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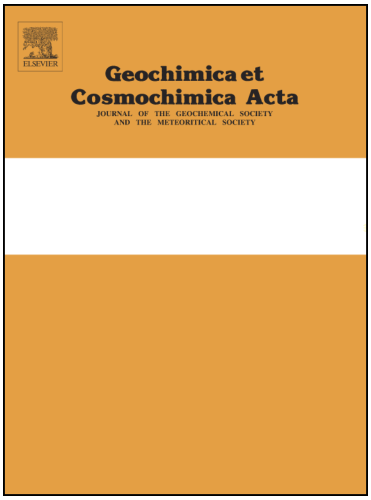
Greenwood, Richard C.; Burbine, Thomas H. and Franchi, Ian A. (2020). Linking asteroids and meteorites to the primordial planetesimal population. Geochimica et Cosmochimica Acta (Early Access). (In Press)

Version: Accepted Manuscript

Link(s) to article on publisher's website:
http://dx.doi.org/doi:10.1016/j.gca.2020.02.004



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PII: S0016-7037(20)30105-8
DOI: https://doi.org/10.1016/j.gca.2020.02.004
Reference: GCA 11643

To appear in: *Geochimica et Cosmochimica Acta*

Received Date: 30 November 2018
Revised Date: 3 February 2020
Accepted Date: 3 February 2020

Please cite this article as: Greenwood, R.C., Burbine, T.H., Franchi, I.A., Linking asteroids and meteorites to the primordial planetesimal population, *Geochimica et Cosmochimica Acta* (2020), doi: https://doi.org/10.1016/j.gca.2020.02.004

Linking asteroids and meteorites to the primordial planetesimal population

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Abstract

Meteorites provide a unique insight into early Solar System processes. However, to fully interpret this record requires that these meteorites are related back to their source asteroids and ultimately to the original planetesimal population that formed early in Solar System history. As a first step in this process an assessment has been undertaken of the likely number of distinct source asteroids sampled by meteorites and related extraterrestrial materials. The results of this survey indicate that there are between 95 and 148 parent bodies represented in our sample collections. This number has been steadily increasing as new "anomalous" meteorites are characterized. Attempts to link these parent bodies to identified asteroidal sources has so far been of limited success, due to the non-unique reflectance spectra of almost all known asteroids. Asteroid (4) Vesta and the HEDs (howardites, eucrite, diogenite) meteorites is the best example of a relatively non-disputed asteroid-meteorite linkage.

As part of this study the "parent body" concept has been examined and it is found to be a widely, but loosely, used term in the literature to designate "a body that supplies meteorites to Earth." This concept could be rendered more meaningful by discriminating between primary and secondary parent bodies. A primary parent body is the source asteroid from which the meteorite is ultimately derived, and a secondary parent body is an asteroid derived through impact or break-up of the primary body. A clear example of this usage is provided by (4) Vesta, with the main asteroid being the primary parent body and the Vestoids representing secondary parent bodies. The concept of primary vs. secondary parent bodies may have important implications for early Solar System evolution. Chondritic parent bodies are known to have accreted between 1 and 4 Myr after CAIs. This timing difference may reflect the fact that their source asteroids, particularly those of the carbonaceous chondrites, are secondary bodies, with the original CAI-bearing primary bodies destroyed during early collisional processing.

The number of primary parent bodies represented by meteorites (95 to 148) appears low when compared to the estimated number of asteroids in the main belt (> 100,000 with diameters exceeding ~2 km). A range of potential reasons may explain this apparent mismatch: i) meteorites provide an unrepresentative sampling of the main belt, ii) the belt may only contain a limited number of primary parent bodies, iii) meteorites may be preferentially derived from the ~120 identified asteroid families, iv) loosely consolidated types are filtered by Earth's atmosphere, v) multiple, near-identical, "clone" parent bodies may be present in the belt. At present, it is not possible to determine which of these potential mechanisms are dominant and all may be operating to a greater or lesser extent.

Based on classical accretion models the meteorite record appears to be highly unrepresentative of the primordial asteroid population. In contrast, pebble accretion models suggest that these first-generation bodies may have been relatively large, in which case meteorites may provide a more unbiased record of early Solar System processes.

1. INTRODUCTION

Meteorites provide us with a great diversity of extraterrestrial materials. However, to interpret this record effectively we need to link these meteorites to their source asteroids and ultimately relate both to the original asteroidal population. This involves addressing a number of key issues: i) how many asteroids/parent bodies are represented in the worldwide meteorite collection? (Wasson, 1995; Burbine et al., 2002a; Hutchison, 2004); ii) how well can we link meteorites to particular asteroids (e.g., Burbine, 2016); iii) how useful are contemporary meteorites and asteroids as indicators of the composition and structure of the first-generation of planetesimals, those that accreted early in the evolution of the Solar System? (e.g. Weidenschilling 1988; Ruzicka et al., 1997; Day et al., 2009, 2015, 2019; Scott et al., 2018). Relevant to this final point are the proposals that: (i) giant planet migration was a major control on main belt structure (Walsh et al., 2011) and (ii) that early planetesimal fragmentation resulted in a differential loss of mantle material (Burbine et al., 1996). Understanding the compositional diversity of the original planetesimals is a crucial step in constraining the composition of the building blocks of the terrestrial planets (e.g., Burbine and O'Brien, 2004).

Dynamic models suggest that inward-then-outward migration of the gas giants first cleaned out the main belt, then repopulated its inner regions with planetesimals that accreted in the inner Solar System (~1-3 AU) and repopulated its outer regions with bodies that formed between and beyond the orbits of the giant planets (Walsh et al., 2011). This migration has been postulated to have occurred over 4480 Myr ago due to the lack of widespread crustal reset ages of various parent bodies after ~4450 Myr ago (Mojzsis et al., 2019). Dynamical models have been invoked to suggest that (4) Vesta may have formed in the inner Solar System (e.g., Bottke et al., 2006), although the origin of Vesta is uncertain and its mode of formation remains controversial (Consolmagno et al., 2015; Tian et al., 2019). In contrast, Ceres may have formed in the outer Solar System (e.g., Grazier et al., 2018). The distribution of asteroid taxonomic classes in the main belt (Gradie and Tedesco, 1982; DeMeo and Carry, 2014) is consistent with this scenario. The distinct separation of carbonaceous chondrites from most other meteorite groups on plots such as Δ^{17}O vs. ε^{54}Cr (Warren, 2011; Scott et al., 2018) is consistent with distinctly different formation regions for non-carbonaceous (NC) and carbonaceous (CC) chondrite material in the Solar System (Warren, 2011; Kruijer et al., 2017; Desch et al., 2018; Scott et al., 2018). These isotopic differences may be due to the rapid formation of Jupiter, which as a consequence formed a barrier to the inward movement of material across the disk

(Kruijer et al., 2017). Alternatively, such isotopic differences may reflect secular changes in the composition of the materials from which Solar System bodies were formed (Schiller et al., 2018).

Asteroids with interpreted mineralogies consistent with forming at relatively high temperatures in the solar nebula (e.g., Mg-rich olivine and pyroxene) (Grossman, 1972) are more abundant in the inner main belt, whereas asteroids with interpreted mineralogies consistent with forming at lower temperatures (e.g., hydrated silicates, organics) are more abundant in the outer part of the belt. Parent body processes (aqueous alteration and/or thermal metamorphism) may alter these primary mineral assemblages (e.g., Alexander et al. 2018a). Many bodies melted and differentiated through the radioactive decay of ^{26}Al (e.g., Reeves and Audouze, 1968; Grimm and McSween, 1993; Hevey and Sanders, 2006). Almost all of these bodies were subsequently disrupted through impacts (Fig. 1).

We currently have approximately 62, 000 meteorites in our collections (nearly ~23, 000 non-Antarctic and just over ~39, 000 Antarctic meteorites) (source: Meteoritical Bulletin Database). The vast majority of these meteorites are likely to be fragments of asteroids (Burbine et al., 2002a). However, we certainly do not have samples from 60, 000 distinct meteoroids. Due to lack of relevant information, many individual named meteorites listed on the Meteoritical Bulletin Database are likely to be paired samples. This problem is particularly acute with respect to desert finds. Meteorites are derived from both chondritic bodies that did not melt (except for impact melts that are sometimes present) and achondritic bodies that experienced variable degrees of melting Approximately 80% (Burbine, 2014) of meteorites seen to fall during the last ~200 years are samples from only three meteorite groups, namely the H, L and LL ordinary chondrites. However, the meteorite flux is known to change over timescales of hundreds of millions of years, with achondrite falls more prevalent in the past (Heck et al., 2017).

In this paper, we examine the relationship between the meteorite and asteroid populations. We are motivated not simply to link meteorites to the current asteroid population, but also to assess what information meteorites provide about the original planetesimals that populated the early Solar System. Accordingly, we attempt to build on earlier studies (e.g., Burbine et al., 2002a; Burbine 2014; Greenwood et al., 2017). We expand on the study of Greenwood et al. (2017) that was mainly concerned with achondrites. While we principally look at the information available for larger extraterrestrial samples, i.e. meteorites, we also briefly examine micrometeorites, cosmic dust and various types of breccia fragments.

2. DATA SOURCES AND DEFINITIONS

2.1 Methods and data sources

We use a range of evidence to link meteorites and asteroids. Meteorite classification forms the basic framework to our current understanding of the relationships between different types of extraterrestrial materials (Weisberg et al., 2006; Krot et al., 2014). An overview of these studies is given in the Electronic Annex. We use oxygen isotopes as our primary tool for assessing whether meteorite groups are derived from a single source (see section 2.3 below). All of the oxygen isotope data plotted in Figs. 2, 4, 5, 6, 7, S2, S3, S4, S5 are provided in the Electronic Annex (Tables S1 and S2). Analytical methods for oxygen isotope analyses obtained at the Open University are given in Greenwood et al. (2017).

The parameter $\Delta^{17}O$ has proved extremely useful in interpreting extraterrestrial oxygen isotope data and can be defined as the offset of a sample from the Terrestrial Fractionation Line (TFL). In earlier studies it was defined as $\Delta^{17}O = \delta^{17}O - 0.52\ \delta^{18}O$ (e.g. Clayton et al., 1991; Clayton and Mayeda, 1996, 1999). More recently, the linearized format proposed by Miller (2002) has frequently been adopted, although the slope factor λ used may vary between 0.5247 and 0.5305 (Pack and Herwartz, 2014; Greenwood et al., 2017). For comparison purposes, $\Delta^{17}O$ values plotted in this paper have been recalculated using a slope factor of 0.525 and the simplified formula $\Delta^{17}O = \delta^{17}O - 0.525\ \delta^{18}O$. In tables S1 and S2 the original value of $\Delta^{17}O$ is also given where this was provided in the primary data source.

Most asteroids are linked to meteorites through spectral similarities in the visible and near-infrared. Asteroids are spectroscopically observed using telescopes on Earth while meteorites are studied using laboratory-based spectrometers. (Thomas and Binzel, 2010; Burbine, 2017). However, the main issue when attempting to make an asteroid-meteorite linkage is that most asteroids do not have a “unique” spectrum which would render any proposed linkage “certain”. Also complicating any proposed linkage is the fact that many asteroid surfaces have been affected by space weathering (e.g., Hapke, 2001), which alters the asteroid’s spectral properties. More detailed chemical analyses of asteroids, which would help with any proposed linkages, have been done through spacecraft missions for only a few objects (Burbine, 2016). Sample return, which would “definitively” link a physical sample with a body, has so far only been done for one near-Earth asteroid (JAXA’s Hayabusa 1 mission), a comet (NASA’s Stardust mission), and the Moon (NASA’s Apollo missions and the Russian Luna remote lander missions).

2.2 Definitions

In Section 4.3 we look in detail at the use of the term “parent body”. We note that in the literature this term generally just refers to “a body that supplies meteorites to Earth”. However, we argue that it would be more meaningful to discriminate between primary and secondary parent bodies. A primary parent body is the source asteroid from which the meteorite is ultimately derived and a secondary parent body is an asteroid derived through impact or break-up of the primary body. We define some other important terms discussed in this article as follows. An asteroid is a small body in the main belt, near-Earth space, or the Jupiter Trojan region. Minor planets include asteroids and other small bodies in the Solar System, such as those in the Kuiper Belt region (e.g., Pluto, Eris). Meteoroids are asteroids that are generally not observable with a telescope due to their small size (IAU recommended size ranges are from 30 micrometres to 1 metre).

2.3 Defining parent body relationships: The strengths and limitations of oxygen isotope analysis.

In this study our principal goal is to link meteorites to their potential source asteroids. As illustrated in Fig. 1, the breakup of a lithologically diverse asteroid can result in the formation of compositionally distinct daughter asteroids, which may initially appear unrelated to each other. This raises the important issue of what are the best geochemical tools to link these apparently disparate fragments and hence try to “rebuild” their source asteroid, commonly referred to as their “parent body” (section 4.3). Clearly, there is no “magic bullet” that can be used to undertake this task. Characterising and classifying meteorites requires a detailed assessment of evidence from a wide range of geochemical and mineralogical techniques (e.g. Weisberg et al., 2006; Krot et al., 2014). However, as a result of the pioneering studies of Robert Clayton and co-workers, oxygen isotope analysis has proved to be a particularly effective tool in establishing potential links between seemingly unrelated groups (e.g. Clayton et al., 1977, 1983, 1991; Clayton and Mayeda, 1978, 1996, 1999). In this study we have made considerable use of the results of whole rock oxygen isotope analysis as a means of defining the number of parent bodies represented in our meteorite collections.

Oxygen isotope analysis is a particularly powerful technique when applied to meteorite groups that have experienced large-scale melting and homogenisation. The groups concerned include the HEDs, mesosiderites, angrites, aubrites, pallasites, magmatic irons, lunar and martian rocks (Greenwood et al., 2017). These samples often show limited $\Delta^{17}O$ variation rarely exceeding ±0.02 ‰ (2σ) (Greenwood et al., 2017). It is thus possible to define an average $\Delta^{17}O$

composition for a particular group, such as the HEDs, and to set statistical limits that provide a means of assessing whether apparently isotopically anomalous samples are derived from the same parent body as the main group or not (Scott et al., 2009; Greenwood et al.' 2017). Where less extensive melting and differentiation took place, as appears to be the case for the primitive achondrites (brachinites and brachinite-like achondrites, winonaites, acapulcoites and lodranites), the use of $\Delta^{17}O$ as a means of defining parent body sources is less clear-cut (Day et al., 2019). A range of evidence is required in such cases (Day et al., 2019) (section 3.3.1). However, it should be noted that the distinction between the winonoaites and the acapulcoite-lodranite clan is essentially based on their differing $\Delta^{17}O$ compositions (Benedix et al., 1998). In the case of chondrites, which generally show significant levels of oxygen isotope variation, defining the number of parent bodies that are the sources for these meteorites is not straightforward and is discussed in detail below.

3. THE NUMBER OF PARENT BODIES SAMPLED BY METEORITES

3.1 Chondrites

Chondrites are an extremely diverse assemblage of extraterrestrial samples and include some of the most "primitive" and apparently "pristine" Solar System materials available for scientific study. Chondrites are divided into three major classes: carbonaceous (C), ordinary (O), enstatite (E). In addition to these three major subdivisions, two further chondrite types are recognized: the R (Rumuruti) chondrite group and the K (Kakangari) chondrite grouplet. These two types are likely related to the non-carbonaceous (NC) cluster of meteorites (Kita et al., 2013, 2015; Scott et al., 2018) (Fig. 3). In this section, we look at each of these chondrite subdivisions with the aim of estimating the likely number of parent bodies that they were derived from (Table S3).

3.1.1 Carbonaceous chondrites

The carbonaceous chondrites are a compositionally varied class of primitive meteorites (Weisberg et al., 2006; Krot et al., 2014). This is clearly demonstrated by the large oxygen isotopic variations they display (Fig. 2). Compositional fields for the CIs and CMs are relatively distinct, whereas the CKs, CVs and COs show significant overlap, as do the CRs, CBs, and CHs (Fig. 2). Thus, it is not be possible to use oxygen isotope evidence alone to discriminate between these various groups. However, oxygen isotope variation combined with other petrographic and geochemical evidence (Weisberg et al., 2006; Krot et al., 2014) means that individual carbonaceous chondrite groups are relatively well characterized.

A clear distinction between carbonaceous (CC) and non-carbonaceous chondrite (NC) groupings is seen in plots of ε^{62}Ni vs. ε^{54}Cr; ε^{54}Cr vs. ε^{50}Ti and ε^{54}Cr vs. Δ^{17}O (Fig. 3) (Warren, 2011; Scott et al., 2018). One interpretation of these relationships is that carbonaceous chondrite parent bodies formed in the outer Solar System, whereas non-carbonaceous types have an inner Solar System origin (Warren, 2011; Scott et al., 2018). These isotopic differences have also been interpreted as reflecting secular changes in the composition of the materials from which Solar System bodies were formed (Schiller et al., 2018).

One major problem in estimating the number of primary sources from which the carbonaceous chondrites were derived is that their parent bodies were never fully homogenized, so different fragments from the same body may potentially have very different characteristics. A good example of this problem is the controversy surrounding the relationship between the CV and CK chondrites (Greenwood et al., 2010; Wasson et al., 2013; Chaumard and Devouard, 2016; Dunn et al., 2016; Yin and Sanborn, 2019). CV chondrites are lithologically and isotopically diverse, with three subgroups recognized: CV reduced, CV oxidized Allende-like and CV oxidized Bali-like (Krot et al., 1998, 2014). This diversity would probably have given rise to the definition of three distinct groups were it not for the fact that all three lithologies can be present in the same meteorite (Krot et al., 1998, 2014). CK chondrites show a number of mineralogical, textural and isotopic similarities to the CVs and as a consequence it has been proposed that both groups are related and may have originated from a single, heterogeneous parent body (Greenwood et al., 2010; Wasson et al., 2013; Chaumard and Devouard, 2016). It has been postulated that the (221) Eos asteroid family (Mothé-Diniz et al., 2008) might be the disrupted source body of the CVs and CKs (Greenwood et al., 2010). However, a single parent body source for the CVs and CKs is disputed (Dunn et al., 2016; Yin and Sanborn, 2019) and it is certainly the case that CK-like material does not appear to be present within CV regolith breccias.

The CK-CV relationship illustrates the difficulties involved in trying to establish just how many distinct parent bodies are required as sources for the carbonaceous chondrites. A similar problem exists with the CM2 chondrites. Distinct fractions from the same meteorite can show extreme levels of oxygen isotope heterogeneity. This is clearly illustrated in the case of EET 96029 (Table S1) (Lee et al., 2016). A further complicating factor is that some ungrouped C2 chondrites with relatively extreme oxygen isotope compositions could either be derived from the same parent body as the CMs, or from separate parent bodies (sections 3.1.2.2 and S4.2)

(Lee et al., 2019). At present there is no clear criteria to distinguish between these two possibilities.

The metal-rich CB and CH chondrites are generally considered to be genetically related groups and may be derived from a single parent asteroid (Krot et al., 2010a, 2102, 2014). A possible genetic relationship between the CM and CO chondrites was suggested by Clayton and Mayeda (1999) on the basis of oxygen isotope evidence. Schrader and Davidson (2017), while affirming a likely genetic relationship between the two groups, provide evidence against a single parent body source for the CMs and COs. The same conclusion was reached by Chaumard et al. (2018), who suggested that, while the two groups may have accreted from a common compliment of high-temperature components, their respective parent bodies may have formed on either side of the snow line.

Based on the current evidence, it seems that a minimum of seven parent bodies is required for the main carbonaceous chondrite groups (CB/CH, CI, CK, CM, CO, CR, CV) (Table S3).

3.1.2 Ungrouped carbonaceous chondrites

About two-thirds of the ungrouped chondrites currently listed on the Meteoritical Bulletin Database (2019) are carbonaceous chondrite-related. The oxygen isotope compositions of many of these samples are shown in Figs. 4 and 5

3.1.2.1 CY chondrites - thermally altered C2 ungrouped chondrites

CM-like chondrites, which show evidence of having experienced a significant degree of thermal metamorphism (Akai, 1988; Tomeoka, 1989; Ikeda, 1992; Clayton and Mayeda, 1999; Ivanova et al., 2008, 2010; Harries and Langenhorst, 2013), form a relatively tight cluster close to the terrestrial fractionation line (TFL) at high δ^{18}O values (Fig. 4). These meteorites have been termed CY chondrites by King et al. (2019) and are likely derived from a single parent body (see section S4.1 for further details).

3.1.2.2 C2 ungrouped chondrites – evidence for multiple hydrated parent bodies

C2 ungrouped samples (Fig.4), based on detailed evidence presented in section S4.2, most likely represent material derived from between 5 and 8 distinct parent bodies (Table S3).

3.1.2.3 C3 ungrouped chondrites

Ungrouped type 3 chondrites, with the exception of NWA 033, NWA 5377 and NWA 11961, form a relatively tight cluster in Fig. 5, with compositions that plot within the CV-CK-

CO field. DaG 055 and DaG 430 are probably paired samples (Meteoritical Bulletin Database, 2019) and have affinities to both the CKs and CVs (Weber et al., 1996; Choe et al., 2010). DaG 055 may be an anomalous member of the CV3 reduced subgroup (Choe et al., 2010). Ningqiang has been variously identified as an anomalous CV (Rubin et al., 1988) and an anomalous CK (Kallemeyn et al., 1991), but appears more likely to be unrelated to either group (Kallemeyn, 1996). GRA 98025 (Fig. 5) is currently classified as a CR chondrite but was shown by Schrader et al. (2011) to have an oxygen isotope composition that plots in the CV-CK-CO field. Further work is required to establish whether GRA 98025 is a member of the CV group. Based on its small chondrule size, NWA 5377 appears to have affinities with the CO3 chondrites (Meteoritical Bulletin Database, 2019). However, its extremely ^{16}O-rich oxygen isotope composition lies well outside the field of CO chondrites (Fig. 5). A number of ungrouped CO3-like chondrites have oxygen isotope compositions that plot close to or within the CO field, but have features which suggest they are anomalous. These include El Medano 200, NWA 8781, NWA 12416 Y-82094 (Meteoritical Bulletin Database; Kimura et al., 2014). In the case of Y-82094, Kimura et al. (2014) concluded that it might be derived from a distinct parent body to the COs. Based on evidence from Δ^{17}O vs. ε^{54}Cr and Δ^{17}O vs. ε^{50}Ti plots, ungrouped chondrite NWA 2994 is a CR-related meteorite and has an isotopic composition that lies close to other CR chondrites (Sanborn et al., 2019).

Northwest Africa 11750 (Meteoritical Bulletin Database, 2018) is a relatively fine-grained, highly unequilibrated chondrite (C3.0-ung) with a distinct oxygen isotope composition that plots away from the main carbonaceous chondrite groups in Fig 5. NWA 11750 may be a sample from a unique source, but this possibility requires further detailed evaluation.

Northwest Africa 8418 has been identified as a possible CV4 (Mallozzi et al., 2018). The Coolidge-Loongana 001 grouplet (Kallemeyn and Rubin, 1995) comprise equilibrated carbonaceous chondrites that are compositionally distinct from the more populated CK group. HaH (Hammadah al Hamra) 073 and Sahara 00182 may be additional members of this grouplet (Weber et al., 1996; Choe et al., 2010).

3.1.3 Ordinary chondrites

Ordinary chondrites are the most abundant meteorite type, representing greater than 87% of all approved meteorites (both finds and falls) (Meteoritical Bulletin Database, 2019). Ordinary chondrites are most commonly subdivided into three groups, H, L and LL (Fig. 6) (Weisberg et al., 2006). There is also evidence to support a separate L/LL group (Kallemeyn et al., 1989; Weisberg et al., 2006). A small number of ordinary chondrites (Acfer 370, Burnwell, Cerro los Calvos, EET 96031, LAP 04757, Moorabie, NWA 7135 Suwahib (Buwah), Willaroy, Y-982717) (Fig. 6) have more reduced characteristics than the H group, with olivine and pyroxene typically displaying anomalously low fayalite and ferrosilite contents (Wasson et al., 1993; McCoy et al., 1994; Russell et al., 1998; Troiano et al., 2011; Irving et al., 2015; Pratesi et al., 2019; Yamaguchi et al., 2015, 2019). These reduced ordinary chondrites have been referred to variously as: low-FeO chondrites and HH chondrites (Russell et al., 1998; Troiano et al., 2011) and may be related to the reduced chondritic material found in the IIE iron Netschaëvo (Bild and Wasson, 1977; McDermott et al., 2016). Currently the status of these reduced ordinary chondrites is unclear (Pratesi et al., 2019; Yamaguchi et al., 2019). They may represent a distinct group, or groups (Pratesi et al., 2019), or alternatively simply represent an extension to the compositional range of the H group (Troiano et al., 2011; Yamaguchi et al., 2015; 2019). The elevated bulk δ^{18}O composition of some of these reduced ordinary chondrites (Fig. 6) probably reflects the influence of terrestrial weathering.

GRO 955551 and NWA 5492 are metal-rich chondrites with extremely reduced silicate compositions (average olivine $Fa_{1.3}$ and $Fa_{0.3}$ respectively) (Weisberg et al., 2015). Referred to as G chondrites (after GRO 95551) by Weisberg et al. (2015) , GRO 95551 and NWA 5492 plot in the NC group in Fig. 3 (Sanborn et al., 2015) and based on a range of mineralogical evidence appear to be related to the ordinary, enstatite and R chondrites (Weisberg et al., 2015).

Ordinary chondrites with characteristics intermediate between the H and L groups, designated H/L, are a small but important subdivision and include the well-studied falls Bremervorde, Tieschitz and Cali (e.g., Hutchison et al., 1980; Trigo-Rodriguez et al., 2009) (Fig. 6). It has also been suggested that H/L chondrites may originate from a distinct, disrupted cometary source (Trigo-Rodriguez and Williams, 2016). However, the H/L chondrites do not have the expected properties of cometary meteorites, such as high porosities and low densities (Campins and Swindle, 1998). In view of both the mineralogical and oxygen isotopic variation displayed by the ordinary chondrites, it is generally accepted that they originate from multiple parent body sources. Based on the evidence outlined in this section it would appear that the ordinary chondrites represent between 3 and 6 distinct groupings (Low-FeO, H, H/L, L, L/LL, LL) and by implication could be derived from 3 to 6 parent bodies, with the G chondrites potentially representing a further source body.

Due to spectral similarities, the Flora family has been linked with the LL chondrites (e.g., Vernazza et al., 2008) while (6) Hebe (diameter of ~186 km) has been linked with the H chondrites (e.g., Gaffey and Gilbert, 1998). Hebe is located near the 3:1 resonance and is also a large object. The Gefion family has been argued both for (e.g., Nesvorný et al., 2009) and against (e.g., McGraw et al., 2018) being the parent body of the L chondrites. However, ordinary chondrite-like spectral properties among main belt asteroids tend not to be unique. For example, Vernazza et al. (2014) identified a number of S-type asteroids with spectral properties similar to H chondrites near the meteorite-supplying 3:1 resonance in addition to Hebe. Fieber-Beyer and Gaffey (2019) suggest that the group of asteroids on either side of the 3:1 resonance and which have H chondrite-like mineralogies are in fact part of an old dispersed family associated with Hebe. This would indicate that the source of the H chondrites was originally a single body, rather than multiple asteroids formed under similar conditions. However, Noonan et al. (2019) presented evidence that asteroid (3) Juno has an H-chondrite mineralogy and is a potential H chondrite parent body candidate. As a consequence, the possibility that ordinary chondrites are derived from multiple primary parent bodies appears to remain viable,

3.1.4 Ordinary chondrite-like ungrouped chondrites

About one third of the ungrouped chondrites currently listed on the Meteoritical Bulletin Database (2019) are ordinary chondrite-related. The oxygen isotope compositions of many of these samples are shown in Fig. 7 (Table S2). The reason for the difficulty in classifying these meteorites could, at least in part, be due to the effects of terrestrial weathering. Deakin 001 may be an example of this problem. It has a mineralogy consistent with being a normal LL3 chondrite (Bridges et al., 1997), but has an extremely elevated bulk δ^{18}O composition of 8.8 ‰ (Fig. 7) and accordingly has been classified as an ungrouped chondrite (Bevan and Binns, 1989). However, terrestrial weathering of iron and sulphide-rich meteorites results in the formation of secondary iron hydroxides and oxyhydroxides, leading to the incorporation of a significant terrestrial oxygen component (Lee and Bland, 2004). As a consequence, weathered finds often display large oxygen isotopic shifts away from the primary compositional fields defined by fall samples (Greenwood et al., 2012). Such a process may have been responsible for the anomalous isotopic shift of Deakin 001. In a similar way, Dho 535, HaH 180 (Bischoff et al., 1997) and NWA 10769 are all weathered finds, which apart from their elevated bulk δ^{18}O compositions (Fig. 7) appear to be normal ordinary chondrites. In all of these cases the anomalous oxygen isotope composition of these meteorites is most likely a consequence of terrestrial alteration.

El Medano 301(Poukhorsandi et al., 2017) and Sierra Gorda 009 contain silicates more reduced than those typically present in H chondrites and may be related to either the Low-FeO or G chondrites. Northwest Africa 5717 is an unequilibrated (subtype 3.05), ungrouped chondrite, which contains two distinct lithologies, one dark one light. Initial suggestions (Bunch et al., 2010) that these lithologies had very distinct mineral and geochemical compositions is not supported by more recent studies (Cato et al., 2017). However, it is clear that the two lithologies in NWA 5717 are not in oxygen isotopic equilibrium (Fig. 7). RaS (Ramlat as Sahmah) 211, Sahara 97009, Sahara 97039 and Sahara 97042 (Sexton et al. 1998) all seem to be essentially LL chondrites with somewhat anomalous oxygen isotope compositions. NWA 12273 and NWA 12379 appear to be paired samples which have many characteristics in common with ordinary chondrites, but have an elevated metal content.

The oxygen isotope composition of various ordinary chondrite-related impact melt breccias are shown in Fig. 7. These generally have isotopic compositions that plot within the field of the main ordinary chondrite groups to which they show mineralogical affinity. MIL 07273 appears to be an exception, and so while it shows affinity to the H group, its oxygen isotope composition plots in the L field (Ruzicka et al., 2017a) (Fig. 7). However, despite its somewhat anomalous oxygen isotope composition, MIL 07273 appears to be derived from the H chondrite parent body (Ruzicka et al., 2017a).

Based on the above analysis, the ungrouped ordinary chondrites and impact-melt breccias do not appear to extend the range of possible parent bodies beyond the 3 to 6 indicated by the main groups discussed in section 3.1.3. While an oxygen isotope composition outside the normal range shown by the ordinary chondrites is often cited as the principal evidence for a particular sample being anomalous, such evidence needs to be treated with caution. Terrestrial weathering of metal-rich meteorites, including ordinary chondrites, can often result in the incorporation of a major atmospheric component, resulting in significant oxygen isotopic shifts relative to primary values (Lee and Bland, 2004; Greenwood et al., 2012). Consequently, in the case of weathered finds, oxygen isotopic evidence should not be used as the sole criteria for designating a sample as ungrouped.

3.1.5 Enstatite chondrites

Enstatite chondrites are highly reduced meteorites, such that their mineralogy is dominated by virtually Fe-free enstatite (Keil, 1989). They also contain appreciable amounts of Si-bearing FeNi metal, troilite and a unique assemblage of minerals in which, as a result of the extremely reducing conditions, normally lithophile elements have behaved as chalcophile elements (Krot et al., 2014). Enstatite chondrites are divided into the EH and EL groups, with both groups showing evidence of significant brecciation. The main compositional differences between these groups are thought to reflect nebular, rather than planetary processes (Keil, 1989). Enstatite chondrites are generally thought to be derived from two distinct parent bodies (Keil, 1989). In contrast, Kong et al. (1997) argued for a single enstatite chondrite parent body based on the evidence of continuous elemental variation between the EH and EL groups.

A number of enstatite chondrites have anomalous compositions and mineralogies and consequently do not fit easily into either the EH or EL groups. Yamato 791510 contains a glassy matrix enriched in CaO and has an opaque mineralogy that is distinct from either the EH or EL groups (Kimura and Lin, 1999). Lewis Cliff 87223 has a mineralogy and composition intermediate between the EH and EL chondrites and may be derived from a unique source (Grossman et al., 1993; Weisberg and Kimura, 2012). Yamato 793225 also has a composition that falls between the EH and EK groups and, along with QUE 94204, was suggested by Lin and Kimura (1998) to be derived from a distinct source to that of the two major enstatite chondrite groups.

In terms of their oxygen isotopic compositions, EH group chondrites display significantly greater levels of heterogeneity than members of the EL group (Fig. S2) (Newton et al., 2000). However, despite the fact that the EL group plots completely within the EH group, as discussed above, both are considered to be derived from separate parent bodies (Keil, 1989). In addition, anomalous enstatite chondrites appear to require at least one further asteroidal source. It therefore seems likely that a minimum of three parent asteroids are required as sources to the enstatite chondrite meteorites. Likewise, while aubrites also overlap the EH and EL chondrites with respect to their oxygen isotope compositions, a range of evidence indicates that they are not derived from either the EH or EL parent bodies (Keil, 1989; Barrat et al., 2016) (section 3.3.2).

Possible enstatite chondritic source (or parent) bodies are difficult to spectrally identify due to their relatively featureless reflectance spectra (Gaffey, 1976), which is characteristic of many types of asteroids.

3.1.6 R and K chondrites

The R (Rumuruti) chondrites, originally defined on the basis of a range of criteria derived from only about 12 specimens (Weisberg et al., 1991; Bischoff et al., 1994; Rubin and Kallemeyn, 1994; Schulze et al., 1994; Kallemeyn et al., 1996), are now a relatively well-populated group, currently comprising over 200 specimens (Meteoritical Bulletin Database, 2019). Rumuruti chondrites typically have a high matrix abundance, high oxidation state (olivine $Fa_{37\text{-}40}$), small chondrules, abundant sulphides, low FeNi metal content and a very low abundance of refractory inclusions (Kallemeyn et al., 1996). The suggestion by Kallemeyn et al. (1996) that the R chondrites belong to the "non-carbonaceous superclan of chondrites" is corroborated by more recent evidence provided by ε^{54}Cr vs Δ^{17}O variation (Fig. 3). Kallemeyn et al. (1996) additionally suggested that R chondrites may have formed at a greater heliocentric distance than the ordinary chondrites. Sunshine et al. (2007) identified two A-type asteroids, (246) Asporina and (289) Nenetta, as having olivine compositions consistent with R chondrites. Asporina has a semi-major axis of 2.69 AU, while Nenetta has one of 2.87 AU. Both of these objects are located farther from the Sun than the Flora family, which has been linked with the LL chondrites, and (6) Hebe, which has been linked with the H chondrites.

R chondrites are the meteorite group with the most positive Δ^{17}O values (approx. 2.1 to 3.1 ‰) (Fig. S3). They also display a relatively wide range of δ^{18}O values, from approx. 3.5 to 8.0‰, defining a broad linear trend on a diagram of δ^{18}O versus. Δ^{17}O (Fig. S3). Despite the significant level of oxygen isotope variation displayed by R chondrites there is no clear evidence in favour of multiple sources for these meteorites and so a single parent body source seems likely.

The K (Kakangari) chondrite grouplet (Weisberg et al., 1996) presently has only 4 recognized members (Kakangari, Lea County 002, Lewis Cliff 87232, NWA 10085) (Meteoritical Bulletin Database, 2019) (Fig. 5). Kakangari chondrites have high matrix abundances, an oxidation state intermediate between enstatite and ordinary chondrites, and oxygen isotopic compositions near the CR chondrite region (Weisberg et al., 1996). Based on the mineralogical and isotopic similarities between all the members of the K grouplet it would seem likely that are all derived from a single parent body.

3.1.7 The number of chondritic parent bodies

Based on the relationships discussed in the previous sections and as detailed in Tables 1 and S3, the main chondrite groups would appear to be samples from between approximately 15 to 20 parent bodies, with the ungrouped chondrites being derived from between 11 and 17 parent bodies. This analysis suggests that the chondrites provide us with samples from between 26 to 37 parent bodies in total (Table S3). However, this estimate is subject to significant uncertainty. In large part this reflects the heterogeneous character of chondrites. We have no reliable way of assessing whether individual meteorite groups come from distinct parent bodies, or whether multiple groups could come from a single source. This situation may improve once we have been able to study additional material from sample return missions such as OSIRIS-REx and Hayabusa 2.

3.2 Irons

Here we accept the conventional view that iron meteorites are derived from ~60 parent bodies (Burbine et al., 2002a), but note that this might be as few as 26 (Wasson, 2013). There are currently 11 recognized fractionally crystallized iron groups (also known as magmatic irons) (Ruzicka et al., 2017b), which are commonly thought to be the result of iron core formation on distinct differentiated bodies. Possible exceptions are the IIAB and IIG irons, which have been linked by Wasson and Choe (2009). Fractionally crystallized iron groups are found in both the non-carbonaceous and carbonaceous regions of the Warren (2011) diagram (Kruijer et al., 2017; Rubin, 2018b). In all but a few cases it has not proved possible to link the major iron meteorite groups to the silicate-dominated groups (Krot et al., 2014). Notable exceptions include the winonaites with the IAB irons (Hunt et al., 2017) and the H chondrites with the IIE irons (McDermott et al., 2016). Proposed linkages between the IIIAB irons and main group pallasites and the IVA irons and L and LL chondrites appear to be unlikely based on currently available evidence (Krot et al., 2014). Recognition that some iron groups such as the IVA and IVB irons may have formed within oxidised parent bodies, raises the possibility of a genetic link between them and FeO-rich achondrites, such as the brachinites and brachinite-like meteorites (Day et al., 2019). This potential linkage merits further detailed investigation.

Of the identified ~1,200 iron meteorites, over 200 are listed only as an iron (unassigned to any particular group), or as an ungrouped iron (Meteoritical Bulletin Database, 2019). Unassigned and ungrouped irons could potentially represent samples from a much larger number of parent bodies than the 60 or so that are conventionally recognised as being the sources for iron meteorites (Burbine et al., 2002a). Further work is required to identify the relationships between the main iron groups and these unassigned and ungrouped samples.

3.3 Achondrites

3.3.1 Primitive achondrites

The three main primitive achondrite groups and clans (acapulcoite-lodranite clan, ureilites, and winonaites/IAB-IIICD irons) appear to be derived from three different parent bodies (e.g., Clayton et al., 1983; Clayton and Mayeda, 1996; McCoy et al., 1997; Greenwood et al., 2012, 2017; Dhaliwal et al., 2017) (Fig. S4). Despite significant levels of oxygen isotope variation, ureilites are generally regarded as samples from a single, large, disrupted “ureilite parent asteroid” (Downes et al., 2008).

The brachinites and brachinite-like achondrites are almost certainly derived from multiple parent bodies, although the exact numbers involved is uncertain (Day et al., 2012, 2019; Greenwood et al., 2017). A conservative estimate would require two; one for the "main-group" brachinites, and a second for Mg-rich, brachinite-like samples (Divnoe, NWA 4042, NWA 4518, RBT 04255, RBT 04239 and Zag (b)] (Greenwood et al., 2017) (Fig. S5). LEW 88763 is presently classified as a brachinite, but plots in the acapulcoite-lodranite field. Day et al. (2015) argue that this meteorite should be reclassified as an anomalous achondrite. Day et al. (2019) have looked in detail at FeO-rich achondrites, including brachinites and brachinite-like meteorites and concluded, on the basis of Cr, Ti and O isotope systematics, that they are derived from at least four distinct parent bodies. One is required for the brachinites and the GRA 06128/9 meteorites (Day et al., 2012), a second for the brachinite-like achondrites, a third for LEW 88763, NWA 6693 and 6704 and a fourth for Tafassasset and NWA 011 and its pairs (see section 3.3.2).

3.3.2 Differentiated achondrites and stony-irons

Apart from the pallasites, which may be derived from between six to nine distinct parent bodies (Greenwood et al., 2017; Ruzicka et al. 2017b) and the aubrites which are probably samples from three (one for main-group aubrites; one for Shallowater; and one for Mount Egerton and Larned) (Keil et al., 1989; Keil 2012; Barrat et al., 2016), most of the other differentiated groups (angrites, HEDs, mesosiderites) are each derived from unique parent bodies (Keil, 2012, McSween et al., 2013) (Fig. S3).

Based on near identical oxygen isotope compositions and similar petrographic and mineralogical characteristics, it has been argued that the mesosiderites and HEDs originated from the same parent body (Greenwood et al., 2017; Haba et al., 2019). However, clear evidence that the mesosiderites are present on asteroid 4 Vesta was not obtained by the Dawn spacecraft (Peplowski et al., 2013), so here we adopt a conventional approach and assign HEDs and mesosiderites to distinct sources.

Most HEDs are believed to originate from asteroid (4) Vesta based on long-known spectral similarities (McCord et al., 1970; Larson & Fink, 1975) and spectral and chemical analyses by the Dawn spacecraft (e.g., McSween et al., 2013). The origin of basaltic meteorites with anomalous, non-HED, oxygen isotopic compositions, such as NWA 011 (Yamaguchi et al., 2002, Day et al., 2019) and Bunburra Rockhole (Benedix et al., 2017), is the subject of ongoing debate and the exact number of parent bodies from which these meteorites originated is uncertain (Greenwood et al, 2017; Barrett et al., 2017; Mittlefehldt et al., 2017; Day et al., 2019; Wimpenny et al., 2019). It is important to note that while the majority of basaltic achondrites plot in the NC field in Fig. 3, NWA 011 plots in the CC field. This suggests that basaltic achondrites were produced on multiple asteroids in both the inner and outer Solar System. A conservative estimate for the number of basaltic achondrite source bodies in addition to Vesta is five: (i) one for NWA 011 and pairs; (ii) one for Ibitira; (iii) one for A-881394, Bunburra Rockhole, Emmaville, Dho 007, EET 92023; (iv) one for Pasamonte and PCA 91007; and (v) one for the newly classified sample NWA 11916. A more extreme position is that each anomalous basaltic achondrite is from a distinct source, in which case about eleven parent bodies are required. The possibility that multiple parent bodies with basaltic crusts are present in the main belt is consistent with astronomical studies that have identified bodies with HED-like spectra throughout the asteroid belt (e.g., Lazzaro et al., 2000; Hardersen et al., 2018; Fulvio et al., 2018).

3.3.3 Ungrouped achondrites

The Meteoritical Bulletin Database (2019) currently lists more than ninety ungrouped achondrites, many of which are primitive in composition. Greenwood et al. (2017) reviewed the relationships of many of these ungrouped achondrites and concluded that they were likely derived from about 16 distinct parent bodies. This number included the brachinite-like group discussed in section 3.3.1. Since the review of Greenwood et al. (2017), a number of new important, ungrouped achondrites have been identified and characterized, including NWA 10503, and NWA 11119. NWA 10503 is a highly recrystallized carbonaceous chondrite-related sample, with an oxygen isotope composition that plots between the fields of CR and CV chondrites (Irving et al., 2016). Northwest Africa 11119 is the oldest known, silica-rich meteorite of likely volcanic origin (Srinivasan et al., 2018) and while it shows some affinities to the unique achondrite NWA 7325 (Barrat et al., 2015; Goodrich et al., 2017), both are probably from distinct sources.

Defining the exact number of parent bodies represented by the ungrouped achondrites is hindered by the fact that most examples have not been studied in detail; notable exceptions include NWA 6704 (Sanborn et al., 2018, 2019; Hibiya et al., 2019); NWA 6693 (Warren et al., 2013) and NWA 7325 (Irving et al., 2013; Barrat et al., 2015; Koefoed et al., 2016; Weber et al., 2016; Goodrich et al., 2017; Cloutis et al., 2018). Based on the evidence presented by Greenwood et al. (2017) and including the additional samples NWA 10503, NWA 11119 and NWA 11562, ungrouped achondrites and related samples appear to be derived from about 23 distinct parent bodies (Table 1, S3).

3.4 Breccia fragments and inclusions

Meteoritic breccias are known to contain inclusions derived from a wide variety of sources, and in some cases incorporate material that is unrepresented elsewhere in the meteorite record (Endress et al., 1994; Zolensky and Ivanov, 2003; Zolensky et al., 2003; Bischoff et al., 2006, 2018; Sokol et al., 2007; Bonal et al., 2010; Horstmann et al., 2010; Ziegler et al., 2012; Horstmann and Bischoff, 2014; Goodrich et al., 2019; Patzek et al., 2019). Dark inclusions in carbonaceous chondrites preserve evidence of complex evolutionary processes, including aqueous alteration that took place prior to incorporation within the final host parent body (e.g. Bischoff et al., 2006, 2018; Sokol et al., 2007; Bonal et al., 2010). Bischoff et al. (2006, 2018) suggested that the evidence from meteoritic breccias and dark inclusions is consistent with the formation and destruction of multiple generations of precursor asteroids prior to the accretion of the final parent body.

The Kaidun and Almahata Sitta meteorites provide clear examples of the wealth of information that these breccias can furnish concerning the diversity of asteroid types. The Kaidun microbreccia, which fell in Yemen in 1980, contains a diverse assemblage of materials, from a wide range of asteroidal sources (Zolensky and Ivanov, 2003). While conventional meteorite types, including EH3-5, EL3, CV3, CM1-2 and R chondrites, are well represented in the Kaidun assemblage, there are also novel C1 and C2 chondrites, various impact melt materials and a diverse range of achondritic clasts (Zolensky and Ivanov, 2003). The evidence from Kaidun suggests that the main asteroid belt is significantly more diverse than indicated by the materials deposited on Earth as larger-sized meteorites.

In the case of Almahata Sitta the vast majority of fragments appear to correspond to known meteorite types, with approx. 70% being ureilitic and 30% chondritic (Bischoff et al., 2006; Goodrich et al., 2019). However, within the chondritic assemblage there are a small number of both carbonaceous and non-carbonaceous fragments that appear to be unique. A clear example is the Almahata Sitta chondritic fragment MS-CH which, while it shows affinities to the R chondrites, may be derived from a different source (Horstmann et al., 2010). Breccias such as Kaidun and Almahata Sitta clearly warrant significant further study, as in both cases many unique clasts still remain to be characterized (Zolensky and Ivanov, 2003; Goodrich et al., 2019).

Inclusions of one meteorite type within a predominant host of a different composition are a relatively commonplace occurrence, particularly amongst the HEDs and ordinary chondrites (Zolensky et al., 1996; Bridges and Hutchison, 1997; Ruzicka et al., 2019). In the HED meteorites CM2-type inclusions predominate, with a lesser component of CR2-related material (Zolensky et al., 1996). Ordinary chondrites often contain a diverse range of clast types (Bridges and Hutchison, 1997). However, a recent survey indicates that although these formed as a result of a variety of both nebular and planetary processes; in general, the material that forms these inclusions is genetically related to the same ordinary chondrite reservoirs sampled by larger-sized meteorites (Ruzicka et al., 2019).

As pointed out by Bischoff et al. (2006, 2018), meteoritic breccias are critical samples in attempting to understand the early evolution of planetesimals (section 4.4). However, for this survey we have not defined any additional parent bodies on the basis of evidence from meteoritic breccias alone. Many meteorite types, and in particular carbonaceous chondrites, are by definition breccias and so inherently heterogeneous. Distinct and sometimes unique clast types are to be expected in such meteorites and do not necessarily indicate that an additional parent body is required, over and above that which supplied the host material. The CV chondrites provide a clear example of significant lithological diversity within a single meteorite group that is likely derived from a unique parent body (section 3.1.1). So, while a unique inclusion in a meteorite breccia might appear to warrant a distinct asteroidal source, it might equally indicate that an already defined group is more heterogeneous than has hitherto been considered.

3.5 Micrometeorites and cosmic dust

A large proportion of the extraterrestrial material accreted by the Earth each year arrives, not as large meteorites, but as sub-millimetre-sized particles (Love and Brownlee, 1993; Dobrica et al, 2009; Baecker et al., 2018). Such materials are collected either as interplanetary dust particles (IDPs) in the stratosphere (<50 µm diameter), or as generally larger micrometeorites (20 to 500 µm diameter) from various surface environments, such as Antarctic ice (Dobrica et al, 2009; Baecker et al., 2018).

Given that they comprise such a large fraction of Earth's extraterrestrial inventory, an important question that arises is whether these dust-sized fragments are derived from the same or distinct parent bodies to those represented in the conventional meteorite inventory. The friable nature of IDPs, particularly the chondritic porous IDPs, suggests that they are derived from distinct sources compared to larger, more cohesive meteorites (Vernazza et al., 2015). It has been suggested by Vernazza et al. (2015) that the conventional meteorite population is essentially derived from the inner Solar System (0.5 to 4 AU), whereas IDPs sample bodies that reside in the outer belt (>5 AU). Oxygen isotope studies of IDPs suggest that they are essentially derived from objects with carbonaceous chondrite affinities (Aleon et al., 2009). Keller and Flynn (2019) have proposed that solar flare track-rich IDPs are derived from Kuiper Belt Objects due to the long lifetimes of these particles in the Kuiper Belt and higher exposure to galactic cosmic rays compared to main-belt sources.

The presence of chondrules and CAIs in Stardust material from Comet 81P/Wild 2 has been cited as evidence that there is a continuum between primitive cometary and asteroidal materials (Dobrica et al., 2009). However, there seems little doubt that IDPs sample very primitive, porous objects that are highly underrepresented amongst larger-sized meteorites (Bradley, 2003). Tagish Lake may be a notable exception and might represent material from a cometary meteoroid (Brown et al., 2002). Based on historical records, Gounelle et al. (2006) were able to reconstruct the orbit of the Orgueil (CI) meteoroid and concluded that it was probably a Jupiter-family comet. On the basis that it is possible that cometry material is already represented within our current meteorite collections we have not assigned any additional parent bodies as sources for IDPs and micrometeorites. However, this remains an area of significant uncertainty and there is some evidence from cosmic spherules indicating that some of these particles may be derived from parent bodies currently unsampled by meteorites (Goderis et al., 2020).

3.6 Meteorites on other Solar System bodies

Rovers on Mars have identified a number of distinct meteorites (Schröder et al., 2008) and the Apollo astronauts returned meteorites from the Moon, such as the ungrouped C1 chondrite Bench Crater (McSween, 1976). Studies of lunar regolith breccias have revealed an apparent distinction between the meteoritic material impacting the Moon prior to and after 3.4 Ga (Joy et al., 2012). Before 3.4 Ga impactors were primarily primitive chondritic types, whereas after 3.4 Ga there was a greater lithological diversity of meteorites striking the Moon (Joy et al., 2012). However, this younger population still included primitive types, such as the feldspathic chondrule fragment located by Day et al. (2006) in the lunar meteorite Pecora Escarpment 02007. This fragment was later shown by Joy et al. (2012) to be derived from a carbonaceous chondrite impactor. However, apart from these lunar studies, very little is known about the meteorite flux on other planets. The evidence from lunar regolith breccias indicating long term changes in the inner Solar System meteorite flux (Joy et al., 2012), is pertinent to the results from terrestrial studies, which suggest that significant fluctuations can also take place over shorter periods (e.g. Heck et al. 2017). Further work in this area has the potential to link changes in the meteorite population over time, with the dynamic evolution of the asteroid belt and hence provide additional evidence relevant to large-scale events, such as the Late Heavy Bombardment (Bottke and Norman, 2017).

3.7 An updated parent body inventory

We can now update the parent body inventory of Burbine et al. (2002a). Based on the evidence presented here we appear to have material in our collections derived from between 95 and 148 parent bodies. Note that the meteoritic record is dominated by differentiated objects (achondrites and irons) with between 69 and 111 bodies, compared to 26 to 37 chondritic bodies. This preponderance of igneous meteorites is probably the result of melting and subsequent cooling producing "stronger" bodies that are more resistant to breakup in space than chondritic material (Ruzicka et al. 2017b). We note that some achondrites could be from the same parent bodies as some iron meteorites, which would lower the number of estimated parent bodies.

4. DISCUSSION

4.1 A two stage problem

In assessing the relationship between meteorites, asteroids and the primordial composition of the main belt we need to address two related issues. Firstly, we have to assess whether meteorites are representative of the present-day composition of the main belt. To answer this question we need to look at how meteorites are delivered to Earth. We need to assess how many asteroids are actually sampled by meteorites and relate this to what is known about the present-day structure of the main belt. Our second line of enquiry is to try and relate the present-day asteroidal and meteoritic populations to the primordial population of planetesimals that were originally present in the main belt. To answer this second question we need to examine how planetesimals formed, their likely size and overall mass distribution and their subsequent fate during the process of planetary accretion. We start by looking at how fragments of asteroids are delivered to Earth.

4.2 Meteorite delivery mechanisms and asteroid-meteorite links

Meteoroids are thought to be transferred from the main asteroid belt to near-Earth space by entering mean-motion (e.g., 3:1, 5:2) and secular ($\nu6$) resonances (e.g., Wisdom, 1982, 1983, 1985, 2017; Froeschlé and Scholl, 1986; Granvik and Brown, 2018), which can cause large changes in the eccentricity of the object and result in Earth-crossing orbits. Meteoroids are formed through impacts on larger asteroids and can be either directly injected into a resonance or drift to the resonance due to the Yarkovsky effect (e, g, Farinella et al., 1998). The Yarkovsky effect is the force acting on rotating bodies due to the anisotropic emission of photons, which carry momentum from blackbody radiation due to temperature differences across the surface of the body. Smaller bodies will tend to drift faster than larger bodies. Dynamical models (e.g., Granvik and Brown, 2018) find that most meteorites appear to originate from the inner main belt.

The cosmic ray exposure ages for stony meteorites tend to be consistent with entering near-Earth space through Yarkovsky drift (Farinella et al., 1998) for tens of millions of years to a meteorite-supplying resonance. This is based on the evidence that the cosmic ray exposure ages of different meteorite groups also tend to be on the order of tens of millions of years (Eugster et al., 2006). These cosmic ray exposure ages tend to be much longer than the dynamical lifetimes of bodies (millions of years) delivered to near-Earth space directly from a resonance (Gladman et al., 1997; Farinella et al., 1998). Cosmic ray exposure ages measure the time a meteorite was exposed to galactic cosmic rays, which means when the meteorite was located within ~1 metre of the surface of a body in space.

Due to the limitations of spectroscopy and the non-unique reflectance spectra of almost all asteroids, only a relatively few meteorite groups have been linked to specific main-belt asteroids or families. Most meteorite types are only linked to a taxonomic class. We list in Table 2 various proposed meteorite-asteroid linkages. The only near-certain asteroid –meteorite linkage is that of the HEDs with asteroid 4 Vesta (McCord et al., 1970; Binzel and Xu, 1993; McSween et al., 2013). One proposed linkage is the CM chondrites with (19) Fortuna (Burbine, 1998) due to similar spectral features, low albedo, and this large (diameter of ~225 km) body's location near the 3:1 resonance. CM chondrite meteoroids would not be expected to survive for "long" times in space due to their fragile nature (e.g., Rubin, 2018a) and a source (or parent) body near a resonance would increase the probability that CM chondritic material could "survive" passage to Earth. Aubrites have been linked to E- or Xe-types in the Hungaria family region (~1.8-2.0 AU) due to the high albedos of both types of objects (Zellner et al., 1977; Ćuk et al., 2014). E- or Xe-type Hungaria family bodies also tend to have an absorption feature at ~0.5 μm (Bus and Binzel, 2002), which is interpreted as indicating the presence of oldhamite (CaS) (Burbine et al., 2002b). Oldhamite is commonly found in aubrites (Watters and Prinz, 1979).

4.3 The parent body concept

Following its recovery, a meteorite find, particularly those with an unusual composition, will normally become the subject of intensive scientific study. Such sample-focused investigations have resulted in major advances in our understanding of the origin and evolution of extraterrestrial materials. Important examples of such major international studies include those that followed the falls of the Allende (Clarke et al., 1971), Tagish Lake (Brown et al., 2000) and Almahatta Sitta (Jenniskens et al., 2009) meteorites. Following such detailed investigations the observations made are generally extrapolated to the source asteroid and the term "parent body" is almost universally invoked. There is no doubt that the use of the term "parent body" is extremely widespread and popular amongst the scientific community.

The SAO/NASA Astrophysics Data System (ADS) returned ~22,000 entries for the period 1892 to 2019, in which the words "Parent Body" or "Parent Bodies" were used in the text. The parent body concept has grown almost exponentially in popularity since the early 1950s, with over 21,700 mentions since 1953. It is clear, from both early articles (e.g., Mueller, 1953; Urey and Craig, 1953; Lovering, 1957a,b; Urey, 1958) and more modern usage (e.g. Michikami et al., 2019; Christou et al., 2020), that the term parent body is widely used to refer to an unknown source object from which a particular sample is ultimately derived. But is "parent body" synonymous with an asteroid? This is clearly not the case for meteorites derived from either the Moon or Mars, termed planetary achondrites by Yamaguchi et al. (2017). However, there appears to be a widespread acceptance that the vast majority of meteorites are ultimately derived from asteroids with new parent bodies postulated all the time (e.g., Gaffey and Fieber-Beyer, 2019; Noonan et al., 2019). Links between meteorites and asteroids are supported by the evidence from fireball trajectory data (Devillepoix et al., 2018; Brown et al., 2019; Jenniskens et al., 2019). Hence it seems reasonable to suggest that the term "parent body" should somehow relate to the asteroidal population, both present and past.

4.4 Primary vs. secondary parent bodies

While "parent body" can be defined simply as "a body that supplies meteorites to Earth" (section 2.2), this definition says little about the nature of the body that supplied the meteorite. Applying such a broad definition to the case of Vesta and the asteroids derived from it, known as the Vestoids (Binzel and Xu, 1993; Burbine et al., 2001; Fulvio et al., 2018), all members of this family could be classed as parent bodies. Such an extreme application of the "parent body" concept renders it essentially meaningless. In the case of Vesta and the Vestoids, almost all meteorticists would agree that asteroid (4) Vesta is the ultimate parent body. But herein lies the problem. In the case of the HED meteorites there is a reasonable level of certainty that Vesta represents their original parent body, even though there are a number of distinct routes by which meteoroids from it might be delivered to Earth (Fig. 1). However, in most other cases, particularly for the ordinary chondrites, there is little consensus about the nature of the original source body. Asteroids such as (6) Hebe have been suggested to be the original source of the H chondrites (Gaffey and Gilbert, 1998), but this is not universally accepted and it remains a possibility that ordinary chondrites are supplied by multiple primary parent bodies (Vernazza et al., 2104).

To clarify this issue we would advocate a two-fold division of "parent bodies". Thus, while all asteroids can be parent bodies, they are not all of equal significance. This concept has been discussed extensively in the literature (e.g. Bischoff et al. 2006, 2018; Bonal et al., 2010). Bischoff et al. (2006) point out that there is abundant evidence from meteoritic breccias that a primary generation of early-formed asteroids were rapidly destroyed and material from them incorporated into a second generation of "daughter" bodies, Accordingly, and based on the example of (4) Vesta (Fig. 1), we designate the ultimate source of meteoritic material arriving on Earth as the "primary" parent body. All bodies derived from the primary body are by definition "secondary" parent bodies. It is likely that the vast majority of asteroids supplying meteoritic material are "secondary" bodies. A "primary" parent body could be a member of the initial asteroid population; Vesta and Ceres would be two examples. A "primary" parent body could also be a planetary-scale object such as the Moon and Mars, or even Venus or Mercury. The Mars Trojan asteroids are proposed to be fragments of Mars (Polishook et al., 2017) and could therefore be "secondary" martian parent bodies. Meteorites from Mercury (Gladman and Coffey, 2009) and Venus (Dones et al., 2018) have been postulated but are currently not thought to be present in our meteorite collections. We may have material from comets in the form of CI chondrites and Tagish Lake (Brown et al., 2002; Gounelle et al., 2006) (section 3.5). A body ('Oumuamua) that originated from outside the Solar System (e.g., Meech et al., 2017; Portegies Zwart et al., 2018) has been detected, implying that extrasolar meteorites are possible and hence the potential exists to have material delivered to Earth from parent bodies outside the Solar System.

4.5 Why do our collections contain samples from so few parent bodies?

Based on the evidence presented in previous sections of this paper, our estimates are somewhat larger than earlier studies (Section S3) (Burbine et al., 2002a; Hutchison, 2004); Greenwood et al., 2017) and indicate that we have samples of between 95 and 148 primary parent bodies in our meteorite collections. There is a significant level of uncertainty about these figures, as the criteria used to discriminate between different parent body sources are complex and somewhat arbitrary. In addition, parent body estimates are only likely to increase as further new and unique meteorites are characterized. However, even with these caveats, there is a clear mismatch between the large number of asteroids (> 100,000 with a diameter exceeding 2 km) present in the main belt (Bottke et al., 2005a) and the small number of primary parent bodies from which classified meteorites appear to be derived (<150). There are a number of possible explanations for this mismatch, which are discussed below.

4.5.1 Unrepresentative sampling

One straightforward explanation for this apparent mismatch between parent body and asteroid numbers is that the material that is delivered as meteorites represents an extremely selective sampling of the asteroid belt. As discussed in section 4.2, the material that arrives on Earth will preferentially come from objects that lie in relative close proximity to the main orbital resonances. For this reason it is unlikely that the middle and outer belt are well represented in our meteorite collections (Burbine, 2014). This may mean that carbonaceous chondrites are undersampled compared to their presence in the main belt.

4.5.2 Asteroids may be fragments from a limited number of parent bodies

It is possible that most bodies in the asteroid belt are fragments derived from a relatively limited population of primary parent bodies. Dermott et al. (2018) argue that ~85% of objects in the inner main belt (2.1 to 2.5 AU) originate from five families (Vesta; Flora; Nysa-Polana-Eulalia complex, which they count as three families) and the remaining ~15% are either from these families or, they argue more likely, a few ghost families. Vesta is thought to be the parent body of most HEDs, while the Flora family has been linked with the LL chondrites (e.g., Vernazza et al., 2008). Nysa is an E-type asteroid found in a cluster of S-complex bodies, while Polana and Eulalia, both C-complex bodies, have been linked to objects that have spectral properties and albedos consistent with carbonaceous chondrites (Walsh et al., 2013). Nysa is most likely an interloper into the Nysa-Polana-Eulalia complex due to its “anomalous” spectral characteristics compared to the S-complex members. Complex bodies tend to have spectral features consistent with pyroxene and/or olivine and tend to be linked with ordinary chondrites. E-type asteroids have relatively featureless visible and near-infrared reflectance spectra and high visual albedos and have been linked with aubrites. C-complex bodies have visible and near-infrared reflectance spectra that tend to be consistent with carbonaceous chondrites.

Dermott et al. (2018) reached their conclusion after finding that the diameters of family and non-family asteroids, respectively, in the inner main belt are both correlated with their eccentricities and anti-correlated with their inclinations, implying a relationship. Note that the Dermott et al. (2018) analysis is only for the inner main belt and not the whole asteroid belt region. Many more parent bodies could potentially be represented in the middle and outer main belt.

4.5.3 Meteorites are mainly derived from asteroid families

Another possibility is that most meteorites are fragments of the ~120 identified families (Bottke et al., 2005b). The creation of most of these families would have resulted in huge numbers of fragments that could potentially drift into meteorite-supplying resonances. Remnants of these families would be much more abundant than fragments of non-family bodies throughout the main belt. Note that this explanation is distinct from that in section 4.5.2 above. So, although asteroids themselves might not necessarily be derived from a limited number of parent bodies, our meteorite collections may be swamped by fragments from just a few families. A clear example of this would be the large number HED meteorites derived from 4 Vesta, whereas Ceres, a larger potential parent body, is at best, only sampled to a very limited extent in the meteorite record (Fries et al., 2013).

4*.5.4 Selective filtering by the Earth's atmosphere*

It is likely that the Earth's atmosphere is disrupting many types of weak bodies, such that only a very limited amount of material reaches the surface. Thus, high porosity, low strength meteoroids such as Tagish Lake and the CIs will be preferentially destroyed compared to tougher types e.g. ordinary chondrites, irons and achondrites. Sears (1998) argues that carbonaceous chondrites should be 1,000 times more abundant in our meteorite collections. As they are much more friable than ordinary chondrites and achondrites, we may not be sampling all the carbonaceous chondritic material that is striking the Earth's atmosphere.

4.5.5 Multiple "clone" parent bodies

It is possible that multiple primary parent bodies could have formed with virtually "identical" mineralogies and closely similar isotopic properties. Vernazza et al. (2014) argue that the existence of a number of large (diameters between 100 and 200 km) asteroids with interpreted compositions similar to H and LL chondrites, respectively, is evidence that a "natural outcome of planetesimal formation" is the production of separate bodies with "identical" mineralogies. If such bodies were drawn from the same well-homogenized nebular reservoirs, they could also potentially have closely similar isotopic compositions. However, such a scenario would be extremely difficult to test since it would involve sample return from multiple parent bodies that could not be dynamically linked to each other.

Potentially, all of the possibilities discussed above could be, to a greater or lesser extent, viable. The main-belt is unlikely to be systematically sampled by the meteorites arriving on Earth. As a consequence, we probably do not have samples from a large number of primary parent bodies, particularly those in the outer belt. As a result of long term dynamic evolution, the main belt may now only contain remnants of a relatively small fraction of the primary parent bodies it originally contained. Asteroid families could be supplying huge numbers of fragments to the meteorite-supplying resonances. The Earth's atmosphere is likely to act as a filter on the meteoroid population, preventing many friable types from reaching the ground. A large number of parent bodies could have formed with "identical" properties e.g. FeO-rich achondrites (Day et al., 2019). It is at present unknown, which, if any, of these mechanisms is dominant. However, there is a high level of likelihood that significant compositional differences exist between the asteroidal and meteoritic records. Notwithstanding these significant constraints, we now examine what can be learnt about the early evolution of the main belt from the current asteroidal and meteorite populations.

4.6 Linking meteorites and asteroids to early-formed planetesimals

4.6.1 The early evolution of the main belt

The current main belt contains only about 5 x 10^{-4} Earth masses (Weidenschilling, 2019), with more than half of this represented by the four largest asteroids (Raymond and Izidoro, 2017). However, based on solar nebular models, which assume a relatively smooth variation of surface density with distance from the proto-Sun, the area now occupied by the main belt would originally have contained several Earth-masses of solids (Weidenschilling, 2019). The depletion in mass of the main belt most likely took place after the formation of the first asteroids and is generally linked to the formation and early evolution of Jupiter (Walsh et al., 2011; Weidenschilling, 2019).

Planetary accretion in the inner Solar System, including the main belt region, is generally considered to have proceeded via a series of distinct stages (Walsh and Levinson, 2019; Weidenschilling, 2019). The initial stage involved the formation from nebula dust of a relatively uniform population of planetesimals (Walsh and Levison, 2019; Weidenschilling, 2019). Although widely considered to be km-sized bodies, Weidenschilling (2019) points out that primary planetesimals may have been only tens of metres in diameter, based on the definition that they represent objects whose motion is dominated by solar gravity rather than by nebular gas drag forces. Following planetesimal formation, the next accretion stage is "runaway growth" in which, as a result of gravitational focussing, the largest planetesimal in a given local region grows at a faster rate than its smaller neighbours. Once this larger body reaches about half the local mass it starts to perturb the orbits of its smaller neighbours, increasing relative velocities and causing a transition into "oligarchic growth" (Walsh and Levison, 2019). At the end of this phase a bimodal population is formed consisting of relatively few, large planetary embryos and a much larger number of remaining planetesimals. The final accretion phase leads to the building of planets via giant impacts between embryos and is termed the "giant impact" or "chaotic growth" stage (Walsh and Levison, 2019).

Each of these stages would not necessarily have taken place simultaneously throughout the inner disc (Walsh and Levison, 2019). Numerical simulations using an initial population of 30 km diameter planetesimals, with gas present for the first 2 Myr and with a 3.32 Earth mass of solids present from 0.7 to 3.0 AU, showed a strongly inside-out growth pattern (Walsh and Levison, 2019). At 1 AU planetary embryos grew rapidly so that by 2 Myr 90 % of the region by mass was occupied by embryos, with the planetesimal population highly depleted. In contrast, at 2 AU the point at which 90 % of the mass was represented by embryos was reached after 50 Myr and the largest bodies never attained Mars mass due to collisional grinding and planetesimal drift (Walsh and Levison, 2019). In these simulations the planetesimal population at 2 AU never displayed the extent of depletion seen at 1 AU and the embryos and planetesimals present after 20 Myr were highly excited and displayed elevated eccentricity relative to those at 1 AU. Well-developed inside-out growth has also been reported in various earlier studies (Kenyon and Bromley, 2006; Carter et al., 2015). However, simulations in which significantly smaller planetismals (<10 km radius) were used, combined with a high disc mass, resulted in rapid growth of embryos throughout the disc (Kobayashi and Dauphas, 2013; Walsh and Levison, 2019). This suggests that initial planetesimal size would have played an important role in determining the early stages of planetary evolution. Unfortunately, there is little agreement on this parameter, with Morbidelli et al. (2009) suggesting that diameters of 100 km or more were needed to explain the main belt mass distribution, whereas Weidenschilling (2011) argue that 100 metre-sized bodies was a more realistic initial size estimate.

4.6.2 Constraining the size of primary planetesimals – are chondrites secondary parent bodies?

It is now well established that the parent bodies of chondritic meteorites accreted later than many of those from which the irons and achondrites were derived (Kruijer et al., 2014, 2017; Budde et al., 2018; Scott et al., 2018). This is somewhat paradoxical as chondrites are typically regarded as representing the planetary building blocks (Scott et al., 2018), and in the case of the carbonaceous chondrites, contain abundant CAIs, the oldest dated Solar System solids. Chondrules, the principal high-temperature constituent of chondrites, typically formed 1 to 3 Myr after CAIs (e.g. Hertwig et al., 2019; Pape et al., 2019). A significant and as yet unresolved issue is where CAIs were located prior to incorporation within their final chondritic parent bodies (Desch et al., 2018). As discussed in sections 3.4 and 4.4 there is clear evidence from meteoritic breccias that chondrites are secondary bodies and incorporate fragmented material from an earlier generation of fully disrupted “primary” planetesimals (Bischoff et al., 2006,2018; Bonal et al., 2010). One possibility is that CAIs were originally incorporated into a first generation of planetesimals. While these bodies would likely have had a high ratio of CAIs to chondrules, they would probably not have been completely chondrule-free. There is some evidence that chondrule and CAI formation overlapped (Connelly et al., 2012). However, a recent study by Pape et al. (2019) indicates that the main chondrule-forming interval post-dated CAIs by about 2 Myr. While these primary, early-formed, CAI-enriched, planetesimals could potentially have undergone significant heating, driven by the decay ^{26}Al, this would not have taken place if they had stayed below a radius of about 10 km (Weidenschilling, 2019).

The numerical simulations discussed above (section 4.6.1) indicate that outwards of about 1.5 AU embryos and the remaining planetesimal population would have experienced significant grinding and fragmentation. Small, friable, primary planetesimals would probably not have survived for long in such an environment. So, not only would they have remained relatively unheated due to their small size, this earliest generation of planetesimals likely suffered significant attrition and would eventually have been ground down and the material they contained liberated and incorporated into second generation bodies.

By the time these secondary chondritic asteroids started to accrete, up to 3.7 Myr after CAI formation (Budde et al., 2018), sufficient ^{26}Al would have decayed, such that no matter how large they grew they would not have melted. If this scenario is correct, it may provide some constraints on the initial size of the primary planetesimals. Rather than the 100 km or larger-sized bodies proposed by Morbidelli et al., (2009), it suggests that the first generation of planetesimals were probably much smaller, possibly as little as a 100 metres in diameter, as suggested by Weidenschilling (2011, 2019).

4.6.3 The meteorite compositional dichotomy

To explain the depleted mass of the main belt and the relatively small size of Mars, it has been proposed that the newly-formed Jupiter initially migrated inwards and then subsequently outwards to its present position, a scenario that has been termed the "Grand Tack" (Walsh et al., 2011; O'Brien et al., 2014). The initial inwards migration of Jupiter to about 1.5 AU would have cleaned out the main belt, while its outwards migration, caused by Saturn catching it up and trapping it in a 2:3 resonance, would have repopulated its inner regions with asteroids that accreted in the inner Solar System (1–3 AU) and its outer regions with bodies that formed in the outer Solar System (Walsh et al., 2011; O'Brien et al., 2014). The relatively small size of Mars is inferred to be a consequence of the depletion of its feeding zone during the "Grand Tack" and the predictions of the model appear to be consistent with martian geochemical and isotopic constraints (Brasser et al., 2017). On a larger scale, the "Grand Tack" scenario may provide a viable mechanism to explain the delivery of volatile-rich materials to the inner Solar System (Carlson et al., 2018).

An important implication of the "Grand Tack" model (Walsh et al., 2011; O'Brien et al., 2014) is that the asteroid belt should be populated by material that accreted at widely different heliocentric distances. This possibility appears to be consistent with the bimodality observed in plots of various stable isotopes, such as ε^{54}Cr vs. ε^{50}Ti and ε^{54}Cr vs. Δ^{17}O (Fig. 3) (Warren, 2011). The two groupings, carbonaceous (CC) and non-carbonaceous (NC), have been interpreted in terms of an outer and inner Solar System origin, respectively (e.g., Warren, 2011; Gerber et al., 2017; Kruijer et al., 2017, Scott et al., 2018).

With the notable exception of oxygen, mass-independent isotopic variation in extraterrestrial samples, not due to either spallation or radioactive decay, reflects nucleosynthetic processes in the feeder stars to the Solar System (Dauphas and Schauble, 2016; Scott et al., 2018). One explanation for the isotopic difference between the CC and NC groups is that the higher temperatures that prevailed in the inner Solar System (NC group) resulted in partial evaporation of the presolar grains carrying the nucleosynthetic anomalies (Scott et al., 2018). Whole-rock nucleosynthetic anomalies have now been identified for a wide range of elements, with Cr, Ti, Ni and Mo in particular displaying clear evidence for bimodality (Budde et al., 2016; Kruijer et al., 2017, Scott et al., 2018; Worsham et al., 2019). In the case of oxygen, the mass independent variation present in a wide range of Solar System materials is no longer regarded as being due to the selective addition of a presolar, ^{16}O-rich phase, as was originally proposed by Clayton et al. (1973). Instead, more recent models have invoked UV dissociation of CO coupled with self-shielding of the major ^{16}O isotope (Clayton, 2002). This process is considered to have taken place either in the presolar giant molecular cloud (Yurimoto and Kuramoto, 2004), or in the solar nebula (Clayton, 2002; Lyons and Young, 2005). The oxygen isotope anomalies produced during this process may have been locked into different phases, including water ice, gas and dust (Yurimoto and Kuramoto, 2004). Preservation of these anomalies being the result of incomplete homogenization in the protosolar nebula (Krot et al., 2010b).

One of the clear implications of the “Grand Tack” model is that the material now present in the main belt may not have formed there. The main belt most probably represents a highly impoverished assemblage of materials that originally accreted at variable heliocentric distances. Remnants of the inner Solar System planetesimal population (NC) scattered into the main belt would inevitably be deformed remnants, pulled apart by multiple impact encounters (Asphaug et al., 2006). Recent models for the evolution of iron meteorites and pallasites bear witness to major collisional reprocessing that took place early in their history (Yang et al., 2007; Tarduno et al., 2012; Scott et al., 2015; Ruzicka et al., 2017b). Even large asteroids, such as (4) Vesta, may not have accreted in their present locations and instead represent main belt “interlopers” (Bottke et al., 2006). Recent potassium isotope data for HED meteorites show that they are significantly δ^{41}K enriched relative to terrestrial materials (Tian et al., 2019). It is suggested by Tian et al. (2019) that this may reflect the fact that Vesta formed from uniquely volatile-depleted precursor materials, with further K isotopic fractionation taking place during accretion and magma ocean degassing. One way to explain these results would be if Vesta formed closer to the proto-Sun, in keeping with the suggestion of Bottke et al. (2006).

4.6.4 How representative are our meteorites of the early planetesimal population?

Finally, an important question is whether we have material in our collections that are representative of the first generation of asteroids, the vast bulk of which would have been consumed building the terrestrial planets (Burbine and O’Brien, 2004; Brasser et al., 2017; Dauphas, 2017; Carlson et al. 2018). As discussed earlier, we have been able to identify between 95 and 148 primary parent bodies in our meteorite collections. In comparison, using the minimum planetesimal size estimate of Morbidelli et al. (2009) and a density of 3400 kg/m^3, the mass of the current asteroid belt (3.0 x 10^{21} kg) would be equivalent to 1,667 bodies with a diameter of 100 km. Based on the initial 100 m diameter planetesimal estimate of Weidenschilling (2011) the current main belt mass would be equivalent to 1.7 x 10^{12} asteroids. If these were realistic estimates of the number of parent bodies that should be present in the belt, our meteorite collections would be highly unrepresentative. However, such a judgement is certainly too simplistic.

As discussed in sections 4.6.1, the evolution of the asteroid belt did not halt at the planetesimal stage, but instead has experienced a long and complex history, losing an estimated 99.9 % of its primordial mass (Bottke et al., 2015). The number of asteroids that are thought to be primary, non-disrupted parent bodies is relatively small. Only one asteroid, Ceres, now classified as a dwarf planet, has a diameter greater than 900 km. Two (Pallas, Vesta) have diameters between 500-600 km, one (Hygiea) has a diameter between 400-500 km, and ~20 have estimated diameters between 200-400 km. More than 200 asteroids have diameters greater than 100 km. The four largest asteroids contain more than half of the main belt's mass (Raymond and Izidoro, 2017) and a pessimistic interpretation could be advanced that these bodies represent the only surviving intact primary asteroids in the belt.

It is also important to consider the ~120 asteroid families currently identified in the main belt (Nesvorný et al., 2015). Members of asteroid families cluster in proper elements (semi-major axis, proper inclination and proper eccentricity). Asteroid families are objects, either parent bodies or fragments of parent bodies that either disrupted or experienced a major crater-forming event. Estimated ages of the families range from tens of millions of years to billions of years old (Spoto et al., 2015), implying that much older families may have dispersed and are not currently recognizable. If meteorites are preferentially sampling asteroid families, as discussed in section 4.5.3, this might in part account for why we seem to have so few parent bodies represented in our meteorite collections.

A further complicating factor in assessing how representative meteorites are in sampling primary parent bodies relates to the possibility that these bodies were never as small as classical accretion models suggest. Planet formation via the classic processes of "runaway growth" followed by "oligarchic growth" (Chambers, 2004), has been called into question by models that invoke "pebble accretion" (Levison et al., 2015; Morbidelli, 2018). In this scenario, planetesimals grew essentially by accretion of small cm-sized lumps, which were coupled to the gas and so drifted relative to the growing planetesimal. This drift means that the feeding zone that surrounded the planetesimal were never empty (Morbidelli, 2018). An important implication of pebble accretion is that much larger bodies than Vesta-sized objects could grow in the disc, possibly as massive as Mars-sized (Morbidelli, 2018). The final collisional stage of planetary growth, which took place once the gas had dissipated, would then have involved a smaller population of larger-sized objects compared to classical accretion scenarios. About 19

Mars-sized protoplanets are required to form the planets of the inner Solar System, or about 160 Moon-sized bodies.

Compared with this relatively small number of big planetesimals, the 150 or so parent bodies represented in our meteorite collections looks much more representative. Evidence that at least some meteorite parent bodies may originally have been on the scale of protoplanets, rather than smaller planetesimals, has been presented for the ureilites based on the presence of large diamonds containing inclusions of chromite, phosphate and sulphides (Nabiei et al., 2018). It is suggested by Nabiei et al. (2018) that such inclusions could only have formed at pressures in excess of 20 GPa, making the ureilite parent body a "Mercury to Mars-sized body". Alternatively, diamonds in ureilites may have formed as a result of high pressures generated during an impact events (Nakamuta and Aoki, 2000). If the latter explanation is correct then the case for a large-sized ureilite parent body is significantly weakened.

5. CONCLUSIONS

We have examined the relationship between meteorites and the current asteroidal population. Our estimates suggest that we have samples from between 95 to 148 parent bodies in our meteorite collections. This number has been slowly increasing over time with the discovery each year of more "anomalous" meteorites, but will never rival the number of known asteroids. Unfortunately, due to the limitations of spectroscopy and the non-unique reflectance spectra of almost all asteroids, so far only a relatively few meteorite groups have been linked directly to specific main-belt asteroids or families. We provide examples of some suggested meteorite-asteroid connections, but note that apart from (4) Vesta and the HED meteorites almost all such proposed linkages have been disputed.

We have drawn attention to the popularity of the "parent body" concept amongst planetary scientists, but note that it is usually used in a fairly loose way, essentially as representing "a body that supplies meteorites to Earth." To clarify this issue we would advocate a two-fold division of "parent bodies". So that while all asteroids can be parent bodies, they are not all of equal significance. We suggest that the ultimate source of meteoritic material arriving on Earth be designated the "primary" parent body, with asteroids derived from this primary body representing "secondary" parent bodies. A clear example of this concept is provided by Vesta, with the main asteroid being primary and the Vestoids being secondary.

The number of parent bodies represented by meteorites (<150) appears very low when compared to the estimated number asteroids in the main belt (> 100,000 with a diameter exceeding 2 km). A range of potential reasons can be advanced to explain this apparent mismatch: i) meteorites provide an unrepresentative sampling of the main belt, ii) the belt may only contain a limited number of primary parent bodies, iii) meteorites may be preferentially derived from the ~120 identified asteroid families, iv) friable meteorite types are filtered out by the Earth's atmosphere, v) multiple, near-identical, "clone" parent bodies may be present in the belt. At present it is not possible to decide which mechanism is dominant and all may be operating to a greater or lesser extent.

We have also attempted to relate the current asteroidal and meteoritic populations to primordial constituents of the main belt; the asteroids that populated the early Solar System. Based on classical accretion models the meteoritic and asteroidal record are numerically highly unrepresentative of these first generation asteroids. However, our sample collections may provide a more representative sampling of these primordial bodies, if the first generation asteroids accreted as large bodies via pebble accretion.

A clear conclusion of this survey is that although the number of primary parent bodies represented in our sample collections is steadily increasing, the mismatch with both the present and primordial main belts remains large. In order to better resolve the question of how representative meteorites are of the current main belt further detailed work is required. In particular, sample return from key main belt objects would greatly help in matching up asteroids with meteorites. More detailed remote sensing observations of the main belt would also help to resolve its overall structure. Perhaps these two tasks could be combined into a single future space mission. The results obtained would also be important in terms of evaluating theoretical models such as the Grand Tack. The return of material by the Hayabusa2 and OSIRIS-REx missions will be an important step in linking meteorites to the NEO population.

In terms of relating meteorites to the primordial asteroid population, we have highlighted the issue of planetesimal size. Were the initial bodies in the main belt small or large? The answer to this question would significantly improve our understanding of how the planets accreted. Central to this issue is the nature of chondritic asteroids. Dating studies suggest that the primary chondritic parent bodies formed late, which is a paradox as they contain CAIs, the oldest dated Solar System solids. One possibility is that the asteroids which currently supply chondritic meteorites to Earth are all secondary bodies formed from the debris of primary chondritic bodies which were destroyed early in Solar System history. We conclude that significant progress in understanding the early evolution of the main belt could be made by undertaking further detailed isotopic and dating studies of chondritic clasts and breccia fragments.

6. ACKNOWLEDGEMENTS

This paper is dedicated to the memory of Lawrence “Larry” Taylor (1938-2017), who made seminal contributions to the studies of planetary bodies. We are grateful to the Associate Editor James Day and the Guest Editor Alex Ruzicka for their very helpful and incisive comments. We thank Ed. Scott for his very detailed review of the manuscript and two anonymous reviewers for their constructive comments and suggestions. THB would like to thank the Remote, In Situ, and Synchrotron Studies for Science and Exploration (RIS4E) Solar System Exploration Research Virtual Institute (SSERVI) for support. THB would also like to thank Open University for hosting him for a week to write this paper. Oxygen isotope studies at the Open University are funded by a consolidated grant from the Science and Technology Facilities Council (STFC), UK GRANT NUMBER: ST/L000776/1

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Figures

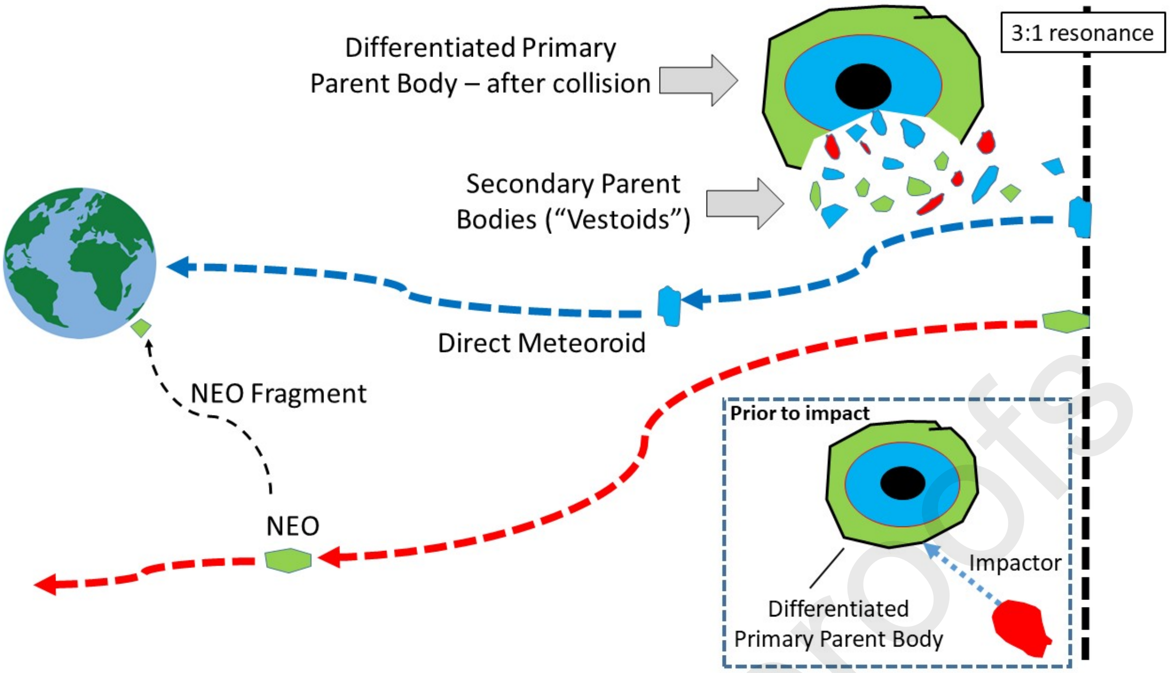

Figure. 1 Schematic diagram showing possible relationships between main group asteroids, NEOs and meteoroids. This diagram is loosely based on the Vesta-Vestoid relationship (Binzel and Xu, 1993; Burbine et al., 2001; Fulvio et al., 2018). Here a fully differentiated member of the Solar System's initial asteroidal population undergoes a collision. It does not totally destruct, but a large mass of fragments are produced. All of these bodies are themselves capable of producing meteoroids which can intersect the Earth's orbit. However, we designate the initial asteroid as the "primary"parent body and all other later-formed asteroids as "secondary" parent bodies. In the case of the fragments (secondary parent bodies) produced during the impact event with the primary parent body, two routes are available for delivery of material to Earth. Initially some fragments will drift into the 3:1 resonance. This material could be delivered in a single event to Earth as a "direct" meteoroid, or alternatively become a member of the Near Earth Object (NEO) population. At some later stage a fragment from the NEO arrives on Earth as a meteoroid. While a range of lithologic types are ejected from the differentiated primary asteroid, with the exception of impactor-related material, all these rock types will have closely similar $\Delta^{17}O$ compositions. This would not be the case for chondrites and primitive achondrites (see section 2.3 for further discussion).

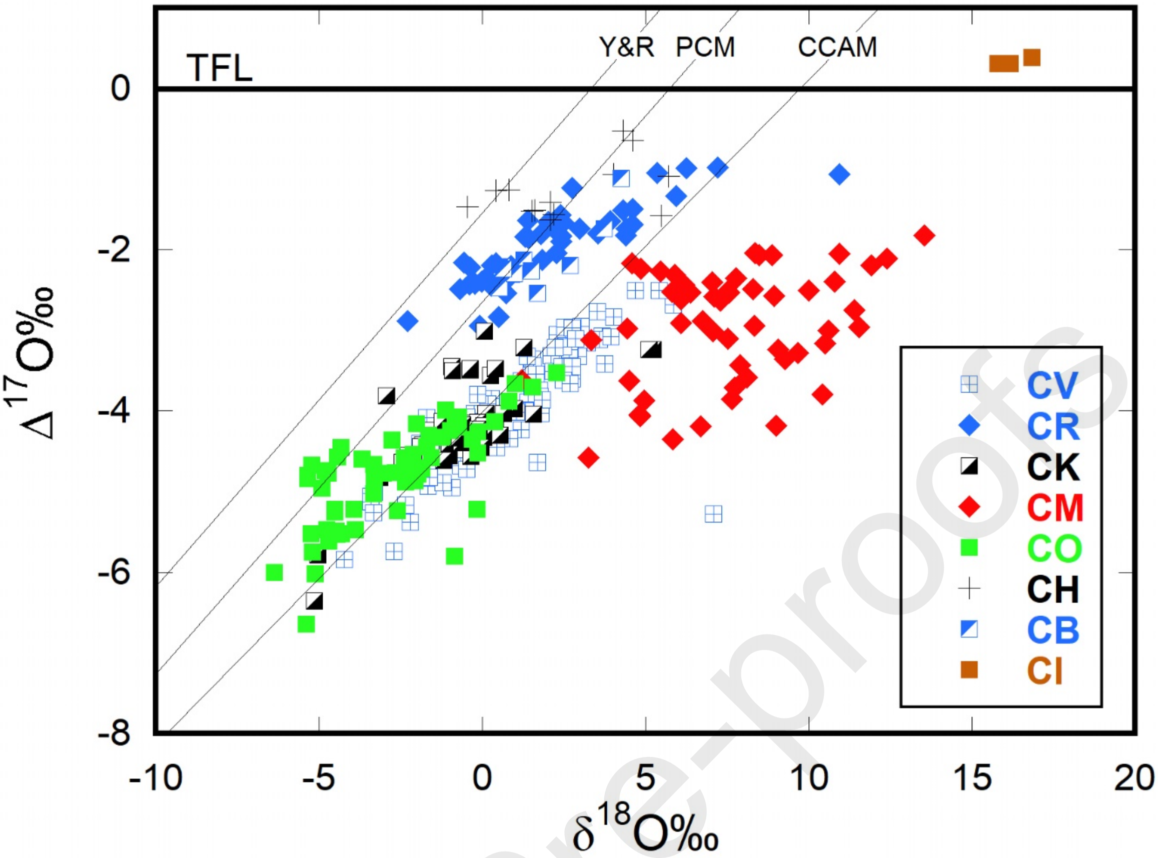

Figure. 2. Oxygen isotope composition of main carbonaceous chondrite groups. Reference lines: Y&R (Young and Russell, 1998) Slope 1 Line; PCM (Primitive Chondrule Minerals) line (Ushikubo et al., 2012); CCAM (Carbonaceous Chondrite Anhydrous Mineral) line (Clayton et al., 1977; Clayton and Mayeda, 1999); TFL: Terrestrial Fractionation Line. Data Sources: Alexander et al. (2018b); Clayton and Mayeda (1999); Greenwood et al. (2010); Ivanova et al. (2008); Lee et al. (2019); Schrader et al. (2011, 2014); Tyra et al. (2007); Wiesberg et al., (2001); Meteoritical Bulletin Database: https://www.lpi.usra.edu/meteor/ Full Data given in Table S1.

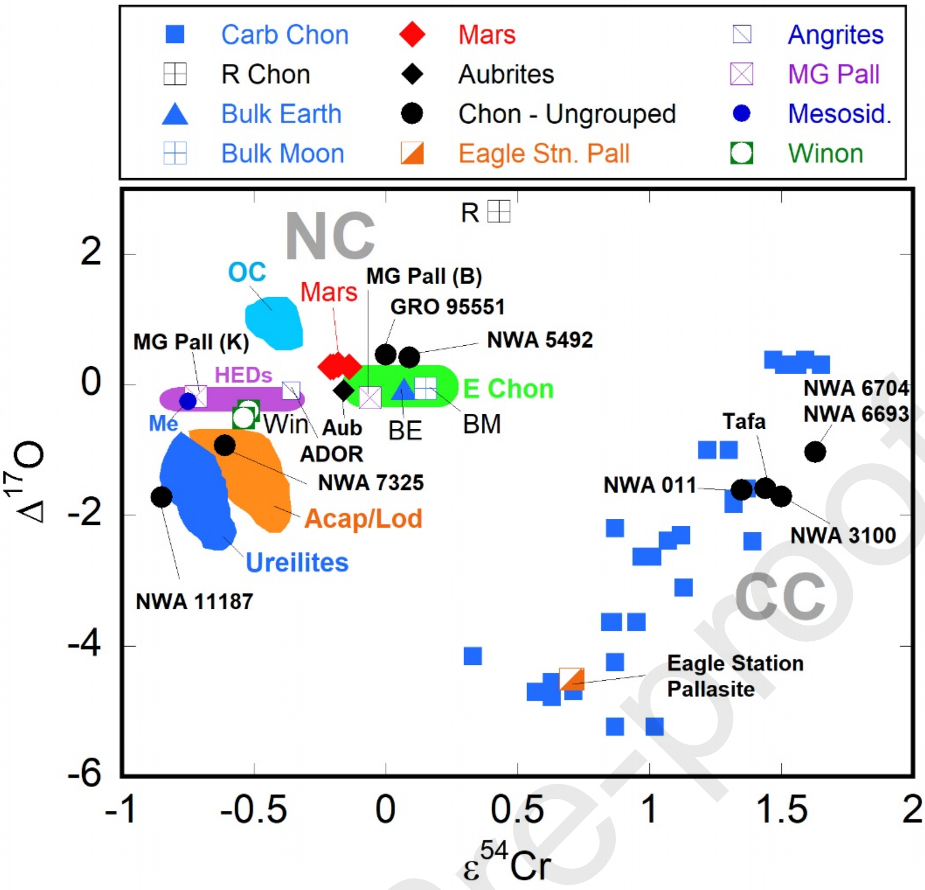

Figure. 3. ε^{54}Cr vs Δ^{17}O plot for a range of planetary materials. Carbonaceous (CC) and non-carbonaceous (NC) groups are clearly separated on this diagram. Eagle Station pallasites, the basaltic eucrite NWA 011 and the ungrouped achondrites NWA 6693/NWA 6704 (Sanborn et al., 2019) and Tafassasset (Gardner-Vandy et al., 2012; Sanborn et al., 2019) plot within the carbonaceous chondrite (CC) grouping, whereas most other achondrite groups plot in the same field as the ordinary and enstatite chondrites. Data sources: Alexander et al. (2018b); Bogdanovski and Lugmair (2004); Clayton and Mayeda (1996,1999); Clayton et al. (1991, 1999); Franchi et al., (1999); Gardner-Vandy et al. (2012); Greenwood et al. (2006, 2010, 2012, 2017, 2018); Goodrich et al. (2017); Guo et al. (2019b); Li et al. (2018); Newton et al. (2000); Qin et al. (2010a,b); Sanborn et al., (2015, 2019); Schrader et al. (2011); Shukolyukov and Lugmair (2006); Trinquier et al. (2007); Weisberg et al. (2001).

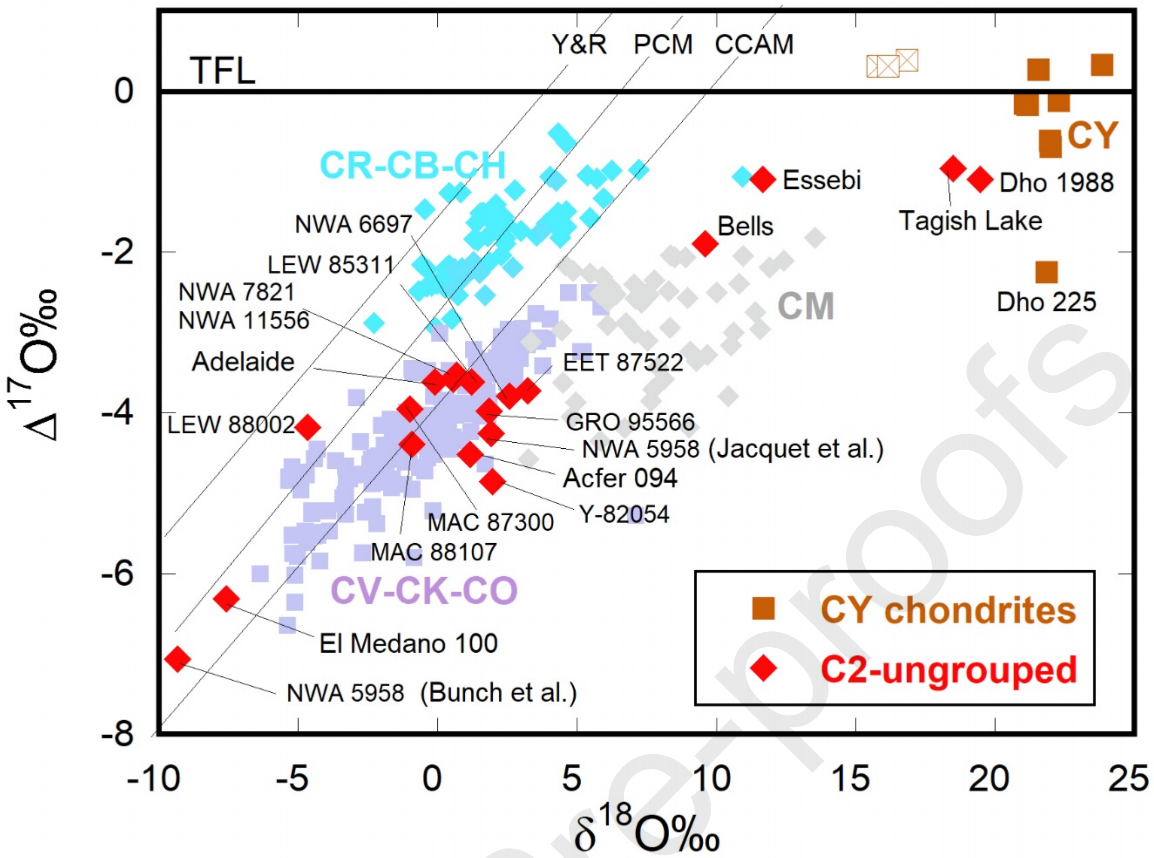

Figure. 4. Oxygen isotope compositions of ungrouped type 2 carbonaceous chondrites plotted in relation to the main carbonaceous chondrites groups (Fig. 2). Data Sources: Brown et al. (2000); Bunch et al. (2011); Clayton and Mayeda (1999); Jacquet et al. (2016); Lee et al. (2019); Meteoritical Bulletin Database: https://www.lpi.usra.edu/meteor/ Full Data given in Table S1.

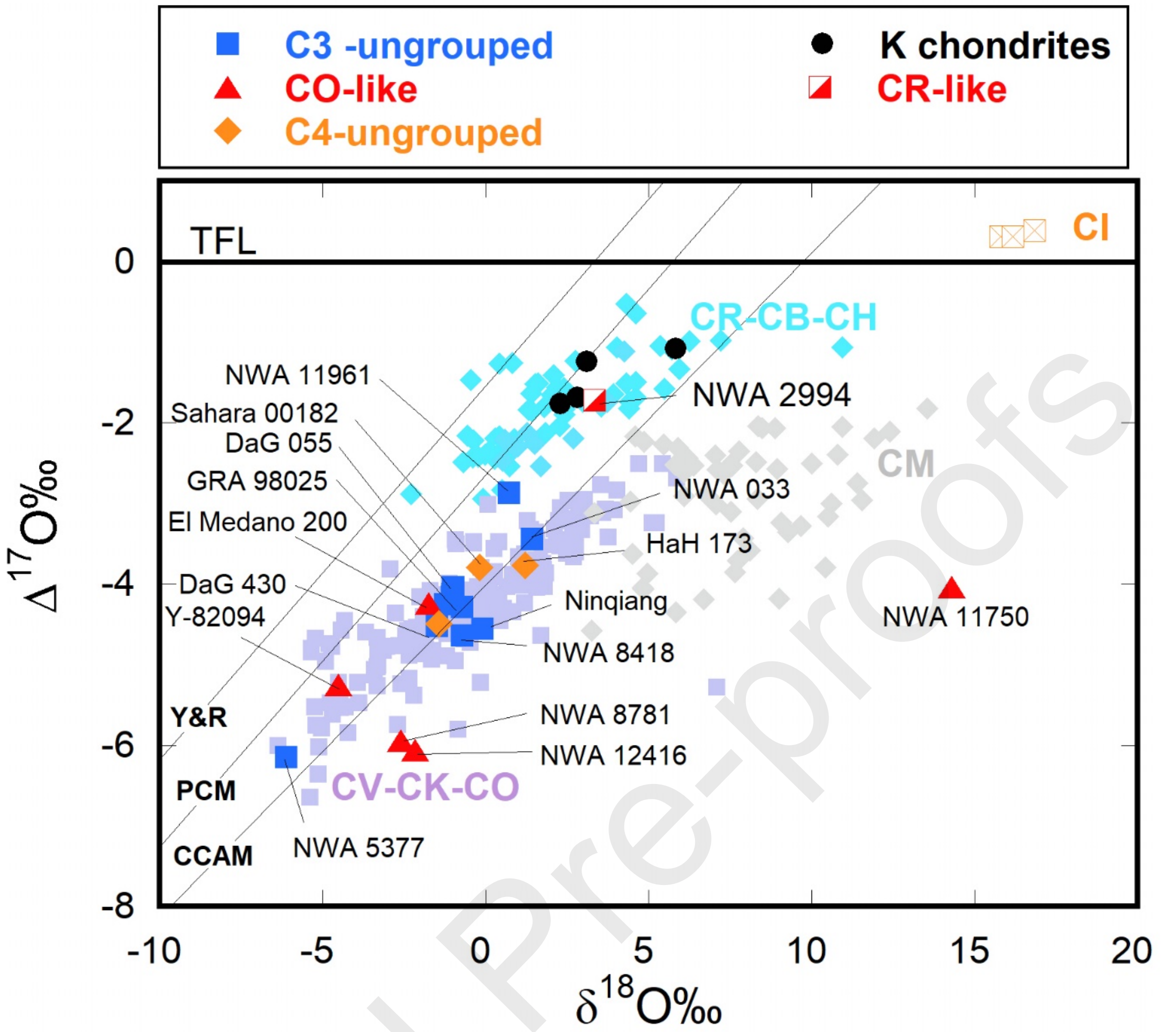

Figure 5 Oxygen isotope compositions of ungrouped type 3 carbonaceous chondrites plotted in relation to the main carbonaceous chondrites groups (Fig. 2). Data sources: Clayton and Mayeda (1999); Greenwood et al. (2010); Schrader et al. (2011); Weisberg et al. (1996); Meteoritical Bulletin Database: https://www.lpi.usra.edu/meteor/ Full Data given in Table S1.

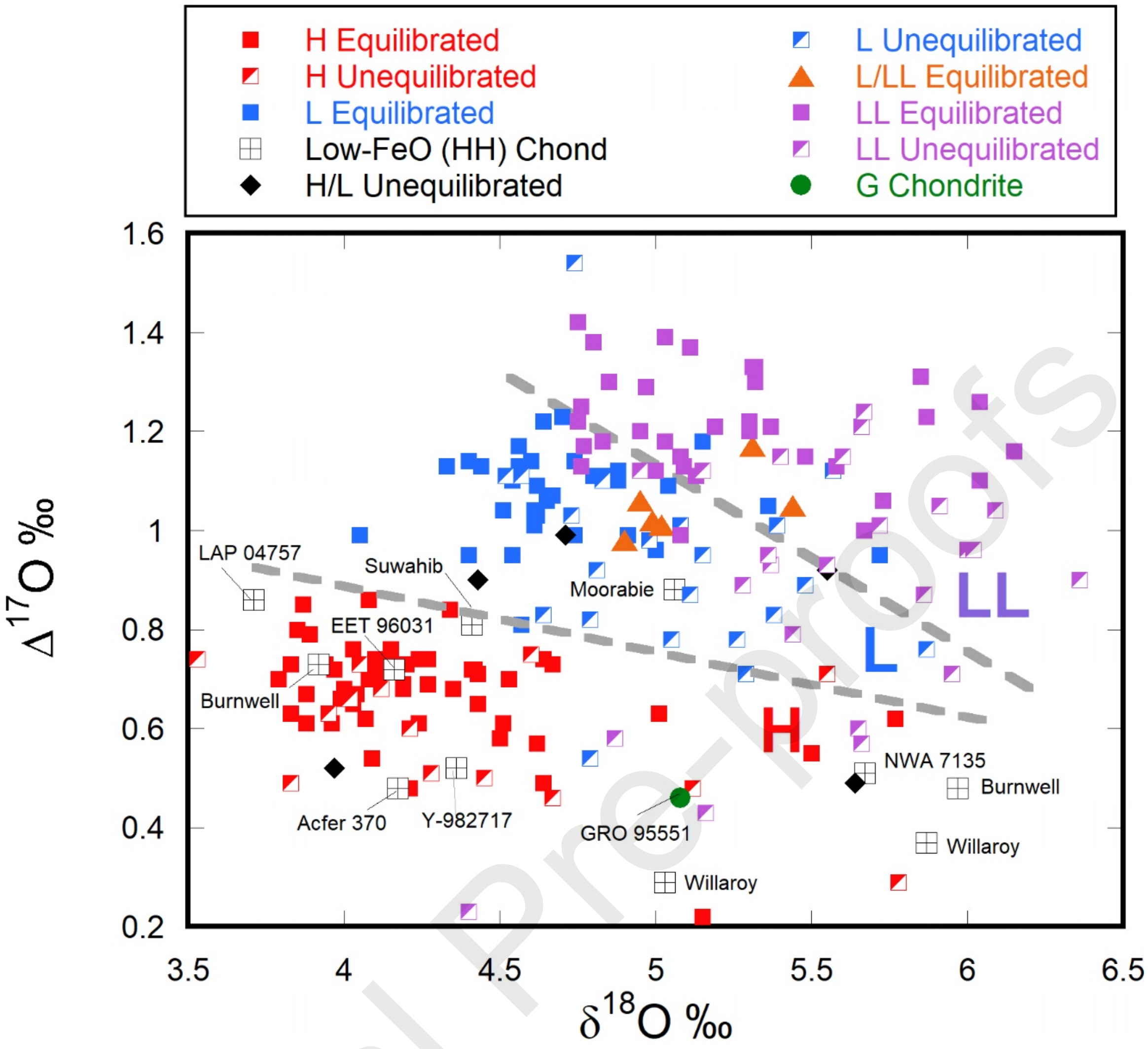

Figure. 6. Oxygen isotopic composition of ordinary chondrites. In addition to the three main ordinary chondrite groups (H, L, LL), there is the suggestion of three further groupings: Low-FeO (HH) chondrites (Yamaguchi et al., 2019), H/L and L/LL. See main text for further discussion. Note that in the three main groups, unequilibrated types show a shift towards higher $\delta^{18}O$ and lower $\Delta^{17}O$ values. Data sources: Clayton et al. (1991); McDermott et al. (2016); Russell et al. (1998); Ruzicka et al. (2017a); Troiano et al. (2011); Weisberg et al. (2001); Yamaguchi et al. (2019); Meteoritical Bulletin Database: https://www.lpi.usra.edu/meteor/ Full Data given in Table S2.

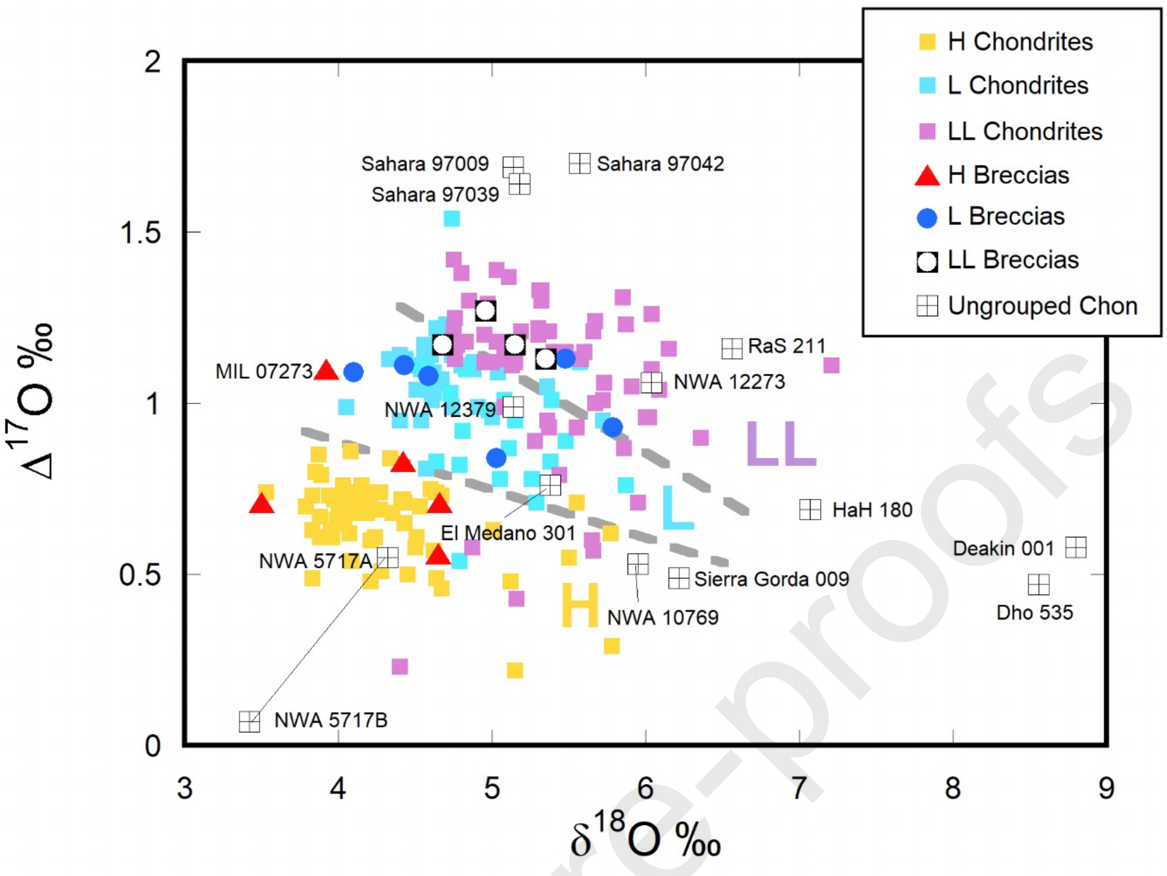

Figure. 7. Oxygen isotopic composition of ordinary chondrite impact and melt breccias and various ungrouped chondrites shown in relation to the main ordinary chondrite groups. Data sources: Bevan and Binns (1989); Bischoff et al. (1997); Bunch et al. (2010); Sexton et al. (1998); Meteoritical Bulletin Database: https://www.lpi.usra.edu/meteor/ Full Data given in Table S2.

Table 1 Number of parent bodies*	**Low Estimate**	**High Estimate**
Main chondrite groups (inc. G chondrites)	15	20
Ungrouped chondrites	11	17
Primitive achondrites - main groups	4	5
Primitive achondrites – ungrouped	23	23
Differentiated achondrites and stony irons	11	12
Anomalous basaltic achondrites	5	11
Irons	26	60
TOTALS	**95**	**148**

*Full details in Table S3

Table 2 Postulated best parent body or taxonomic class linkages for different meteorite types in order of decreasing fall percentage. The fall percentages are calculated using data for classified meteorites from the Meteoritical Bulletin Database (2019) for 1118 meteorites. The table is revised from Burbine (2017). The HED (howardite, eucrite, diogenite) and acapulcoite/lodranite meteorites, respectively, are grouped together. For parent body linkages, we put in parentheses our likelihood (possible, likely, or certain) for that linkage.

Type	Fall percentage	Postulated linkages
L	37.7	Q-type (Binzel et al., 2004, 2019); S- complex (Gaffey et al., 1993)
H	33.1	(6) Hebe (possible) (Gaffey and Gilbert, 1998); S-complex (Gaffey et al., 1993); Q-type (Binzel et al., 2004, 2019)
LL	8.5	(8) Flora family (possible) (Vernazza et al., 2008); Q-type (Binzel et al., 2004. 2019); S-complex (Nakamura et al., 2011)
HED	6.0	(4) Vesta family (likely) (Binzel and Xu, 1993); V-type (McCord et al., 1970; Consolmagno and Drake, 1977; McSween et al. 2013)
iron	4 .3	M-type (Cloutis et al., 1990; Shepard et al., 2010, 2011)
CM	1.6	(19) Fortuna (possible) (Burbine, 1998); C-complex (Vilas and Gaffey, 1989; Cloutis et al., 2011b)
L/LL	1.0	Q-type (Binzel et al., 2004, 2019); S-complex (Gaffey et al., 1993)
EH	0.9	M-type (Chapman and Salisbury, 1973; Shepard et al., 2010)
aubrite	0.8	(434) Hungaria family (possible) (Zellner et al., 1977, Ćuk et al. 2014); E-type (Zellner, 1975; Clark et al., 2004)
EL	0.7	M-type (Gaffey and McCord, 1978; Shepard et al., 2010)
CV	0.6	Eos family (possible), K-type (Bell, 1988)
mesosiderite	0.6	M-type (Shepard et al., 2010); S-complex (Gaffey et al., 1993)
CO	0.5	Eos family (possible), K-type (Bell, 1988; Clark et al., 2009)
ureilite	0.5	C-complex (Jenniskens et al., 2009); S-type (Gaffey et al., 1993)
CI	0.4	C-complex (Johnson and Fanale, 1973; Cloutis et al., 2011a)
Martian	0.4	Mars (likely) (Bogard and Johnson, 1983)
H/L	0.4	Q-type (Binzel et al., 2004, 2019); S-complex (Gaffey et al., 1993)
pallasite	0.4	A-type (Cruikshank and Hartmann, 1984; Sunshine et

		al., 2007)
C2-ungrouped	0.3	D-type (Hiroi et al., 2001); T- type (Hiroi and Hasegawa, 2003)
CR	0.3	C-complex (Hiroi et al., 1996; Sato et al., 1997)
acapulcoite/lodranite	0.2	S-complex (Gaffey et al., 1993)
CK	0.2	K-type (Clark et al., 2009; Cloutis et al., 2012)
K	0.1	C-complex (Gaffey, 1980)
R	0.1	A-type (Sunshine et al., 2007)
C3-ungrouped	0.1	K-type (Clark et al., 2009)
CB	0.1	M-type (Shepard et al., 2010)
angrite	0.1	S-complex (Rivkin et al., 2007)
winonaite	0.1	S-complex (Gaffey et al., 1993)
CH	all finds	M-type (Shepard et al., 2010)
CY	all finds	Ryugu (speculative) (King et al., 2019)
brachinite	all finds	A-type (Cruikshank and Hartmann, 1984; Sunshine et al., 2007)
lunar	all finds	Moon (certain) (Marvin, 1983)

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: