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The meteorite flux of the past 2 m.y. recorded in the Atacama Desert

A. Drouard[1,2], J. Gattacceca[2], A. Hutzler[3], P. Rochette[2], R. Braucher[2], D. Bourlès[2], ASTER Team[2]*, M. Gounelle[4], A. Morbidelli[5], V. Debaille[6], M. Van Ginneken[6,7,8], M. Valenzuela[9,10], Y. Quesnel[2], and R. Martinez[11]

[1]Aix-Marseille Université, Centre National de la Recherche Scientifique (CNRS), Centre National des Etudes Spatiales (CNES), Laboratoire d'Astrophysique de Marseille (LAM), 13013 Marseille, France
[2]Aix-Marseille Université, CNRS, Institut de Recherche pour le Développement (IRD), Collège de France, Institut de la Recherche Agronomique (INRA), Centre Européen de Recherche et d'Enseignement en Géosciences de l'Environnement (CEREGE), 13545 Aix-en-Provence, France
[3]Lunar and Planetary Institute, Houston, Texas 77058, USA
[4]Institut de Minéralogie, de Physique des Matériaux et de Cosmochimie (IMPMC), Muséum National d'Histoire Naturelle, Sorbonne Universités, CNRS, UPMC & IRD, 57 rue Cuvier, 75005 Paris, France
[5]Laboratoire Lagrange, UMR 7293, Université de la Côte d'Azur, CNRS, Observatoire de la Côte d'Azur (OCA), 06304 Nice, France
[6]Laboratoire G-Time, Université Libre de Bruxelles, B-1050 Brussels, Belgium
[7]Analytical, Environmental and Geochemistry (AMGC), Vrije Universiteit Brussel, B-1050 Brussels, Belgium
[8]Geological Survey of Belgium, Royal Belgian Institute of Natural Science, B-1000 Brussels, Belgium
[9]Servicio Nacional de Geología y Minería (SERNAGEOMIN), Santiago, Chile
[10]Millennium Institute of Astrophysics (MAS), Santiago, Chile
[11]Museo del Meteorito, San Pedro de Atacama, Antofagasta, Chile

ABSTRACT

The evolution of the meteorite flux to Earth can be studied by determining the terrestrial ages of meteorites collected in hot deserts. We measured the terrestrial ages of 54 stony meteorites from the El Médano area, in the Atacama Desert, Chile, using the cosmogenic nuclide ^{36}Cl. With an average age of 710 ka, this collection is the oldest collection of nonfossil meteorites at Earth's surface. This allows both determination of the average meteorite flux intensity over the past 2 m.y. (222 meteorites larger than 10 g per km^2 per m.y.) and discussion of its possible compositional variability over the Quaternary Period. A change in the flux composition, with more abundant H chondrites, occurred between 1 and 0.5 Ma, possibly due to the direct delivery to Earth of a meteoroid swarm from the asteroid belt.

INTRODUCTION

The delivery of extraterrestrial matter to Earth is controlled by the complex dynamic evolution of the solar system bodies. The past flux of extraterrestrial matter to Earth's surface has been studied at different spatial and time scales. Impact craters allow quantification of the long-term flux, but only for large impactors (e.g., Mazrouei et al., 2019). At the other end of the size spectrum, micrometeorites allow study of the extraterrestrial dust reaching Earth (e.g., Genge, 2008; Heck et al., 2017). Meteorites allow estimation of the flux of intermediate-size (centimeter- to meter-scale) meteoroids to Earth's surface. Fossil meteorites may shed light on the very ancient flux (for a 1.75 m.y. time window during the Middle Ordovician, see, e.g., Schmitz et al., 2001; Schmitz, 2013). Meteor observations have allowed the intensity of the current flux of meteorites to Earth to be estimated (e.g., Halliday et al., 1989; Zolensky et al., 2006), while observed meteorite falls (1312 registered meteorites as of May 2019) provide information about meteorite flux composition over the last two centuries. On the other hand, meteorite "finds" (for which the fall has not been observed; 66,165 meteorites as of May 2019) allow the intensity and composition of the meteorite flux to be constrained on longer time scales more relevant to geological and astronomical processes (e.g., Bland et al., 1996; Benoit and Sears, 1996; Graf et al., 2001). Most meteorite finds come from Antarctica (64%) and hot deserts (~30%), which are suitable areas for both preservation and recovery. The terrestrial ages of hot desert meteorites are usually in the 30–0 ka range and rarely exceed 50 ka (Jull, 2006). Antarctic meteorites have older terrestrial ages, varying between ice fields, but they rarely exceed 150 ka (Welten et al., 2006). These time scales are still short with respect to those involved in the dynamic evolution of the solar system bodies (e.g., Bottke et al., 2005). Moreover, the large Antarctic meteorite collection, with older terrestrial ages, cannot be easily used to constrain the meteorite flux due to biases introduced by meteorite concentration mechanisms (Whillans and Cassidy, 1983), and the difficulty in identifying paired fragments (Zolensky, 1998), as opposed to passive in situ accumulation in hot deserts. The Atacama Desert in Chile is the oldest and driest of the hot deserts on Earth (Clarke, 2005; Dunai et al., 2005). It has been shown to be an important meteorite reservoir, with the highest meteorite density ever determined in hot deserts (Gattacceca et al., 2011; Hutzler et al., 2016). We present in this study the terrestrial ages of 54 meteorites recovered from the Atacama Desert.

SAMPLES

We randomly selected 54 unpaired meteorites from 388 that were found in the El Médano and Caleta el Cobre dense collection areas

*Georges Aumaître and Karim Keddadouche

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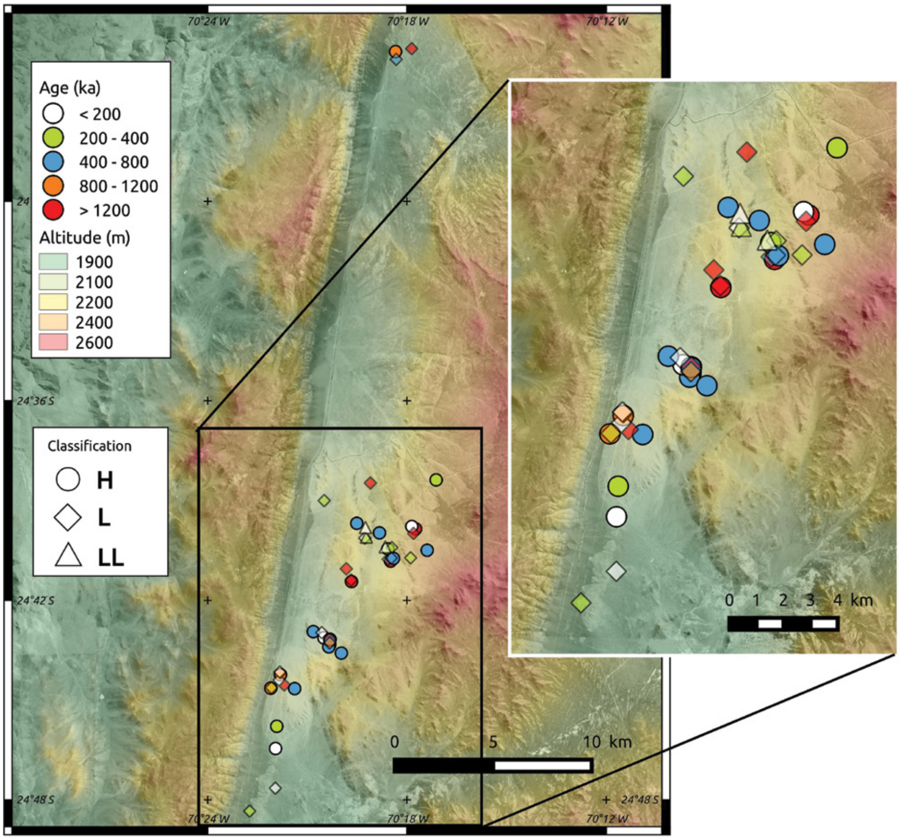

Figure 1. Map of El Médano and Caleta el Cobre areas of the Atacama Desert, Chile, with 54 dated samples, with their class (H, L, or LL) and their age. H—high iron; L—low iron; LL—low iron, low metal.

(Fig. 1). These two adjacent areas are collectively termed El Médano in this paper. These areas have been shown to bear the highest meteorite concentration in hot deserts (Hutzler et al., 2016). These 54 meteorites are all ordinary chondrites. Ordinary chondrites are the most abundant class of meteorites, and they are overrepresented in the El Médano collection (where they represent 96% of the meteorite population) because of recovery biases (Hutzler et al., 2016). The 54 meteorites span the three groups of ordinary chondrites: high-iron (H type; 25 meteorites), low-iron (L type; 26 meteorites), and low-iron low-metal (LL type; 3 meteorites). Based on recovery location, petrography, silicate geochemistry, and magnetic susceptibility, special care was taken to discard possibly paired meteorites to avoid statistical overrepresentation of large falls that can produce multiple meteorites. Terrestrial ages were determined by measuring the ^{36}Cl (half-life: 301 ± 0.01 k.y.) concentration in the FeNi metal fraction of these meteorites (see the GSA Data Repository[1] for complete data and methods).

OLDEST COLLECTION OF NONFOSSIL METEORITES

The absence of a geographic trend in the ages (Fig. 1) confirms that pairing did not affect the age distribution and was properly assessed by Hutzler et al. (2016). As an extra precaution, the few groups of meteorites with similar classification and terrestrial age were checked again for possible pairing using a variety of criteria, in particular, petrography. No pairing was evidenced. Although shielding in large meteoroids may account for overestimation of some ages, the measured cosmogenic radionuclide content of ordinary chondrite falls shows that shielding has affected only 3 out of 31 studied meteorites (Graf et al., 2001; Dalcher et al., 2013). Furthermore, the meteorite fall population is strongly biased toward large masses (more likely to be observed and recovered), as evidenced by their mass distribution compared to that of meteorite finds or theoretical estimates (e.g., Huss, 1990). We note that the three ordinary chondrites showing significant shielding (Richardton [USA], Uberaba [Brazil], and La Criolla [Argentina] meteorites) all have masses >40 kg. Such large meteorites are exceedingly rare in unbiased meteorite collections like the El Médano collection. Therefore, only a few percent of the El Médano meteorite collection may have been affected by shielding. This would correspond to a couple of meteorites with no consequence on the overall age distribution. With a mean terrestrial age of 710 ka, the El Médano collection is by far the oldest collection of nonfossil meteorites on Earth's surface (Fig. 2). Approximately 30% of the samples are older than 1 Ma, and two are older than 2 Ma.

For comparison, meteorites from other hot deserts and Antarctica have an average terrestrial age of only 12 ka and 99 ka, respectively (computed from 152 and 398 terrestrial ages, respectively, from the MetBase database [Koblitz, 2005]; in agreement with Jull, 2006). The results of the present study are consistent with the old ages of the Atacama Desert surfaces associated

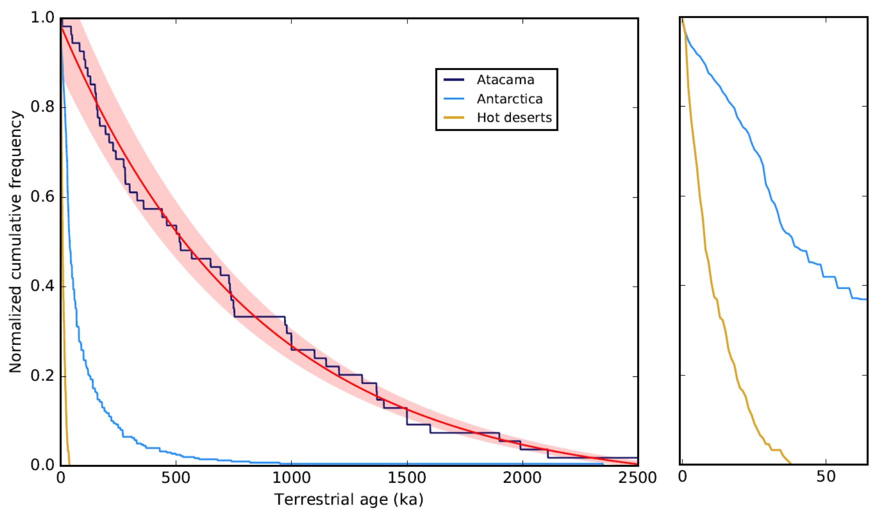

Figure 2. Cumulative terrestrial age distribution measured by ^{36}Cl (blue) and exponential best fit (red). Right panel is a focus on range 65–0 ka. Shaded area corresponds to maximum age uncertainty of 90 k.y., derived by propagation. Our results are compared to cumulative age distribution of Antarctic (light blue) and hot desert (yellow) meteorites. Both ^{14}C and ^{36}Cl age measurements were selected for Antarctica meteorites, whereas data for hot desert meteorites (Atacama Desert samples excluded) only consist of ^{14}C measurements.

[1]GSA Data Repository item 2019247, methods and terrestrial ages of the 54 meteorites studied in this work, is available online at http://www.geosociety.org/datarepository/2019/, or on request from editing@geosociety.org.

with long-standing hyperaridity (Clarke, 2005; Dunai et al., 2005), and they offer an explanation for the unusually high number of meteorites that were found in the El Médano area (~190 unpaired meteorites larger than 10 g per km^2 ; Hutzler et al., 2016). The age distribution can be fitted with an exponential law decrease with a half-life of 590 k.y. (Fig. 2). The smooth exponential decrease suggests that no discrete meteorite removal event, such as surface reworking, occurred over the last 2 m.y., but instead, that meteorites are removed by continuous processes, likely wind abrasion and fragmentation. This distribution suggests that ordinary chondrites are unlikely to be preserved for more than 2.5–3 m.y. in the Atacama Desert, except perhaps for the large stones (>10 kg), which are exceedingly rare.

METEORITE FLUX ESTIMATE

The smooth decrease of the age distribution is consistent with a constant meteorite flux combined with meteorite removal by weathering. This assumption means that the resulting meteorite surface density $N(t)$ on the ground satisfies the following evolution equation:

$$dN(t) = \alpha \times dt - \lambda \times N(t) \times dt, \quad (1)$$

where α is the meteorite flux, and λ is the decay rate ($\lambda = \ln(2)/t_{1/2}$). This equation can be solved as:

$$N(t) = (1 - e^{-\lambda t}) \times \alpha/\lambda + N(t = 0). \quad (2)$$

Whatever the value of $N(t = 0)$, an equilibrium state is reached after a few half-lives (590 k.y.), after which the meteorite surface density remains constant at a saturated value $N_{sat} = \alpha/\lambda$. We consider here meteorites with mass >10 g. Using the meteorite density of 189 ± 14 per km^2 according to Hutzler et al. (2016), and the decay rate computed analytically from the terrestrial age distribution (Fig. 2), we determined a fall rate of 222 ± 15 meteorites above 10 g per km^2 per m.y. This estimate is similar to the 225 ± 81 meteorites above 10 g per km^2 per m.y. over the past 50 k.y. given by Bland et al. (1996) by dating meteorites from Nullarbor (Australia). However, these values are higher than the estimate of 83 meteorites above 10 g per km^2 per m.y. determined by Halliday et al. (1989). This latter estimate is less representative of the average meteorite flux because of the low number of events (56 meteorite fall events versus 388 meteorites in this work) and the short time window (11 yr versus 2 m.y. in this work).

METEORITE FLUX VARIABILITY DURING THE QUATERNARY?

H and L chondrites represent the vast majority (78%) of meteorites, and offer the most robust statistical indicator of possible variation in the composition of the meteorite flux to Earth. The H chondrite fraction with respect to total (H + L) chondrites is presented in Figure 3. The overall H/L ratio of our sample selection (25/26) is different from the H/L ratio of the total El Médano collection (1.74 after pairing; Hutzler et al., 2016). To correct for this bias introduced by our random selection, we applied scaling factors to the H and L numbers so that the overall H/L ratio is 1.74, while the total number of (H + L) meteorites remains 51. The error bars were computed as the standard deviation of a Poisson distribution that describes the number of independent events occurring in an interval of time. The plot shows that H chondrites dominated the flux between 1.2 and 0.4 Ma. A change, leading to nearly equal proportions of H and L meteorites, occurred at 0.5 Ma, and this broadly fits with the proportions of falls and finds in other hot deserts (Fig. 3). Previous studies have shown that H chondrites weather more rapidly than L chondrites, most likely because of their higher metallic iron content, which is more sensitive to weathering (Bland et al., 1998; Munayco et al., 2013). This effect may account for the higher proportion of L chondrites before 1 Ma, but it contradicts the observed higher proportion of H chondrite between 1 and 0.5 Ma. Therefore, a dynamic explanation must be invoked. The delivery of meteorites to Earth from the main asteroid belt starts when the meteoroid orbits are dynamically excited above the Earth-crossing eccentricity threshold by a resonance in the asteroid belt (e.g., Bottke et al., 2000). A population of meteoroids on resonant orbits has a typical lifetime of 0.5 m.y. before decaying in number, mostly by colliding with the Sun (Gladman et al., 1997). The duration is fully consistent with the time scale of the bump in Figure 3. Consequently, a potential scenario could be the direct delivery of a population of meteoroids in a resonant orbit from the main belt following the breakup of or cratering event on a close-by asteroid. A population of debris (the meteoroids) would have entered the resonance ~1 m.y. ago, and the eccentricities of the meteoroids increased rapidly, such that their trajectories started to intersect Earth's orbit. The flux of meteorites from this population started to decay after 0.5 m.y. Another hypothesis is that a swarm of meteoroids on very similar orbits, similar to a cometary trail but generated by the breakup of a near-Earth asteroid (e.g., Wiegert and Brown, 2005), had a favorable encounter configuration with Earth between 1 and 0.5 m.y. ago. The geometry of intersection of an inclined orbit with Earth depends on the value of the argument of the perihelion relative to the ecliptic. In that way, the precession rate of the argument of the perihelion sets the duration of the favorable encounter configuration and the

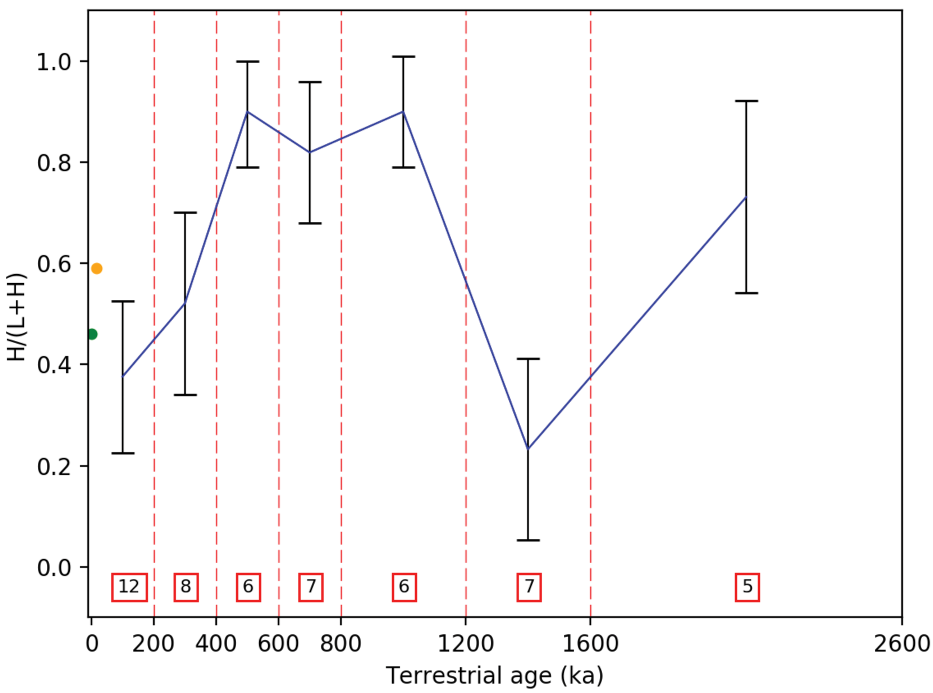

Figure 3. High-iron (H) chondrite fraction evolution (with respect to total H + L [low iron] chondrites) during the past 2.6 m.y. Values derived from our data set have been corrected by a scaling factor so that the overall H/L ratio matches the H/L ratio of 1.74 estimated for the entire El Médano collection (see text). Vertical dashed lines show bins, and numbers in boxes are number of samples within bin. Uncertainties were computed as the standard deviation of a Poisson distribution. Green dot is the current ratio computed from the meteorite fall population; orange dot is value computed from hot desert collection (uncertainties are too small to be shown).

time scale on which the configuration repeats. The typical precession rates of the argument of the perihelion of near-Earth asteroids are in the range 10–90 arcsec yr^{-1}. This implies that each orbital intersection is short-lived and repeats every 40 k.y. This period is 20 times smaller than the duration of the H-peak evidence in our results, which does not favor this scenario. Both scenarios remain hypothetical and need to be investigated in detail, especially by measuring the cosmic-ray exposure age of the data set. Indeed, a short exposure age for the excess of H chondrites making up the bump is required for such a rapid delivery from the asteroid belt to Earth.

CONCLUSION

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