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Small impact cratering processes produce distinctive charcoal assemblages

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ABSTRACT

The frequency of crater-producing asteroid impacts on Earth is not known. Of the predicted Holocene asteroid impact craters of <200 m diameter, only ~30% have been located. Until now there has been no way to distinguish them from "normal" terrestrial structures unless pieces of iron meteorites were found nearby. We show that the reflective properties of charcoal found in the proximal ejecta of small impact craters are distinct from those produced by wildfires. Impact-produced charcoals and wildfire charcoals must derive from different heating regimes. We suggest that charcoal with specific reflective properties may help to recognize the meteoritic origin of small craters.

INTRODUCTION

Extraterrestrial solid material enters Earth's atmosphere daily. Most of this material is small enough that it burns up in the atmosphere. In contrast, the largest asteroids or comets reach Earth's surface with great speed and little deceleration, forming hypervelocity impact craters that are identifiable due to shock metamorphism (Osinski et al., 2022). Asteroids tens of meters in diameter collide with Earth more than twice per millennium. Where they retain enough kinetic energy upon impact, a shock wave creates a small impact crater. These small impacts produce the most frequent risks to human populations.

Humankind can only prepare for this natural hazard if we can understand how often small impacts have occurred and how they have influenced the environment (Bland and Artemieva, 2006). However, identification of small impact craters (<200 m in diameter) is problematic, because the methodologies employed have been developed for large hypervelocity impact structures. The most unequivocal criteria are the presence of shock metamorphic indicators (such as planar deformation features in quartz or shatter cones) and, to a lesser extent, the detection of geochemical traces of extraterrestrial matter (French and Koeberl, 2010). But in the case of small impact craters in unconsolidated target rocks, such signatures are detectable only within a small volume of target material that is distributed as ejecta over tens of square kilometers, diluting a measurable shock metamorphic signal (Bronikowska et al., 2017). As a result, out of 14 confirmed small impact craters (Table S1 in the Supplemental Material[1]; Schmieder and Kring 2020), planar deformation features and high-pressure phases have been reported only from two recent impact craters: Kamil in Egypt (Folco et al., 2018) and Wabar in Saudi Arabia (Gnos et al., 2013). A small number of potential shatter cones have been reported from Kaali in Estonia (Reinwald, 1939) and from a suspected crater called Sobolev in Russia (Khryanina, 1981). Fragments of melted rocks have been reported from only 4 of 14 cases. In practice, the only widely used impact indicator of confirmed, non-witnessed (excluding Carancas [formed in 2007 in Peru]: Kenkmann et al., 2009) impact craters of <200 m in diameter is the association with iron meteorite fragments (13 of 13 cases).

Several confirmed small impact craters have been shown to contain fragments of charcoal within their proximal ejecta blankets: (1) Campo del Cielo, Argentina (Cassidy et al., 1965); (2) Whitecourt (Herd et al., 2008, Kofman et al., 2010); (3) Kaali Main (Losiak et al., 2016); (4) Kaali 2/8 (Losiak et al., 2018); and (5) Morasko, Poland (Szokaluk et al., 2019). Similar charcoals are reported from two suspected craters: Sobolev (Khryanina, 1981) and Ilumetsa, Poland (Losiak et al., 2020). Previously, these charcoals were widely interpreted to represent pre-impact forest fires. However, because the charcoal assemblages are found within the same stratigraphic and geomorphological context within numerous craters, and have ^{14}C ages consistent with the timing of crater formation (see the Supplemental Material for details), they appear to be linked to the impact events.

Recent research has shown that the properties of charcoals studied in reflected light vary according to the thermal regime to which they were subjected (Belcher et al., 2018; Belcher et al., 2021) and are proportional to the level of graphitization of the material (Cohen-Ofri et al., 2006). For example, charcoal reflectance from low-energy surface fires (where the flaming front burns surface shrubs, leaf litter, and fallen branches) is lower than that from high-intensity crown wildfires (where flames reach up

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[1]Supplemental Material. Detailed description of the reflectance measurement method and samples/craters, as well as results provided in a numerical rather than graphical format. Please visit https://doi.org/10.1130/GEOL.S.20466060 to access the supplemental material, and contact editing@geosociety.org with any questions. Unprocessed data and samples available upon request from A. Losiak.

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to the canopy; Roos and Scott, 2018). Research has indicated that the amount of energy received by the wood or bark determines the reflective properties of the charcoal (Belcher et al., 2018).

We measured and analyzed the range of reflectance values of charcoals found within the proximal ejecta blankets of four small impact craters: (1) Kaali Main and (2) Kaali 2/8 in Estonia, (3) Morasko in Poland, and (4) Whitecourt in Canada. We then compared these to charcoals formed by six different wildfires of a range of intensities. Our aim was to determine whether the charcoal particles found in the ejecta blankets of small impact craters have a signature similar to that of wildfires, or whether they may be distinctive enough to provide novel information about impact cratering processes and aid in identifying the origin of small, crater-like structures on Earth.

MATERIALS AND METHODS

The charcoal particles were sampled from the four craters at depths >50 cm below the surface, in trenches dug in the proximal ejecta blankets (Fig. 1). Charcoals are present as small, dispersed pieces, from millimeter scale to 2 cm long (Fig. S1). All charcoals were sampled at the same position with respect to the crater rims (adjusted for crater size). Charcoals were most common within the lowest part of ejecta blanket at a distance starting near the rim up to <0.5 × the crater radius. For detailed descriptions of the ejecta sequences, charcoal locations, and a comparison of the ^{14}C age of the charcoals with respect to their parent craters, see the Supplemental Material.

The wildfire charcoals analyzed here were collected from a range of fire types, ages, and ecologic settings representative of areas where impact craters were formed. Directly following four wildfires, samples were collected from the ground surface or from *in situ* charred twigs across burned areas: (1) an intense heathland wildfire at Ferndown Common, UK, in July 2019 (fuel: heather and gorse); (2) an intense surface fire at Wareham Forest, UK in May 2020 (fuel: pine twigs); (3) a low-intensity surface fire at Pinepoint, Canada in July 2017 (Belcher et al., 2018); and (4) a high-intensity experimental crown fire at Triangle, Canada in June 2016 (Belcher et al., 2018). The fuel for fires 3 and 4 was western red cedar and jack pine. Although previous research has indicated that reflectance properties of charcoals are stable over thousands of years (Cohen-Ofri et al., 2006; Ascough et al., 2010), we also tested charcoals of various ages. We analyzed Holocene charcoals (1) at the 1910 CE "Big Burn" site at moon Pass, Idaho,

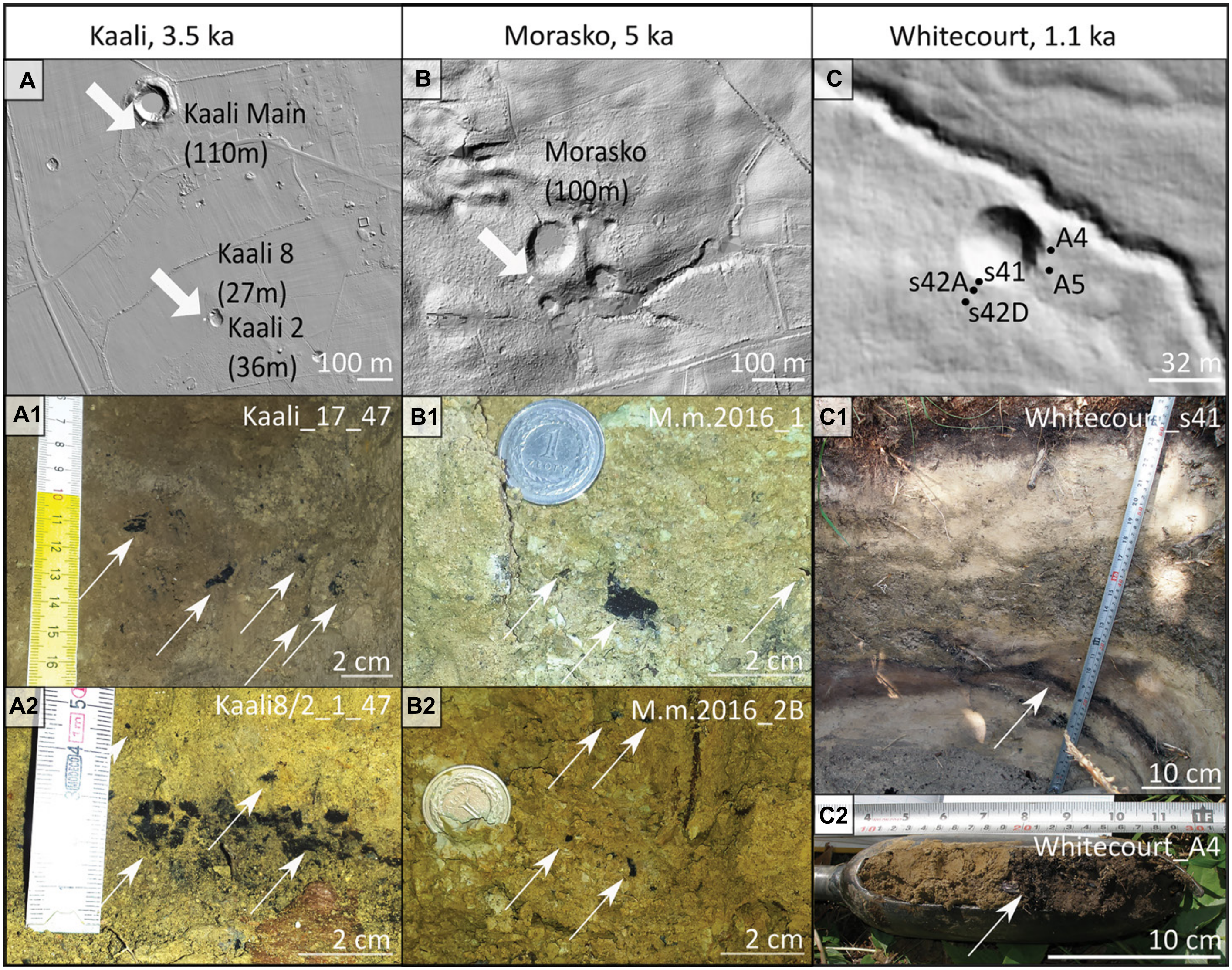

Figure 1. Location, age, and diameter of confirmed impact craters: (A) Kaali Main and Kaali 2/8, both in Estonia; (B) Morasko in Poland; and (C) Whitecourt in Canada, along with field images of *in situ* charcoals (at thin white arrows) found within their proximal ejecta blankets. Charcoals are present throughout the ejecta (panels A1, B1, and B2) but are most abundant close to the base (panels A2, C1, and C2). Thick white arrows in panels A and B point out the locations of trenches where charcoals visible in A1, A2, B1, and B2 were collected. Numbers in C and in the field photos refer to sample numbers.

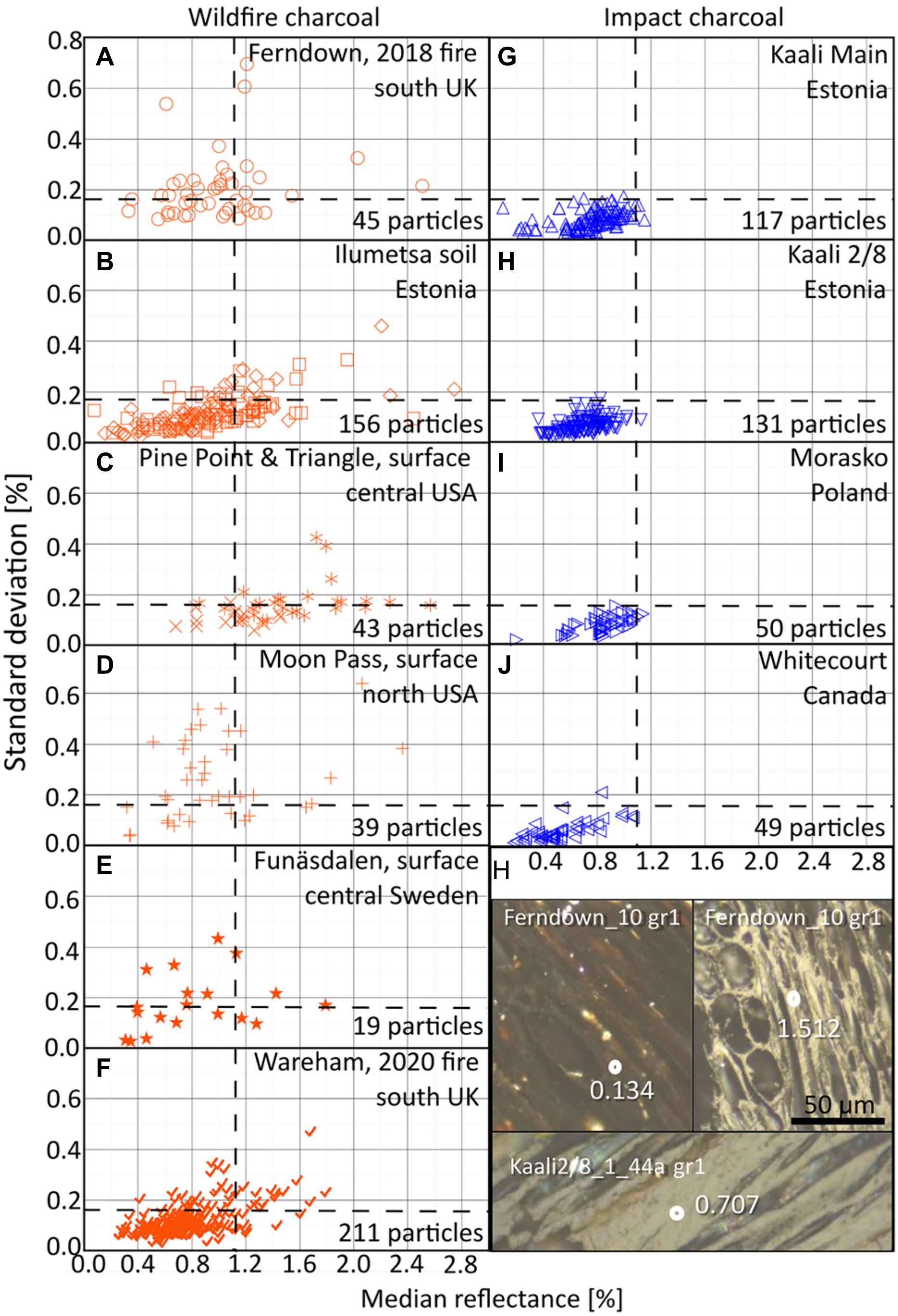

Figure 2. Comparison of charcoal reflectance from wildfires (A–F) and those from proximal ejecta of confirmed small impact craters (G–J). Median reflectance (*x* axis) represents the average energy of the environment in which a particular charcoal particle was formed. Standard deviation (*y* axis) represents the heterogeneity of measurements within a single particle. Wildfire charcoals are spread out throughout the entire plot, reflecting the heterogeneity of their wildfire environments. The presence of particles with a reflectance (Ro) median of >1.15% indicates prolonged contact with a flame. All impact charcoals plot in the same, low-Ro median, low-standard-deviation section of the diagram, which reflects formation in a slow-cooling, homogenous environment without contact with a flame. Inset H shows photos (on the same scale and microscope setting) of impact (Kaali 2/8) and wildfire (Ferndown) charcoal samples under a reflectance microscope; numbers indicate Ro measurements taken at the locations marked by white dots.

USA, from charcoal that remains on upstanding "snags" and was fueled by cedar; (2) from the forest floor at Ljusnedal, Sweden, fueled by spruce, and up to few hundred years old ; and (3) from soils near Ilumetsa in southern Estonia, charcoals <7 k.y. old and from mixed fuels.

All charcoal was embedded in polyester resin, and the charcoal's exposed surface was polished (Belcher and Hudspith, 2016; see the Supplemental Material). The charcoal particles were studied under oil with a 50 × objective lens (32 × eyepiece magnification) using a Zeiss Axio Scope A1 reflectance microscope with a TIDAS-MSP 200 microspectrometer. It was calibrated using the following standards: strontium titanite (5.41% reflectance [Ro]), gadolinium gallium garnet (1.72% Ro), and spinel (0.42% Ro). The measurement error is up to Ro ± 0.03%; 30–50 reflectance measurements were taken across transects from edge to edge of each charcoal particle.

We measured Ro across the polished cross sections of 347 charcoal particles from the proximal ejecta blanket of the impact craters (n = 12,988 point measurements) and 513 wildfire-derived charcoal particles (n = 23,495) (Table S2). Charcoals have a well-preserved wood structure that is sufficient for performing genus-level identification (Losiak et al., 2016).

RESULTS

Wildfire charcoals are characterized by a wide range of measured median reflectance values (Fig. 2; Table S2) from Ro = near 0% (indicating that wood is nearly unprocessed thermally) up to Ro ~3.00% (indicating a highly energetic environment). This was true for samples taken from the ground directly after wildfires (Ferndown, Pine Point, and Wareham) and decades after the fires (Moon Pass and Funasdalen), as well as for those taken from soil-sampled charcoals (Ilumetsa; Fig. 2). Soil charcoal samples from Estonia were collected at two locations (near Ilumetsa Large and Ilumetsa Small), from six soil survey holes, and at sample depths of 0–40 cm. Each sample location and depth profile retains a similar range of reflectance as the surface wildfire samples (Fig. S2). The wildfire charcoal population is characterized by a high proportion of highly reflective particles with a median Ro of >1.15% (Fig. 3; Table S2). Additionally, a significant proportion (>10%) of wildfire charcoal particles include portions of the particle that have reflectance where the 95th percentile of their distribution is Ro > 1.40% (Table S2). Reflectance varies from the surface edge to the center of the wildfire charcoal particles, with the edges typically showing higher reflectance than toward the center (Fig. 2H; Fig. S3). As a result, standard deviation of the reflectance measurements within a single wildfire charcoal particle are >0.15% for significantly more than 10% (up to 75%) of the particles (Table S2).

The charcoals found in the proximal ejecta of the impact craters (hereafter termed as "impact charcoals"), despite representing four craters on two different continents and thousands of years of temporal distance, are largely homogenous in their reflective properties, both from the edge to the center of the individual particles (Figs. 2 and 3; Table S2) and as a population. Almost

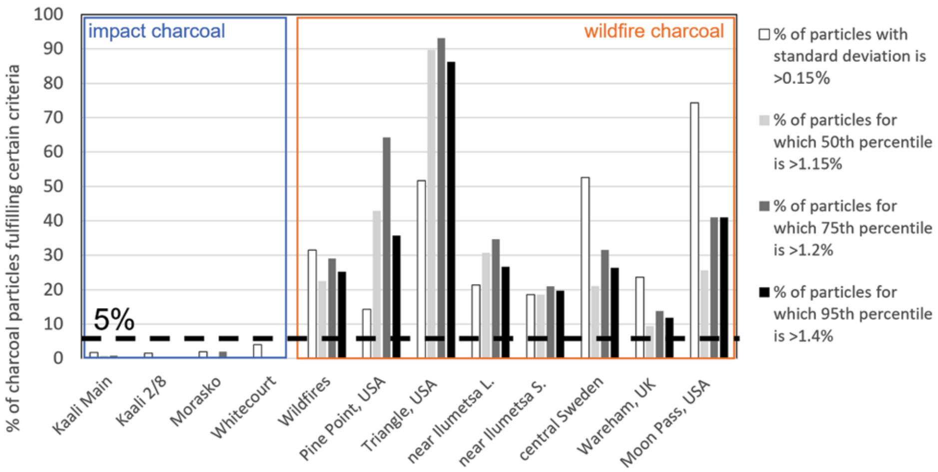

Figure 3. Comparison of wildfire and impact charcoals, in terms of parameters that allow differentiation among the two types of charcoal populations. Impact charcoal populations have less than 5% of particles with standard deviation >0.15% (white bars); 50th percentile/median reflectance (Ro) >1.15% (light-gray bars); 75th percentile Ro >1.2% (dark-gray bars), and 95th percentile Ro > 1.4% (black bars). In the case of wildfire charcoals, the high values of those parameters result from the heterogenous heating regime and interaction with a flame during a wildfire.

all impact charcoals have a median of <1.15% that formed in a low-energy environment and a standard deviation of <0.15%, and they lack particles with portions characterized by high reflectivity, meaning there are no particles with a 95th percentile of >1.40% (Fig. 3). Reflectance values do not change with increasing distance from the crater rim at Whitecourt (see Fig. S4).

DISCUSSION

Does Impact Charcoal Differ from Wildfire Charcoal?

Our measurements reveal, for the first time, that the distribution of reflectance within and between charcoal particles found in the proximal ejecta of the impact craters studied is different from that generated by wildfires (Figs. 2 and 3; Table S2). On a plot of particle median reflectance versus standard deviation, all impact charcoals plot within a narrow region (Ro median of <1.15% and standard deviation of <0.15%; marked with dashed lines in Fig. 2), while particles derived from wildfires occupy a much broader range of reflectance values. We suggest that although no single charcoal particle can be recognized as being of impact origin based on its reflectance properties, analyses of a population of charcoal particles found within a putative small impact crater setting show them to be distinguishable from wildfire-derived assemblages due to their <1.15% median reflectance values, standard deviation of <0.15%, and the lack of particles of high reflectance (Table 1). Of particular significance is that wildfire particles are commonly highly reflective (Ro >> 1.40%) at the edges of particles while inside there is a transitional zone where reflectance decreases. For example, a single particle of the Ferndown wildfire charcoal (Fig. S3) shows a significant range of reflectance: 0.13–1.51%. Conversely, the charcoals found in the four studied craters are homogeneous in their reflectance on three different scales: (1) all measurements within a single particle are similar; (2) all particles from a single site are similar; and (3) populations from different impact craters are similar (Fig. 2). This suggests that the heating-cooling regime for the formation of impact charcoals must be different from that of wildfires.

Possible Mechanism of Formation

The thermal regime of a fire front passing a tree can be recorded by a temperature-time trace from a thermocouple attached to a tree during a wildfire (see Fig. S5A). It shows that the temperature rises rapidly as the fire front arrives, and decays in a matter of minutes as it moves past. This rapid and transient heating process leads to charcoals that have the highest reflectance on the outer part of the particle that received the most heating, which then decays inward away from the heat source (e.g., Belcher et al., 2018, their figure 5). Therefore, the population of impact charcoals examined here cannot have been formed by pre-impact wildfires as suggested by Cassidy et al. (1965), Herd et al. (2008), and Losiak et al. (2016) or by vegetation ignited by the heat pulse of an incoming impactor (Svetsov, 2008) with the particles mixed into "cold" ejecta, because the reflective properties of those charcoals would be similar to those of other wildfire charcoals.

The crater charcoals were not formed in pre-impact or impact-linked wildfires with their reflectance later homogenized after burial. While it has been shown that low-reflecting charcoals can be overprinted by higher reflectance by secondary heating in a higher energy regime (Belcher and Hudspith, 2016), high charcoal reflectance does not decline on secondary heating at a lower temperature (Hudspith and Belcher, 2020, their figure 7) or via long durations of heating. If these chars were originally formed by wildfires, the surfaces of the particles would maintain their higher reflectance (as per a wildfire heating regime), even if burial slowed their cooling, or the ejecta remained warm, leading to increased reflectance in the center of the particles (Hudspith and Belcher, 2020).

We suggest that the charcoals must have been formed by burial in warm ejecta of twigs already lying as litter or directly from branches of trees; a hypothetical long-duration cooling curve for the formation of these impact charcoals is shown in Figure S5B. Although there have been few attempts to numerically model the energy involved in small impact cratering processes, none thus far have suggested that the ejecta of 100-m-diameter craters would likely remain warm throughout (Weiss and Head, 2016). Hence, we propose that only warm pockets within small impact ejecta deposits must remain that enable the formation of impact charcoals by taking hours to cool. This would allow low

TABLE 1. CHARCOAL TOOLKIT CRITERIA FOR AIDING THE IDENTIFICATION OF SMALL IMPACT CRATERS

	Field Observations and Sampling	Age	Charcoal Reflectance
Requirement	Charcoals must be located within specific location of the proximal ejecta blanket.	The ^{14}C age of the charcoal must overlap with other independently determined ages of the crater.	Reflectance properties from a population of charcoal particles must be measured. Reflectance measurements must be found to be largely homogeneous both within single particles and between particles (standard deviation <0.15%). Median overall reflectances should be <1.15%, and there should be no particles with 95th percentile >1.4% reflectance.
Notes	Ejecta blanket thickness decreases away from the crater rim. Beware of reworking or bioturbation of younger charcoals from soils above. To date charcoals have been found from the crater rim up to a distance of <0.5 m crater radii and at >40 cm depth.	Measurements should be within the ^{14}C data error after consideration of the old wood problem (Losiak et al., 2018) and reconciled with estimates that date the crater sediment fill. It is advised that >5 samples be assessed using ^{14}C (Losiak et al., 2020)	A single piece of charcoal is not sufficient to indicate that it was formed by impact cratering processes. It is recommended that at least 40 particles require study from a single deposit and that ∼50 individual reflectance measurements should be taken across the surface of each particle

temperatures to produce charcoal that, owing to entombment within warm ejecta, would enable the "baking" of particles from all sides, allowing the heat to penetrate the entire particle due to the long duration of heating. This is similar to the process by which wood is entrained in pyroclastic flows; entombment at 200–300 °C produces charcoals with a median reflectance of ~0.8% (Scott and Glasspool, 2005). To date, we know of no studies that have fully considered the intra-particle homogeneity of reflectance of pyroclastic-linked charcoals.

CONCLUSIONS

Ejecta from small meteoritic impacts in unconsolidated sediments in vegetated areas on Earth contain particles of charcoal within their ejecta blankets that are characterized by specific reflectance properties that distinguish them from wildfire charcoals. We suggest that charcoals found in potential small impact crater settings that satisfy the criteria described in this study may be identifiable as "impact charcoals." The charcoal reflectance approach may provide an additional toolkit for confirming the impact origin of very small impact craters (<200 m in diameter). This will better define the current impact rate on Earth, as well as help to map the distribution of energy around such features.

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