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Recovery and curation of the Winchcombe (CM2) meteorite

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Abstract–The Winchcombe meteorite fell on February 28, 2021 and was the first recovered meteorite fall in the UK for 30 years, and the first UK carbonaceous chondrite. The meteorite was widely observed by meteor camera networks, doorbell cameras, and eyewitnesses, and 213.5 g (around 35% of the final recovered mass) was collected quickly—within 12 h—of its fall. It, therefore, represents an opportunity to study very pristine extra-terrestrial material and requires appropriate careful curation. The meteorite fell in a narrow (600 m across) strewn field ~8.5 km long and oriented approximately east–west, with the largest single fragment at the farthest (east) end in the town of Winchcombe, Gloucestershire. Of the total known mass of 602 g, around 525 g is curated at the Natural History Museum, London. A sample analysis plan was devised within a month of the fall to enable scientists in the UK and beyond to quickly access and analyze fresh material. The sample is stored long term in a nitrogen atmosphere glove box. Preliminary macroscopic and electron microscopic examinations show it to be a CM2 chondrite, and despite an early search, no fragile minerals, such as halite, sulfur, etc., were observed.

INTRODUCTION

The arrival of the Winchcombe CM2 meteorite on February 28, 2021 marked the recovery of the first UK fall in 30 years (Daly et al., 2021; King et al., 2022; O'Brien et al., 2022; Rowe, 2021). Indeed, the UK to date has had a mere 19 meteorite falls, around half as many as Germany and less than a third of those seen to fall and be recovered in France (Winchcombe, 2022). Most of the UK falls are ordinary chondrites, with the notable exceptions of the winonaite Pontlyfni and the iron meteorite Rowton, and before the fall of Winchcombe, included no carbonaceous chondrites (Grady, 2000; Winchcombe, 2022).

Although the recovery of meteorite falls is historically a rare event in the UK, it has triggered scientific breakthroughs. In particular, the fall of the first recovered UK meteorite that still exists, Wold Cottage, in Yorkshire, 1795, settled a debate about the origin of meteorites (Pillinger & Pillinger, 1996). At this time, the idea that meteorites were extra-terrestrial was controversial, but the meteorite fall inspired a study that showed that such stones across the world have chemical similarities and, therefore, were likely to all have been the products of meteors, that “have fallen on the Earth” (Howard, 1802). Over the next 200 years, the UK has witnessed and recovered an average of one fall per decade, including the largest UK meteorite (by size and mass), Barwell (L6), which landed on Christmas Eve in 1965 (Grady, 2000).

Over the last decades, meteor observation cameras have been established in several countries to increase the probability of recovering falls. Since 1991, our ability to record fireballs and locate potential falls has expanded dramatically thanks to the establishment and expansion of networks of such cameras (e.g., Colas et al., 2020; Devillepoix et al., 2020). In the UK, the UK Fireball Alliance (UKFAll) was created in 2018 to enable the six fireball networks (The UK Fireball Network [UKFN; part of the Global Fireball Observatory], the SCAMP network [part of the French Fireball Recovery and InterPlanetary Observation Network (FRIPON)], UK Meteor Observation Network [UKMON], NEMETODE, All Sky7, and the Global Meteor Network) active in the country to collaborate and share data. It currently consists of over 160 cameras and covers most of the UK (https://www.ukfall.org.uk/; McCullen et al., 2023 [this volume]; Rowe et al., 2020). Although the UK is surrounded by sea and is blessed with notoriously cloudy skies, around three potential meteorites >100 g are observed to fall across Western Europe every year (Colas et al., 2020) and UKFAll was established to help coordinate the recovery of such new falls.

The Winchcombe fireball was widely observed and reported by over 1000 eyewitnesses as well as by meteor camera networks. Given its slow speed (14 km s^{-1}; King et al., 2022) and over-land trajectory, the possibility of a meteorite on the ground was known within hours. Images and videos of the fireball were assembled overnight and approximate trajectories had been calculated by FRIPON and Desert Fireball Network (DFN) before 6 a.m. on March 1, 2021. An accurate trajectory calculated by DFN (using data from three SCAMP cameras, three UKFN cameras, and one NEMETODE camera) was available by 8:25 a.m. By 9:30 a.m. (11.5 h after the fall), UKFAll released a press release showing the approximate strewn field, and a media campaign to increase public awareness of a possible meteorite fall was undertaken. This public awareness campaign was triggered by the timing of the event when the UK was under a strict national COVID-19 lockdown, where unless there were essential business reasons to travel, people were only permitted to exercise locally to where they lived, for health benefits. This required a nuanced message to the public, to advise people to look out for meteorite fragments when they were in the area in any case, but not to encourage traveling to search for it, which may have been against UK law at the time. Guidance was also issued on how to ideally collect any samples which were thought to be meteorites, to avoid contaminating the samples as much as possible.

After the press release was shared (see supporting information), and local media coverage disseminated the information about a fireball event, several potential stones were identified by members of the public and reported to the UKMON or UKFAll websites, or to the Natural History Museum (NHM). Images of possible finds were forwarded to Dr. Ashley King (NHM) for triaging by a group of UK meteorite scientists. For images that were identified as being potentially meteorite-like, home visits were made by the authors to confirm whether the samples were meteorites or not. The recovery was made more challenging than usual because the UK was in a lockdown due to the COVID-19 pandemic at the time of the fall.

The purpose of this paper is to provide a record of the recovery process of the meteorite, along with the curatorial arrangements and preliminary analysis, and forms part of the *Meteoritics & Planetary Science* Special Issue to discuss this important meteorite fall.

TECHNIQUES

A nondestructive, noninvasive scanning electron microscopy with energy-dispersive X-ray spectrometry (SEM/EDS) analysis was undertaken within days of the fall using a Quanta 650 field emission (FE)-SEM, equipped with a Bruker Quantax EDS system that features a high-sensitivity, annular, four-channel Bruker FlatQUAD silicon drift detector (SDD) (Hodoroaba et al., 2016; Terborg et al., 2017). The annular SDD is inserted between the pole piece and sample within the main chamber of the SEM. The four integrated SDD segments are arranged in radial symmetry around a hole through which the electron beam passes. The annular SDD has a 10–100 times higher collection efficiency when compared to conventional EDS detectors with inclined geometry. It allows sufficient data collection on uncoated, beam-sensitive, and nonconductive samples with substantial surface topography using ultra-low beam currents under high vacuum. Compared to low vacuum analysis using the variable pressure mode of the SEM, this approach avoids beam skirting effects and enhances the spatial resolution for EDS. In addition, the contamination of hydrocarbons is reduced. To decrease the interaction volume of emitted X-rays and enhance the spatial resolution for elemental analysis to the sub-micrometer scale, low to intermediate accelerating voltages were applied. An accelerating voltage of 6 and 9 kV and a beam current of 30–190 pA resulted in an input count rate up to 55,000 counts per seconds. Several of the unprocessed fragments were initially mapped at 3 and 4 μm pixel resolution using automated stage control to identify features of interest, which were then further analyzed at a pixel resolution down to 16 nm.

RECOVERY

Wilcock Driveway

The main mass of the meteorite fell onto a driveway in the small Cotswolds town of Winchcombe, around 12 km north-east of Cheltenham in Gloucestershire, at around 10 p.m. on February 28, 2021. The homeowners, Rob and Cathryn Wilcock, were downstairs and unaware of the fall. Their adult daughter Hannah, the only other person in the house at the time, in a front facing bedroom upstairs, reported hearing a clattering noise, which she thought may be a photo frame falling out of the window, but she was not able to immediately locate the source of the noise, and could see nothing from her window in the dark night. The evening and night were settled, cold and cloudy, with no precipitation and minimum temperatures around 2°C.

The following morning, Cathryn and Hannah spotted the newly arrived dark pile of rocks and dust on their driveway when they opened their curtains between 7 and 8 a.m. The dark material was piled over an area of around 1 m^2 (Figure 1a) between the front door and a car, with other fragments being scattered across the driveway and grass lawn. After consultation with other members of their family, they learned about the news regarding a fireball from the previous evening and realized that the driveway material was likely extra-terrestrial in origin. The material was then carefully collected by Rob Wilcock wearing polyethylene gloves and using a stainless-steel knife into cleaned polystyrene/polypropylene yoghurt pots and polyethylene sealing sandwich bags (Figure 2), at around 9:30 a.m. The largest single stone (17.2 g), which had bounced into their next-door neighbor's (Pam Godfrey's) driveway around 10 m from the main impact site, was also recovered using aluminum foil later the same day.

Images from the Wilcock family were reported to UKMON on March 1. Dr. Richard Greenwood (Open University [OU]) saw the driveway images and was immediately reminded of similar small falls onto hard surfaces such as the Braunschweig meteorite that fell in Germany in 2013, which similarly disintegrated on impact (Bartoschewitz et al., 2017). He visited the family on the afternoon of March 3 and confirmed the carbonaceous chondrite fall by hand specimen inspection, noting its visual similarity to the Cold Bokkeveld CM2 chondrite. He phoned Dr. King who arrived later that day. Preliminary characterization was carried out that night on a table set out in the Wilcock's garden to conform with UK lockdown guidance that did not allow households to mix indoors (Figure 3). The Wilcock family allowed the meteorite to be removed by the scientists; a handwritten receipt for the samples was made. Later that day, Dr. Greenwood took two stones to the OU, where oxygen isotope measurements made on March 5 confirmed the CM2 classification (Winchcombe, 2022).

On March 4 other members of the team arrived in Winchcombe including Prof. Sara Russell (NHM), Dr. Luke Daly (University of Glasgow), and Prof. Katie Joy (University of Manchester) and assisted in the retrieval of many additional small fragments and dust from the driveway and garden over the next 3 days, using powder-free nitrile gloves, tweezers, a paintbrush, and a toothbrush. Fragments were collected into aluminum foil, glass vials, and polyethylene sample bags. Aluminum foil is routinely used to collect Antarctic friable carbonaceous chondrites and also for the Sutter's Mill CM fall (Jenniskens et al., 2012). The total recovered from this site was ~319 g. Samples were also collected of the surrounding soil and vegetation, and data from this material are discussed in Chan et al. (2023).

A small indentation of around 1 cm deep and 4 cm across had been made into the tarmac by the meteorite fall. In early September 2021, the driveway itself was excavated and a slab approximately 1 m^2 containing the small indentation from the impact was removed. It has been transported to the NHM for storage, analysis of the small impact pit, and future exhibition.

Woodmancote Gardens

Val and David Carrick, from Woodmancote, reported recovering a single stone of around 11 g on their lawn on the morning of March 1, 2021 to UKMON. Having been troubled over the previous days by cat feces in their back garden, they undertook a thorough search of their lawn, which uncovered the single black stone. After reporting their find, Dr. Greenwood visited their home on March 4 to identify the meteorite (after a house-to-house search as he did not have their full address). The stone is approximately cuboid in shape and largely fusion crusted with a dull black crust. The partial fusion may represent

FIGURE 1. Fragments of the Winchcombe meteorite as found in situ. (a) Wilcock driveway material, material covers an area approximately 1 × 1 m. Image credit: Rob Wilcock; (b) 152-g stone found by search team at Rushbury House Farm. Image credit: Míra Bianka Ihász; (c) 5.2-g fragments found by Luther Jackson in Woodmancote. Image credit: Luther Jackson. (d) 19.2-g stone found on grass verge in Bishop's Cleeve. Image credit: Chris Casey. (e), (f), stones found on the solar farm.

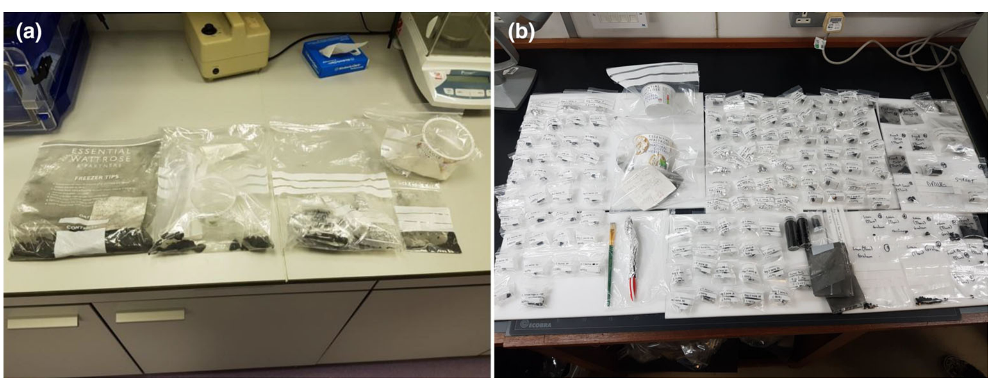

FIGURE 2. (a) The Wilcock family driveway meteorite samples in the Natural History Museum clean room, prior to sample processing. (b) The fragments of meteorite and ephemera curated from the Wilcock driveway material. Copyright Trustees of the Natural History Museum, reproduced with permission.

fragmentation at a late stage during the fireball or fragmentation on impact with the Carrick family roof. However, no corresponding additional fragments were found, despite a thorough search by the Carricks and Dr. Daly on March 5.

The Mounsey family, also from Woodmancote, reported a fall of fragments onto their driveway. On the evening of the fall, they heard a loud bang, which they thought may have been someone breaking into their house or, perhaps the release of a firework close outside. The

FIGURE 3. Ashley King and Richard Greenwood work outside the house of the Wilcock family to take a first look at the Winchcombe meteorite material. Image credit: Rob Wilcock.

next morning, they observed multiple black fragments on their driveway, some of which may have hit their back door, and reported their finding to UKMON. Subsequently, some may have been run over by a car. The sample had fragmented on impact with the driveway and multiple fragments and dust were recovered from a 7.2 m long stretch of the tarmac driveway trending toward 296° over the next few days, with a total mass of around 20 g, including one large fragment of 13.7 g. These stones were collected and recovered on March 5, 2021 by Dr. Daly using nitrile gloves and geological sample bags. A small fragment was also found on the driveway of their next-door neighbor.

UKFAll Field Search

UKFAll team members, as well as planetary science PhD students and early career researchers assembled on the morning of March 4, 2021 to begin a search of the meteorite strewn field, led by Prof. Joy and Dr. Daly. The ground team was guided in where to search by additional more sophisticated strewn field calculations provided by Dr. Hadrian Devillepoix (Curtin), using data from the UKFAll camera networks, and knowledge of the location of the Wilcock driveway recovered stone (King et al., 2022; McCullan et al., 2022). The team members who gathered to join the search were from several UK universities (Universities of Manchester, Glasgow, Plymouth, OU, Imperial College London) and the NHM, with up to around 15 people searching at any one time (see Table S1).

The area searched included a mixture of common and private land, where permission to search could be obtained. The strewn field is in the western part of the Cotswolds region (Figure 4) and is an undulating area of Jurassic sediments. The landscape was formed during the Quaternary period, and especially from the action of melting ice after the last Ice Age (McKerrow et al., 1964). This has produced a hilly region, with elevations along the strewn field ranging from around 50 m above sea level (a.s.l.) in Bishop's Cleeve village, to around 200 m a.s.l. on Cleeve Hill, and 100 m a.s.l. in the town of Winchcombe.

After an initial briefing and training in systematic search techniques involving all the team members, the search divided into two smaller, more manageable, teams who searched in systematic line formations approximately 2–10 m apart (Figure 5), over several days (Table S1). The terrain searched was mainly grassy fields, including long grass (10 cm), short grass (<1 cm, the majority being used for grazing sheep and other livestock), heath-land composed of a mix of shrubs and rough grass, and the Cleeve Hill golf course. Some wooded areas could not be as systematically searched. The weather during the search was generally cold and overcast providing a flat light, but with no rain. Temperatures ranged from −2°C (on the night of March 6) to 9°C in the daytime. The ground was often damp with dew. The grazing land searched included areas of sheep fields, cow fields (some of which could not be searched because of the presence of bulls), and grazing alpacas and horses. Animal droppings were widespread and difficult to distinguish from the fusion crust of carbonaceous chondrites from a distance. Data highlighting the searched areas are shown in Figure 4.

On March 7, the fourth day of searching, a smaller team from the University of Glasgow was searching in the fields of Rushbury House Farm between Winchcombe and Woodmancote, when team member Míra Bianka Ihász found a 152-g stone at around 9:39 a.m. (Figure 1b). The intact stone was embedded ~5 cm into mud and split into two fragments (48 and 103 g and crumbs) during extraction. It was collected using nitrile gloves and geological sample bags. Ground samples were also collected of the surrounding soil and vegetation, and data from this material are discussed in Chan et al. (2023).

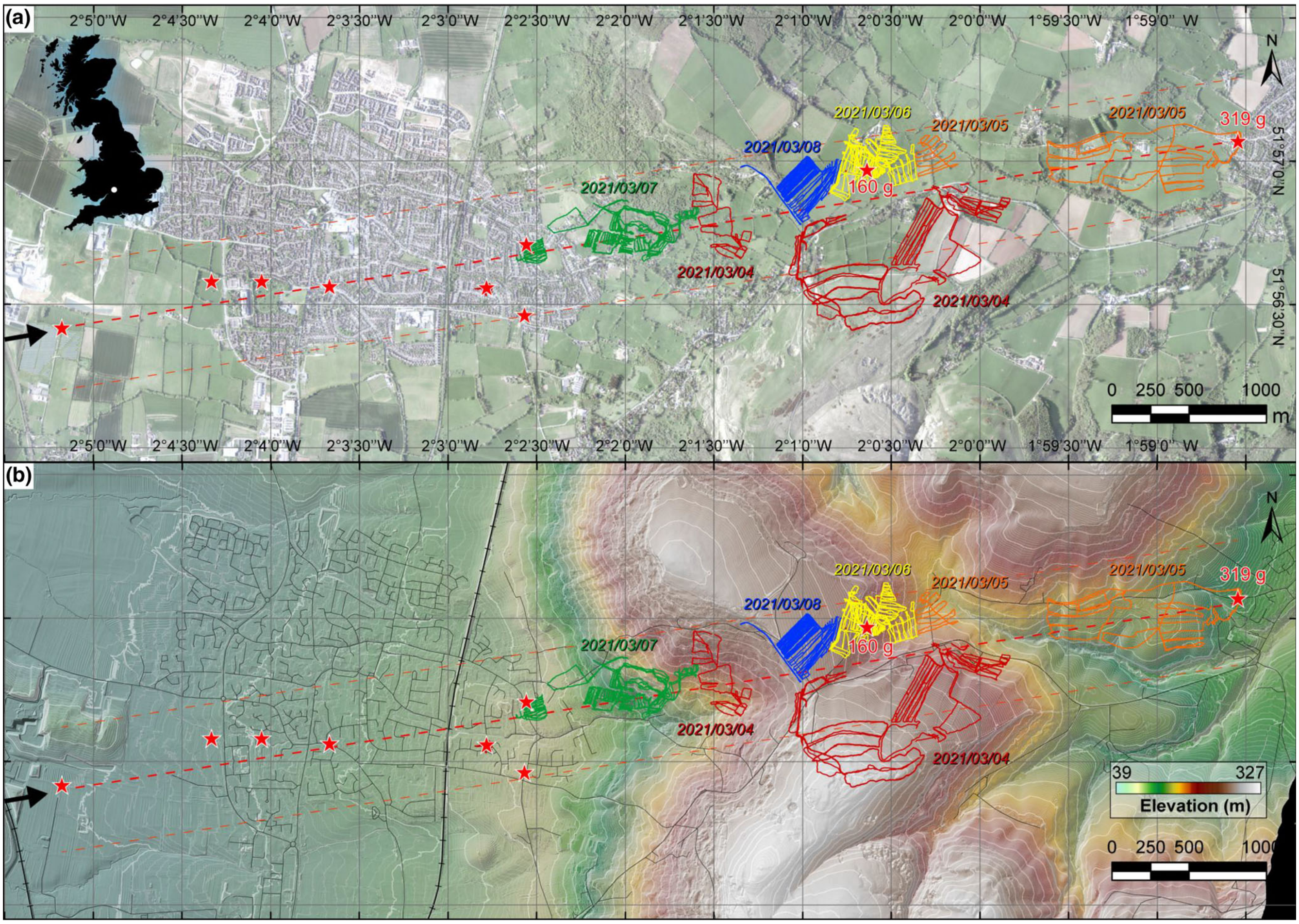

FIGURE 4. The meteorite strewn field. Shown in each case are the meteorite locations (red stars), GPS search tracks by date, and the best fit (bold, dashed red line) and 1 standard deviation (faint, dashed red lines) for the meteorite locations. Masses for the two largest meteorites are given, with all others being <20 g. (a) Aerial photograph base image, with a spatial resolution of 25 cm per pixel (© Getmapping Plc). Inset shows the location of Winchcombe on a map of Great Britain. (b) Topographic hillshade base image, and contours at 10 m (bold white lines) and 1 m (faint white lines), made from light detection and ranging (LiDAR) data with a spatial resolution of 1 m per pixel (Environment Agency copyright and/or database right 2022. All rights reserved). Local roads (black lines) and rail tracks (hashed line) are also shown (© Crown copyright and database rights 2022 Ordnance Survey [100025252]).

The UK was in lockdown due to the COVID-19 pandemic at the time; this meant that only essential travel was allowable by law and placed severe constraints on the ability for people to mix indoors and within cars. The team was limited in size to one household per vehicle and per hotel room, and no communications about the search were put on social media, to discourage additional searchers who were not authorized to travel to the area. The meteorite fall was considered an essential reason for the team members to travel in order for them to undertake their jobs, but this entailed a huge amount of paperwork, detailed risk assessments, and their host organization's permissions needed to be submitted and only a minimal team were able to attend the site over the days following. Each search team member had to obtain official permission from their institutions at very short notice, including completing risk assessments including the risks of catching and transmitting COVID-19. Interactions with residents living around the strewn field were heavily restricted, which made gaining permission to search more problematic. Rules on mixing indoors and the cold outdoor weather made it difficult for the search team to discuss progress and strategy at the start and end of each day, and rules about transport sharing resulted in many cars being involved, which made parking on country roads more difficult. The pandemic meant that the meteorite recovery was unlike any other and restrictions on movement meant that far fewer people could search in person than would normally be the case for a UK meteorite fall.

FIGURE 5. The search team at work in the initial systematic search at Cleeve Hill common on March 4, 2020. Image credit: Katherine Joy.

Other Field Searches

Solar Farm

Jason Williams alerted Dan Kirk of Toucan Energy that the Brockhampton Solar Farm was within the meteorite strewn field. Jim Rowe sent Dan some information on March 12 about how to identify meteorites, and a team composed of solar farm employees searched the farm area as part of their normal inspection activities (Table S1). On March 16, several small stones and fragments (total mass 17 g) were retrieved from the solar park, which is to the south-west of the village of Bishop's Cleeve (Figure 1e,f).

Casey, Jackson, and Ensor Search

Chris Casey spent a total of 6 weeks searching in the Winchcombe area, using an independently derived strewn field map. Search areas consisted of mainly grassy fields, roadsides, and paths between Winchcombe and Bishop's Cleeve and also to the east of Winchcombe. On March 21, 2021, he found a 12-g half stone on a grass verge in Woodmancote, which had possibly fragmented after hitting a tree. This was followed by another find of 17.5 g on March 23, 2021 on "The Grange," a public open space in Bishop's Cleeve often used by dog walkers. This stone had broken into two pieces. On March 25, 2021, Chris Casey and Luther Jackson found a 19.2-g stone, on a grass verge by the footpath on Two Hedges Road, Bishop's Cleeve (Figure 1d). This stone had apparently been driven over by a car, which caused it to fragment into three pieces plus a pile of dust. On April 1, 2021 Luther Jackson, while hunting with Chris Casey and Graham Ensor, found another 5.2-g stone on a footpath in the West of Bishop's Cleeve, by the A435. The impact with the hard path had caused it to fragment into many pieces (Figure 1c).

EEARO Search

A team from the East Anglian Astrophysics Research Organisation (EEARO) searched the region close to the solar farm and in Woodmancote. On the morning of March 28, they reported finding a fragment in a muddy horse field. The meteorite, of unknown mass, was embedded in mud and so a cuboid of mud and meteorite was removed for later processing in laboratory conditions (Derek Robson, personal communication).

Other small fragments have reportedly been recovered from the field area, but their exact location and masses are unknown. Generally, stones that fell onto grass or mud tended to survive mostly fusion crusted, whereas those that fell onto hard surfaces like tarmac fragmented (Figure 1).

TABLE 1. Winchcombe meteorite fall locations and masses. (location coordinates given to 3sf to preserve privacy of homeowners)

Date (day/month/year)	Mass (g)	Largest fragment (g)/no. fragments >1 g	Location	Finder	Coordinates: latitude, longitude
Winchcombe					
01/03/21	206.5	8.8/44	Driveway/Lawn	Wilcock	51.951, −1.976
02/03/21	49.7	5.2/13	Driveway/Lawn	Wilcock	
04/03/21	39.5	7.3/1	Driveway/Lawn	Wilcock, King, Russell, Ensor	
05/03/21	23.0	6.2/2	Driveway/Lawn	Wilcock, Daly, Joy	
07/03/21	0.8	—	Driveway/Lawn	Wilcock, Suttle	
Total mass	319.5				
Winchcombe 01/03/21	20.6	17.2/2	Driveway	Godfrey	51.951, −1.976
Woodmancote 02/03/21	11.2	11.2/1	Lawn	Carrick	51.942, −2.047
Woodmancote 05/03/21	20.1	13.7/2	Driveway	Mounsey	51.945, −2.043
Rushbury House 06/03/21	160.1	152.0/1	Field	Ihasz, Daly, O'Brien, Hallis, Bond	51.950, −2.012
Solar farm 16/03/21	16.5	7.5/4	Field	Farrelly, Spencer, Naqvi, Mayne, Skilton, Kirk	51.941, −2.089
Woodmancote 21/3/21	12.0	12/1	Grass verge	Casey	51.941, −2.045
Bishop's Cleeve 23/3/21	17.5	17.5/2	Park	Casey	51.942, −2.069
Bishop's Cleeve 25/3/21	19.2	19.2/3	Grass verge	Casey, Jackson	51.943, −2.063
Bishop's Cleeve 1/4/21	5.2 g	5.2/1	Footpath	Jackson, Casey, Ensor	51.943, −2.073
Total	601.9 g				

Strewn Field

The Winchcombe stones together define a very narrow strewn field with a length of around 8.5 km (from Winchcombe to the solar farm) and width ~600 m, that follows a line in the direction 080°; approximately west to east (Figure 4). The largest mass, from the Wilcock driveway, defines the easternmost point of the strewn field, at the end of the fireball trajectory. Fall sites and masses are given in Table 1. Smaller fragments spalled off earlier in the trajectory, with the stones found at the solar farm being the most westerly samples collected. The low wind speeds on the night of the fall likely contributed to the thin and narrow strewn field, and the bolide likely experienced winds no greater than ~10 m s^{-1} during the dark flight (King et al., 2022; McCullen et al., 2023).

Using fireball observations, an estimate of the total weight entering Earth's atmosphere is 13 $\pm$ 3 kg with an expected terminal mass reaching the Earth's surface of ~500 g (King et al., 2022). The total known weight of the meteorite is currently 602 g, although there are a few other additional small fragments in the hands of dealers and collectors that have not been well documented. Therefore, the modeling would suggest that most of the meteorite has probably been found and collected. UKFAll systematically searched ~30% of the strewn field (Figure 4), and over the following weeks meteorite searchers investigated accessible areas along the fall line and ~750 m each side. While it is possible that some small stones have been missed, it is likely that most of the fall has been recovered.

CURATION

Most of the total documented weight of the Winchcombe meteorite (~86%) has been kindly donated to the NHM by the finders and landowners. Fragments were also donated to the Winchcombe Museum and to the Wilson Art Gallery and Museum in Cheltenham by the Wilcock family. The multiple donors have enabled access to all parts of the strewn field and to stones that fell into differing media (field, tarmac, etc.). In addition to the stones, collection tools used such as cleaned cottage cheese pots, sandwich bags, takeaway boxes, a toothbrush, and a paintbrush have also been preserved as ephemera and witness plates (Figure 2b). To help better understand any interactions between the meteorite and its environment, soil samples from the Wilcock driveway and the sheep field at Rushbury House were also collected and stored. All specimens are now accessioned, with registration numbers according to donor, location, and collection date, as per the table in King et al. (2022). Table 2 lists the specimens accessioned by the Museum (not total mass collected at each location). Individual fragments and vials of crumbs (< ~100 mg) and/or powder have been given subsample numbers to facilitate accurate tracking of the material. Similarly, material allocated for research purposes is individually numbered.

Storage

CM chondrites are easily altered once they fall to Earth. Organic and other volatile contamination can occur by interaction with vegetation, soil, air, and water, either in the ground or absorbed from the air, and can have a very significant impact on the mineralogy and composition of CM chondrites (Lee et al., 2021). For example, Sutter's Mill quickly presented the signs of chemical alteration due to interaction with terrestrial water (Burton et al., 2014; Jenniskens, 2014; Jenniskens et al., 2012). Likewise, Winchcombe fragments recovered from the Rushbury field showed signs of minor mineralogical changes in response to terrestrial alteration over a time scale of months (Jenkins et al., 2023). Therefore, curation processing and conditions have to be especially mindful of keeping the samples in clean and dry conditions. For highly aqueously altered carbonaceous chondrites, Herd et al. (2016) recommend that ideal storage would be in argon, and at <10°C; however, we required a more affordable and sustainable approach.

Magnetic analyses of meteorites can be affected by interaction with magnetic fields on Earth. Magnets were not used near any of the Winchcombe samples. Mobile phones and other electronic devices were, however, not deliberately kept away from the meteorite. Later analysis showed that the meteorite magnetic data are unequivocally inconsistent with the interior of the sample being magnetically overprinted on Earth, so any magnetic alteration during collection and curation was not significant (Bryson et al., 2023).

The initially retrieved Wilcock drive material was transferred to the NHM on March 4, 2021 and was weighed and curated on March 5, 2021. The size distribution of the rock fragments retrieved from the driveway is shown in Figure 6. The smallest fragments and dust (< ~200 mg) were not individually weighed and the size distribution likely increases exponentially with decreasing size of fragment. In all, 23 of the larger fragments (> ~2.5 g) were encased in high purity aluminum foil (Alujet Universal, purchased through VWR) and stored in acid-free trays with Mitsubishi RPK oxygen scavengers within heat-sealed Escal enclosures. Smaller fragments and powder were sealed in glass vials stored within polyethylene sample bags (Figure 2). The NHM samples were initially stored in a table-top desiccator and samples are taken out only for analysis or outreach. Not having ideal storage for a large fresh new carbonaceous chondrite, funding was sought from UK Research and Innovation (UKRI) funding body the Science and Technology Facilities Council (STFC) for a specialist glovebox to curate the samples in the longer term. The glovebox purchased from these funds is manufactured by MBraun GMBH. It is freestanding, with a footprint of approximately 1 × 2 m. The meteorite is now being kept in the long term in a clean nitrogen atmosphere with oxygen levels <0.5 ppm; a built-in microscope will aid sample manipulation.

Two of the larger stones with a total weight of 15.8 g were picked from the retrieved material on March 4, 2021 in Winchcombe using nitrile gloves, and taken directly to the OU to facilitate rapid analysis of oxygen and other light element isotopes. The material remains at the OU, on long-term loan from the NHM collection, and is stored in ultraclean glassware (previously prepared for the NASA Genesis mission) in a nitrogen purge cabinet within a class 100 cleanroom. The individual containers were purged with nitrogen before the lids were sealed, and the cabinet is fed by a continuous flow of pure nitrogen. As the material currently stored at the OU has followed a separate curation route to the majority of Winchcombe samples, they provide a means of monitoring the level of terrestrial contamination, if any, that the bulk of samples have experienced.

TABLE 2. Masses accessioned into the NHM collection.

Registration number	Mass (g)	Locality	Collection date
BM.2022,M1	193.54	Winchcombe	March 1, 2021
BM.2022,M2	49.68	Winchcombe	March 2, 2021
BM.2022,M3	39.53	Winchcombe	March 4, 2021
BM.2022,M4	22.99	Winchcombe	March 5, 2021
BM.2022,M5	0.7993	Winchcombe	March 7, 2021
BM.2022,M6	20.61	Winchcombe	March 1, 2021
BM.2022,M7	11.18	Woodmancote	March 2, 2021
BM.2022,M8	20.14	Woodmancote	March 5, 2021
BM.2022,M9	156.20	Rushbury House	March 6, 2021

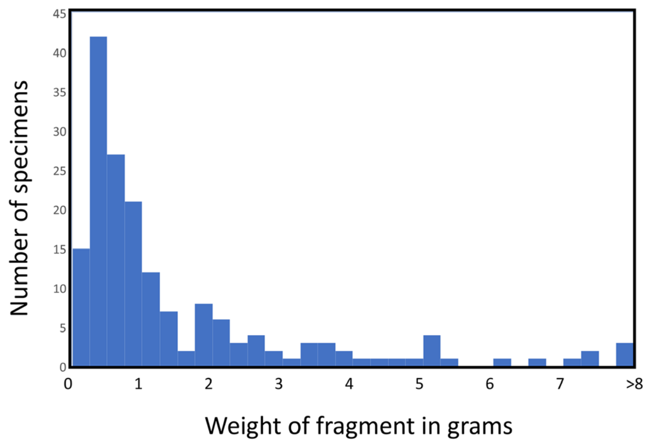

FIGURE 6. The size frequency distribution of material recovered from the Wilcock driveway. Smaller grains (< ~200 mg) were not individually weighed. The distribution is approximately exponential.

The largest of the field collected stones is on public display at the NHM and is exhibited within a desiccator, with desiccant (RP Agents Oxygen Absorbers) packed into the bottom half of the container (Figure 7). The Winchcombe Museum, to whom a meteorite fragment that fell on the Wilcock's driveway was donated, has designed an exhibit that opened in summer 2021 dedicated to the meteorite fall. Their sample of Winchcombe is exhibited in a similar manner to that at the NHM.

Sample Analysis Plan

The UK cosmochemical community together form an organization called the UK Cosmochemistry Network, that works together to deliver world class sample analysis and to bid for funding to ensure our instrumentation base is suitable for next generation extra-terrestrial sample analysis. This community forms the core of the team members involved in Winchcombe sample analysis.

The fortuitous arrival of Winchcombe excited the research community in the UK and internationally. The timing of the fall, just 3 months after the return of fragments of asteroid Ryugu from Hayabusa2, inspired the structure of the sample analysis plan. Led by Dr. King, Dr. Daly, and Prof. Joy, this initial demand for samples was managed by dividing into teams: Coarse Grained Petrology, Fine Grained Petrology, Organics, Magnetism, Light Elements, Isotopes, Fireball, and Curation. These mirror the structure of the Preliminary Analysis teams for the Hayabusa2 mission analyzing material returned from asteroid Ryugu (Tachibana et al., 2017). Given the intense demand of material to study, members of the UK cosmochemical community were invited to share their wishes for sample analysis onto a shared document, which was then consolidated into the teams above and requests were managed by the NHM curators. Within this analysis phase, 47 loans, comprising a total of 76.8 g or 13% of the total NHM meteorite mass, was used, including nondestructive analyses; 52.5 g of this has since been returned to the NHM collection. Thus far, 20 polished sections, made without the use of water or diamond polish, have been made available to the consortium.

Preliminary analyses and the conclusions of the other teams are given in companion papers in this volume as well as in King et al. (2022).

Macroscopic Description

The interior of all samples of Winchcombe is a dull black (Figure 8). There is considerable variation in the meteorite between and within fragments (Suttle et al., 2023), that are visible with the naked eye. Some lithologies, especially those from the driveway, contain multiple white and occasionally orange sub- to millimeter-sized flecks, whereas other stones (e.g., the field collected stone) contain far fewer white flecks, pointing to a centimeter to decimeter scale brecciation of the meteoroid. These flecks are likely carbonates (not calcium–aluminum-rich inclusions, which are rare in Winchcombe). The meteorite fusion crust is lighter than the interior; gray to brownish in color and occasionally iridescent. Polygonal cracks are typically observed on fusion crust fragments. More details on the fusion crust are given in the companion paper by Genge et al. (2023).

Initial Survey of Unprocessed Fragments Using Nondestructive, Noninvasive SEM/EDS

Other very fresh falls have been reported to contain delicate and water-soluble minerals such as halite (e.g., Rubin et al., 2002), oldhamite (Haberle & Garvie, 2017; Jenniskens et al., 2012). To detect such minerals, within a week of the fall we investigated uncoated and unprepared fragments of the meteorite using SEM-EDS. Samples of a few millimeters across from the quickest-collected Wilcock driveway material were mounted onto carbon-based electrically conductive, double-sided adhesive discs, also known as Leit tabs, stuck to the flat surface of two aluminum SEM pin stubs. The fragments were then quickly transferred to the SEM.

Physically, many of the fragments were found to be coated in a fine-grained meteoritic dust, suggesting that it is highly electrostatic in nature. Mineralogically, we found it to be composed of silicates, sulfides, and phosphates with occasional globules of carbonaceous material, often associated with carbonate (Figure 9). Despite a search, we found no evidence for halite or other

FIGURE 7. The largest intact fragment, found by Míra Bianka Ihász, now on display at the Natural History Museum, London in the Vault gallery. Copyright Trustees of the Natural History Museum, reproduced with permission.

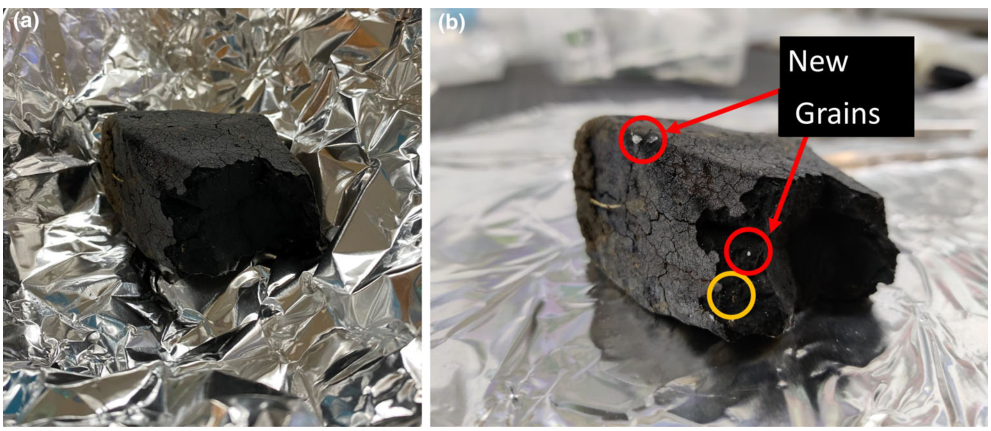

FIGURE 8. The Winchcombe meteorite Rushbury stone in hand specimen (approximately 5 cm in largest dimension). (a) On first arrival at the Natural History Museum. (b) After a few weeks, some white grains had grown on the surface of the stone. Copyright Trustees of the Natural History Museum, reproduced with permission.

salts, or elemental sulfur, oldhamite, or similar fragile minerals.

Terrestrial Alteration

Despite curation conditions as reported above, observations by eye in the weeks following the fall revealed a millimeter sized white deposit forming on the fusion crust of the field-collected stone. This deposit was not present when the stone arrived at NHM in early March (Figure 8a), but was present on re-inspection on May 10, 2021 (Figure 8b). This material was removed and X-ray diffraction analysis showed it to be amorphous in nature. A more detailed study of the terrestrial alteration of Winchcombe is given in the companion paper by Jenkins et al. (2023).

CONCLUSIONS AND LESSONS LEARNED

Context of Other Recent Carbonaceous Chondrite Falls

Winchcombe is one of several recent CM and other highly aqueously altered falls over the last few years. Others of note include Aguas Zarcas (CM), a large 27 kg shower in Costa Rica in 2019, Tarda (C2-ung that fell in Morocco in 2020; Chennaoui et al., 2021), and the 2019 German fall Flensburg (Type 1 ungrouped; Bischoff et al., 2021). Of the 52 carbonaceous chondrite meteorite falls to

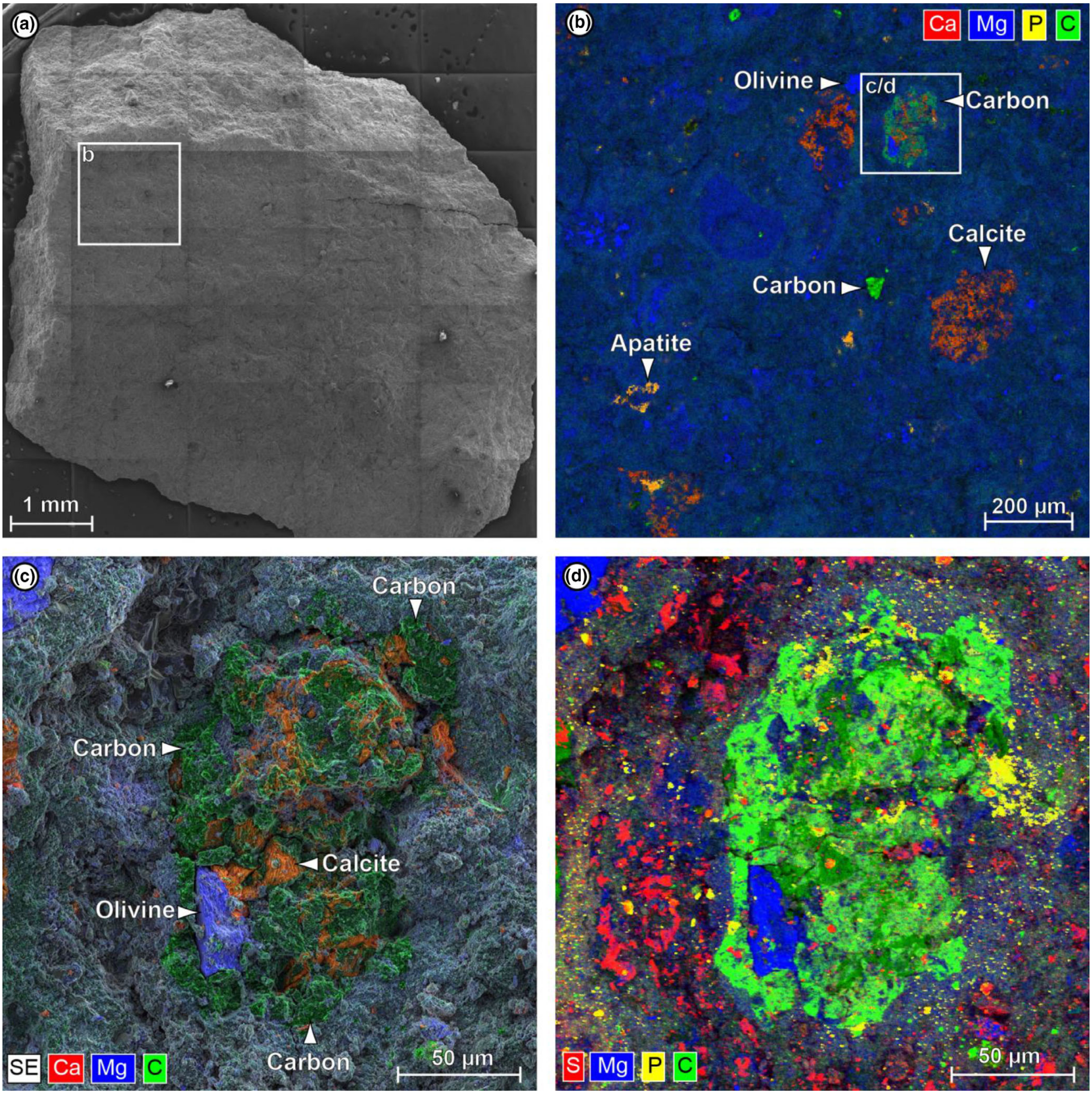

FIGURE 9. Nondestructive, noninvasive scanning electron microscopy (SEM) and energy-dispersive X-ray spectrometry (EDS) of a Winchcombe fragment that was analyzed using a high-sensitivity, annular silicon drift detector without conductive carbon coating at high vacuum. (a) Secondary electron (SE) mosaic of the area that was analyzed with EDS using automated stage control (6 kV, 87 pA, 27,000 counts per second, 2451 × 2209 pixels, 3 µm pixel size). (b) Net intensity elemental map of the outlined rectangle in (a). Carbon is represented in green and locally enriched, for example, at the outlined rectangle. Calcite is represented in dark orange by mixing calcium (red) with carbon. Apatite is shown in bright orange by mixing phosphorous (yellow) with calcium. The highest magnesium (blue) intensities show the presence of olivine. (c) Net intensity elemental map (6 kV, 105 pA, 35,000 counts per seconds, 1880 × 1880 pixels, 116 nm pixel size) mixed with the SE image of the outlined rectangle shown in (b). At larger calcite grains (orange), cleavages can be observed. Calcite is mantled with carbonaceous material that is enriched in carbon (green) and nitrogen (supplemental material). (d) Net intensity elemental map showing the distribution of sulfides represented by sulfur (red). Apatite grains >300 nm in size are represented by phosphorus (yellow). Copyright Trustees of the Natural History Museum, reproduced with permission.

date, seven—13% of all known carbonaceous chondrite falls—have fallen since 2017 (Mukundpura [CM2]; Shidian [CM2]; Aguas Zarcas [CM2]; Flensburg [C1-ung]; Kolang [CM1/2]; Tarda [C2-ung]; Winchcombe [CM-2]; Winchcombe, 2022). In addition, the 2008 fall Almahatta Sitta is predominantly a ureilite, but contains Type 1 carbonaceous clasts (e.g., Goodrich et al., 2019). Furthermore, all of these carbonaceous chondrites are Type 1 or Type 2; whereas taking the meteorite population as a whole, one would expect only around half to be these petrographic grades. To put it another way, carbonaceous chondrites make up only 3.8% overall of the world's classified meteorite falls, but among meteorite falls since 2017, 16.7% have been carbonaceous (7/42), implying a possible change in the types of meteorites represented by the meteorite flux over the last few years. Lee et al. (2021) recently noted that CM chondrites over the last 100 years appear to have fallen in two clusters that spanned a few years each.

Sample Return Missions

As a very fresh carbonaceous chondrite, from a known orbit (King et al., 2022; McCullen et al., 2023), that was collected 12 h after its fall, in some ways Winchcombe is comparable to asteroid sample return missions and like other carbonaceous chondrites can be used as a reference for such missions (Zolensky et al., 2014). There have so far been two such missions that have successfully returned to Earth (JAXA's Hayabusa and Hayabusa2, e.g., Yada et al., 2022) and one that is in-flight (NASA's OSIRIS-Rex, e.g., Lauretta et al., 2017). As described above, the protocols we used for the preliminary examination and analysis of Winchcombe were inspired by those used for material recently returned from asteroid Ryugu by the Hayabusa2 mission (Tachibana et al., 2017).

NASA's OSIRIS-REx mission is en route to Earth with its cargo of fragments of asteroid Bennu expected to return in September 2023. While the mission's objective is to return at least >60 g of material, analysis of the successful collection event and sample holder (TAG-SAM) afterward suggests that the returned amount may be larger than this in mass (Lauretta and The OSIRIS-REx TAG Team, 2021). The Winchcombe meteorite may be, in some ways, comparable to this sample return mission; Bennu is likely to be carbonaceous chondrite-like material (e.g., Bates et al., 2020; Hamilton et al., 2022). The expected size distribution of the material returned from Bennu will be pebbles up to 2 cm across and many much finer-grained fragments, very much like the postimpact size distribution of the Wilcock driveway stone. Therefore, there may be an opportunity to use Winchcombe in rehearsals for the curation and initial examination of Bennu fragments.

Lessons Learned

Overall, the recovery of the Winchcombe meteorite was very successfully undertaken despite the unusual circumstances of the COVID-19 pandemic. Future searches may benefit from having generic risk assessments already completed and permissions from institute administrators in place, to enable researchers to act immediately. Many aspects were worked out as we went along; we found it was essential to have a single point of contact for reports of fireballs, and for possible meteorite finds. There are no specific laws on meteorites as property in the UK, and questions of meteorite ownership have never been tested in court, raising potentially confusing situations where finder, property owner, and occupier are not the same. Seeking quick legal advice for any disputes is essential. A team WhatsApp group ensured good communication between team members that were not in the same location. We recommend that search teams should all agree to "Rules of the Road" that include, for example, the use of social media during searches (or not), and rules about ways to acknowledge the wider team during media interviews. Many people are involved in such an event, from those setting up cameras and analyzing fireball data, to those searching for meteorites and producing first results. Having clear expectations of each team member is essential. To the extent possible, co-authorship of resulting publications needs to be agreed in advance of the recovery effort, as does funding sources and requirements.

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Data Availability Statement—The data that support the findings of this study are openly available at the NHM data portal (https://data.nhm.ac.uk/).

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article.

Table S1. Winchcombe searchers for UKFAll field search.

Data S1. The UKFAll press release of March 1, 2021.