The astrophysical context of collision processes in meteorites

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Abstract

Chondrites are leftover solids from the early evolution of the solar protoplanetary disk that never experienced melting since their formation. They comprise unequilibrated assemblages of low- and high-temperature components, including volatile-rich, fine-grained matrices, Fe-Ni metal, [sulfides](#), refractory inclusions, and chondrules. Consequently, chondrites are commonly described as *pristine*, *primitive*, or *primordial* rocks of the solar system. However, impact-generated secondary features are abundant in chondrites, suggesting that collisions among early-formed planetesimals and their fragmentation and reassembly have been effective throughout the evolution of the solar system. In this report, we review evidence of the major role of impacts in generating the current mineralogical and petrographic characteristics of chondrites. We provide perspective to these meteoritic features by discussing recent analyses of large-scale structures of the main asteroid belt and remote-sensing observations of asteroids. Observations at various spatial scales all attest [that](#) the 'primitive' materials formed during the evolution of the solar system have largely been

reprocessed, confirming previous studies that primitivity is relative, not absolute. This implies that (i) chondrites (and some differentiated meteorites) should systematically be envisioned as reprocessed and heterogeneous materials and (ii) brecciated meteorites should be considered the norm and unbrecciated meteorites the exception.

Keywords: chondrites, clasts, brecciation, asteroids, impacts

1- Introduction

Meteorites are asteroidal (or rarely cometary; Gounelle et al. 2006) fragments recovered at the Earth's surface either promptly after their falls (e.g., Hiroi et al., 2001; Jenniskens et al. 2012; Marrocchi et al. 2020) or during field trips to cold/hot deserts (e.g., Bischoff and Geiger 1995; Evatt et al. 2020; Gattacceca et al. 2011; Harvey 2003; Schlüter et al. 2002). Meteorites' parent bodies are leftovers from the planetary formation processes that operated during the evolution of the solar system. Differentiated parent bodies recorded processes such as metal-silicate differentiation, early volcanism, [granite-like magmatism](#) and magma ocean episodes (e.g., Bischoff et al. 2014; [Terada and Bischoff, 2009](#)). In contrast, chondritic parent bodies did not experience melting and comprise high-temperature components formed in the solar protoplanetary disk (SPD) before planetesimal accretion, namely refractory inclusions (Ca-Al-rich inclusions, CAIs, and amoeboid olivine aggregates, AOAs; e.g., Marrocchi et al. 2019a) and chondrules (e.g., Connolly and Jones 2016). Chondrites thus represent invaluable witnesses of the SPD's evolution because they are made of components that formed at different times and locations in the SPD (Bollard et al. 2019; Connelly et al. 2012; Kawasaki et al. 2019; MacPherson et al. 2012; Pape et al. 2019; Petit et al. 2011; Villeneuve et al. 2009).

However, most chondrites experienced subsequent thermal and hydrothermal alteration during asteroidal evolution, which blurred their initial textures, mineralogies, and chemical and isotopic compositions (Amsellem et al. 2020; Brearley 2006; Fujiya et al. 2015; Huss et al. 2006; Marrocchi et al. 2018a, 2021; Turner et al. 2021; Vacher et al. 2017, 2019a, 2019b, 2020). Based on these modifications, chondrites are assigned petrologic types on a scale from 1 to 6, reflecting the progressive roles of low-temperature aqueous alteration (from type 3 to 1) and thermal metamorphism (from type 3 to 6; van Schmus and Wood, 1967).

Type-3 chondrites thus correspond to materials that underwent minimal modifications after their agglomeration. Despite having suffered hydrothermal alteration of varying intensity, high-temperature components in type-2 chondrites are thought to preserve evidence of the conditions of dust formation in the SPD (e.g., Chaumard et al. 2018; Kööp et al. 2016; Marrocchi et al. 2018b, 2019b; Piani et al., 2021). Consequently, these peculiar chondrites are commonly described as *pristine*, *primitive*, or *primordial* rocks of the solar system (Gounelle 2011; Libourel et al. 2017).

In addition to secondary alteration processes, hypervelocity impacts are of fundamental importance and played a key role in the early solar system and during its evolution (Bischoff et al., 2021; Raymond and Morbidelli 2020), yet have often been overlooked or treated in unrelated contexts (e.g., Lauretta and McSween 2006). The classical model of planetary formation involves three main steps, all entailing collisional processes. In the first, dust particles experience low-velocity collisions while migrating toward the disk's midplane, thus forming fractal aggregates that subsequently form pebbles through collision-induced compaction (Blum and Wurm 2008; Johansen et al. 2007). The second step is characterized by the collision-induced coagulation of planetesimals, which forms massive planetary embryos and cores (Morbidelli et al. 2016). In the third step, gravitational instabilities induce collisions between planetary embryos, forming terrestrial planets on a time scale of 10^7 – 10^8 years (Raymond and Morbidelli 2020; Raymond et al. 2009). Furthermore, the Moon, whose presence next to the Earth has shaped its evolution, is the result of a giant impact within the first 100 million years of the formation of CAIs (Canup 2012; Canup and Asphaug 2001). Fundamentally, all steps of planetary formation involve collisional processes, implying that they played a key role in shaping the present architecture of the solar system and that they are not an epiphenomenon that can be treated independently of other processes.

Collisions have occurred continually through the present and are now the main factor driving the evolution of the asteroid belt, planetary and moon surfaces, and the formation and sustainability of Saturn's rings (Crida and Charnoz 2012). This is exemplified by the complex structures of boulders on near-Earth asteroids (101955) Bennu and (162173) Ryugu, as recently revealed by high-spatial-resolution images obtained by NASA's and JAXA's sample return missions OSIRIS-REx and Hayabusa2, respectively (DellaGiustina et al. 2019; Jaumann et al. 2019; Lauretta et al. 2019a, 2019b; Sugita et al. 2019). In particular, the discovery of craters in the surfaces of Bennu's boulders revealed the effects of meteoroid impacts on this asteroid, which occurred only in the last 1.75 Myr (Ballouz et al. 2020). Furthermore, recent analyses of the main asteroid belt have revealed that only a very limited number of the asteroids that we catalogue today have survived intact from primordial times (Delbo et al. 2017), whereas the large majority of asteroids are fragments (Dermott et al. 2018) that experienced disruption of their parent bodies and re-accumulation (Michel 2001; Michel and Richardson 2013; Michel et al. 2020). In this report, we thus aim to (i) detail the astrophysical context of collisional processes in meteorites and (ii) put recent astrophysical and planetological observations in a chondritic perspective.

2- Meteoritic evidence of widespread collision processes in the asteroid belt

Asteroidal collisions represent a major evolutionary process for solid bodies in the solar system and have played a key role in establishing chondritic features, even in the putative 'primitive' type-2 and -3 chondrites. This is attested by the ubiquitous occurrence of brecciated textures in meteorites, with ~30% of ordinary chondrites (OCs) and almost all CM carbonaceous chondrites showing brecciation features (Fig. 1A; Bischoff et al. 1998; 2006; Gattacceca et al. 2017; Lentfort et al., 2021; Suttle et al., 2021). Such characteristics are

fundamental because (i) OCs are by far the most common meteorites falling on Earth (~80%) and (ii) CMs represent 25% of all carbonaceous chondrite falls (Gounelle et al. 2005). Even rarer chondrite types like CI carbonaceous chondrites (Alfing et al. 2019), Rumuruti chondrites (Bischoff et al. 2011), C1 chondrites (Bischoff et al., 2021), CB/CH chondrites (Briani et al., 2009; Bonal et al., 2010), and enstatite chondrites (Fig. 1B; Piani et al., 2016, 2020) have brecciated textures, thus implying that all chondrite types have been reprocessed after the accretion of their respective parent bodies.

Different types of brecciation are commonly observed among meteorites, revealing that collision and re-agglomeration processes occurred at varying scales and intensities (Bischoff et al. 2006; Rubin 1983). *Monomict breccias* are the most common and correspond to meteorites formed by the *in situ* progressive fracturing and compaction of a single lithology at a scale much smaller than their asteroidal parent bodies. *Impact-melt breccias* (Fig. 1B) are rocks in which the matrix cementing the brecciated fragments crystallized from impact-generated melts. *Genomict breccias* define meteorites containing fragments of the same compositional group, but with different metamorphic or hydrothermal alteration histories (Fig. 2; Gattacceca et al. 2017; Vacher et al. 2018; Verdier-Paoletti et al. 2019; Stöffler et al., 2018); these textures reflect large-scale brecciation processes occurring within a given parent body. In contrast, *polymict breccias* define meteorites composed of fragments originating from different parent bodies (Fig. 3; Bischoff et al. 2006; Zolensky and Ivanov 2003); these are of fundamental importance as they (i) record asteroidal mixing processes and (ii) contain unique clasts not observed as individual samples (Patzek et al. 2018, 2020). The violent evolution of the solar system is also evidenced by commonly observed petrofabrics and/or flattened chondrules and refractory inclusions (Fig. 4; Gattacceca et al. 2005; Greashake 2014; Hanna et al. 2015; Rubin 2012; Vacher et al. 2018), which are generally interpreted to result from impact-induced preferential orientations.

Furthermore, all classes of meteorites contain xenolith clasts (Fig. 5)—characterized by different lithologies than their respective host rocks (e.g., Bischoff et al. 2006; Bonal et al. 2010; Briali et al. 2009, 2012; Liu et al. 2020; Patzek et al. 2020; Zolensky et al. 1996)—resulting from the low-velocity incorporation (i.e., $<1 \text{ km s}^{-1}$; Briali et al. 2011) of micrometeoroids by asteroidal parent bodies (Briali et al. 2011; Rubin and Bottke 2009). Such clasts differ from polymict breccias because they could have been incorporated into asteroids throughout the evolution of the solar system. The mixing of the host and xenoliths probably at low-velocity is also attested by the lack of thermal metamorphism between the clasts and their host meteorites (Fig. 6). Interestingly, the very few occurrences of CC clasts in OC chondrites could result from the fragile nature of carbonaceous materials relative to their OC counterparts. Taken together, brecciated textures, xenolith clasts, and petrofabrics thus all attest to the violent evolution of the solar system, both during the first ~5–10 Myr of the SPD's evolution and continuing today.

Finally, the presence of high-pressure minerals in most meteorite groups is strong evidence of pervasive impacts on their parent bodies. Indeed, most of these minerals have been found within or adjacent to dark shock veins. Following the discovery of ringwoodite—the spinel-structured polymorph of olivine—in Tenham, a large variety of shock-induced minerals have been discovered, including majorite, akimotoite (the ilmenite-structured polymorph of MgSiO_3), and plagioclase with the hollandite structure (Sharp and DeCarli, 2006). At present, high-pressure minerals are used to constrain the pressures, temperatures, and timescales of collision-induced shocks.

3- The chaotic origin of the main asteroid belt

The first step of asteroid formation occurred ~4.56 Ga when dust grains within the protoplanetary disk surrounding the Sun accreted to form rocky/icy planetesimals ~100 km in

diameter. These were the first solid objects in the solar system whose internal strengths were dominated by self-gravity (Johansen et al. 2007; Klahr and Schreiber 2020; Marcus 1967; Morbidelli and Raymond 2016; Safronov and Zvjagina 1969). Although these objects represent the main building blocks of terrestrial planets and the cores of giant planets, their formation conditions and initial size distribution remain a matter of debate (Klahr and Schreiber 2020). Classical models are based on the bottom-up progressive coagulation of small solids into planets via merging collisions. However, during the disk's evolution, such bottom-up planetesimal accretion is fundamentally limited by the 'meter-sized barrier': meter-sized planetesimals will experience (i) rapid drift toward the central star and associated evaporation and (ii) destruction during high-speed collisions (Wetherill 1990; Wurm et al. 2005). Recent models thus suggest that planetesimals were initially large (100–1,000 km) due to high concentrations of small solid particles in turbulent structures of the SPD (Cuzzi et al. 2008; Johansen et al. 2007; Morbidelli et al. 2009). Such models are in agreement with studies reconstructing the size distribution of planetesimals from analyses of the current asteroid population (Bottke et al. 2005; Delbo et al. 2017, 2019; Morbidelli et al. 2009; Tsirvoulis et al. 2018). However, most known asteroids are much smaller than planetesimals (Masiero et al. 2014), indicating that they are remnants produced by the collisional fragmentation of larger parent bodies, including planetesimals, throughout the history of the solar system. An investigation of the dynamical behavior of asteroids reached the same conclusion (Dermott et al. 2018). These results imply that (i) the current asteroid population is the result of a dramatic collisional evolution that must also be reflected in the physical and textural properties of meteorites and (ii) similar to meteorites, the current architecture of asteroid belt [cannot be considered](#) as a direct witness of the early solar system.

[Most of planetesimal collisions have occurred in the main asteroid belt, between the orbits of Mars and Jupiter \(heliocentric distances of ~2–3.2 AU\), where most known asteroids](#)

are currently located. Contrary to common perceptions, the main belt is mostly empty, containing only 5×10^{-4} Earth masses (i.e., ~4 % of the mass of the Moon), with asteroids spread over an annular area more than three times as wide as the distance between Mercury and Mars. In addition, about half of the main-belt mass is contained in the four largest asteroids: Ceres, Vesta, Pallas, and Hygiea (DeMeo and Carry 2014). The main belt is dynamically excited, with orbital eccentricities (e) up to 0.3 and inclinations (i) of 0 to $>20^\circ$, and is characterized by the presence of spectroscopically distinct asteroids that, in general, correspond to distinct compositions (Fig. 7; Bus and Binzel 2002a, 2002b; DeMeo and Carry 2014): C-type asteroids are water-rich and genetically linked to carbonaceous chondrites, whereas S-type asteroids are dry and related to OCs. The compositions of asteroids vary as a function of their orbital semimajor axis (a): S-type asteroids are more abundant in the inner and central main belt ($2.1 < a < 2.7$ AU) whereas C-type asteroids are more abundant in the outer regions ($2.7 < a < 3.2$ AU).

Since the discovery of the first asteroids in the early nineteenth century, the main belt was long considered to be a ‘living relic’ of planetary formation. Canonical planetary formation theories postulated that (i) asteroids remained at the heliocentric distances at which they formed (as for planetesimals; Gradie and Tedesco 1982) and (ii) the compositional gradient of the main belt reflects that of the SPD from the inner border of the protoplanetary disk (a few tenths of an AU from the Sun) out to Jupiter (Raymond et al. 2006). However, these views began to shift in the mid-2000s. First, it was proposed that iron-meteorite parent bodies could have formed in the region of terrestrial planets before being scattered to the main belt by gravitational interactions with the growing terrestrial protoplanets (Bottke et al. 2006). Second, dynamic models suggested that the D-type asteroids observed today in the main belt are not indigenous, but instead correspond to trans-Neptunian objects that were scattered into the main belt by the giant planets during their instability phase (Fujiya et al. 2019; Levison et

al. 2009; Marrocchi and Piani 2019; Morbidelli et al. 2010; Tsiganis et al. 2005). Following these pioneering works, main-belt asteroid implantation models were advanced using new dynamic models involving giant-planet formation and migration early in the solar system. These models were developed to address two principle stumbling blocks of the classical ‘static’ models: they systematically produce (i) Mars analogs as massive as the Earth, rather than about a tenth of the Earth’s mass, and (ii) eccentricity and inclination distributions of asteroids that do not match those of the current belt. Although important uncertainties remain, the following three recent models (Fig. 7) have successfully reproduced these peculiar characteristics and suggest that the entire main belt population of dynamically excited and radially mixed S- and C-type asteroids are not indigenous, but were implanted in their current locations between the terrestrial- and giant-planet regions.

(i) The “grand tack” model proposed that the inward and subsequent outward migrations of Jupiter and Saturn in the protoplanetary disk truncated the disk at 1 AU, limiting the material available for the formation of Mars (Fig. 7; Walsh et al. 2011). In this scenario, an initial population of planetesimals was expelled from the main belt by the inward migration of Jupiter, which plunged through the main belt. The main belt was subsequently repopulated by planetesimals during the outward migration of Jupiter (Walsh et al. 2011). In this scenario, planetesimals suffered mutual collisions at velocities $> 10 \text{ km s}^{-1}$ (Johnson et al. 2016).

(ii) The low-mass asteroid belt model preserves the concept of implanting planetesimals into the main belt from the terrestrial- (S-types) and giant-planet regions (C-types; Raymond and Izidoro 2017a, 2017b). However, contrary to other models such as the grand tack model, these authors showed that the main belt could have initially had a low mass (or could have even been empty) and that large-scale migrations of the giant planets are not required to

populate it with the current mixture of asteroid types (Fig. 7). In this model, C- and S-type asteroids were implanted not only from different sources but also at different times: C-type planetesimals that formed in the giant-planet region were scattered inward during the gas phase of the protoplanetary disk (i.e., within a few million years after the formation of CAIs; Raymond and Izidoro 2017a, 2017b), whereas S-type asteroids were implanted from the terrestrial-planet region into the main belt after the gas in the protoplanetary disk had dissipated (i.e., later than ~ 10 Myr after the formation of CAIs). The implantation of S-type asteroids was slower and more prolonged than that of C-type asteroids, possibly lasting 100 Myr (Raymond and Izidoro 2017b) because, in this model, S-type planetesimals must have been scattered via multiple close encounters with planetary embryos. In such models, Mars' small mass results from a primordial mass deficit between the present-day orbits of Earth and Jupiter (Hansen 2009).

(iii) **The early instability model** recently provided an alternative view in which the giant planets did not undergo large migrations during the gas phase (Fig. 7; Clement et al. 2018, 2019a, 2019b). In this model, as in the canonical scenario, a sea of planetesimals spanning the inner rim of the protoplanetary disk (out to Jupiter) was perturbed by an early orbital instability of the giant planets around 10 Myr after gas dispersal, which triggered the formation of the terrestrial planets. This instability also removed significant mass from the main-belt region and broadened the ranges of the eccentricities and inclinations of main-belt planetesimals to the current values, thereby starting the violent collisional evolution of these bodies.

Although the current orbital structure (semi-major axis, eccentricity, inclination) of the asteroid belt is consistent with an initially uniform distribution of asteroids (Minton and

Malhotra 2009), its self-excitation requires several orders of magnitude more mass than is present today (e.g., O'Brien and Sykes 2011). This implies that the belt experienced violent processes that considerably modified its initial structure. Whatever the process that dominantly shaped the asteroid belt, collisional processes were important and common during the early evolution of the solar system. Depending on the scenario invoked, the main belt reached its current dynamic configuration after tens to hundreds of millions of years (e.g., after giant-planet instability). Since then, collisions have continued to occur with typical impact velocities between asteroids of $\sim 5.3 \text{ km s}^{-1}$ (Bottke et al. 2005 and references therein), although the impact velocities define a broad distribution and collisions at higher-than-average speeds are not uncommon, particularly for objects with high i and/or e values. One such case is the [third-largest](#) asteroid (2) Pallas ($i = 34.8^\circ$, $e = 0.23$), for which impact velocities [are estimated to be \$\sim 12 \text{ km s}^{-1}\$ on average](#) (Marsset et al. 2020). Collisions at such speeds can yield temperatures high enough to induce the dehydration and thermal metamorphism of asteroidal materials, which should be observable in the meteorites that we may receive from these bodies (Amsellem et al. 2020 and references therein). This collisional evolution is responsible for the formation of the families of asteroid fragments (Nesvorny et al. 2015) that we observe in the main belt. The effects of these collisions, which can lead to the mixing of asteroidal materials of different compositions, is also visible in some physical properties of asteroids, as it is detailed in the next section.

4- Evidence for collisional processes from *in-situ* exploration of asteroids

[In situ](#) exploration by space missions and telescopic observations of asteroids provide growing evidence of the effects of impacts and the resulting material mixing produced by the infall of exogenic impacting objects.

The first evidence of the violent collisional evolution of asteroids is the presence of craters on their surfaces. This has been clear since NASA's Galileo mission, the first spacecraft to fly by an asteroid, which imaged (951) Gaspra in 1991 (Veverka et al. 1994) and showed that its surface is covered by impact craters (Stooke 1996). Since then, impact craters appear to be ubiquitous structures as they have been observed on all imaged asteroids. These craters range in size from the ~500-km-diameter Rheasilvia basin near the south pole of (4) Vesta (Schenk et al. 2012; Thomas et al. 1997) to decimeter-scale craters in boulders on the surface of the 500-m-diameter near-Earth asteroid (101955) Bennu (Ballouz et al. 2020). On Vesta, the deposition of the so-called 'dark material' that is often associated with craters has been attributed to impacts by carbonaceous asteroids (McCord et al. 2012). This dark material is then (i) diffused throughout the regolith of the surface of Vesta over time (McCord et al. 2012) and (ii) compressed by subsequent impacts on the surface and cemented together with original Vestan material (brighter in color) into breccia-like rocks. This process is in good agreement with the common presence of clasts of carbonaceous chondritic materials within Howardites (e.g., Fig. 5; Buchanan et al., 1993; Liu et al. 2020; McSween et al. 2011; van Drongelen et al., 2016), regolith breccia meteorites belonging to the HED group and originating from the surface of Vesta.

Because Vesta is a differentiated asteroid, it has been proposed that impacts could excavate its basaltic crust, revealing its underlying olivine mantle. However, very little olivine has been detected at Vesta's surface, even in and around the giant impact basins Rheasilvia and Venenia (Ammannito et al. 2013; De Sanctis et al. 2012). Therefore, the rare occurrences of olivine signatures on Vesta's surface may rather correspond to material implanted by olivine-rich impactors (Turrini et al. 2016). Indeed, laboratory impact experiments performed at velocities similar to the average impact velocity on Vesta demonstrated that impactor material could be preserved at Vesta's surface (Daly and Schultz 2016). Although the

survivability and implantation of impactor material is a function of impact velocity, laboratory hypervelocity impact experiments on porous and non-porous targets showed that impact-generated material implantation is a general process occurring throughout the solar system (Avdellidou et al. 2016, 2017). This implies that the mixing of asteroidal materials was possible not only during the early gas phase of the SPD when impact velocities were lower, but throughout the history of the solar system. Interestingly, high-speed collisions (i.e., 12 km s^{-1} ; Marsset et al. 2020) can also yield temperatures high enough to induce the dehydration and thermal metamorphism of asteroidal materials (Amsellem et al. 2020 and references therein).

Very recent observations at cm-scale spatial resolution of the surfaces of the near-Earth asteroids (101955) Bennu and (162173) Ryugu by NASA's OSIRIS-REx (Lauretta et al. 2019a, 2019b) and JAXA's Hayabusa2 (Okada et al. 2020; Tatsumi et al. 2021) sample return missions, respectively, provide a wealth of indications about the mixing of asteroidal materials and the presence of brecciated rocks on these asteroids. OSIRIS-REx spectroscopic and spectrophotometric observations revealed the presence of bright, pyroxene-rich boulders of Vesta-like composition on the dark, carbonaceous surface of Bennu (DellaGiustina et al. 2020). This suggests that some asteroids of the Vesta collisional family impacted Bennu, or more likely its parent body, mixing the two materials (DellaGiustina et al. 2020). This is also attested by the peculiar textures of some of Bennu's pyroxene-rich, hummocky boulders, which show potential layering or brecciation (DellaGiustina et al. 2020). Furthermore, two bright, pyroxene-bearing clasts appear embedded within a large, partially buried boulder, the latter having an albedo similar to the average of Bennu (DellaGiustina et al. 2020). Interestingly, the Hayabusa2 orbiter also detected bright material on the dark surface of Ryugu (Tatsumi et al. 2021), thus suggesting that brecciation is a common process during asteroidal evolution.

In contrast to Bennu, the spectral signatures of Ryugu indicate two distinct units of bright material. One appears to be more compatible with an S-type asteroidal composition (rather than a pyroxene-rich, Vesta-like nature; Tatsumi et al. 2021) that could have been delivered by an impact (or series of impacts) on Ryugu's parent body. The second unit has spectral features similar to the bulk of Ryugu, but with a less pronounced upturn at ultraviolet frequencies compared to the Ryugu average (Tatsumi et al. 2021). This unit may represent a more thermally metamorphosed material compared to that covering most of the surface of the asteroid (Tatsumi et al. 2021). It thus appears that Ryugu's surface comprises materials originating from various depths within its parent body. Such diverse materials may also be present on other similar asteroids, compacted together by small-scale impacts to form breccias.

OSIRIS-REx images of the surface of Bennu show diverse rocks including (i) boulders with albedo and/or color heterogeneities and (ii) non-fractured boulders containing meter-sized clasts (Lauretta et al. 2019a). Such assemblages have been interpreted as impact breccias (e.g., see Fig. 1b of Walsh et al. 2019). However, the collisional processes capable of producing breccia-like boulders several meters in size and containing meter-scale clasts are probably too energetic to be withstood by Bennu itself (Bischoff et al. 2006). Hence, these boulders probably formed on Bennu's parent body and may record (i) the parent body's accretion in the SPD (Walsh et al. 2019), (ii) compaction of regolith blocks on the parent body, or (iii) collisional events that fragmented the parent body to form Bennu. The surfaces of some boulders larger than ten meters in size also appear to be "littered" with brighter centimetric rocks that, in some cases, appear to be cemented together (Bennett et al. 2021). Although the origin of this material is unclear, it may result from (i) impacts on the boulders themselves (Bennett et al. 2021) or (ii) particles falling back onto the asteroid after particle-ejection events, such as were observed on Bennu (Lauretta et al., 2019b).

To summarize, the presence of clasts and exogenic components in Bennu and Ryugu imply that material-mixing *via* impacts is a common process on these bodies, and likely throughout the solar system. These observations also give context to what was once a breakthrough in asteroid and meteoritic science, namely the discovery of distinct meteorite classes within the strewn field of the Almahata-Sitta meteorites, which were produced by the atmospheric breakup of asteroid 2008 TC₃ (Bischoff et al. 2010; [Goodrich et al., 2015, 2019](#); [Horstmann and Bischoff, 2014](#); Jenniskens et al. 2009). Before the Almahata-Sitta recovery, the canonical concept was that one class of meteorite originates from one class of asteroid. These recent spacecraft observations have thus demonstrated that 2008 TC₃ is perhaps not an exception and that individual asteroids can host materials corresponding to diverse meteorite classes.

5- Implications and perspectives

Brecciated textures, xenolith clasts, and petrofabrics in meteorites attest to the chaotic evolution of the solar system, both during the first ~5–10 Myr of the evolution of the SPD and continuing until today. Given our knowledge of the structure of the asteroid belt and our theoretical understanding of the evolution of the solar system, this testifies that so-called *primitive materials* formed during the evolution of the SPD have been largely reprocessed, implying that primitivity is relative, not absolute (Bischoff et al. 2019; Gounelle 2011; Libourel et al. 2017). This is not greatly surprising as the spectra of ~20% of nearby solar-type stars of various ages show infrared peaks related to the presence of debris disks, low-mass (i.e., less than the mass of the Earth), low-density, dust-dominated disks that are continuously replenished by collisions between large planetesimals (Hughes et al. 2018). Debris disks are analogous to our solar system's Kuiper Belt and zodiacal light and are

fundamentally different from protoplanetary disks, which are dominated by agglomeration processes whereas debris disks are destruction-dominated. This implies that early-formed planetesimals (i) were largely reprocessed during the evolution of the solar system and (ii) experienced fragmentation and subsequent reassembly as asteroids observed today. Indeed, the astronomical survey of the asteroid belt suggests that only a few hundreds of asteroids have remained unchanged since their formation (Delbo et al. 2017), clearly indicating that solar system materials have been largely reprocessed *via* impacts. In addition, planetesimals that accreted during the two million years following CAI formation likely experienced melting due to ^{26}Al decay (Bizzarro et al. 2005; Hevey and Sanders 2006; Sahijpal et al. 2007), which, at least partially (i.e., primitive achondrites), erased their primordial features.

The complex evolution of asteroids is an ongoing process; recent reports suggest that impact-generated fluid circulations, probably triggered by hypervelocity impacts, have occurred within the past few hundreds of thousands of years (Amsellem et al. 2020; Turner et al. 2021). This is also highlighted by the ubiquitous presence of xenolith clasts in chondrites and achondrites (Bischoff et al. 2006; Bonal et al. 2010; Briani et al. 2009, 2012; Cohen et al., 2004; Liu et al. 2020; Patzek et al. 2018, 2020; Zolensky et al. 1996), which may have been incorporated into their current bodies by implantation processes and/or regolith gardening throughout the evolution of the solar system. Therefore, ‘primitive’ samples are probably extremely rare, and the concept of primitivity should only be used to relatively describe two or several objects, and always in terms of processes.

A direct consequence is the limitation of the so-called bulk composition of meteorites, as –depending on the scale sampled– the average composition could have been modified by various processes operating all along the solar system evolution. For example, although CI chondrites are commonly used as a reference for chemical normalization (Lodders 2003), CIs show brecciated structures and are significantly heterogeneous at a scale of just ~100 mg

(Morlok et al. 2006) or up to 1 g for elements sensitive to fluid circulation (Barrat et al. 2012). Therefore, virtually all chondrites (and some differentiated meteorites) should be viewed as reprocessed, heterogeneous materials, and analyses of their bulk chemical and isotopic compositions can only provide usable results when specifying the sampling scale. Taken together, all these observations suggest the need for a new perspective on meteorites, considering (i) highly brecciated meteorites (i.e., Kaidun and [Almahata Sitta](#), typically viewed as anomalies) as the norm and (ii) monomict breccias as the exception. In addition, the numerous outstanding questions regarding the origin, distribution, and evolution of xenolith clasts require (i) extensive mineralogical, petrographic, and isotopic characterizations of xenolith clasts (especially in OCs, for which only a limited number have been described), (ii) an understanding of the dynamics and chronology of their incorporation into their host bodies, and (iii) further development of the physics of small-scale implantation processes.

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Figure captions

Fig. 1: A) Reflected-light photograph of a piece of the Boriskino CM chondrite, courtesy of L. D. Bayle. Diverse lithologies, characterized by different shades of gray, are easily distinguished. B) Reflected-light photograph of the enstatite chondrite Abee showing impact-generated veins (Bischoff et al., 2006; Rubin, 2015). Courtesy of Laurette Piani.

Fig. 2: Back-scattered electron image of the brecciated Cold Bokkeveld CM chondrite. Individual fragments (some are traced by red dashed lines) are variable in composition, as indicated by their different shades of gray.

Fig. 3: Energy-dispersive X-ray elemental map of the Mg, Al, Si, Ca, and Fe distributions in the polymict breccia Kaidun, revealing its complex nature.

Fig. 4: Back-scattered electron image of CV3 Efremovka, showing a high degree of chondrule flattening induced by hypervelocity impacts. A fine-grained clast is also observed in this section.

Fig. 5: Back-scattered electron images of xenolith clasts (central in each image) observed in (A) CB Isheyevo and (B) the Kapoeta Howardite.

Fig. 6: A) Back scattered electron image of the Paris chondrites showing the presence of light-colored clasts (red boxes). B) and C) Back scattered electron images of the contacts between the clasts and the host chondrites. No specific sign of thermal metamorphism is observed.

Fig. 7: Schematic comparison of the three global models currently proposed for explaining the peculiar structure of the main asteroid belt and the solar system formation (described in section 4).

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Fig. 1

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Fig. 2

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Fig. 3

Fig. 4

Fig. 5

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Fig. 6

Fig. 7