Accumulation of impact markers in desert wetlands and implications for the Younger Dryas impact hypothesis

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The Younger Dryas impact hypothesis contends that an extraterrestrial object exploded over North America at 12.9 ka, initiating the Younger Dryas cold event, the extinction of many North American megafauna, and the demise of the Clovis archeological culture. Although the exact nature and location of the proposed impact or explosion remain unclear, alleged evidence for the fallout comes from multiple sites across North America and a site in Belgium. At 6 of the 10 original sites (excluding the Carolina Bays), elevated concentrations of various "impact markers" were found in association with black mats that date to the onset of the Younger Dryas. Black mats are common features in paleowetland deposits and typically represent shallow marsh environments. In this study, we investigated black mats ranging in age from approximately 6 to more than 40 ka in the southwestern United States and the Atacama Desert of northern Chile. At 10 of 13 sites, we found elevated concentrations of iridium in bulk and magnetic sediments, magnetic spherules, and/or titanomagnetite grains within or at the base of black mats, regardless of their age or location, suggesting that elevated concentrations of these markers arise from processes common to wetland systems, and not a catastrophic extraterrestrial impact event.

In 2007, an interdisciplinary team of scientists proposed a startling hypothesis. An extraterrestrial body, possibly a comet, exploded over North America approximately 12.9 ka, significantly altering climate, ecosystems, human populations, and faunal assemblages across the Northern Hemisphere (1). The team reported evidence for a possible extraterrestrial (ET) impact event at multiple archeological and paleontological sites in North America and a site in Belgium. At each site, they identified physical and chemical evidence, collectively called impact markers, in sediments dating to 12.9 ka* that they attributed to an ET impact event. Lines of evidence used to support the hypothesis are varied and include elevated levels of iridium in bulk and magnetic sediments, a spike in the abundance of magnetic spherules and titanomagnetite grains, fullerenes that contain ET helium, the presence of polycyclic aromatic hydrocarbons, carbon spherules, and nanodiamonds associated with glass-like carbon.

The Younger Dryas impact hypothesis is intriguing because it addresses three fundamental issues in Quaternary science: the cause of the Younger Dryas cooling, the extinction of large herbivores and their predators in the New World, and the demise of the Clovis Paleoindian culture. Traditionally, these phenomena have been attributed to disparate causes. The prevailing theories are that the rapid return to cold conditions during the Younger Dryas resulted from freshening of the North Atlantic and a slowing of the Atlantic meridional overturning circulation (2); megafaunal extinctions were caused by human predation and overkill, climate change, or some combination thereof (3); and Clovis simply evolved into other Paleoindian cultures (4). In contrast, proponents of the impact hypothesis maintain that an ET airburst or surface impact contributed to all three of these phenomena simultaneously (1).

Shortly after the impact hypothesis was proposed, critics began questioning whether some of the markers were necessarily related to an ET impact event (5–11), whereas others argued against the hypothesis after they were unable to find supporting evidence in other depositional settings (12, 13) or existing datasets (4, 14). Still others raised concerns over issues of replicability and laboratory protocols used in the original study (15). Here, we provide evidence that supports an alternative hypothesis for the accumulation of some of the markers in late Quaternary sediments. We suggest that, rather than resulting from an ET impact event, elevated levels of iridium in bulk and magnetic sediments, magnetic spherules, and titanomagnetite grains are the result of differential accumulation and concentration of naturally occurring, noncatastrophic levels of dust† in depositional settings, characterized by slow sedimentation rates, low-energy deposition, and biogeochemical reactions occurring at the sediment–water interface. In other words, apparent "spikes" of some of the markers are due to geomorphic processes common to wetland systems, likely via the accumulation and concentration of dust, rather than a catastrophic impact event.

At 6 of the 10 original sites (excluding the Carolina Bays), Firestone et al. (1) found markers just below or within organic-rich, dark-colored sedimentary layers called "black mats." Black mats are common features in Pleistocene and Holocene wetland deposits worldwide and are formed in shallow marsh environments (16, 17). They are typically comprised of organic-rich silt and small amounts of clay and/or sand, and vary in age, composition, organic content, and thickness. In addition, they often contain the remains of invertebrate fauna (gastropods, ostracodes), diatoms, pollen, plant macrofossils, and other indicators of past environmental conditions.

The combination of wet ground and dense plant cover allows marshes and wetlands to act as efficient dust traps, particularly in arid environments where atmospheric dust concentrations are

EARTH, ATMOSPHERIC, AND PLANETARY SCIENCES

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*The 12.9 ka age designation is based on calibration of 20 radiocarbon ages of black mats in the San Pedro Valley, Arizona (Murray Springs; 10.89 ± 0.05 $_{14}$C ka B.P.; $n = 8$ and Lehner Ranch; 10.94 ± 0.05 $_{14}$C ka B.P.; $n = 12$) using the IntCal04 dataset, and the timing of the onset of the Younger Dryas cold event in the Greenland Ice Sheet Project (GISP) 2 ice core record. Using the more recent IntCal09 dataset, these radiocarbon ages calibrate to 12.77 ± 0.15 and 12.80 ± 0.17 ka, respectively. For the sake of consistency, however, we use the 12.9 ka age in our discussion.

†We use the term "dust" to refer to a mixture of airborne silt, clay, and fine sand.

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Fig. 1. Generalized location of study sites in the American Southwest and the Atacama Desert of northern Chile.

relatively high (18). Wetland systems are low-energy, relatively stable environments and, because of their nature and position on the landscape, they often preclude or minimize the input of clastic fluvial sediments. Thus, black mats and related wetland sediments typically contain higher concentrations of dust than other depositional environments. Moreover, wetland sediments are subject to redoxymorphic reactions associated with diverse and abundant microbial ecosystems, which may serve to further concentrate nonreactive components of dust (19)

To determine if the accumulation of markers might result from processes common to wetland systems rather than an ET impact event, we revisited several black mats and paleowetland sequences in the southwestern United States and the Atacama Desert of northern Chile (Fig. 1). Our research group investigated these sites previously to reconstruct late Quaternary climatic and hydrologic change in arid settings in the Americas (20–23). Examination of deposits in these regions allowed us to evaluate the occurrence of markers in black mats of different ages and in different hemispheres, including localities far removed from the presumed impact location and its fallout.

Results

We chose eight localities as part of this study (see Dataset S1 for site details). Three are located in the southwestern United States: Murray Springs, Arizona (two sites, one black mat at each site), Dove Spring, CA (one site, three black mats), and South Sierra, CA (one site, one black mat). Five other localities are in the Atacama Desert of northern Chile; the El Salto sections at Salar de Punta Negra (two sites, a total of five black mats), Quebrada Agua de Cascabel (two sites, one black mat at each site), Quebrada del Chaco (three sites, a total of eight black mats), Rio Salado (one site, three black mats), and Tilomonte (one site, three black mats). The black mats sampled in this study were dated previously by radiocarbon and range in age between approximately 6 and more than 40 ka, including some that date to 12.9 ka (Dataset S2). At each site, samples were only taken from black mats that contained a well-defined basal contact in order to ensure that the markers, if they were present initially, were not diluted with underlying sediments via bioturbation (Fig. 2).

Iridium concentrations in bulk sediment (Ir_{bs}) ranged from 0 to 2.5 ppb (Fig. 3; Dataset S3), similar to levels found by Firestone et al. (1). (Note that Ir_{bs} was measured on bulk samples of 10 g or larger to avoid any "nugget effects"; ref. 13). The highest concentrations were found in an 8.2 ka black mat at Tilomonte (1.20 ± 0.21 ppb), a 10.6 ka mat at Quebrada Agua de Cascabel (QAC 4; 0.86 ± 0.21 ppb), a 13.0 ka mat at El Salto 1 (1.65 ± 0.10 ppb), and a >40 ka mat at Rio Salado (2.51 ± 0.15 ppb).

Iridium concentrations in the magnetic fraction (Ir_{mag}) of black mats and basal samples ranged from 0 to 129 ppb, also similar to levels found by Firestone et al. (1). The highest Ir_{mag} concentration we found, 200 ppb, was in a sample of carbonate-rich silt positioned approximately 10 cm below a black mat at Murray Springs 1. This carbonate-rich unit, called the Coro Marl or Stratum E (24), represents a paleowetland that was active at least 1,000 y before deposition of the black mat at 12.9 ka (25). We found elevated Ir_{mag} concentrations in a 10.8 ka black mat at South Sierra (5.80 ± 1.16 ppb), a 12.5 ka mat at Dove Spring (6.91 ± 1.17 ppb), a 12.9 ka mat at Murray Springs 1 (129 ± 26 ppb), a 15.9 ka mat at Quebrada del Chaco 12 (24.49 ± 0.73 ppb), and three >40 ka mats at Rio Salado (ranging from approximately 2 to 5 ppb).

Magnetic spherules ranging from approximately 10 to 100 μm in diameter were present at five sites in concentrations up to 993 spherules per kilogram, again similar to abundances reported by Firestone et al. (1). The highest concentrations of magnetic spherules were found at the base of an 11.5 ka black mat at Quebrada del Chaco 5 (993 kg^{-1}). Magnetic spherules were also found in a 12.9 mat at Murray Springs 1 (14 kg^{-1}), a 16.6 ka mat at Chaco 12 (50 kg^{-1}), and a >40 ka mat at Rio Salado (20 kg^{-1}). We also found >100 spherules per kilogram in an unnamed silt unit approximately 10 cm below a 12.3 ka black mat at Quebrada del Chaco 2.

Finally, concentrations of titanomagnetite[‡] grains within or at the base of black mats ranged from 0 to 36.8 $g\,kg^{-1}$. Elevated concentrations were found in a 12.3 ka black mat at Quebrada del Chaco 2 (36.8 $g\,kg^{-1}$), a 12.5 ka mat at Dove Spring (17.4 $g\,kg^{-1}$), a 12.9 ka mat at Murray Springs 1 (0.47 $g\,kg^{-1}$), and a 13.0 ka mat at El Salto 1 (2.1 $g\,kg^{-1}$). We also found elevated levels of titanomagnetite grains in sediments either above or below black mats of various ages at Quebrada del Chaco 2, QAC 2, El Salto 2, and Tilomonte.

In sum, the results of our investigation into black mats of various ages on two different continents reproduced three major features of the original Firestone et al. (1) study. First, when evaluating samples from within or at the base of black mats, both studies found similar maximum concentrations of Ir_{bs}, Ir_{mag}, magnetic spherules, and titanomagnetite grains (this study vs. Firestone et al.); Ir_{bs}, 2.5 vs. 3.8 ppb; Ir_{mag}, 129 vs. 117 ppb; magnetic spherules, 993 vs. 2,144 kg^{-1}; and titanomagnetite grains, 36.8 vs. 9.9 $g\,kg^{-1}$. Second, neither group found every marker at every site. Third, both groups found elevated levels of some of the markers in sediments that do not date to 12.9 ka. Most of our data come from sediments that do not date to 12.9 ka. Firestone et al. (1) found elevated levels of magnetic spherules and titanomagnetite grains in sediments dating to 13.3 ka and older at the Blackwater Draw, NM site, as well as titanomagnetite grains in sediments dating to 15.2 ka at the Topper, SC, and sediments below the 12.9 ka level at the Morley Drumlin, Alberta and Gainey, MI sites (figure 1 in ref. 1).

Discussion

Our results suggest that elevated concentrations of iridium in bulk and magnetic sediments, magnetic spherules, and titanomagnetite grains are the result of processes common to wetland systems rather than a catastrophic impact event. Concentrations of these markers are often highest at the base of black mats, which may reflect differential settling of dense magnetic grains relative to lighter, more felsic grains. Regardless, concentrations of the markers are just as likely to spike within or at the base of 12.9 ka black mats in North America as they are in Holocene or late Pleistocene (>13 ka) mats in South America. The Younger Dryas impact hypothesis predicts that elevated concentrations of

[‡]Titanium concentrations measured by instrumental neutron activation analysis in the magnetic sediment samples ranged from approximately 0.1% to 8.0%.

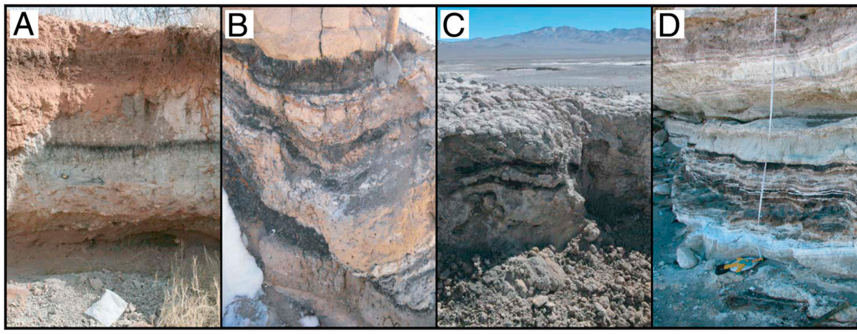

Fig. 2. Examples of late Pleistocene and Holocene black mats from (*A*) Murray Springs, (*B*) Quebrada del Chaco 2, (*C*) El Salto 1, and (*D*) Rio Salado. Ages of the black mats that we investigated ranged from approximately 6 to more than 40 ka.

the markers should be found only in sediments dating to 12.9 ka or, speaking more broadly, in sediments dating to other impact events. Unless all black mats found worldwide are related to ET impact events (and nobody is claiming this to be the case), then we must invoke an alternative hypothesis to explain the observed data. The basic premise of our hypothesis is not new, as both Haynes et al. (6) and Pinter et al. (9) have suggested similar alternatives. Our study is unique, however, in that we clearly show elevated concentrations of many of the markers invoked by Firestone et al. (1) as evidence of an ET impact at the beginning of the Younger Dryas event are common to black mats of various ages and locations.

As stated above, wetlands act as effective dust traps, especially in arid environments where there are high concentrations of atmospheric dust. A large component of paleowetland deposits found in arid lands is comprised of silt and clay, which are the most common grain sizes of eolian sediment outside of dune settings in the American Southwest (26, 27). Dust trapped in wetlands comes largely from terrestrial sources, but, by extension, cosmic dust is probably trapped in these environments as well. To determine the source (terrestrial or cosmic) of titanomagnetite grains in our samples, we measured concentrations of rare earth elements (REEs) by instrumental neutron activation analysis in bulk and magnetic sediments at all 13 of our sites (Dataset S4). REEs are approximately two orders of magnitude more common in terrestrial (crustal) rocks than in chondrites and, presumably, cosmic dust (28). Moreover, when normalized to chondritic ratios and plotted in series against their atomic numbers (29), REEs in average upper continental crustal rocks exhibit three pervasive characteristics: elevated concentrations of lighter REEs (La-Sm), a negative Eu anomaly, and depleted values of heavier REEs (Gd-Hf) (30). The bulk and magnetic sediment samples measured in this study exhibited some or all of these characteristics (Fig. S1), which points strongly toward a terrestrial (upper crustal) source. This finding is similar to that of Paquay et al. (13), who analyzed platinum group elements and osmium isotopes in Younger Dryas (YD)-age sediments from different depositional settings and arrived at the same conclusion. If the iridium is carried in the magnetic sediments, as it appears to be based on Firestone et al.'s data (1), then the REE results imply that the iridium likely has a terrestrial origin as well.

The origin of the magnetic spherules cannot be constrained by our data. Magnetic spherules are produced by a number of different terrestrial processes, including volcanism and various anthropogenic activities, but are also known to fall to Earth as cosmic dust (31). Cosmic dust is largely the result of meteorites that continuously bombard the Earth (32). Up to 25% of large (>10 cm) meteorites and approximately 10% of micrometeorites (<1 mm) survive passage through the Earth's atmosphere (33, 34). Those that survive do so as either intact meteorites or are ablated along the way and eventually settle to the ground as micrometeorites or dust, which can include spherules. Magnetic spherules have been documented in a wide range of depositional settings, including Arctic and Antarctic ice (34, 35), deep-sea sediments (36), lake sediments (37), alluvial sediment (38), and peat bogs (39, 40), and have even been collected directly from the atmosphere (41). Thus, some of the magnetic spherules present in our samples may have a cosmic origin. Regardless of their origin, their presence in elevated concentrations in wetland sediments that are approximately 6 to more than 40 ka in age indicates that they are being concentrated in wetland settings and are not the result of a catastrophic impact event.

To be clear, the results of our study do not allow us to dismiss the Younger Dryas impact hypothesis outright, nor do they address the origin or significance of the remaining markers of Firestone et al. (1). However, our study illustrates the importance of positing and testing alternative hypotheses to explain the presence of these markers in Quaternary sediments. Most arguments both for and against the Younger Dryas impact hypothesis have focused on whether or not the presence of certain markers in sediments dating to 12.9 ka were related to an ET impact event. In our view, such a narrow approach has made it difficult to rigorously test the hypothesis directly. For example, how do we evaluate a situation in which one research group finds markers in the same subsample in which another does not (e.g., as described by Haynes et al., ref. 6)? And if looking only at a single site, how do we assess the potential significance of fluctuations in the nature and rate of sediment accumulation, diagenetic (biotic or abiotic) alterations to the deposits, and variations in depositional environments (e.g., ref. 42)? When assessing the importance of various lines of evidence that are, at best, present in trace amounts, the minutia of laboratory protocols, variations and differences in analytical background levels, and interpretation of near-background data become paramount. These issues have led to disagreements about how to prepare and analyze samples, allowed multiple interpretations of the same datasets, resulted in questions on how to evaluate the data, and ultimately fostered entrenchment on both sides of the YD impact argument.

The approach taken here avoids most of these issues in that a single event cannot be invoked to explain the presence of the markers studied here in deposits dating from approximately 6 to more than 40 ka in both North and South America. Our data clearly show that elevated concentrations of some of the markers put forth by Firestone et al. (1) as evidence of an ET impact event, specifically iridium in bulk and magnetic sediments, magnetic spherules, and titanomagnetite grains, are common within or at the base of black mats, regardless of age or location. These results suggest that the markers are likely concentrated by processes inherent to wetland systems and are not the result of a catastrophic impact event.

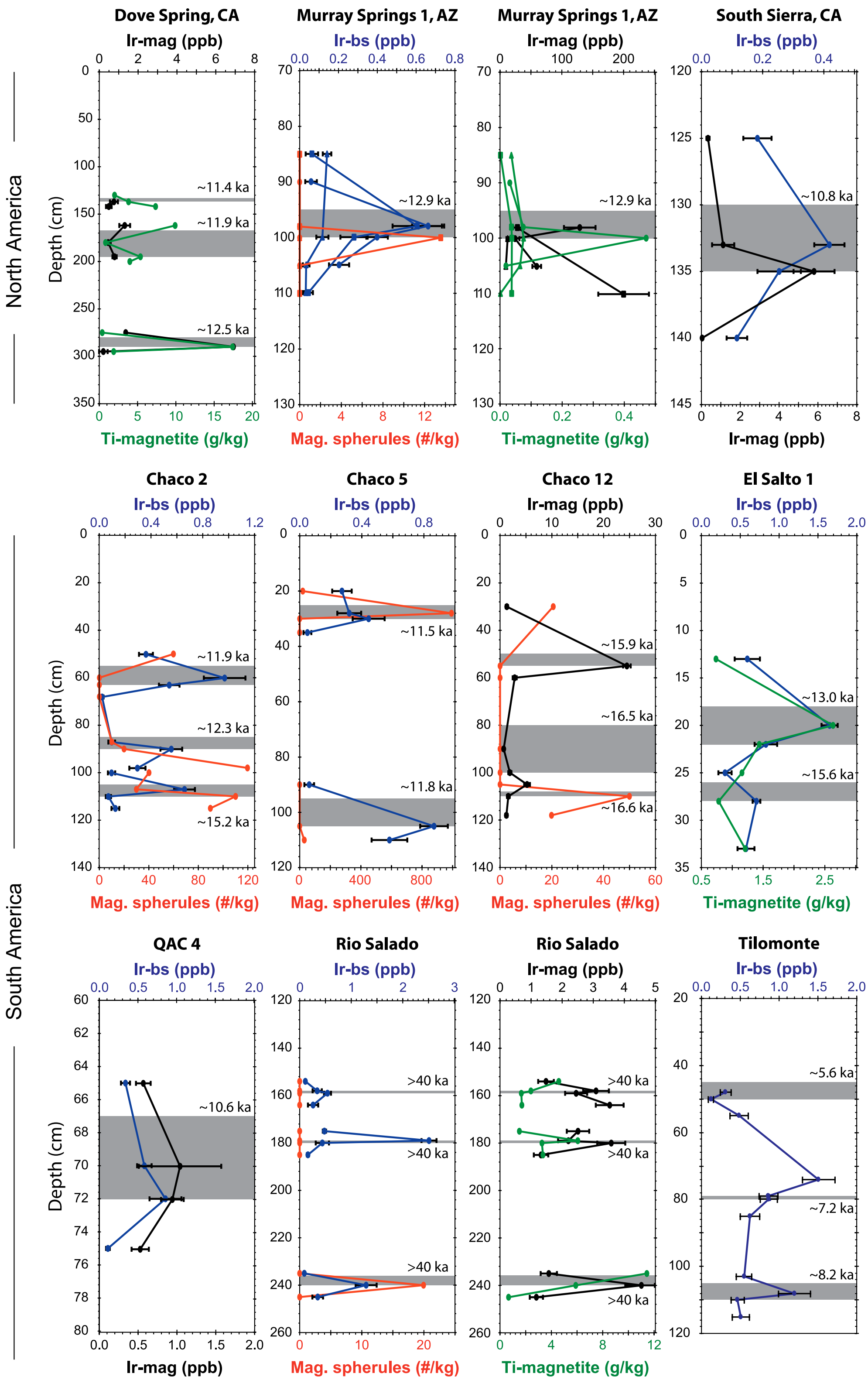

Fig. 3. Concentrations of iridium in bulk and magnetic sediments (designated as Ir_{bs} and Ir_{mag} and shown in blue and black, respectively), magnetic spherules (red), and titanomagnetite grains (Ti-magnetite; green) in stratigraphic sections from 10 sites in the Americas. Depth below the ground surface at each site is shown on the *y* axis. Black mats at each site are represented to scale by horizontal gray boxes. Ages shown for each mat are based on radiocarbon dating of plant macrofossils, carbonized wood, or unidentified organic matter, and were calibrated using the IntCal09 dataset (43).

Materials and Methods

A common misconception of the Younger Dryas boundary (YDB) layer of Firestone et al. (1)—the horizon in which the markers are most concentrated—is that black mats themselves actually represent the YDB layer; this is incorrect. The YDB layer is physically located at the *base* of 12.9 ka black mats, and is likely no more than a few millimeters thick. At a given site, therefore, the YDB layer represents a brief moment in time dating to 12.9 ka and the overlying black mat represents the decades to centuries that followed. In an effort to maximize the possibility of capturing the YDB or corresponding layer, we collected 2-cm-thick (maximum) samples from four distinct intervals per black mat: the basal contact of the black mat (this sample included no more than 1 cm above and below the contact), from within the black mat itself, and from 5–10 cm above and below the black mat to obtain background data. We followed the sample preparation procedures of the original Firestone et al. (1) as closely as possible to minimize any differences in our data due to laboratory procedures. Details of our sample preparation and analytical methods can be found in the *SI Text*.

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