found during quarrying of marine limestone that formed within two million years after the LCPB event, providing strong empirical support for an enhanced flux of meteorites at the time [1]. Both the spatial density of the meteorites on the Ordovician seafloor and the ratio of fossil L chondrites versus other types of meteorites found provide appealing evidence for a two orders-of-magnitude increase in the flux of L chondrites. Only one non-L-chondritic meteorite has so far been found.



**Figure 3.** Examples of two large fossil ordinary chondrites found in the Thorsberg quarry, southern Sweden, in recent years. The measuring stick in the image to the right is 20 cm long.

**Micrometeorite flux:** A similar pattern as in the cratering and K-Ar isotopic records, with only one prominent flux peak, is emerging in studies of the flux of micrometeoritic chrome-spinel through the Phaner-

ozoic. Searches for micrometeoritic chrome-spinel grains in 8484 kg of sedimentary limestone representing fifteen different time windows through the past 540 Myr indicate a nearly constant flux of ordinary chondritic chrome-spinel grains [8]. The only exception is after the LCPB event, when the flux increased by at least two orders of magnitude. The recovered chrome-spinel grains dominantly represent large micrometeorites (>300  $\mu m$ ) and as such are representative also of the flux of larger meteorites to Earth. This is confirmed by the observed parallel flux increases for larger fossil meteorites and micrometeorites in the two million years after the LCPB event, as well as in studies of recent micrometeorites.



**Figure 4.** (a) Percentages of H, L and LL chondrites among ordinary chondrites during fifteen Phanerozoic time windows studied and today, see [1, 8] for details. (b) Extraterrestrial flux data from the same fifteen Phanerozoic time windows based on the >63  $\mu$ m 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 [1, 8] for details.

**Helium-3 records:** The sedimentary record for the past 100 million years has been studied in detail for helium-3 isotopic anomalies that document increases in the flux of the most fine-grained (typically  $<20~\mu m$ ) extraterrestrial dust to Earth, e.g. [9]. None of the five discovered helium isotopic anomalies indi-

cates flux enhances higher than a factor of five. This implies that any accompanying (at a lower level) increase in the flux of larger micrometeorites, meteorites or asteroids hardly would be discernible in the geological record, see also [1, 9].

**Discussion:** We argue that the present situation, with a clear dominance of ordinary chondritic matter in the large (>300  $\mu$ m) micrometeorite and macroscopic meteorite fractions, has prevailed at least for the last 540 Myr [1, 8]. 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.

Our chrome-spinel data together with the abundance of fossil meteorites on the Ordovician sea floor sets an upper limit at one order of magnitude in the increase in flux of large (>0.1 km-diameter) L-chondritic projectiles to Earth following the LCPB.

Astronomical backtracking studies of the orbits of asteroid family members indicate about 70 major family-forming breakups within the past ~540 Myr of which none apparently has left any profound imprint in Earth's geological record, see [1]. The L chondrites have still not been convincingly linked to any of the known asteroid families. One possible explanation is that this collision was more violent, fragments were completely dispersed and no asteroid family formed. The apparent uniqueness of the signature of the LCPB event represents a major enigma in planetary science.

Concluding argument: The Ordovician peak in the crater-age record is best attributed to an asteroid shower following the LCPB breakup. A one order of magnitude increase in flux of larger, crater-forming L-chondritic projectiles would not stand out in the global cratering record if ordinary chondritic impactors had only represented a small fraction of all Phanerozoic impactors [1]. We suggest therefore that the origin of large impactors delivered to Earth during the past 540 Myr has mirrored the flux of micrometeorites and meteorites, with ordinary chondrites being an important or, most likely, the dominant (in numbers) component throughout.

References: [1] B. Schmitz et al. (2022) *Geol. Soc. Am. Spec. Pap.* 557, in press. [2] M. Schmieder and D.A. Kring (2020) *Astrobiology* 20, 91-141. [3] T. Kenkmann (2021) *MAPS* 56, 1024-1070. [4] Liao et al. (2020) *EPSL* 547, no. 116442. [5] M. Schmieder et al. (2019) *MAPS* 54, 1808-1827. [6] D.D. Bogard (2011) *Chemie der Erde* 71, 207-226. [7] T. Swindle et al. (2014) *Geol. Soc., London, Spec. Pub.* 378, 333-347. [8] F. Terfelt and B. Schmitz (2021) *PNAS* 118, no. 24. [9] K.A. Farley et al. (2012) *Geochim. Cosmochim. Acta* 84, 314-328.