**Abundance and importance of petrological type 1 chondritic material**

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**Abstract**—We review the mineralogy, petrology, and abundance of petrological type 1 extraterrestrial material. Such material has been completely altered by aqueous processing on its parent bodies. As well as the four meteorite groups that contain type 1 members (CI, CM, CR, and CY), we summarize data from the 2019 fall Flensburg and a recent reanalysis of the “meteorite” Bench Crater found on the Moon, along with fine-grained micrometeorites, interplanetary dust particles, and xenoliths in meteorites. Type 1 materials exhibit a remarkably high diversity of alteration conditions (temperature, water-to-rock [W/R] ratios, and fluid composition) and starting mineralogy. Type 1 material comprises a significant component of the modern extraterrestrial flux to the Earth and was likely common throughout the solar system during the whole course of its history, pointing to both widespread accretion with ices and heating of parent bodies. Type 1 materials are composed predominantly of various phyllosilicates, carbonates, sulfides, and magnetite. Some type 1 materials appear to be part of a “CM clan” typified by serpentine-rich phyllosilicate compositions and an oxygen isotope composition that falls in the $^{16}$O-rich part of the CM field. Others span a wide range in $\delta^{18}$O (>30‰) and fall on or above the terrestrial fractionation line (+ve $\Delta^{17}$O). Positive $\Delta^{17}$O values are unusual for carbonaceous meteorites but are relatively common in type 1 materials. The wide variation in oxygen isotopes, as well as in textures, mineralogy, and bulk chemistry, points to multiple parent bodies that may originate in the inner and/or outer solar system. Cometary materials, or transition objects such as Main Belt comets or type D asteroids, are likely the source of much of the type 1 materials on Earth but relating them to specific parents requires more study.

**INTRODUCTION**

Extraterrestrial material comprises a remarkable diversity in geochemistry, oxygen isotope composition, and textures (e.g., Weisberg et al., 2005). Many meteorite types show the effects of alteration by water to varying degrees, from incipient alteration around grain edges and cracks to complete alteration of all anhydrous minerals (e.g., Brearley, 2006; Noguchi et al., 2017), with the formation of phyllosilicates being the main product of hydration. Among the rarest meteorites are the most water-rich type 1, a term coined by Van Schmus and Wood (1967) to describe fine-grained meteorites lacking chondrules and with high volatile element abundances. In type 1 meteorites, the primary anhydrous minerals have been unequivocally affected by the actions of water to produce secondary phases such as phyllosilicates, carbonates, and magnetite. All type 1 materials have a mineralogy dominated by sheet silicate phyllosilicates that trap water between the atomic layers and hold hydroxyl groups in M-OH bonds. We define a meteorite as petrologic type 1 if it has a phyllosilicate fraction/total silicate ratio (phyllosilicate fraction, or PSF) of ≥0.90 (Howard et al., 2015; King et al., 2015, 2019), although we note that not all recorded type 1 meteorites in the literature have PSFs quite this high. In many cases, this ratio is not quantified, in which case we follow the conclusions of the researchers working on each specimen, and often textural observations are the overriding factor in petrological classification. Type 1 chondrites typically also contain a few percent carbon, mostly organic material, that has experienced changes due to oxidation during aqueous processing (e.g., Alexander et al., 2007; Le Guillou et al., 2014). For
example, type 1 chondrites usually have lower levels of amino acids than type 2 chondrites (Glavin et al., 2011).

There is ample evidence that aqueous alteration in low petrologic type carbonaceous chondrite (CC) meteorites occurred mainly on their parent bodies (e.g., Brearley, 2006; Suttle et al., 2021), most likely predominantly through the melting of co-accreted ices (e.g., Matsumoto et al., 2019). Observations of the effects of the action of water on asteroids can provide quantitative constraints on their geological history (e.g., temperatures, water-to-rock [W/R] ratios, and fluid compositions) and can show how minerals interacted with co-accreting ices.

These water-rich meteorites are important because such objects are critical in the transport of water and other volatiles around the solar system. Hydrated asteroids likely played a significant role in supplying water to the Earth (e.g., Alexander et al., 2012; Sarafian et al., 2014) and to the Moon (Barnes et al., 2016; Saal et al., 2013). Water is essential for many geological processes, such as plate tectonics that we observe on Earth, as well as being important to the sculpting of planetary surfaces, to the evolution of the atmosphere, and ultimately to the evolution of life (Genda, 2016). Because of the importance of such objects to our understanding of the formation of the solar system and the evolution of habitable planets, space missions such as JAXA’s Hayabusa2 and NASA’s OSIRIS-REx have both visited asteroids that may have been significantly affected by the presence of water (Lauretta et al., 2017; Watanabe et al., 2017).

The purpose of this paper is to review the mineralogy, petrology, geochemistry, and oxygen isotope characteristics of type 1 material recorded in the literature in meteorites, micrometeorites, and xenolith material, and to discuss the importance of type 1 material in terms of number of asteroids and potential contributions to the Earth and other bodies. Recent studies and analysis of new meteorite falls have continued to highlight the diversity of type 1 material (e.g., Bischoff et al., 2021; Goodrich et al., 2021; Joy et al., 2020). Being petrographically rather featureless, the classification of type 1 material can be more challenging than for other petrological grades. We focus here solely on pure “type 1” material rather than transitional type 1–2 samples that still contain at least some anhydrous chondrules, such as the ungrouped and widely studied Tagish Lake meteorite (Zolensky et al., 2002) and the recent fall Tarda (King et al., 2021; Marrocchi et al., 2021).

EXAMPLES OF TYPE 1 MATERIALS

Meteorites

Type 1 meteorites are rare among our meteorite collections, with less than 2% of CCs being ascribed to this type (41 of 2697 known CCs as of July 2021, see Fig. 1). In hand specimen, they typically appear black or very dark with a fine-grained and very friable texture. Type 1 meteorites lack chondrules or calcium-aluminum-rich inclusions (CAIs), although in some samples, geochemical signatures and relict shapes of these objects remain as pseudomorphs (e.g., Weisberg & Huber, 2007). Textural clues are the most important keys to classifying type 1 material. Usually, chemical data and oxygen isotope measurements are also required to definitively classify type 1 material, for example, the presence of Mg-rich phyllosilicates. There are currently four established groups of type 1 meteorites in our collections: CI, CM, CY, and CR, as well as ungrouped type 1 meteorites described below.

CI

The CI (Ivuna-like) meteorite group nominally comprises five meteorite falls: Orgueil (fell in France...
1864, 14 kg total known weight), Alais (fell 1806, 6 kg total known weight), Ivuna (fell in Tanzania 1938, 705 g total known weight; see Fig. 2), Tonk (fell in India in 1911, 7.7 g total known weight), and Revelstoke (fell in Canada in 1965, 1 g total known weight). The Meteoritical Bulletin lists a further four CI meteorites that were found in the Yamato Mountains in Antarctica: Y-86029, Y-86737, Y-980134, and Y-980115. Of these, Y-86029 and Y-980115 have been reclassified as CY meteorites (King et al., 2019) and Y-86737 and Y-980134 are small and have not been examined in detail.

The CI chondrites are a relatively well-studied group, consisting solely of petrologic type 1 meteorites and often considered the archetypal type 1 material; indeed, the terms CI and Cl are often wrongly used synonymously in the literature. These meteorites have a bulk chemical composition similar to the solar photosphere and are considered to be the most chemically primitive of all meteorite groups being notably rich in volatile elements (e.g., King et al., 2019; Lodders, 2003). Indeed, several recent models have suggested that the chemical and isotopic composition of all meteorites can be explained by the mixing of a small number of components, of which bulk CI chondrite is one (e.g., Alexander, 2019; Bryson & Brennecka, 2021), a testimony to the primordial chemistry of this group.

In hand specimen, CI chondrites exhibit a dark and typically featureless interior except for terrestrially formed flecks of white sulfate (Fig. 2; Gounelle & Zolensky, 2003). CIs are typically highly brecciated on an ~100 μm scale (Alfin et al., 2019; Morlok et al., 2006), so heterogeneity is always an issue with sampling of these meteorites. They are friable and porous meteorites, with porosity of around 35% and a density of only 2.4 g cm⁻³ (Macke et al., 2011). They show little evidence of shock, although impact-produced agglutinates and glassy beads have been reported in Orgueil (Zolensky et al., 2015).

CI chondrite mineralogy is dominated by a fine-grained phyllosilicate composed of intergrown serpentine ([Mg, Fe]₃Si₂O₅(OH)₄) and saponite (Ca₀.₂₅[Si, Al]₃[(Si, Al)₄O₁₀]⋅n[H₂O]; Brearley, 1992; Tomeoka & Buseck, 1988; Figs. 3 and 4). Embedded in this matrix are abundant frambooidal magnetite (Kerridge et al., 1979), sulfides (Bullock et al., 2005), and various carbonates (Fig. 3). Carbonates are dominated by dolomite, although calcite, breunnerite, and siderite are also present (Endress & Bischoff, 1996; Lee & Nicholson, 2009). The most common sulfide is pyrrhotite, with a hexagonal or prismatic morphology, although pentlandite ([Fe, Ni]₉S₈) and cubanite (CuFe₂S₃) are also found (Bullock et al., 2005). The mineral abundances in the three best-studied CIs (Alais, Orgueil, and Ivuna) are similar to each other: 81–84% phyllosilicates, 4–7% sulfides, 6–10% magnetite, and a few percent carbonate and olivine. Orgueil and Alais also have a few percent of ferrihydrite but Ivuna does not (King et al., 2015). Anhydrous silicates are rarely preserved but when present appear as small irregular-shaped anhedral grains (e.g., Leshin et al., 1997). Magnetite abundance is higher than in any other meteorite group, although some ungrouped water-rich meteorites can have similarly high abundance, for example, Bells, Essebi, and WIS 91600 (Howard et al., 2015), Tagish Lake (Blinova et al., 2014), and Tarda (King et al., 2021), as do some CO chondrites (Rubin & Li, 2019).

Much of what we consider to be typical CI characteristics are based on Orgueil, Alais, and Ivuna alone. Tonk has a similar mineralogy to the other CIs but with an apparently lower abundance of sulfides and carbonates (Endress & Spettle, et al., 1994). The smallest CI chondrite, Revelstoke, is made up only of 1 g of disaggregated material and has not been studied in detail by modern methods. It is composed of phyllosilicate, magnetite, and sulfides (including ~20 μm grains of pentlandite; Folinsbee et al., 1967). The phyllosilicate phase most closely matches serpentine (Folinsbee et al., 1967), hinting that it may be better considered as a CM1 or Flensburg-type meteorite rather than CI, in which case the number of bona fide CI meteorites is only four. The oxygen isotope composition of CI meteorites lies close to the terrestrial fractionation line in a three-isotope plot (Fig. 5), with a Δ¹⁷O of +0.38 ± 0.09‰ and δ¹⁸O ranging...
The H abundance in CIs is ~1.5 wt%, corresponding to ~20 wt% H$_2$O, higher than for any other meteorite group (Alexander et al., 2012). However, recent studies suggested that despite being falls, CIs are easily contaminated with terrestrial water and have a lower indigenous water content of ~1 wt% H that is more similar to CM meteorites (Patzek et al., 2019). Nitrogen abundances are 0.15–0.20 wt% with $\delta^{15}$N $\approx +40\%_o$ (Alexander et al., 2012). The light
element characteristics of CI chondrites suggest that they accreted the same isotope composition of water as CM and CO meteorites, but different to the CR chondrites (Alexander et al., 2012).

The mineralogy of CI chondrites suggests that they have been entirely formed under conditions of high W/R ratios and at temperatures of ~150 °C (Zolensky et al., 1989). Oxygen isotopes suggest slightly lower temperatures of alteration, 50–150 °C (Leshin et al., 1997). Water-to-rock ratio estimates for the CI chondrites are poorly resolved but generally are >0.6 (Breatley, 2006; Clayton & Mayeda, 1999; Pravdivtseva et al., 2018; Zolotov, 2012), in relative terms higher than any other CC group (Fig. 6). There is a clear need for O-isotope analyses of carbonates in CIs to determine alteration conditions in the same way as the recent advances for CMs (e.g., Guo & Eiler, 2007; Vacher et al., 2019).

Reflectance spectra of CI1 chondrites are extremely dark with week absorption bands due to magnetite and phyllosilicates (Bates, King, Donaldson Hanna, Bowles, & Russell, 2020; Cloutis et al., 2011). The 3 μm “water” band is narrow and centered at ~2.71 μm (Takir et al., 2019).

**CM**

The CM (Mighei-like) chondrites are the largest meteorite group that has experienced pervasive aqueous alteration; the vast majority of CM meteorites, >90%, are petrological type 2. Twenty-seven CM chondrites have been classified as CM1 in the Meteoritical Bulletin, and thus, this group contains more type 1 meteorites than the other groups added together. In addition, a further 26 meteorites are classified as type 1–2. Like CI chondrites, CMs have a bulk composition close to that of the solar photosphere, but slightly less volatile-rich; they are 1.2x enriched in refractory lithophile elements compared to CI abundances, and 0.63x depleted in volatile elements compared to CI values (Bland et al., 2005; Braukmüller et al., 2018).

CM chondrites are black to dark gray rocks that can often have small inclusions and chondrules visible to the naked eye. CM1s typically have a dull black interior often exhibiting white crystalline flecks. Texturally these meteorites are composed entirely of matrix, though pseudomorphic chondrule and CAI textures are often observed (e.g., Zolensky et al., 1997) (Fig. 3). Many CM meteorites are brecias, and some brecciated examples such as Boroskino contain CM1 clasts (e.g., Vacher et al., 2018). While several CM1 clasts have been found within CM2 falls (e.g., Boroskino, Mukundpura), to date there have been no unambiguous CM1 chondrite falls; they are all finds from hot or cold deserts. Currently, the most altered CM fall is Kolang (CM2.2), which landed in Indonesia in 2020 (King et al., 2021), and also contains CM1 clasts (Schrader et al., 2021). The new Winchcombe CM2 fall is also very highly aqueously altered, containing CM1/2 and CM1 lithologies (Gattacceca et al., 2021). CM1 meteorites can be either friable or brittle. The CM1 meteorite Moapa Valley has a foliation suggestive of gentle shock (Irving et al., 2009).

The CM1s are composed of phyllosilicates (84–91 vol%), with minor olivine (4–8 vol%), magnetite (2–3 vol%), variable amounts of sulfide (<5 vol%), and carbonate (<2 vol%; Howard et al., 2015; King et al., 2017; Lee et al., 2014). CM1 meteorites have a higher magnetite abundance and lower calcite abundance than CM2 meteorites (King et al., 2017). Phyllosilicate compositions cluster around the serpentine solid solution (Fig. 4), including both Mg-serpentine (Mg₃Si₂O₅[OH]₄) and cronstedtite (Fe₂⁺Fe³⁺₂[Si, Fe³⁺₉O₅][OH]₄). Unlike CM2 meteorites, Mg-serpentine is more abundant than Fe-cronstedtite, and tochilinite is rarer in CM1s (King et al., 2017).

The oxygen isotope composition of CM1s is similar to that of CM2s although they plot at the ¹⁸O-rich end of the CM range suggesting that they were affected by the same water reservoir at a similar W/R ratio (Fig. 6), but their increased alteration may be due to higher temperatures of water interaction (King et al., 2018; Suttle et al., 2021; Vacher et al., 2019; Zolensky et al., 1997). In addition, the ¹⁸O-rich composition could also

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Fig. 4. Phyllosilicate compositions of selected type 1 materials. Also plotted are serpentine composition (variety antigorite) and smectite (variety saponite). Most type 1 phyllosilicates plot between serpentine and saponite compositions; to values more Mg-rich than their type 2 counterparts. Data from King et al. (2019), Harju & Rubin (2013), Goodrich et al. (2021), Bischoff et al. (2021), MacPherson et al. (2009), Greshake et al. (2019), Harju and Rubin (2013), Goodrich et al. (2021), and Sakamoto et al. (2010). (Color figure can be viewed at wileyonlinelibrary.com.)
partly reflect terrestrial alteration as all of these meteorites are finds (King et al., 2018). The H abundance of CM1 meteorites is around 1.0–1.4 wt% ($\delta D \sim -200$‰), carbon abundance $\sim$1.2–1.4 wt% ($\delta^{13}C \sim -10$‰), and nitrogen abundance $\sim$0.07 wt% ($\delta^{15}N \sim -5$‰), measured from MET 01070, SCO 06043, and the potentially heated LAP 02277 (Alexander et al., 2012).

The paucity of tochilinite and the lower abundance of carbonates in CM1 meteorites suggest a relatively high temperature of alteration compared to CM2 meteorites, $>120$ °C and possibly much higher ($>300$ °C), to remove tochilinite (King et al., 2017; Zolensky et al., 1997; Telus et al. (2019) report similar temperatures of alteration between CM2 and CM1 based on oxygen isotopes in carbonate, in which case the more extensive alteration of CM1 compared to CM2 may be due to more effective circulation of water or longer duration of alteration conditions.

The visible and infrared spectral characteristics of CM1 meteorites have been investigated by Bates, King, Donaldson Hanna, Bowles, and Russell (2020), who found that the 3 µm, Christiansen, and transparency features are all shifted to shorter wavelengths relative to the CM2s consistent with mineralogical changes due to increased alteration.

**CR**

The CR (Renazzo-like) meteorite group consists of 189 meteorites, of which almost all are type 2, although examples of higher petrological type also exist (CR3-CR7: Rubin & Li, 2019). Many of these may be paired and so this does not represent this many unique falls (e.g., there are 52 CR meteorites from Elephant Moraine in Antarctica, not all of which are distinct falls). The highest petrologic type CRs are not necessarily genetically related to the lower petrologic types (e.g., Gardner Vandy et al., 2012). One meteorite, Grosvenor Mountain (GRO) 95577, has been classified as the only type 1 CR meteorite (Weisberg & Huber, 2007).

GRO 95577 has a bulk chemical composition that is enriched in refractory Al and Sc compared to CI and CR, and is more similar to CM chondrites. Moderately volatile element abundances are depleted, most closely resembling CM levels. Chalcophile elements show an unusual uniform 0.6xCI depletion that is not volatile dependent (Weisberg & Huber, 2007). The meteorite contains large (~2 mm) pseudochondrules that are a similar size to those of other CR chondrites, but differ from others in this group as they have been entirely aqueously altered. Chondrule textures are well preserved but have been fully replaced by serpentine-rich phyllosilicates, magnetite, and sulfides (Weisberg & Huber, 2007; Fig. 3). Howard et al. (2015) give mineral abundances for GRO 95577 of 67 vol% phyllosilicate, 7 vol% olivine+pyroxene, 10 vol% oxides, 9 vol% Fe sulfide, and 6 vol% calcite.

GRO 95577 is linked to the CR group by its oxygen isotope composition, which plots along the same line as other CRs but at heavier $\delta^{17}$O and $\delta^{18}$O values (Clayton & Mayeda, 1999; Harju et al., 2014; Schrader et al., 2011, 2014). It has a high H content (1.2 wt%) and its hydrogen is isotopically heavier than other type 1 meteorites ($\delta D = 266.4 \pm 4.5$‰). GRO 95577 has a C abundance of 1.1 wt% and N abundance of 0.6 wt%; somewhat lower than for CM1 meteorites (all light element data from Alexander et al., 2012).
The CR chondrites were altered by hydrothermal fluids at temperatures originally estimated to be >250 °C based on carbonate compositions (Weisberg et al., 1993) or around 300 °C based on oxygen isotope fractionation between magnetite and phyllosilicates (Clayton & Mayeda, 1977). More recent studies have argued for a lower temperature of alteration of 55–88 °C based on oxygen isotopes in secondary carbonates and magnetite (Jilly-Rehak et al., 2018) and <90 °C based on experimental alteration studies (Le Guillou et al., 2015).

The overall reflectance spectrum of GRO 95577 is low, with weak phyllosilicate features at ~1.1 and ~2.35 µm (Cloutis et al., 2012; Garenne et al., 2016). Unlike for other CR chondrites, Cloutis et al. (2012) also identified a possible feature at ~0.7 µm. The position and shape of the 3 µm band and features in the mid-IR for GRO 95577 are similar to those for highly altered CM and CI chondrites (Beck et al., 2014; Cloutis et al., 2012; Garenne et al., 2016).

**CY**

The CY (Yamato-like) meteorite group was first suggested by Ikeda (1992) to describe three unusual meteorites then recently recovered from the Yamato and Belgica regions of Antarctica: Y-82162, Y-86720, and B-7904. Subsequently, several other similar meteorites have been described, leading King et al. (2019) to reinforce the suggestion that these meteorites are sufficiently distinct that it is appropriate to consider them as their own group of currently 11 potential members (Suttle, Greshake, et al., 2020). They have a bulk chemical composition that is intermediate between that of CM and CI meteorites (Paul & Lipschutz, 1990). They have fractionated REE patterns and depletions in thermally mobile trace elements (e.g., Ce, Ag, Cd, etc.) that are interpreted as due to mobilization by thermal processing (Tonui et al., 2002, 2014).

CY meteorites are very dark black stones in hand specimen and are much less friable than other type 1 meteorites. They are dominated (~70 vol%) by a dehydrated amorphous phyllosilicate phase (originally a mixture of serpentine and Na-bearing smectite) and poorly crystalline secondary olivine having experienced short-lived, post-hydration thermal metamorphism at temperatures >500 °C (King et al., 2019; Suttle, Greshake, et al., 2020; Tomeoka et al., 1989). The CYs are also distinct from other type 1 materials in having a very high abundance of sulfides (10–30 vol%; King et al., 2015; Fig. 3) which present almost exclusively as low Ni-troilite. While some sulfides in the CYs likely formed during the heating event that destroyed the phyllosilicate phase, perhaps by the decomposition of tochilinite and subsequent reaction of liberated S₂ gas with Fe-Ni metal and Fe-oxides, the remainder of the sulfide component likely formed as a primary phase (Schrader et al., 2021; Suttle, Greshake, et al., 2020).

Other accessory phases in CYs are carbonates, magnetite, phosphates and, in type 1 CYs (e.g., Y-82162, Y-86029 and Y-980115), periclase (King et al., 2019). In some CY chondrites, chondrules composed of anhydrous silicates are present, and this group clearly spans the petrological grades 1–2 based on the presence or absence of chondrules.

The average oxygen isotope composition of CY chondrites (Clayton & Mayeda, 1999; Mayeda et al., 1987) is heavier than for any other chondrite group with average values of δ¹⁸O ~12‰ and δ¹⁷O ~22‰ (Fig. 5). Light element systematics have been measured for CY chondrite Y-980115; it has a H content of 0.7 wt%, δD = −100‰ (lower than CI chondrites but...
higher than CM chondrites) and a C content of ~3 wt %, which is at the top end of the range for CM chondrites and less than for CI chondrites (Vacher et al., 2019).

The aqueous alteration of CYs is assumed to be at temperatures of less than 200 °C (King et al., 2019). The inferred presence of former tochilinite-cronstedtite intergrowths (TCI) in Dhofar 1988 implies that this meteorite experienced similar alteration conditions to the CMs, at least during the early stages of hydration (Suttle, Greshake, et al., 2020). However, the dehydrated amorphous phyllosilicate phase and poorly crystalline secondary olivine provide good evidence that all CY meteorites experienced short-lived, post-hydration thermal metamorphism at temperatures >500 °C. This heating has caused the original phyllosilicates to become completely desiccated (King et al., 2019; Nakamura, 2005) and the Fe/S of sulfide to increase (Schrader et al., 2021).

The near-infrared reflectance spectra of CY chondrites are very dark, while in the mid-infrared, they are easily distinguishable from CI and CM chondrite spectra (Bates et al., 2021). They exhibit a plateau around the Christiansen feature and show features at longer wavelengths in the Si-O bending region that may be due to dehydrated phyllosilicates. The 3 μm water feature shifts to longer wavelengths with increasing peak metamorphic temperature (Bates et al., 2021).

Flensburg

Flensburg is a unique 24.5 g stone that fell on September 12, 2019 in Flensburg, Germany, and has been described in a comprehensive paper by Bischoff et al. (2021), from which the following description is entirely derived. It has a bulk chemical composition similar to that of CM meteorites, but with depletions in the (moderately) volatile elements Zn, Cu, and Pb.

In hand specimen, a black fusion crust partially covers a greenish brown interior; the stone has a density of only 2 g cm$^{-3}$. Flensburg is not as clearly brecciated as CI chondrites, but the presence of lithic clasts and a single chondritic-textured clast provide evidence for soft-impact brecciation of clasts into the still fluid-rich parent body (Bischoff et al., 2021).

Analyzed quickly after its fall, it was found to be predominantly composed of a fine-grained phyllosilicate (serpentine) matrix that makes up 91.5 ± 4.4 vol% of the meteorite. It also contains abundant magnetite, a diverse array of carbonates (including calcite, Mn-bearing dolomite, and a Na-rich phase), and 3–4 vol% sulfides. Tochilinite was not observed. The meteorite contains pseudochondrules that are often surrounded by multiple pyrrhotite laths, perhaps originally armored chondrules later altered to sulfide by fluids. Pseudochondrules make up 20% of the section and have an average size of 170 μm, distinctly smaller than CM chondrules (average 270 μm, Rubin & Wasson, 1986). Magnetite in Flensburg is unusually rich in SiO$_2$ and distinct from that in other chondrite groups.

The oxygen isotope composition of Flensburg lies at the $^{16}$O-end of the CM field (Bischoff et al., 2021), but this meteorite is distinct from CMs because of its chondrule size, bulk composition, and high abundance of carbonates and magnetite. Flensburg contains 1.10 wt% H, corresponding to around 10 wt% H$_2$O and formed at a lower W/R ratio than the CM meteorites (Bischoff et al., 2021; Fig. 6). Its $\delta D$ of $-311 \pm 4 wt\%$ is lower than any other type 1 or 2 chondrite; it has a carbon abundance of just over 1 wt% and a low nitrogen abundance of 0.03 wt% (Bischoff et al., 2021).

Aqueous alteration conditions are inferred to have started at low W/R ratios and under similar conditions to CM chondrites but the temperature then increased to >200 °C, releasing more Fe- and S-rich fluids that crystallized as pyrrhotite and magnetite (Bischoff et al., 2021).

The spectral properties of Flensburg resemble those of CI meteorites, but with three features between 10 and 12 μm that are not present in Alais and Orgueil. Like other water-rich CCs, it exhibits a sharp trough at 2.7 μm and shows features related to the presence of organic material (Bischoff et al., 2021).

Miller Range (MIL) 090292 is a small (8.9 g) ungrouped CI chondrite found in Antarctica in 2009, with a brown/black fusion crust and black interior. The meteorite contains large, 1 cm-sized relict chondrules that have been completely replaced by aqueous alteration products, while sulfides are also present alongside altered metal and rare magnesian olivine and pyroxene. Primary metal grains have been almost entirely altered to oxides and sulfides (Harju et al., 2014); the presence of magnetite-bearing chondrule pseudomorphs suggests that metal-rich chondrules were originally present (Jilly-Rehak et al., 2018). MIL 090292 was originally classified as a CR1 meteorite (Harju & Rubin, 2013) and has a bulk oxygen isotope composition within the CR field (Schrader et al., 2014); however, an oxygen isotope composition of magnetite that differs from other CR chondrites, combined with the presence of cubanite, led to the suggestion that it is anomalous (Jilly-Rehak et al., 2018).

The presence of Ni-rich metal and the lack of carbonates suggests a different alteration regime to that of CR chondrites, such as a lower pH, higher Si activity, or higher temperatures (Jilly-Rehak et al., 2018).

Lunar Meteorite

Bench Crater is a millimeter-sized CC meteorite found within the Apollo 12037 soil sample brought back
to Earth by the Apollo 12 astronauts in 1970 (McSween, 1976). Since it is listed as a meteorite in the Meteoritical Bulletin, we describe it in this section. McSween (1976) noted that Mg/Si is higher and Fe/Si is lower than other chondrite groups, and it is strongly enriched in P and S compared to other meteorites. It has a weak petrofabric caused by a preferred fracture orientation (Joy et al., 2020). The groundmass is mainly saponite (Zolensky, 1997). Lath-shaped sulfides, including pyrrhotite and pentlandite, are common and co-occur with rare chalcopyrite grains, often decorating pseudochondrules (Joy et al., 2020). It also contains abundant framboidal chalcopyrite grains, often decorating pseudochondrules among both small (<100 µm) and large (>300 µm) apatite grains (Joy et al., 2020). The abundance of hydrogen and carbon is low overall (McSween, 1976). The oxygen isotope composition of silicates from pseudochondrules lies between the fields of CM and CI chondrites with an average $\delta^{18}O$ of 0.12 ± 0.45‰ (Joy et al., 2020 and Fig. 5). Joy et al. (2020) concluded that Bench Crater is unique among CCs known in our collections.

Micrometeorites

The flux of extraterrestrial material arriving on Earth is dominated by micrometeorites; submillimeter-sized grains of cosmic dust that survive atmospheric entry to become deposited and preserved in terrestrial sediments (Folco & Cordier, 2015; Genge et al., 2008). They account for approximately 2000 times more extraterrestrial material by mass than meteorites (Engrand & Maurette, 1998; Love & Brownlee, 1993; Suttle & Folco, 2020; Zolensky et al., 2006) and therefore provide a unique perspective on the diversity of geological materials present in the asteroid belt.

Owing to the effects of atmospheric entry, most micrometeorites melt completely, forming molten droplets (termed cosmic spherules, Genge et al., 2008). This extreme thermal processing makes inferring their initial texture and mineralogy challenging (e.g., Goderis et al., 2020). However, the small fraction of particles that survive unmelted (<10%, Kurat et al., 1994) is dominated (>75%, Taylor et al., 2012) by fine-grained precursors with affinities to hydrated CCs (Cordier & Folco, 2014; Kurat et al., 1994; Taylor et al., 2012).

“CI-like” micrometeorites were first reported by Kurat et al. (1992) who studied small (50–100 µm-sized) particles from the Cap Prud’homme collection (derived by melting Antarctic blue-ice). These CI-like particles are characterized by abundant magnetite embedded in smectite-rich phyllosilicates (Kurat et al., 1992). Kurat et al. (1992) estimated that CI-like particles account for just 6% of the unmelted micrometeorites. Such low relative abundances occur despite the CI lithology being the most thermally resilient type of micrometeorite and thus most likely to preferentially survive atmospheric entry unmelted (Suttle et al., 2017). Furthermore, the abundance of CI-like micrometeorites decreases dramatically as particle size increases, with only a handful of CI-like particles with sizes >200 µm having been reported (Dionnet et al., 2020; Van Ginneken et al., 2012). By contrast, fine-grained micrometeorites with affinities to CR1 and CM1 chondrites occur abundantly among both small (<100 µm) and large (>300 µm) size fractions (Kurat et al., 1994; Suttle, Folco, et al., 2019; Taylor et al., 2012).

Engrand and Maurette (1998) concluded that although most unmelted micrometeorites are petrographically similar to CR and CM chondrites, their apparent lack of chondrules and higher C/O ratios imply that micrometeorites originate from different parent bodies from their larger meteorite counterparts. Conversely, Suttle, Folco, et al. (2019) argued that the lack of chondrules implies that most micrometeorites come from intensely aqueously altered (petrologic type 1) asteroids—this necessarily includes both established chondrite groups (CI, CY, CM, and CR) as well as otherwise unsampled parent bodies.

Increasingly, research attention has been directed toward micrometeorites that have no equivalent in our meteorite collections, including newly reported type 1 materials. Battandier et al. (2018) found that the organic component of aqueously altered micrometeorites is distinct from that of type 1 and type 2 meteorites. Furthermore, these differences are not attributable to alteration during atmospheric entry but rather point to an origin on separate parent bodies. Sakamoto et al. (2010) reported a collection of water-rich micrometeorites that entirely lack anhydrous silicates. They have higher saponite/serpentine ratios than CI chondrites and also contain Mg-rich carbonates, Ni-bearing pyrrhotite, and carbonaceous nanoglobules; overall, their mineralogy bears some similarities to the Tagish Lake meteorite but are not a direct match. More recently, Suttle, Dionnet, et al. (2020) reported two fine-grained micrometeorites (TAM19B-7 and TAM50-25) that are petrographically similar to CR1 or CM1 chondrites but whose bulk O-isotope compositions do not match any meteorite group. They have $^{16}$O-poor signatures (Fig. 5 $\delta^{18}O$: +1.1‰, $\delta^{17}O$: +1.1‰ and $\delta^{17}O$: +15.4‰, $\delta^{18}O$: +28.1‰, respectively) and small pseudomorphic chondrules (~160 µm). Their O-isotopic composition suggests a relationship either to the CY chondrites (Ikeda, 1992; King et al., 2019; Suttle, Greshake, et al., 2020) or to a poorly characterized population of melted cosmic spherules referred to as the “Group 4” class and previously reported by Yada et al. (2005), Engrand et al. (2005), Suavet et al. (2010), and others. The oxygen isotope composition of magnetite
measured in five Cl fine-grained micrometeorites also suggests that they sample fluid of a distinct composition to that of known carbonaceous and ordinary chondrites, further supporting the suggestion that they are from different parent bodies (Dobrica et al., 2019).

**Interplanetary Dust Particles**

In addition to micrometeorites that are collected from the Earth’s surface, even smaller extraterrestrial dust grains (typically <50 μm in size) have been collected from the stratosphere by high-altitude aircraft (Sandford, 1987; Warren & Zolensky, 1994). Chondritic interplanetary dust particles (IDPs) can be either hydrous or anhydrous and they also expand the range of known extraterrestrial material (Bradley, 2007; Mackinnon & Rietmeijer, 1987). Around 70% of hydrous IDPs are smectite-rich and resemble Cl meteorites, and others are serpentine-rich and resemble CM meteorite matrix (Thomas et al., 1990). However, IDPs are not a perfect match for either meteorite group (Mackinnon & Rietmeijer, 1987; Tomeoka & Buseck, 1985) and appear to have altered from glass and pyroxene (Zolensky & Lindstrom, 1992). Oxygen isotopes in hydrated IDPs were measured by Aléon et al. (2009) and span the composition of CM, CI, and CY meteorites, although some data points lie lighter values, similar to magnetite separated from CI chondrites (Rowe et al., 1994) (Fig. 5). For such small particles, the isotope spread may in part be due to unrepresentative sampling.

**Xenoliths in Meteorites**

Type 1 materials are commonly reported as xenolithic fragments in other meteorites, including other CCs and achondrites such as howardites and ureilites (e.g., Gounelle et al., 2003; Patzek et al., 2018, 2019; Zolensky et al., 2009). The xenoliths were likely incorporated very early in solar system history and so give us an idea of the composition of interplanetary dust at that time, in contrast to Antarctic micrometeorites, which represent a relatively modern flux; released from their parent bodies <2 million years ago (Rochette et al., 2008). Incorporation into achondrites is of particular interest because this can provide insights about mixing in the protoplanetary disk of outer solar system CC material with inner solar system noncarbonaceous (NC) material (Goodrich et al., 2021; Patzek et al., 2019). Because they are fossilized examples of transport between early planetary bodies, such materials can test models describing the formation of Jupiter and the movement of the giant planets by the Grand Tack (Walsh et al., 2012) and Nice Model (Gomes et al., 2005). Studies of xenoliths have proved a powerful tool to monitor mixing between diverse solar system bodies (e.g., Nittler et al., 2019).

**Carbonaceous Chondrites**

There are numerous reports of type 1 and related materials present as xenoliths within CCs of other petrological types (e.g., Goodrich et al., 2021; Gounelle et al., 2003; Vacher et al., 2019). The CM2 meteorites often contain clasts of type 1 (typically CM1) material. Notable examples include the Boriskino CM2 meteorite, which contains cm-sized rounded clasts of various petrological types including CM1 (Vacher et al., 2018). The brecciated CM2 chondrite LON 94101 contains clasts of CI material, including highly unusual lithologies, one containing 46 vol% carbonate, and one containing ~mm-sized laths of pyrrhotite, suggesting heterogeneous fluid compositions (Lindgren et al., 2013). The CM2 meteorite Aguas Zarcas is a breccia containing type 1 material composed of phyllosilicates, magnetite, sulfides, and carbonates (Kerraouch et al., 2021); the phyllosilicate composition is similar to that of inclusion 91A in Almahatta Sitta (see “Ureilites” section below; Goodrich, Zolensky, Kohl, et al., 2019). The CR chondrites contain dark inclusions (~8 area %; Klemme, 1994) that record variable degrees of alteration and which can resemble CI-like clasts (Weisberg et al., 1993), although the oxygen isotope composition of these clasts falls closer to CM chondrites (Endress, Keil, Bischoff, et al., 1994; Endress, Spettel, et al., 1994). The CH and CB meteorites often contain clasts of hydrated carbonaceous material, composed of phyllosilicates (serpentine + saponite), carbonates, sulfides, and magnetite, with no anhydrous silicates (Greshake et al., 2002). For example, the CH/CB meteorite Isheyevo contains three distinct types of clasts of which one (“Group 1”) is entirely hydrated, consisting of phyllosilicates, carbonates, sulfides, and magnetite. These clasts resemble Cl chondrites but differ in their mineral chemistry; phyllosilicates cluster around serpentine compositions and in Isheyevo clasts; dolomite is more Fe-rich and less corroded than in Cls (Bonal et al., 2010). Such clasts in CH/CB meteorites contain presolar silicate grains at an abundance (4–22 parts per million) lower than for pristine meteorites and IDPs, suggesting aqueous alteration similar to CM2 and CR2 meteorites. Presolar SiC concentrations in the clasts lie between 9 and 23 ppm, and are comparable to the values for CI, CM, and CR chondrites (Leitner et al., 2018).

Other CCs (e.g., CV and CO) can also contain dark inclusions (e.g., Fruland et al., 1978; Itoh & Tomeoka, 2003). These consist almost entirely of secondary minerals such as Fe-rich olivine, pyroxene, and sulfides formed during hydration followed by dehydration (e.g., Krot et al., 1995, 2002). Since the phyllosilicate texture evident in type 1 materials is absent in such inclusions, we do not consider them further here.
Ordinary Chondrites

Although rarer than in CCs and in howardites (see below), there are many examples of ordinary chondritic material hosting water-bearing type 1 and type 2 clasts (e.g., Briani et al., 2012; Patzek et al., 2018). The H-chondrite-brecciated falls Zag, Monahans (1998), Tsukuba, and Carancas contain type 1 clasts that are very similar to each other (Nakashima et al., 2003; Zolensky et al., 2016). Briani et al. (2011) reported clasts with similar mineralogy to these in a variety of H chondrites. These clasts are composed of phyllosilicates (a mixture of serpentine and saponite), phosphates, carbonates, magnetite, pyrrhotite, organic material, halite, and minor olivine. An oxygen isotope study of an organic-rich clast from Zag is heavier than any known material, halite, and minor olivine. An oxygen isotope study of phyllosilicates (a mixture of serpentine and saponite), phosphates, carbonates, magnetite, pyrrhotite, organic material, halite, and minor olivine. An oxygen isotope study of an organic-rich clast from Zag is heavier than any known meteorites, but similar to some IDP/micrometeorite analyses (Kebukawa et al., 2019; Fig. 5). Zolensky et al. (2016) suggest that halite-bearing clasts may originate from the asteroid Ceres. The presence of still-hydrated clasts demonstrates that they were implanted into their ordinary chondrite parent asteroids after metamorphism had taken place.

Rumuruti Chondrites

The R3-6 meteorite NWA 6828 hosts an angular fragment of a type 1 material, composed of phyllosilicates (serpentine and saponite), magnetite, pyrrhotite, carbonate, and rare olivine. Although this clast most closely resembles CI meteorites out of all the known groups, it has a more Fe-rich phyllosilicate composition, and Ca-carbonate is present almost exclusively as veins. Therefore, this clast is unlike any sampled meteorite (Greshake, 2014).

Vestan Meteorites (Howardites, Eucrites, and Diogenites)

Xenolithic carbonaceous clasts have been reported in several Vesta-derived meteorites. In addition, NASA’s Dawn mission showed that carbonaceous material is currently present in the craters of Vesta itself (Reddy et al., 2012). The xenoliths are most common in regolith howardite meteorites. Most of these clasts are composed of CM2 material, although CR2 material is also present (Brearley, 1993; Gounelle et al., 2003; Patzek et al., 2018; Zolensky et al., 1997). Less abundant type 1 clasts have been identified that are rich in sulfide and magnetite and typically have similar δD-signatures to CI chondrites, implying they are related (Patzek et al., 2019). Liu et al. (2020) reported an unusually high abundance of type 1 material in a single thin section of the Kapaeta howardite meteorite; they conclude that the clasts are from a single ice-bearing asteroid or comet from the outer solar system.

Ureilites

Polymict ureilites can contain abundant xenolithic clasts and type 1 material is not uncommon. Prinz et al. (1987) first reported carbonaceous matrix-like clasts in polymict ureilite Nilpena. Brearley and Prinz (1992) reported that these inclusions are CI-like in composition, albeit with a lower degree of alteration compared to Orgueil. The polymict ureilite NWA 10657 also contains several type 1 and type 2 clasts with a wide variety of mineralogies and oxygen isotope compositions (Goodrich, Zolensky, Kohl, et al., 2019). Two unusual lithologies from the Almahata Sitta ureilite are reported to be CI (Goodrich, Zolensky, Fioretti, et al., 2019). AhS91/91A and 671 are breccias, consisting of phyllosilicates, carbonates (breunnerite and dolomite), magnetite, fayalite, ilmenite, phosphates, and sulfides. These lithologies also contain isolated grains from ureilites (Goodrich, Zolensky, Fioretti, et al., 2019). Their oxygen isotope composition has higher Δ17O than CCs (Fig. 5), and their Cr isotope composition is unlike any meteorite type (Yin et al., 2018). Magnetite in type 1 lithologies in ureilites typically plots above the terrestrial fractionation line at Δ17O = +2−5% (Goodrich, Zolensky, Fioretti, et al., 2019). Hamilton et al. (2020) recently reported a rare amphibole-bearing clast from the ureilite Almahatta Sitta, indicating a formation in a large asteroid capable of sustaining fluid-assisted metamorphism at intermediate pressures and temperatures.

The D/H of carbonaceous clasts in ureilites has been measured by Patzek et al. (2019). They report that CI-like clasts are typically isotopically heavy with respect to D/H, with δD of up to 3000‰, suggesting that although they are mineralogically similar to CI, they have different starting materials.

Kaidun

Kaidun is a unique brecciated meteorite of enstatite and carbonaceous clasts (Ivanov et al., 1984). The carbonaceous clasts are very diverse; the matrix is composed of a CR2 material, but clasts include CI, and a unique type 1 lithology with similarities to CM material composed of phyllosilicates, needle-shaped pyrrhotite, and melaneite garnet, attesting to alteration at very high (450 °C) temperatures (Zolensky, Ivanov, et al., 1996). MacPherson et al. (2009) reported that Kaidun contains a huge diversity in clasts, many of which are type 1. They include CI, CM, and CR clasts but blur the boundaries between these groups by having intermediate oxygen isotope and chemical compositions. The unique nature of Kaidun and its characteristics led Zolensky and Ivanov (2003) to suggest it may have come from Phobos, a body likely to have accumulated a variety of asteroidal material on its surface.

DISCUSSION

Abundance of Type 1 Material and Reasons for Underrepresentation as Meteorites

The common occurrence of type 1 fragments as xenoliths in meteorites or described from micrometeorite
collections suggests that this material is wildly underrepresented in our meteorite collections compared to their apparent astronomical abundance. Their diversity in terms of mineralogy, isotopic characteristics, and alteration conditions suggests that W/R interactions were widespread in the solar system and occurred in a wide variety of environments and to rocks with very different starting compositions.

The current meteorite population is believed to represent between 95 and 148 parent bodies (Greenwood et al., 2020). While type 1 material was historically only thought to be represented by CI chondrites (van Schmus & Wood, 1967; Wasson, 1974), the meteorites reviewed above showed that at least six type 1 parent bodies are represented (CI, CM, CR, CY, MIL 090292, and Flensburg). Adding parent bodies sampled by micrometeorites and xenoliths in meteorites accounts for many more.

The bias against type 1 materials despite their assumed high number of parent bodies could have three main causes. First, there may be a bias in material hitting the Earth’s atmosphere compared to that which exists in the region of the asteroid belt. The asteroidal fragments that land on Earth will preferentially be from parent bodies that originate in the main orbital resonance regions of the asteroid belt, and for this reason, the middle and outer belt are likely to be undersampled (Burbine, 2014). Water-rich type 1 material is likely to originate beyond Jupiter and is therefore most likely to reside in the outer asteroid belt. C/D-type asteroids that are assumed to be water-bearing are more common in this outer belt (DeMeo & Carry, 2014). There is scant information in the literature about the original orbits of type 1 meteorites; only two type 1 meteorites have a determined pre-terrestrial trajectory. Orgueil had an orbit compatible with being from a Jupiter family comet (Gounelle et al., 2006) whereas Flensburg originated closer in, at a heliocentric distance of 2.82 AU, around the 5:2 resonance with Jupiter (Borovička et al., 2021). Despite this, type 1 and type 2 materials have been suggested to dominate the meteoroid flux (Zolensky, Ivanov, et al., 1996). The second and perhaps major cause of the discrepancy is the friability of type 1 material that likely causes it to break up easily during passage through the Earth’s atmosphere and upon impact with the ground. Zolensky et al. (2020) recently reported that highly aqueously altered CM materials all have short cosmic ray exposure ages, implying shorter survivability as meteoroids; however, Krietsch et al. (2021) do not find this relationship. Hypervelocity impact studies have demonstrated that phyllosilicate-rich hydrated CCs preferentially produce an overabundance of fine-grained debris (<100 μm) when disrupted (e.g., Flynn et al., 2009, 2020). Consequently, many of the recovered type 1 meteorites are sadly very small (Tonk, Revelstoke, and MIL 090292 are all below 10 g and Flensburg is only 25 g). Furthermore, an abundance of volatile gases aids fragmentation during atmospheric entry (Suttle, Genge, et al., 2019). The porosity of CC material is relatively high, >20% (Consolmagno et al., 2008) and phyllosilicate material, which cleaves easily along its sheet structure, is delicate. Type 1 materials can be notoriously crumbly and friable and likely to break apart on impact with the Earth.

In addition, fallen type 1 material is difficult to recognize as meteoritic, even for very experienced meteorite hunters, and so there is a likelihood that C1 finds are less likely to be recovered during systematic searches than metal- and chondrule-bearing meteorites. Indeed, George Prior, who produced the first formal classification scheme for meteorites (Prior, 1920), admitted that on first setting eyes on the CI1 Alais meteorite “Thought this spec. was a bit of the soil picked up in mistake and nearly threw it away; looked up information and found it to be bona fide and therefore of special interest” (handwritten lab notes in the NHM archive).

Despite its underrepresentation in our meteorite collection, type 1 material is significantly more common among the micrometeorite flux (Genge et al., 2008; Taylor et al., 2012) attesting to both the abundance of C1 parent bodies within the asteroid belt and implying that large fragments of C1 chondrite are preferentially broken down into fine-grained debris during liberation from their parent body. The presence of “fossil micrometeorites” trapped in HED achondritic meteorites (Gounelle et al., 2003) likewise suggests that hydrated C1 and C2 dust was plentiful during the early solar system.

### Oxygen Isotopes

The measurement of all three stable isotopes of oxygen has long been used to make genetic associations between meteorite groups (Clayton et al., 1973; Clayton & Mayeda, 1999). Since non-mass-dependent stable isotope mass fractionations are complex to achieve on planetary bodies, oxygen isotopes can be used to differentiate between different parent bodies (e.g., Ireland et al., 2020). Meteorite groups plot in distinct regions on a triple oxygen isotope plot (Fig. 5), indicating that they originate in separate parent bodies.

However, in samples that have experienced the action of water, the interpretation of oxygen isotope compositions is more complex. Many studies have concluded that water in the early solar system contributing to our meteorite collection had a higher Δ17O compared to solids (Piralla et al., 2020; Verdier-Paoletti et al., 2017; Yurimoto et al. 2008; and others),
with a $\delta^{17}\text{O}$ and $\delta^{18}\text{O}$ possibly around 50‰ (Fujiya, 2018) or perhaps as high as +180‰ (Sakamoto et al., 2007). Magnetite, a common mineral in type 1 materials, forms by the oxidation of Fe by water and can provide specific constraints (i.e., lower limit of $\Delta^{17}\text{O}$) of the fluid involved in the alteration of asteroidal material (e.g., Telus et al., 2019). Carbonates can also provide an estimate of the water composition (e.g., Vacher et al., 2016) but have been less studied in type 1 materials.

Therefore, the oxygen isotope composition of an aqueously altered meteorite is a function not only of the starting composition of the solid but also of W/R ratio and the degree to which oxygen from water has contributed to mineral formation. In addition, at lower temperatures, mass fractionation during mineral reactions may become significant. Reaction of water with minerals will cause the mineral product to move toward heavier isotopic compositions and the fluid to become lighter by equilibrium mass fractionation (e.g., Nabalek, 1987; Schrader et al., 2011; Yurimoto et al., 2008). Finally, dehydration after alteration may also cause further mass fractionation (Clayton & Mayeda, 1999; Ivanova et al., 2013).

The oxygen isotope composition of various type 1 materials from the literature is shown in Fig. 5. The data show an overall trend from lighter isotopic values to heavier ones, but do not fit on a single line. Instead, they trend up along the carbonaceous chondrite anhydrous mineral (CCAM) line to a $\Delta^{17}\text{O}$ of $\sim+2.3\%_{\text{o}}$, and then fall along a rough mass fractionation trend with $\Delta^{17}\text{O}$ between 0 and 2.3‰ and a slope of roughly 0.5.

Modeling of open-system fluid interaction with anhydrous CC demonstrated that the resulting rock compositions when plotted on a triple isotope diagram would appear smeared out along a line with a slope intermediate between the mass fractionation slope of 0.52 and the slope 1 mixing line between fluid and solid (Young et al., 1999). Our data can be explained by such a model. This implies that (1) the interactions between rock and fluid occurred during heating causing fluid flow from the center to the surface of the body; (2) many parent bodies are not required to explain the oxygen isotope compositions—although it is highly likely that many similar bodies were involved in providing both fossil and modern type 1 material, the number cannot be specifically constrained by the oxygen isotopic data; (3) the parent bodies of type 1 material likely had similarities to each other in starting materials and fluid processes in general, though different in detail.

Finally, the thermal heating seen in CY meteorites may have caused mass fractionation of oxygen isotopes to heavier values. Clayton and Mayeda (1999) suggested that CY meteorites may have been derived from CI meteorites from such a process. Ivanova et al. (2013), working on analog material, found that isotopic fractionation to higher $\delta^{18}\text{O}$ compositions occurred during dehydration and Lindgren et al. (2020) reported similar effects. However, Clayton and Mayeda (1999) artificially heated CI and CM meteorites and found both heavier and lighter compositions were produced. The effects of heating on oxygen isotope composition need further research.

**Geological History of Type 1 Material**

The key criterion for classification of type 1 material is that it has been completely altered by fluids, primarily water. Type 1 material likely accreted beyond the water-ice line (often referred to as the “snowline”) as a mixture of anhydrous silicates, ices, and amorphous material; the dominant alteration processes acting to hydrate silicates and oxides occurred on the parent body (e.g., Brearley, 2006). Ices were likely dominated by water-ice, but carbon dioxide ice may also have been important (Fujiya et al., 2019). Heating by the decay of $^{26}\text{Al}$ and other short-lived nuclides, along with impact heating, caused the water to melt and chemical reactions to take place to form clays and phyllosilicates, carbonates, sulfides, and magnetite. The conditions under which these took place vary between samples, with values between $\sim-50\text{ C}$ for CI (Leshin et al., 1997) and 450 $\text{ C}$ for a clast in Kaidun (Zolensky, Ivanov, et al., 1996).

After the aqueous alteration took place, most parent bodies were disrupted by impacts and reaccreted into secondary parent bodies with brecciated textures (Greenwood et al., 2020). In addition, some samples (e.g., the CYs) experienced post-aqueous alteration heating that dehydrated and recrystallized the phyllosilicate minerals. The heating was likely short-lived and caused by parent body breakup, further impact processing, or perihelion passage close to the Sun (Chaumard et al., 2012; King et al., 2019).

The composition of the fluid was variable; it could be sometimes S-rich (e.g., in the case of Flensburg and the CY chondrites) to produce abundant secondary sulfides. The fluids likely also contained cations and volatiles such as CO$_2$ in variable abundances, to produce differing amounts of carbonate. Ammonia was also a significant fluid in some CC parent bodies (e.g., Pizzarello & Williams, 2012; Schrader et al., 2011) and has been observed on the surface of the CC-like dwarf planet Ceres (McSween et al., 2018).

Rocks that have been heavily aqueously altered are also typically brecciated materials (Bischoff et al., 2021; Lindgren et al., 2013; Morlok et al., 2006; Vacher et al., 2018), pointing to a fundamental and universal process in solar system processing. Type 1 CM chondrites tend
to have strong petrofabrics, perhaps because impacts created fracture networks that facilitated fluid movement (Lindgren et al., 2015; Rubin, 2012). The abundance of xenolithic clasts in multiple classes of meteorites is a testament to the exchange and disorder in the early solar system. Many primary planetesimals were likely destroyed and provided foodstock for later generations of small bodies. Greenwood et al. (2020) go as far as to suggest that primary asteroids were entirely destroyed to form the secondary bodies that we observe today. Meteoritic breccias such as the type 1 chondrites are the result of rapidly formed asteroids that were later incorporated into secondary bodies (Bischoff et al., 2021). In CI1 chondrites, for example, clasts have distinct chemical differences to each other suggesting they formed from discrete and chemically different precursors (Morlok et al., 2006). Almost all heavily aqueously altered meteorites are also breccias composed of clasts of different degrees of alteration (e.g., Bischoff, 1998; Lindgren et al., 2013).

Parent Bodies

Linking meteorites to their parent body has been a key challenge in meteoritics (Burbine et al., 2002; Wasson, 1974). Some progress has been made in recent years; for example, the Hayabusa mission proved that LL chondrite material is likely sourced from S-type asteroids such as Itokawa (Nakamura et al., 2011). Discovering the parent bodies of CCs is more difficult, although they are generally thought to come from low-albedo C-type and related asteroids (e.g., Burbine, 2014). The OSIRIS-REx and Hayabusa2 missions are anticipated to help in providing links between distant small bodies and lab-studied meteorites (Lauretta et al., 2017; Watanabe et al., 2017).

Warren (2011) noted that CCs are isotopically distinct from almost all other sampled solar system material, leading to the suggestion that they may have originated in the outer solar system, beyond Jupiter (Kruijer et al., 2020). A study of the trajectory of the Orgueil meteorite fall determined from contemporary eyewitness reports led Gounelle et al. (2006) to suggest that this meteorite, and by implication all CI1 meteorites, originate from comets. They determined that aphelion distance for Orgueil was larger than 5.2 AU, the semimajor axis of Jupiter orbit, suggesting that Orgueil’s parent body may have been a Jupiter family (JFCs) or even a Halley-type comet (Gounelle et al., 2006). The presence of cubanite in CIs (Bullock et al., 2005) and also in samples returned from Wild 2 by the Stardust mission (Berger et al., 2011) also links these together. Similarly, the link between meteor showers and known cometary dust streams has made it easy for scientists to relate micrometeorites and IDPs with cometary material. Nesvorný et al. (2010) conclude that around 85% of micrometeorites are likely to originate in JFCs.

Since then, it has become clearer that there is a continuum between asteroidal and cometary materials (e.g., Hsieh, 2017). So-called “transition objects” are a population of small bodies that have many of the properties of comets, such as high volatile abundances and ejection of material from their surfaces, while being placed within the classical asteroid belt. These objects include dormant and extinct comets and active asteroids, including the so-called Main Belt comets (Hsieh & Jewitt, 2006). One of the big surprises from the NASA OSIRIS-REx mission was to find that asteroid Bennu is an active asteroid, ejecting material randomly from its surface (Lauretta et al., 2019). However, it is unclear, and perhaps unlikely, that these ejections are exactly equivalent to the outflows of cometary material.

The NASA Dawn mission to the largest asteroid in the Main Belt, Ceres, showed that this dwarf planet has been heavily aqueously altered. It has a surface composition dominated by Mg-rich and ammoniated phyllosilicates, carbonates, as well as a material that darkens the spectral features, perhaps organics, sulfides, and/or magnetite (De Sanctis et al., 2015). McSween et al. (2018) show that these features most closely resemble highly altered (i.e., type 1) CM and CI meteorites.

Comets have nuclei composed of dust and ice. The COSIMA instrument on board ESA’s Rosetta spacecraft recorded the composition of dust grains from the comet; they are approximately chondritic in composition but even more volatile enriched; they have Na/Mg higher than CI chondrites (Schulz et al., 2015). D/H ratios of comets are highly variable and span the ranges observed for CCs (the organics in comets cannot be easily compared to those in meteorites as measurement techniques, e.g., Rosetta are biased toward more volatile organic components, whereas these are less likely to survive in meteorites; Grady et al., 2018). Comets have been considered frozen relicts of early solar system components, unaffected by fluid or other processing. However, the reflectance spectra of some comets (e.g., 1P/Halley, 9P/Tempel, and Hale-Bopp) suggest the presence of phyllosilicates, carbonates, or other secondary phases (e.g., Cu-sulfides, amphibole, and magnetite), implying the once-presence of liquid water (e.g., Lisse et al., 2006). The source of heating to allow ice to become fluid could have been perihelion passage close to the Sun (Suttle, Folco, et al., 2020). In addition, the initial $^{26}$Al/$^{27}$Al in the solar system was evenly distributed across the protoplanetary disk such that all small bodies should have been significantly heated if they formed within a few million years of the beginning of solar system history (Gregory et al., 2020; Prioulk & Podolak, 1995). It seems
likely that some Kuiper belt objects may have generated enough heat by short-lived isotope decay to form liquid water and therefore water–rock interactions (Choi et al., 2002).

Ubiquitous aqueous alteration in comets was ruled out, however, by the return of cometary material from the NASA Stardust mission. The returned samples showed that JFC Wild 2 is composed of grains in some ways similar to chondritic material. The only silicates isolated were anhydrous minerals, with oxygen isotope compositions compatible with CC components (Brownlee et al., 2006). Wild 2 samples are notably not type 1 material, since no phyllosilicates have been detected (Zolensky et al., 2008). The collection mechanism can explain the absence of fragile minerals to some extent, but evidence for phyllosilicates and carbonates would probably have been found if they had been present (Woziakiewicz et al., 2015).

The above discussion implies that comets are at least as complex and diverse as we know the asteroid population to be from our studies of meteorites. In all probability, some comets were heated to produce aqueous alteration reactions (Suttle, Folco, et al., 2020), ultimately forming type 1 material in extreme cases, whereas in other comets (like Wild 2), a lack of heat ensured that the silicate minerals remained pristine. Along with primitive asteroids, comets and intermediate objects, like D-type asteroids, are a likely source of type 1 material, especially the fine-grained components resulting in micrometeorites (Noguchi et al., 2002; Nozaki et al., 2001; Sakamoto et al., 2010). D-type asteroids are spectrally similar to the unusual type 2 meteorites Tagish Lake and WIS-91600, and D-type Jupiter Trojans are similar to CY meteorite spectra (Bates, King, Donaldson-Hanna, Bowles, Lim, et al., 2020), pointing to some links between these objects and our meteorite collections.

The formation of type 1 material requires both the initial presence of ices and also a mechanism for heating to enable melting of water and mineral interactions between fluid and mineral to take place. Tagish Lake, likely from an outer solar system body (e.g., Bryson et al., 2020; Fujiiya et al., 2019), is not a type 1 sample. Therefore, simple distance from the Sun is not an effective predictor of the degree of aqueous alteration. While ice-rich bodies are particularly abundant in the outer solar system, inner solar system objects have higher impact rates and therefore increased probability of reaching hotter temperatures. Ceres may combine both requirements for initial water and heat to produce highly aqueous altered rocks (McSween et al., 2018) despite being today an inner solar system body. Indeed, larger bodies may produce type 1 materials more efficiently than smaller ones because of their increased ability to maintain heat from radioactive decay (e.g., Fujiiya et al., 2019) and to allow for the efficient circulation of water (McSween et al., 2018).

Space missions, including sample return missions, will shed more light on this issue. To date, three sample return missions have collected regolith material from primitive asteroids. Hayabusa returned material from asteroid Itokawa in 2010, Hayabusa2 returned to Earth from Ryugu on December 6, 2020, and OSIRIS-REx will return from Bennu in 2023. Spectral features from Ryugu and Bennu suggest that they have been affected by aqueous alteration (Hamilton et al., 2019; Kitazato et al., 2019; Lauretta et al., 2017; Watanabe et al., 2017) and will enable us to better understand the link between aqueously altered meteorites and their parent bodies. JAXA’s proposed DESTINY+ mission will explore the unusual asteroid 3200 Phaethon (parent body of the Geminid meteor shower; Williams & Wu, 1993). Phaethon is an active asteroid; however, it appears to not have hydrated minerals on its surface (Takir et al., 2020). The NASA Lucy mission will explore the Jupiter Trojan asteroids, and JAXA’s MMX (Mars Moon eXplorer) mission will visit the mysterious Martian moon Phobos to determine whether this body is comprised of primordial solar system materials, or if it formed later in solar system history. Such missions and observations will enable us to learn more about comets and asteroids, the continuum between the two, and whether these objects may be parents to type 1 material recovered on Earth. The recent discovery of interstellar objects with similarities to active asteroids (e.g., ‘Oumuamua; Meech et al., 2017) poses an intriguing idea that these interlopers may also contribute type 1 material to our solar system.

Classification of C1 Materials

Many researchers historically assumed that each chemical group represents one asteroidal parent body (e.g., Clayton & Mayeda, 1999). More recently, there has been a growing consensus that, given the large number of observable asteroids, many of which with similarities in spectral properties, it is more likely that each meteorite group comes from a family of asteroids (e.g., Greenwood et al., 2020). Given the huge numbers and great diversity of small bodies, we now know to be present in the solar system (DeMeo et al., 2015), and probably even greater number in the early solar system (Burbine et al., 2002), combined with complex brecciation and evidence for multiple generations in many meteorites, it is unlikely that all meteorites from a single group originate from one asteroid. Instead, each group likely represents a family of minor bodies with similar starting materials. The classification of meteorites, and especially the very
cosmically abundant water-rich meteorites, links together stones that are mineralogically and isotopically similar without requiring them to be from the same parent asteroid/comet. There is a huge range of actual compositions and textures of which we can sample only a small and biased fraction.

According to Wasson (1974), “The purpose of classification is to group together related objects in order to facilitate comparative investigations. A classification should consist of as few categories as possible without forcing together objects for which the evidence of relationship is inadequate.” As seen in “Examples of Type 1 Materials” section above, there are four clear meteorite groups of type 1 material, plus two known ungrouped meteorites, and many more if meteorites transitional between the type 1 and type 2 classes along with micrometeorites and xenolithic clasts are included (Figs. 3–5). Given the range of mineralogy and petrology as well as the span of oxygen isotope composition, creating further groups is not justified. Many type 1 objects can be sorted into a “CM clan,” with mineralogy dominated by serpentines and an oxygen isotope composition that plots near the CCAM line in the 16O-rich region of the CM serpentines and an oxygen isotope composition that plots into a “CM clan,” with mineralogy dominated by phyllosilicates along with sulfides, carbonates, and magnetite. Although these samples all have in common their extreme degree of alteration, it is clear that the alteration did not occur under a single set of conditions. The temperatures of alteration were highly variable, from <100 to >450 °C. The fluid compositions likewise varied, with both Bench Crater and Flensburg having abundant acicular sulfides suggesting the presence of an S-rich fluid, although they had different starting materials. The timeframe of alteration, though typically not well constrained, is also an important variable. Studies of carbonates in CI and CM meteorites suggest carbonates formed on both around 5 million years after the formation of the solar system (Endress et al., 1996; Endress & Bischoff, 1996; Fujiya et al., 2019), whereas breunnerites may have formed several million years later (Petitat et al., 2009). Assigning a petrological type of a single digit number appears a blunt instrument to describe the asteroidal history of a meteoritic sample when such diversity of alteration conditions exists.

While type 1 material was likely a source of water and other volatiles to the terrestrial planets, the diversity of this material and the lack of representation in our meteorites collection mean that we cannot currently place well-resolved constraints on the bulk composition and stable isotope systematics of these important contributors to the Earth.

CONCLUSIONS

Type 1 materials typically have a mineralogy dominated by phyllosilicates along with sulfides, carbonates, and magnetite. Although type 1 meteorites are very rare in our collections, their abundance among the micrometeorite flux and as xenoliths in a wide range of meteorite groups points to them being significantly underrepresented compared to their cosmic abundance. Classification of type 1 material is complicated by their
complex geological history involving extensive fluid alteration and sometimes also heating causing dehydration. A paucity of chondrule and CAI-like features and possible effects of mixing and fractionation on their oxygen isotope compositions and isotope systematics of other elements also makes interpretation challenging. The field would benefit from a more systematic analysis of the type 1 material from different sources, to include H, N, and O isotope measurements along with mineralogical studies and bulk chemical analyses. Further oxygen isotopic analyses on carbonates, for example, on CI1s, would help better resolve their alteration conditions. However, we can tentatively suggest that as well as in four main meteorite groups (CI, CM, CR, and CY), we can see many type 1 materials that are unique. This in turn points to a multiplicity of parent bodies, which are likely a combination of primitive asteroids and Main Belt comets, pointing to a continuum between the two objects and a wide variety of geological history on these bodies. The sample return missions Hayabusa2 and OSIRIS-REx will teach us much more about the origin and evolution of hydrated primitive solar system material as will future missions such as DESTINY+, Lucy, and MMX.

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