A record of post-accretion asteroid surface mixing preserved in the Aguas Zarcas meteorite

Xin Yang1,2,3, Romy D. Hanna4, Andrew M. Davis1,2,3,5, April I. Neander6 and Philipp R. Heck1,2,3

Particle ejection and redeposition events on the surface of asteroid 101955 Bennu, which led to transport, mixing and loss of material, have been observed frequently by NASA’s OSIRIS-REx mission. Besides large-scale impacts, this may be one of the most important post-accretional processes on small carbonaceous asteroids. Here we looked for relics of such activity in a Bennu analogue, the carbonaceous chondrite Aguas Zarcas. We discovered compact fragments that were strongly shocked, redistributed and deposited onto an unshocked lithology, consistent with surficial re-accretion on Aguas Zarcas’s parent body. Such re-accretion could be driven by large-scale impacts or by frequent pebble transport from endogenous asteroidal activity such as observed at Bennu. The latter hypothesis is supported by the matching size distribution of the Aguas Zarcas compact fragments with that of the Bennu ejecta. Such mixing has hitherto been unexplored in other regolith breccias, and further analysis will determine how common such processes are.

Results

We found a compact lithology by disaggregating ~79 g of AZ fragments from a large and freshly broken sample (1.894 kg) into fine powder with the freeze–thaw method. More than 10 sub-cm-sized compact fragments (3.2 wt%) with a dull, black, smooth lustre similar to the appearance of melt rock survived the disintegration (Methods). The compact lithology was more resistant to the mechanical breakdown and has a higher density (~2.7 g cm⁻³) and compactness compared with the regular host lithology (~2.4 g cm⁻³). Because of the low abundance of the compact lithology, we assumed that a randomly selected AZ fragment is not compact and belongs to the regular AZ lithology.

To better understand the petrological history of AZ, we μCT-scanned Murchison and Leoville meteorites as reference samples. Murchison is a CM2 chondrite that is similar to Aguas Zarcas in petrology and mineralogy5; Leoville is a CV3 chondrite that has undergone strong deformation6. We observed prominent deformation and a preferred orientation of chondrules in the μCT and SEM data of compact AZ and Leoville but no such effect in regular AZ and Murchison (Fig. 1). Murchison is one of the best-studied meteorites with heterogeneous deformation from which an undeformed fragment was studied here10. Leoville is known as one of the most deformed chondrites showing flattened chondrules aligned in parallel11,14. We utilized undeformed Murchison and strongly deformed Leoville as two extreme endmembers for our study.

To assess and quantify the type and strength of deformation, we outlined chondrules in the μCT dataset, fitted ellipsoids following an established method14 and used axial ratios, fabric parameters and shape analysis with ternary diagrams13,14. Fabric is the geometric arrangement of components in a rock. In our case, it refers to the spatial arrangement of chondrules and their preferred orientation...
that manifests itself as elongated (rod-shaped, with lineation) or flattened (disc-shaped, with foliation) shapes. Fabric parameters ($K$ and $C$) are defined by a set of direction vectors of axes of the best-fit ellipsoids of chondrules and can be used to distinguish deformation type (lineation or foliation) and quantify the deformation intensity\cite{15}. Shape parameter $K < 1$ for the longest axes set and $K > 1$ for the shortest axes set demonstrates a foliation, and $K > 1$ for both axes sets indicates a lineation. For the strength parameter $C$, higher values indicate stronger fabrics.

The average axial ratios of fitted ellipsoids of chondrules increase from regular AZ and Murchison to compact AZ and Leoville, which is consistent with the result of $C$ parameters (Supplementary Table 1). The fabric strength varies from ‘moderately weak’ to ‘moderately strong’ with $C$ of longest axes ranging from 0.75 to 2.53 and $C$ of shortest axes ranging from 1.04 to 2.65. These parameters are highest for compact AZ and Leoville and are lowest for regular AZ and Murchison, indicating that the former two are strongly shocked and that the latter are weakly shocked. $K$ parameters for the longest axes in compact AZ and Leoville range from 0.09 to 0.40 while those for the shortest axes range from 1.97 to 13.06, arguing that the fabrics in compact AZ and Leoville are both foliations. That is, the chondrules are more flattened than elongated, though the difference cannot be distinguished by two-dimensional (2D) analysis (Fig. 1). Meanwhile, in the ternary diagram (Fig. 2) that plots an object’s shape as a function of a perfect sphere, elongated rod and platy disc shape, we note two patterns of chondrule shape distribution. One group, represented by regular AZ and Murchison, has the majority of their chondrule shapes located in the top ‘equant shape’ sub-triangle. The other group, represented by compact AZ and Leoville, has a remarkable number of points in the areas signifying more deformed shapes (44.0% for compact AZ, 64.6% for Leoville, 17.4% for regular AZ, 19.0% for Murchison). Combining the indices above, we infer that the deformation intensity sequence is regular AZ < Murchison < compact AZ < Leoville. An exception to this sequence is regular AZ fragment RF-3, which displays a higher axial ratio and $C$ parameter compared with other regular AZ fragments and is closer to compact AZ (Extended Data Fig. 1). Therefore, we classify RF-3 as a compact AZ fragment. The classification is not binary. RF-3 is more deformed than regular fragments but may not be as deformed as the other compact fragments. This deformation sequence is also reflected by the fragments’ average densities (2.72 g cm$^{-3}$ for compact AZ, 2.43 g cm$^{-3}$ for regular AZ and 2.55 g cm$^{-3}$ for RF-3).

Besides deformation, fractures and veins are often used to investigate meteorite stress histories in shock events\cite{3, 16}. In the polished
drules are unfilled, we infer that the chondrule veins formed before fractures would be filled with secondary precipitates. Metal sulfide veins oriented independent of the chondrule flattening direction (10–20 μm wide) and mostly parallel or subparallel to the direction of the chondrule elongation. We also examined the μCT data of regular AZ and found several unfilled fractures (10–20 μm wide, 1–2 mm long) without any preferred orientation (Supplementary Fig. 1).

Fractures and deformation are common in chondrites, and an impact origin is supported by an increasing amount of evidence such as the correlation between shock stages and aspect ratios of chondrules, noncoaxial strain and the abundance of unfilled fractures versus fractures filled with secondary minerals. Meanwhile, fracturing in the compact AZ matrix is approximately in the same orientation as chondrule flattening. As shown in Fig. 1e, angles between the fractures and the direction of chondrule flattening vary within ±8° with a mean of 1.3° and 1 s.d. of 3.7°. Therefore, we propose that the same generation of impact events caused the shock effects observed in the compact AZ lithology and that no remarkable aqueous alteration occurred after the shock; otherwise, these fractures would be filled with secondary precipitates. Metal sulfide veins are not common in CM chondrules but are often seen in ordinary and some CV meteorites that are likely to have experienced collisions and heating events. While veins from impacts are usually large and cross into the matrix, the veins in compact AZ are thin (10–20 μm wide) and only exist in chondrules. Based on cross-cutting relationships and the observation that fractures outside of chondrules are unfilled, we infer that the chondrule veins formed before the impact-induced matrix fractures. Otherwise, we would expect to see all fractures, including those in the matrix, to be filled.

We can exclude deformation by the burial processes: we modelled the lithostatic pressure for chondritic bodies with varying sizes (Supplementary Fig. 2) and find that the maximum pressure in the centre of a Ceres-like asteroid is only about 0.5 GPa. The non-isotropic stress that may cause deformation is typically lower than the lithostatic pressure. This is much deeper than a plausible burial depth and a much lower pressure than needed to explain the deformation of compact AZ (see the ‘Shock pressure estimate’ in the following paragraph).

In many meteorite types, shock effects in olivine are used to determine the shock pressure, but they may not reflect the shock history of CMs well because the abundant matrix (~70 vol%) in CM meteorites can remarkably attenuate a shock wave to a low intensity such that it cannot affect olivine crystals. Indicators of shock pressure in CMs include chondrule flattening and fractures. First, empirical relationships between chondrule aspect ratio and shock pressure were established in impact shock experiments. Based on these relationships for CV and CM chondrites (Fig. 3), we determined shock pressures for Leoville and compact AZ as ~17 GPa and ~18 GPa, respectively. The published shock stage for Leoville is S3, corresponding to a shock pressure of 15–20 GPa in a single impact. The consistency between the shock pressure determined from chondrule aspect ratio and published shock stage for Leoville demonstrates the suitability of this method. Second, the existence and density of fractures are qualitative indicators of shock pressure. In shock experiments with Murchison, the recovered sample showed that the fracture (<5 μm) density in the matrix increased slightly when the pressure increased up to 10 GPa. At 21 GPa, fractures became wider (20 μm) and more preferentially...
that we also observed in compact AZ fragments. Therefore, we infer that the compact lithology must have experienced at least one hypervelocity impact.

**Discussion**

AZ is highly brecciated with multiple lithologies that were thought to be the result of different degrees of aqueous alteration and impact modification. Brecciated carbonaceous chondrites are not unusual. However, the occurrence of strongly deformed fragments that include oblate chondrules next to undeformed rock fragments with spherical chondrules is striking. Aqueous alteration cannot deform rocks and explaining the observations requires another process. Also, because of the cumulative nature of compaction and shock events, heterogeneous shock effects on the sub-millimetre scale can be expected, but shock propagation is not likely to produce deformed and undeformed lithologies in such close proximity. Rather, the deformed compact fragments must have been transported into an undeformed lithology before final lithification.

Fig. 3 | Relationship between aspect ratio and shock pressure. a, Plot of CM meteorites. b, Plot of CV meteorites. The Murchison and Allende data from Tomeoka et al. and Nakamura et al., respectively, acquired from shock experiments were used to create standard curves (red dashed lines). The last two Murchison data points in a with high shock pressures were not included in the linear regression because of the nearly constant aspect ratio at higher pressure >25 GPa. Triangles are used for our data. Error bars represent one s.d., not data uncertainties, so the mean value is still useful in determining shock pressures.

orriented and olivine grains showed undulatory extinction and planar fractures, consistent with shock stage S3. The occurrence of 2–20-μm-wide, unfilled fractures in compact AZ matrix (some pass through the flattened chondrules) parallel or at a low angle to the direction of chondrule deformation is consistent with a shock pressure of 15–20 GPa.

Two types of impact collision have been considered for the origins of meteoritic breccias. Accretionary impacts happened during the accretion of asteroids at relatively slow speeds (typically less than a few hundred m s\(^{-1}\)). Hypervelocity impacts occurred after asteroidal orbits were dynamically excited when asteroids collided at speeds of a few km s\(^{-1}\). An impactor with a speed <1 km s\(^{-1}\) cannot generate pressure greater than 10 GPa (ref. 30). Most of the meteorites that contain high-aspect-ratio chondrules provide independent evidence of hypervelocity impact in the form of shock fractures that we also observed in compact AZ fragments. Therefore, we infer that the compact lithology must have experienced at least one hypervelocity impact.

Particle ejection and re-accretion of millimetre- to centimetre-sized particles onto the regolith of Bennu is an important but until recently undiscovered mass transport process on asteroids. According to the OSIRIS-REx observations, the larger events with more than 70 particles observed each time occurred every 2 weeks and smaller detected events with less than 25 particles observed each time happened every 1–2 days. During the time period of observation, no hypervelocity impact events were detected. This implies that hypervelocity impacts are much less frequent than the particle ejection and re-accretion events. Through the latter, about 10\(^4\) to 10\(^5\) particles may be launched per year, with 85% of them redeposited and the remainder exceeding the escape velocity. Consequently, a large number of pebble-sized fragments...
were relocated on Bennu’s surface, leading to global and thorough mass transport and regolith mixing. Many mechanisms have been proposed to explain the ejection events, while low-energy dust impacts and thermal fracturing received the most attention. Spectral data of Bennu suggest a CM composition, similar to AZ, and therefore thermal stressing and mass transport may have also occurred on the AZ parent body and mixed the compact AZ lithology with the regular one. We compared the size distribution of compact AZ fragments with that of Bennu ejecta and found a good match (Fig. 4) that supports a similar breakup/transport mechanism. Both datasets are truncated at the lower end due to the observational detection limits of OSIRIS-REx for Bennu and sample processing in the laboratory for AZ. To better understand such activity on asteroids and its potential to transport mass globally on the AZ parent body, we conducted a Monte Carlo analysis. Tens of thousands of fragments were released from the surface of asteroids with 1–100 Bennu radii. The ejecta redeposited onto the surface after orbiting the asteroid up to several times or escaped the asteroid’s gravity directly. Fragment trajectories were recorded and the efficiency of global transport was evaluated. To quantify the particle relocation, we used the concept of displacement angle as the central angle between the launching site and landing site. A large displacement angle represents a global transport, otherwise a local one, and we arbitrarily set a threshold equal to π/4 to distinguish between the two types of transport. Our model yields a pronounced equatorial excess of particle redeposition on a Bennu-sized body (Extended Data Fig. 4), consistent with the spacecraft observation of Bennu’s shape. The model also predicts that the particle ejection and redeposition process operates as an effective mixing process on asteroids with a radius of up to 50 Bennu radii (Fig. 5).

The model results support the hypothesis that such a process occurred on the AZ parent body. Hypervelocity impact deformation is a local phenomenon, and specimens from the same meteorite fall have the identical petrofabric in most cases. Nonetheless, if the active pebble transport occurred on the AZ parent body, it was able to eject and reaccrete compact AZ fragments globally. After mass transport, compact AZ fragments were mixed into unshocked regular AZ lithology, and later impacts consolidated the breccia and ejected it to Earth. The consolidating impact may have resulted in the final ejection and delivery to Earth.

Another possible explanation is that the compact fragments are distal ejecta from a large-scale impact. Large hypervelocity impacts are less frequent, and none of them were observed by OSIRIS-REx. An additional strong impact occurring in the impact site to redistribute the shocked lithology into an unshocked one is rarer. Based on our observations, we propose the following scenario for the formation of AZ (Extended Data Fig. 5). (1) A hypervelocity impact caused deformation of chondrules and formed cracks in matrix (2–20 μm wide). (2) The compact lithology of the AZ parent body was fragmented by a combination of meteoroid impacts and thermal fracturing, and a pebble transport process such as observed on Bennu ejected compact fragments that reaccreted into unshocked regolith later. (3) The absence of precipitates in cracks implies that no detectable aqueous alteration occurred after that, and that the AZ breccia was lithified by one or multiple later impacts. (4) A meteoroid containing regular and compact AZ lithologies was ejected from the parent body by an impact and delivered to Earth. The high frequency of pebble transport on Bennu and AZ-like asteroids seems at odds with the low frequency of occurrence of compact fragments in unshocked lithology seen in most carbonaceous chondrites. There are several possible reasons for this. First, the abundance of compact material is relatively low (3.2 wt% in this study), and most studies do not usually survey sample volumes as large as in this study; meanwhile, more common surveys of polished sections only provide information from a small sample of the whole rock. Second, if undeformed pebbles were transported...
in this way into a similar host lithology, we cannot identify them. Third, the ejection process may be more complex than expected and not common on most carbonaceous asteroids. In fact, different shock stages of Murchison have been reported \(^{15-20}\), and the average three-dimensional (3D) aspect ratio of chondrules in Murchison ranges from 1.75 ± 0.39 (ref. \(^{18}\)) to 1.54 ± 0.22 (ref. \(^{12}\)) and 1.30 ± 0.15 (this study), whereas the chondrule aspect ratio in 2D sections ranges from less than 1.2 (ref. \(^{15}\)) to 1.67 ± 0.51 (ref. \(^{18}\)). All the evidence is consistent with similar ejection and redeposition processes on Murchison's parent body.

The OSIRIS-REx observations of pebble transport that redistributes material on the surface of Bennu are undeniable and were frequent during OSIRIS-REx's residence in Bennu orbit. Thus, each volume of rock on Bennu's surface should contain some fraction that was delivered by the pebble transport from a different region. This process breaks the tacit assumption that mixing and brecciation is solely by large-scale impacts and advances our understanding of post-accretion processes. Documenting such activity with meteorites is challenging because of the need to demonstrate that the meteorite fragments experienced relocation on the parent body via the Bennu-type transport, not distal ejection from hypervelocity impacts. While we cannot exclude the latter, we argue that pebble transport analogous to Bennu more likely explains our observations in AZ. The main arguments for this include the much higher frequency of the pebble transport process, the matching size distribution of observed ejected pebbles from Bennu and compact fragments and the predicted redistribution from our Monte Carlo model. Instead of the conventional impact-mixing hypothesis that is usually offered as the sole explanation, active pebble transport is an important process that now needs to be considered, in addition to impacts, to explain mixed lithology in CM chondrites such as in AZ. We predict that other carbonaceous chondrite breccias, in particular CM chondrites, as well as the mission-returned samples from the asteroid Bennu, may contain compact fragments embedded in an unshocked lithology. Studying other carbonaceous breccias will provide new insights into the diversity and relative importance of this and other surface processes on active asteroids.

**Methods**

**Sample preparation.** A large 1.894 kg fragment of Agua Zarcas was recovered rapidly after its fall before rain, purchased by Terry Boudreaux and donated to the Field Museum of Natural History. This specimen, FMNH ME 6112, is stored at the Field Museum in a stainless-steel cabinet in an inert nitrogen atmosphere at room temperature. A total of 79 g of fragments were separated from the large sample of AZ, FMHN ME 6112 with cleaned stainless-steel tools in a nitrogen-filled glove bag. We used freeze–thaw disintegration as the first step of an effort to separate objects of interest including refractory minerals, isolated olivine grains if performed for every chondrule in the dataset. Therefore, we only applied it to small fragments and used a more efficient alternative, the partial segmentation method, for large ones. For partial segmentation, one or more representative cross-sections in each chondrule’s orthogonal plane are chosen for segmentation excluding the ambiguous chondrules such as those that are in contact with each other. The effectiveness of this method to accurately calculate the orientation and degree of anisotropy of objects in rocks relative to the full segmentation has been examined and confirmed \(^{10}\). In this study, we used the whole segmentation method for samples collected at University of Chicago, as these datasets are small due to their lower resolution, as well as for Leoville, where our scanned volume contains only a few chondrules due to their relatively large size. For the remaining datasets, we used the partial segmentation method.

Third, after segmentation with 3D Slicer, we exported all the segments to DICOM (Digital Imaging and Communications in Medicine) files, loaded them into Fiji and converted them to TIFF files. For each chondrule, we used Blob3D \(^{10,17}\) (http://www.cclab.geo.uciones.es/software/blob3d/) to determine the size, location and orientation information of the best-fit ellipsoids to either the full segmentation or partial segmentation via a set of orthogonal planes. Orientation biasing can occur when an object covers only a few pixels. To avoid that, we removed objects with a short axis of less than three voxels \(^{10}\). To make the data volume manageable, we divided each large tomographic dataset into several subvolumes and segmented chondrules within each individual subvolume. This enabled faster processing of the data and a reduction in file size. We segmented 825 dark-toned objects in total. Parameters of best-fit ellipsoids for each object are shown in Supplementary Table 1.

Fabric analysis of the tomographic data in this work follows an established method \(^{10}\), and further details regarding parameter calculations reported in

**Scanning electron microscopy.** After µCT scanning, the compact fragment CF-10 was embedded in Buehler EpoxyCure 2 epoxy and cross-sectioned parallel to the long axis of the flattened chondrules with a Buehler Isomet low-speed diamond wafering saw. The section was coarsely polished with diamond Allied High Tech Products Inc. lapping film followed by a final polish with Allied 1 μm diamond slurry. The polished mount was imaged and mapped with a field-emission TESCAN LYRA3 SEM/Focused Ion Beam (FIB) equipped with two Oxford XMax Silicon Drift Detectors (SDD) 80 mm\(^2\) energy dispersive X-ray spectroscopy (EDS) detectors at the University of Chicago. An EDS map, a backscattered electron map and a secondary electron (BSE) map and a second-order EDS map using Oxford AZTec software.

**Chondrule segmentation and deformation analysis.** First, we determined the µCT components in compact AZ by calibrating the CT data by comparing BSE and EDS maps of the polished cross section of compact AZ fragment CF-10 with a different µCT slice. There are three types of object identified based on their grayscale values within the µCT data (Supplementary Fig. 3): small light-toned objects without well-defined shapes, light-toned objects and dark-toned objects. Here we mainly discuss chondrules and neglect irregular clasts. Earlier µCT studies \(^{15,20}\) of Murchison have shown that the brightest components are metal and sulfides such as pentlandite and that light-toned and dark-toned objects are mostly Fe-bearing chondrules/calcium-aluminum-rich inclusions and Fe-poor/Mg-rich chondrules, respectively. SEM data of the polished AZ CF-10 confirm the same µCT components as in Murchison. In the µCT data of Leoville, we only observed dark chondrules and bright metal/sulfides. µCT data of regular AZ show the same three object types as compact AZ. According to previous research \(^{15,20}\), dark-toned objects (that is, Mg-rich chondrules) are typically more deformed and display a stronger fabric compared with bright (metal and sulfide) and light-toned (Fe-bearing chondrules and calcium–aluminum-rich inclusions) objects.

Regardless of the reason for this observation, we only delineated and segmented those dark-toned objects in µCT data and calculated the fabric strength to avoid any potential observational bias with objects of different X-ray contrast.

Second, we outlined components of interest (here dark-toned chondrules) from the tomographic dataset into distinct volumes of interest. We used manual segmentation in 3D Slicer software (http://slicer.org) where we used the ‘draw’ tool to mark chondrules in individual 2D slices, then filled between slices to obtain a 3D visualization \(^{10}\). The method is labour-intensive and potentially prone to biasing if performed for every chondrule in the dataset. Therefore, we only applied it to small fragments and used a more efficient alternative, the partial segmentation method, for large ones. For partial segmentation, one or more representative cross-sections in each chondrule’s orthogonal plane are chosen for segmentation excluding the ambiguous chondrules such as those that are in contact with each other. The effectiveness of this method to accurately calculate the orientation and degree of anisotropy of objects in rocks relative to the full segmentation has been examined and confirmed \(^{10}\). In this study, we used the whole segmentation method for samples scanned at University of Chicago, as these datasets are small due to their lower resolution, as well as for Leoville, where our scanned volume contains only a few chondrules due to their relatively large size. For the remaining datasets, we used the partial segmentation method.
Supplementary Table 1 can be found in that work. Here we briefly introduce the quantitative analysis of deformation. We take the direction vectors of a set of axes of the fitted ellipsoids as an example. These directions are plotted on stereonets in a lower hemisphere projection, and the GOF parameter is used to determine whether the orientations are non-random. Meanwhile, Woodcock and Naylor11 defined K and C parameters to describe the shape and stretch, respectively, of a fabric. An orientation tensor (3 x 3 matrix) is calculated from the above direction vectors, and three eigenvectors of the tensor are defined as Sx, Sy, Sz. K is defined as K = ln(Sx/Sy)/(Sy/Sz). K ranges from zero (girdle or ‘great circle’ distribution on a stereonet) to 1 (a single maximum of a single orientation). C ranges from zero (no fabric) to four or above (strong fabric) and is manifested as the concentration of data points on a stereonet17. Supplementary Fig. 4 illustrates K and C parameters and the chondrule orientations for four types of rock in this study.

**Shock pressure determination.** Previous studies used Murchison and Allende in shock-recovery experiments to build empirical relationships between aspect ratio and shock pressure in a single impact shock event28. In Murchison, 10 GPa was a threshold over which the aspect ratio started transferring from 1.2 to 1.5 (Fig. 3). Meanwhile, 25 GPa was another threshold over which the aspect ratio kept a constant-magnitude deformation in an impacted sample had a large range, but the distribution of the aspect ratios moved clearly with an increasing shock pressure. Accordingly, the mean values of those ratios rose. Also, the aspect ratios of unshocked Murchison’s and Allende’s chondrules and the data that were acquired under extremely high pressure that did not show further deformation were not used in the linear regression. The shock-recovery experiments, the recovered samples were cut along the shock compacting axis, such that the mean 2D aspect ratio of chondrules in the section was most comparable to the mean ratio of the longest axis to the shortest axis length in our 3D model (called 3D aspect ratio).

**Lithostatic pressure model.** At depth within a spherical asteroid, the force balance is as follows: \( GMm^2/r^2 \times 4\pi \times r^2 \times dr = 4\pi \times r^2 \times P \times dr \), where \( r \) is the radial distance from the centre of the parent body, \( G \) is the gravitational constant, \( M \) is the mass of the material below \( r \), \( p \) is the density and \( P \) is the pressure. The left side is the gravitational force of a shell with a width of \( dr \) at a radial distance \( r \) from the centre and the right side is the supporting force provided by the pressure gradient. Due to \( M = 4\pi r^3 \rho \), the simplified equation of force balance is \( P = \frac{4\pi G M r^2}{4\pi \times 3 r^3} \) = \( \frac{4\pi G M}{r} \). The solution is \( P = \frac{2\pi G M}{r^3} \) (\( R^3 - r^3 \)), where \( R \) is the radius of the parent body. When \( r = R \), \( P \) reaches the maximum, that is, the pressure at the centre. Because most stony meteorites have densities39,40 on the order of 3–4 g cm\(^{-3}\), we take \( \rho = 3.5 \text{ g cm}^{-3} \) in the model. We considered two cases to visualize the pressure profiles in meteorite parent bodies. One is the maximum pressure (centre pressure) for spherical objects with different sizes; the other is the depth–pressure profile for a 100-km-sized body (Supplementary Fig. 2). The calculated maximum pressure for the Moon is 5.2 GPa, and most petrological experiments and seismic detections all support a ~5 GPa pressure at the lunar core or core–mantle boundary19,20. The maximum pressure for a 106-km-sized body is ~0.02 GPa.

**Monte Carlo model.** The movement of ejecta on Bennu is controlled by multiple forces such as Bennu’s gravity, solar radiation, reflected pressure, Poynting–Robertson effect and so on. The gravitational force in the vicinity of Bennu is 2–6 orders of magnitude higher than the other forces2; therefore, and for simplicity, we consider it as the only driving force in our model. Besides this, we set up initial conditions that include initial velocities of particles, launch position and rotation of the central body. The observed velocity of Bennu ejecta ranges from 0.05 m s\(^{-1}\) to >3.3 m s\(^{-1}\), and the observations may not include all particles, especially fast-moving ones. Thus, we take 0.05–5 m s\(^{-1}\) as the initial velocity range. The particles can be ejected from anywhere on the surface, but we were more frequently observed from low latitudes. We adopt the distribution of ejection sites from Chesley et al.1 to our model. Generally, the spin period of asteroids decreases with their size and clusters between 2 and 12 hours (ref. 19). The rotation period for Bennu is 4.3 hours, and we apply this to all the simulations in this study.

First, we modelled movement on a spherical body whose mass, bulk density and radius are the same as that of Bennu. We released 50,000 particles and only those with low velocities (<0.35 m s\(^{-1}\)) fell back on the surface. Extended Data Fig. 4 depicts the distribution of the sines of latitude for ejecta deposition. We also ran our model with larger asteroids with 10 to 100 Bennu radii. Bennu’s bulk density is low, ~1.26 g cm\(^{-3}\), because it is a rubble pile asteroid with a high porosity16. Nevertheless, the fragment density should be close to that of its meteorite analogue AZ (~2.4 g cm\(^{-3}\)). Here we argue that 2.4 g cm\(^{-3}\) is the approximate upper limit for such carbonaceous chondrites, because it ignores the impact-induced brittle deformation, porosity loss, and aqueous alteration in the Murchison chondrite. Geochim. Cosmochim. Acta 171, 256–282 (2015).

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Acknowledgements

P.R.H. thanks the Boudreaux family for donating Aguas Zarcas to the Field Museum’s Robert A. Pritzker Center. Funding from NASA’s Emerging Worlds program (80NSSC21K0389 to P.R.H. and 80NSSC21K0374 to A.M.D.) and from National Science Foundation (grant EAR-1762458 to UTCT Facility) is gratefully acknowledged. P.R.H., X.Y. acknowledge support for this project from the Field Museum’s Science Innovation Award and the TAWANI Foundation. We thank J. Holstein and K. Keating for help with sample preparation, J. Maisano for µCT data acquisition of samples acquired at the High-Resolution X-ray Computed Tomography Facility of the University of Texas at Austin (UTCT), G. Olack for maintaining the FIB-SEM facility at the University of Chicago and J. Greer for discussion regarding components of AZ and scientific illustration. X.Y. acknowledges support from UTCT for attending the UTCT Short Course: Quantitative Analysis with XCT.

Author contributions

X.Y. and P.R.H. conceived the study and wrote the paper with input from all authors. R.D.H provided expertise on the data processing, interpretation and visualization. A.M.D contributed to the investigation and Monte Carlo model. A.N. conducted the initial µCT scanning of samples. X.Y. and P.R.H prepared the samples for SEM/EDS analysis and A.M.D helped explain the data.

Competing interests

The authors declare no competing interests.

Additional information

Extended data is available for this paper at https://doi.org/10.1038/s41550-022-01746-4. Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41550-022-01746-4. Correspondence and requests for materials should be addressed to Xin Yang. Peer review information Nature Astronomy thanks the anonymous reviewers for their contribution to the peer review of this work. Reprints and permissions information is available at www.nature.com/reprints. Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations. Springer Nature or its licensor holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law. © The Author(s), under exclusive licence to Springer Nature Limited 2022.
**Extended Data Fig. 1** | 3D aspect ratios of fitted ellipsoids of chondrules in AZ fragments versus C parameters. Two groups, regular AZ and compact AZ, are clearly separated, with RF-3 in the compact group. Error bars are one standard deviation (n = 22–85).
Extended Data Fig. 2 | Back-scattered electron (BSE) images of regular AZ (left panel; Kerraouch et al. 7) and compact AZ (right panel; this study). Both lithologies show the same texture, that is, chondrules at low abundance embedded in an aqueously altered matrix enriched with phyllosilicates (irregular patchy light grey material in the matrix between the chondrules). Right panel adapted from ref. 7 under a Creative Commons license CC BY 4.0.
Extended Data Fig. 3 | BSE images of chondrules from the compact fragment CF-10. **a**, Chondrule mainly consisting of forsterite (Fo), containing round sulfide grains. **b**, Radial pyroxene (Py) chondrule. **c**, Porphyritic olivine-pyroxene chondrule containing sulfide (Sul) grains. **d**, Porphyritic olivine-pyroxene chondrule containing sulfide veins and phyllosilicate (Phy).
Extended Data Fig. 4 | Distributions of absolute locations (upper panel) and of displacement angles (lower panel) for redeposition onto a Bennu-like asteroid. The modeled body has the same size and bulk density as that of Bennu (490 m in diameter and 1.26 g cm\(^{-3}\) in bulk density).
Extended Data Fig. 5 | Schematic portrayal of the history of the formation of the Aguas Zarcas chondrite. Fractures were generated in chondrules before or during the accretion of the parent body and were filled simultaneously by shock mobilization or later by thermal/aqueous alteration. Then a hypervelocity impact caused chondrule flattening and fracturing in the matrix, and the compact AZ lithology was formed. The compact AZ was fragmented by meteoroid impacts and thermal fracturing. Then particle ejection and reaccretion events redistributed rock fragments with distinct lithologies, mixing compact AZ into regular AZ. Later impacts consolidated the mixed lithologies and resulted in the final ejection.