EARLY SOLAR SYSTEM

Gathering dust

Chondritic meteorites are remnants of the ancient Solar System. Analysis of the dust rims often found on their constituent particles shows that the rims were swept up while the particles wafted about and collided in a weakly turbulent protoplanetary nebula.

Jeff Cuzzi

Chondrites are the most primitive, unmelted meteorites. They are named after their primary constituents: formerly molten, millimetre-sized silicate grains termed chondrules. Because these meteorites sample parts of parent bodies that never melted, they are direct samples of the solids that were present in the protoplanetary nebula where and when their asteroidal parents formed. Chondritic meteorites have a unique texture that resembles a well-sorted sedimentary rock more than an igneous rock or an unsorted pile of collisional fragments. In a chondritic meteorite, each chondrule is generally encased in a rim of fine-grained material; the origin of these fine-grained rims has been controversial. Chondrules could have accreted these rims as they wandered through the dusty nebula, before they were accreted into a parent body[1]. Alternatively, the rims could have formed later, by compression or alteration on the parent body[2]. Writing in *Nature Geoscience*, Bland and colleagues[3] suggest, based on a sophisticated, three-dimensional (3D) textural analysis, that the chondrules did indeed acquire their rims while freely floating (and occasionally colliding with each other) in the protoplanetary nebula.

Just how, where, and when chondrules were melted remains a matter of debate. Strong shock waves in the nebula could be responsible, but there is no obvious way to generate the right kinds of shock at the appropriate place and time[4]. The process by which chondrules formed is probably different from the way in which they accumulated into the parent body we actually sample. Most chondritic meteorites record fragmentation, shocks, or distortions from violent collisions between asteroids after the material had accreted, but the initial accretion of the asteroids was probably much more gentle.

The origin of the fine-grained material in chondritic meteorites is also unclear. This material is not confined to chondrule rims; some of it is contained in the more general matrix between chondrules. The composition of rims and fine-grained matrix is quite similar: both are generally richer in iron and other more volatile elements than the chondrules. Rim composition is usually uncorrelated with that of the underlying chondrules, although the rim thicknesses do tend to correlate with the size of the chondrule they encase. Models in which fine-grained material is swept up by chondrules wafting through a turbulent dusty nebula gas, and then occasionally packed down in mutual collisions[1], are promising in explaining these properties.

However, from a fluid dynamics point of view it is unclear whether turbulence could persist at all in the region where the asteroids formed, or how it varied in space and in time. Moreover, nebula turbulence could produce fluctuations in gas density, and hence gravity, that would lead to collisions of asteroids as large as 1–10 km in diameter, at velocities large enough to erode or destroy them[5]. The process is similar to how stars in the galaxy are scattered by the gravity of giant molecular clouds, and could pose a barrier to the formation of asteroids by incremental growth. These arguments suggest that accretion under the most plausible assumptions is problematic. Because of these inconsistencies, it is highly desirable to constrain the level of turbulence by using the properties of material that was actually there, such as the dust rims of chondrules.

Bland and colleagues[3] performed an unusual analysis to determine the 3D spatial structure of the grainy fabric in a chondritic meteorite, both in chondrule rims and away from them. Cross-sections of the meteorite were observed using 3D electron backscatter diffraction, which yields an angular pattern corresponding to the crystal structure. This pattern thus indicates the average orientation of the grains in a volume. For example, small olivine grains grow in the shape of flat plates. Bland and colleagues showed that these flat grains share a preferred alignment, most probably in response to mechanical compaction and distortion of the porous, grainy material. At sufficient distances from the chondrule surfaces, a single well-defined orientation is found throughout the chondritic meteorite, indicating that the material was compacted on the parent body along a single axis.

By contrast, in the fine-grained rims flattened grains align parallel to the surface of the round chondrule beneath, which is inconsistent with uniaxial compaction. Bland and colleagues conclude that the grains were swept up uniformly around the chondrule and were free to

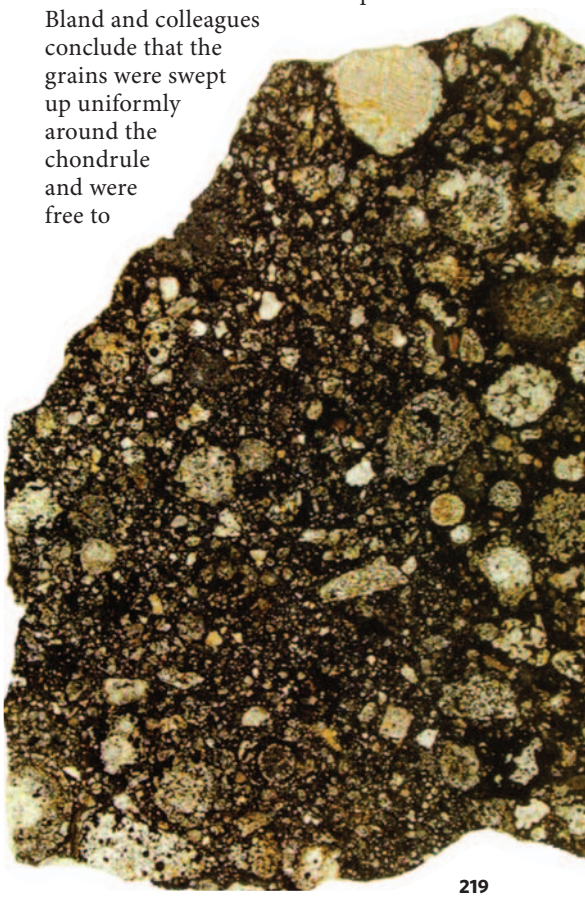

Figure 1 | Chondritic meteorite Vigarano, composed of dust-rimmed chondrules and matrix. Bland and colleagues[3] present analyses of the 3D texture in the fine-grained material of a chondritic meteorite, which suggests chondrules acquired their dust rims as they moved freely through a mildly turbulent nebula. The image is 1.7 cm across. Figure reproduced with permission from ref. 6, © 2004 Golden Retriever/Southwest Meteorite.

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reorientate themselves, probably in response to mechanical deformation of the accreted dust in many gentle collisions between rimmed chondrules and other particles in the nebula.

Typical collision speeds capable of producing the compaction observed by Bland and colleagues would not erode the rims. Instead, they are suggestive of mild turbulence, at levels that would prevent chondrule-sized particles from settling to the nebula. Only after some time as independently floating particles would the rimmed chondrules then be accreted into parent bodies. Perhaps all the dust in chondrites initially arrived on the rims of chondrules and similar-sized objects; the most tenuous outer fringes may have subsequently been abraded off into the matrix, leaving the most firmly packed grains behind in the rims.

Bland and colleagues[3] reconstruct a time long before the Earth formed, when chondrules — after their melting and solidification — wafted freely about in a mildly turbulent nebula. According to their findings, the chondrules swept up dust grains until either no more dust remained, or they were accreted into a parent body. With increasing accuracy in radioisotope age dating it may ultimately be possible to measure these time intervals and obtain more powerful constraints on models of how the first large planetary bodies were formed. ❐

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OCEANOGRAPHY

Chemical twins, separated

How the chemical composition of sea water changes on its journey through the world's oceans is poorly understood. Systematic measurements of dissolved trace metals across the Pacific Ocean suggest that these metals may help track sources and mixing of water masses.

Martin Frank

There is more to sea water than meets the eye. Apart from water and salt, it contains a wide variety of trace elements and particles that have entered the ocean from the land and atmosphere. Near the surface, dissolved trace metals often show a high affinity to particles of biogenic or terrestrial origin. These particles sink, taking the trace metals with them, and then release them again in deep waters. There the metals accumulate in dissolved form: the longer a water mass has been out of contact with the land or atmosphere the higher the trace metal concentration. Two pairs of such trace metals, zirconium (Zr) and hafnium (Hf) on the one hand and niobium (Nb) and tantalum (Ta) on the other, are chemical twins. Within each pair the elements' relative abundance should therefore not be significantly affected by biogeochemical cycling in sea water. Hence, the ratios of Zr/Hf and Nb/Ta are expected to be uniform across the ocean. Writing in *Nature Geoscience*, Firdaus and co-authors[1] present data from two meridional transects across the Pacific Ocean, demonstrating that this expectation is not borne out by observations: the ratios between each pair of these metals vary substantially and systematically with latitude and depth.

The addition of trace elements to the ocean is controlled by continental sources — dust, rivers or shelf exchange processes — and by hydrothermalism (Fig. 1). Once in the ocean, the trace metals are subject to biogeochemical cycling: they are taken up by small organisms, just like micronutrients such as iron or zinc. When the remains of these organisms sink, remineralization and desorption processes release the metals in deeper waters. These metals become progressively enriched along the deep currents if their oceanic residence time permits. The residence time is controlled by the particle reactivity of each metal: if the reactivity is high, the residence time is very short and there is no accumulation in deep waters because the metals are rapidly transferred to the sediments. If the residence time is very long, there is also no accumulation in deep waters because the elements are then homogenously mixed across all basins and water depths. However, the distribution of metals with an intermediate residence time, such as cadmium, closely follows that of nutrients such as phosphate or nitrate.

In the case of cadmium, the similarity to nutrient cycling has been used to reconstruct nutrient patterns in the past ocean. Records of the ratio between cadmium and calcium in the carbonate shells of benthic microorganisms that make up ocean sediments can help delineate past nutrient distributions in the deep ocean[2]. Present-day distributions of most trace metals across the ocean have, however, been poorly understood. Obstacles include the difficulty of obtaining reliable, contamination-free samples and a lack of measurement techniques at suitable accuracy. Applications of most metals, other than cadmium, as similarly reliable tracers for reconstructing the ocean of the past have therefore not been available.

Firdaus and colleagues[1] measured the dissolved concentrations of two pairs of chemically very similar trace metals, Zr and Hf, and Nb and Ta, along two combined meridional transects that span almost the entire Pacific Ocean from 67° S to 50° N. Surprisingly, they found strong deviations of the Zr/Hf and Nb/Ta ratios from those of the continental crust but also from the ratios found in the Atlantic Ocean. The highest Nb/Ta ratios occur in surface waters of the South Pacific Ocean. This finding points either to differences in removal processes in the surface ocean or to changes in the Nb/Ta ratio during weathering on land. In contrast, the highest Zr/Hf ratios were observed in the deep

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