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Droplet Chondrules

Jetting on high-velocity collision of small meteoritic particles may have produced droplet chondrules.

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Droplet chondrules are small spheroidal meteoritic inclusions that appear to have solidified from liquid droplets (Fig. 1). They are found in chondrites—meteorites that most evidence suggests originated in the early stages of formation of the solar system. The origin of the droplet chondrules has been the subject of controversy ever since Tschermak published the first detailed description of their microscopic texture in 1883 (*1*). Although a number of theories have been proposed for their origin, shock melting produced by impact of meteoritic bodies is favored by the bulk of recent evidence (*2*). The problem addressed in this article is the size of the bodies involved in the impacts. Cratering of protoplanets of asteroidal size by meteorites, favored by most authors, produces ejecta with the wrong distribution of sizes and shapes to form chondrites without further sorting that is difficult to explain. This and other difficulties are precluded if droplet chondrules formed by breakup into droplets of "jets" produced by collisions between small comparable-sized meteoritic bodies.

The Problem of the Origin of Chondrules

Petrographic and geochemical studies of chondrules in unequilibrated ordinary chondrites (*2–4*) have placed several constraints on theories for their origin:

1) The diameters of chondrules are limited mainly to the range 0.1 to 5 millimeters (*3*). In ordinary chondrites the distribution is strongly peaked at 0.4 mm (*5*).

2) Many chondrules are roughly equidimensional and spheroidal, but less than half are perfect spheres (*6*).

3) Chondrules may comprise 70 percent or more of the mass of chondrites (*2*).

4) Chondrules consist mainly of high-temperature minerals or glass and occur in a variety of textures. The most common chondrules are classified (*3*) as (i) barred olivine, (ii) radiating pyroxene, (iii) porphyritic, (iv) glassy, (v) agglomeratic, and (vi) lithic. A number of geochemical and textural properties suggest that they formed by rapid solidification of melt droplets: the spheroidal shape, the occurrence of skeletal crystallites, parallel growth patterns, dendritic growth of crystallites, the occurrence of glass, and the metastable preservation of high-temperature phases (*7*).

5) The nonequilibrium composition of chondrules and iodine-xenon ages [summarized in (*2*)] suggest that they were formed before the chondritic meteorites accumulated, that is, that they were not formed in situ in the chondrites.

The term "chondrule" is used by some authors to refer to all rounded fragments (or pieces thereof) in chondritic meteorites, regardless of composition and texture. For clarity, I refer to chondrules that appear to have formed as the result of cooling of liquid droplets as droplet chondrules. The major types of chondrules listed above (i to iv) have droplet members, although in varying proportions to the irregularly shaped members. The origin of the irregularly shaped chondrules is still uncertain; many may be eroded fragments of droplet chondrules, but some may be fragmented pieces of preexisting lithic material (*6*).

Within the chondrites, chondrules are embedded in a matrix of fine-grained crystalline to partially glassy material. Few data are available regarding this matrix material, principally because it is interstitial to and much finer than the chondrules. Olivine and pyroxene grains in the matrix have the same major element chemical compositions as those in the chondrules and many fragments of droplet chondrules are observable in thin section; it is therefore likely that at least some fraction of the matrix consists of crushed droplet chondrules (*7*). Recent data on minor element chemical fractionation patterns, however, suggest that at least some matrix material has not experienced the same high-temperature history as the droplet chondrules (*8*).

Condensation of a gaseous solar nebula or a Jovian protoplanetary atmosphere (*9*), fusion of nebular dust by lightning (*10*), and volcanism (*11*) have been proposed as chondrule-forming processes, but shock-melting due to hypervelocity impacts has been the hypothesis of most current interest (*2, 6, 12*). The presence of ancient impact craters on the moon, Mars, and Mercury leaves no doubt that impact was an active process in the early solar system. The presence of glass spherules at terrestrial impact craters and on the lunar surface demonstrates that some glass spherules similar to droplet chondrules are produced by impact (*13*).

The size of impacting bodies which could have produced droplet chondrules is unknown. Most authors have proposed that the droplet chondrules were formed by impacts of meteorites onto "extended" protoplanets of roughly asteroidal size (*6, 12*). I call such impacts in which one particle is small and the other large "particle-to-parent" impacts. High-velocity impacts in which the target is sufficiently large that the projectile delivers less kinetic energy than 10^7 ergs per gram to the target characteristically produce impact craters (*14*). (For spherical particles of equal density, this energy limit occurs approximately at radius ratios of 8 and 37 for impact velocities of 1 and 10 km/sec, respectively.) If droplet chondrules were formed by particle-to-parent impacts, then it is reasonable to assume that they were at one time part of ejecta assemblages much like

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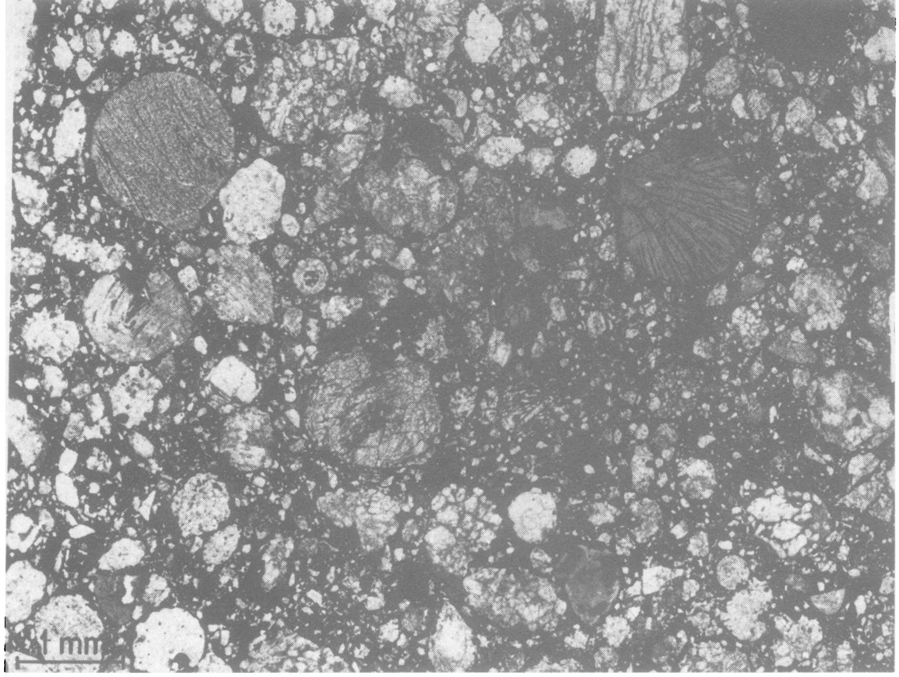
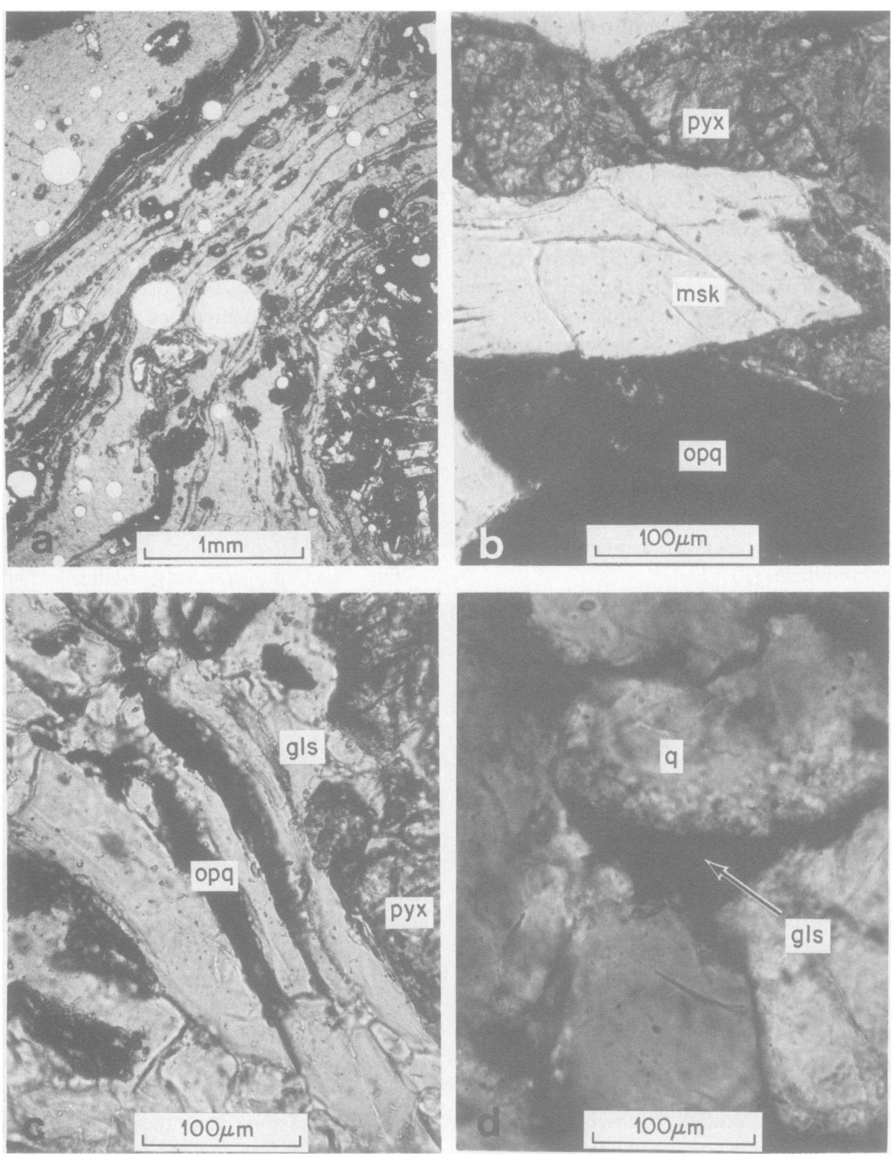


Fig. 1. Bishunpur L3 chondrite with chondrules of diverse sizes, shapes, and textures. Plane polarized light. [Photograph by W. R. Van Schmus; reprinted through the courtesy of Pergamon Press]



those found at terrestrial impact craters.

If, on the other hand, the sizes of the impacting bodies are such that the projectile delivers more kinetic energy than 10^7 erg/g to the target, both particles are destroyed and no impact crater is formed (*14*). I call such impacts "particle-to-particle" collisions, using the word collision (in contrast to the word impact) to imply that the bodies are of the same order of magnitude in size. There are almost no data regarding the nature of the products (particularly the glasses) formed by high-velocity particle-to-particle collisions, in contrast to particle-to-parent impacts, for which a relatively large amount of field data exists. In this article I propose that there are substantial differences between "particle-to-parent" impacts and "particle-to-particle" collisions and that some of the problems of the impact hypothesis for the origin of chondrules are resolved if droplet chondrules were formed by particle-to-particle collisions.

Impact Glasses Characteristic of Particle-to-Parent Impacts

The following four types of glasses are found in the ejecta of impact craters:

1) *Glasses formed by bulk melting of the rock* (Fig. 2a). Impact glasses that are polymineralic in composition or show evidence of flow of individual mineral components toward a mixed state are inferred to have been formed by bulk melting of rock by high-pressure shock waves. The melting may have occurred in a zone fairly close to the penetration path of the meteorite, or in a jet formed at the instant of contact of the meteorite with the ground (see next section). Such glasses generally appear extensively sheared and may have been significantly devolatilized (*13*). They may contain inclusions of lithic fragments incorporated while the glass was molten

Fig. 2. (a) Glass formed by bulk melting of basalt from Lonar Crater, India. Note regions which are reasonably homogeneous and regions which are inhomogeneous, vesicles, and recrystallization around a small grain (upper left) and large lithic inclusion (lower right). Plane polarized light. (b) Thetomorphic labradorite grain, maskelynite (*msk*), in contact with augite (*pyx*) and an opaque (*opq*) ulvospinel in shocked basalt from Lonar Crater. Plane polarized light. (c) Melted labradorite (*gls*) surrounded by shocked augite (*pyx*) and including partially melted opaque (*opq*) grains. Maskelynite was probably formed as an intermediate phase before melting of this grain. Shocked basalt from Lonar Crater. Plane polarized light. (d) Glass (isotropic material in center) formed by pressure melting of quartz (*q*) in shocked Coconino Sandstone at Meteor Crater, Arizona. Crossed polarizers.

(*13, 15*). The glass fragments range in size from micrometers to centimeters in diameter; they range in shape from spherules to angular shards to large bombs (fladen). The size and shape of molten glass fragments are determined by the conditions of ejection from the crater. Impact-melted spherules, shards, and bombs were found intermixed with unshocked and shocked debris in the fallout at Lonar Crater, India, by Frederiksson *et al.* (*13*). Lunar spherules occur in similar association with shocked and unshocked ejecta fragments, as do some chondritic spherules (*6*).

2) *Glasses without evidence of flow, possibly formed by solid-state transformation* (Fig. 2b). Monomineralic glasses that lack flow structures and vesiculation were called thetomorphic glasses by Chao (*16*) in recognition of the fact that they retain the original shape of the grain from which they were formed. Such glasses are found in rocks that have been shocked to low or moderate pressures (*17*) and are generally believed to have formed by solid-state disordering of the mineral lattices (*18*). Thetomorphic plagioclase glass occurs in the Shergotty meteorite (*1, 19*), in lunar samples (*20*), and in shocked rocks from a number of terrestrial craters (*21*), and has been produced in laboratory experiments (*18*); thetomorphic quartz glass and thetomorphic coesite glass are found at Meteor Crater, Arizona (*22*).

3) *Glasses formed locally within a rock from a compressible component* (Fig. 2c). In some shocked rocks, a single mineral component has melted and flowed; for example, in some of the shocked basalts from Lonar Crater labradorite grains were shock-melted but pyroxenes and opaque minerals remained crystalline. The glassy regions are, on the average, equal to the grain size of the minerals in the original rock. High-pressure phases or thetomorphic glasses may have formed as intermediate phases in this melting process (*22*), which occurs under shock-loading to moderate pressures, insufficient to totally melt the rock.

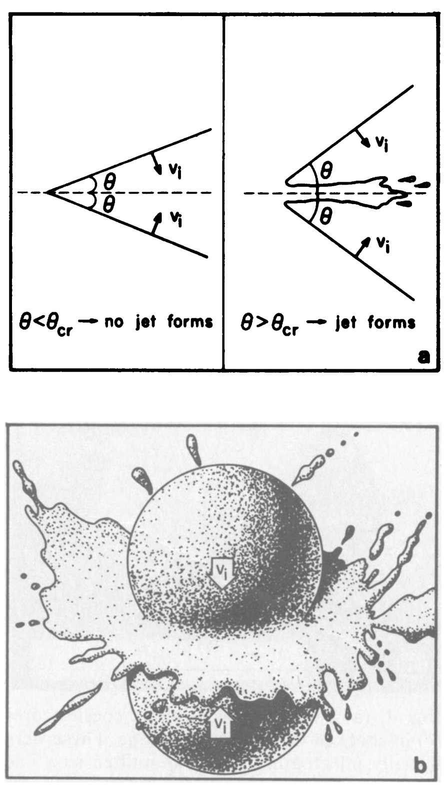
4) *Glasses formed by high stresses at grain boundaries* (Fig. 2d). Observations of shocked Coconino Sandstone from Meteor Crater (*23*) and of lunar breccias (*24*) reveal small amounts of glass or devitrified glass at contacts between grains. High pressures and shear deformation at grain boundaries during shock result in the formation of small amounts of glass in these regions.

The ejecta from impact craters characteristically contains all four types of glass fragments listed above. These fragments have a variety of sizes, shapes, and relationships to other rock components; the glass is not simply in the form of small spherules which resemble droplet chondrules.

In addition to these four glasses, a fifth type of melted material is produced if the impact crater is formed in porous materials. This melt is formed by impact of grains as pores collapse under shock compression. The melt is injected into the pore spaces, where it cools and, generally, crystallizes. I propose that this process, described in the next section, is similar to the process that occurs during particle-to-particle collisions.

Melt Formed by Jetting

The fifth process by which melt is produced during an impact event is jetting, the extrusion of hot material from the intersection of obliquely colliding surfaces (*25, 26*). I refer to the stream of hot material that emanates from the point of collision as the "jet" and to the final products of the jetting process (cooled from high temperature) as "jecta."



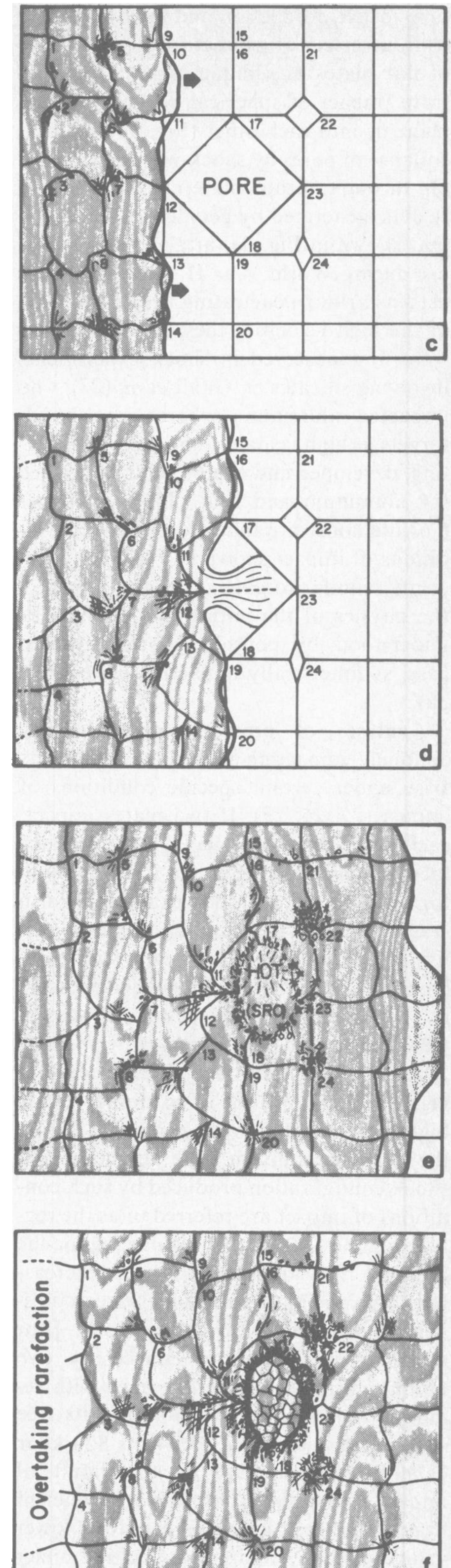


Fig. 3. Geometries that may give rise to jetting: (a) a collapsing wedge and (b) impacting spheres. Schematic drawings of pore collapse in shocked Coconino Sandstone: (c) The shock (heavy line) impinges on a pore; irregularities of pressure in the shock wave are implied by the stippled pattern. Fractures in quartz are shown as thin lines, fractured quartz fragments as open circles, and coesite nuclei as black spots. These features are formed primarily in regions of shear along grain boundaries. (d) The jet is formed from collapsing grains and injected into the pore. (e) A hot amorphous phase (SRO) exists temporarily in the collapsed pore. Stishovite (shown as stars) forms in small regions of high stress. (f) Upon pressure release the jet cools to form a jectum of coesite which nucleates and grows in the core. A thermal aureole forms around the jet as heat flows outward into the cooler quartz grains. The transformation of quartz to coesite is accelerated by the high temperatures within the thermal aureole and results in the formation of an opaque rim.

Obliquely impacting surfaces are necessary for jet production and they may arise from a variety of geometries: from impact of flat plates at oblique angles (Fig. 3a), from impact of spherical particles onto a plane or into each other (Fig. 3b), or from collapse of pores by shock waves propagating through porous materials (Fig. 3, c to f). Jets, generated by geometries similar to that shown in Fig. 3a, attained a practical use during World War II when they were used as armor-penetrating devices because of the high velocities they can attain. Jets were first observed in shock experiments involving silicates by Gault *et al.* (*27*), who impacted aluminum spheres into basalt targets at high velocity. The theories of jetting, developed and experimentally verified for aluminum and lead (*25*) and copper (*26*), demonstrate that the geometric conditions of impact shown in Fig. 3 are sufficiently similar to each other that much of the physics of the jetting process may be understood by considering the simplest case, symmetrically impacting plates (Fig. 3a).

Analyses of pressures generated by obliquely impacting plates show that jets arise under certain specific conditions of impact (*25, 26, 28*). If two plates impact, each with velocity v_p normal to its free surface, the pressure generated is a minimum for head-on collision; for example, Walsh *et al.* (*25*) calculated that for a head-on collision of aluminum plates, each with a velocity of 2.28 km/sec, the induced pressure is 450 kilobars. If the plates are canted from the normal during impact by an angle 2θ, they close along their interface with a velocity $v_i/\tan\theta$ and, in so doing, create higher pressures than are generated during the head-on collision. The geometry and shock configuration produced by such conditions of impact are referred to as the regular regime (*28*). In this regular regime the pressure rises monotonically with increasing angle, giving rise to an increase in pressure by approximately a factor of 2. [For example, the pressure induced by two aluminum plates impacting, each with velocity v_i = 2.28 km/sec normal to its free surface, at angle $2\theta = 25°44'$, is 820 kbar (*25*).] Pressure increases due to obliquity of impact in the regular regime are sufficient to generate melt locally at relatively lower velocities than required for melting under head-on collisions, and this process probably accounts for some of the glass formed at grain boundaries in the Coconino Sandstone or in lunar breccias (glass type 4).

If the impact angle is larger than a critical angle, $2\theta_{cr}$, which varies with impact velocity, the regular regime breaks down and a squirt of hot material emanates from the point of collision (Fig. 3a). This stream of material is the jet. Shock configurations that produce jets are complex and are referred to as irregular regimes (*28*). The point of emanation of the jet is a stagnation point; therefore, in accordance with Bernoulli's theorem, all kinetic energy is transformed into enthalpy at this point (*25*). The pressure at the stagnation point of two aluminum plates impacting at angles slightly above $2\theta_{cr} = 25°44'$, each with velocity 2.28 km/sec, is, according to Bernoulli's theorem, 2.25 Mbar (*25*). The shock configuration that produces jets gives rise to a directional focusing of shock energy, with the consequent formation of high-temperature melt; sufficient energy is deposited to make jets in metals self-luminous.

Jets may form in two regions of an impact crater: (i) upon initial contact of the meteorite and regolith surface, a jet can be extruded from the meteorite-target interface (*27*), and (ii) upon collapse of grains across pores in a regolith, jets may be injected into pores. The first process should produce melt of the bulk composition of the target rock (glass type 1) perhaps enriched in meteoritic components. The second process occurs only if impacts are into porous regoliths and produces jets which cool to form jecta of unique characteristics, described below.

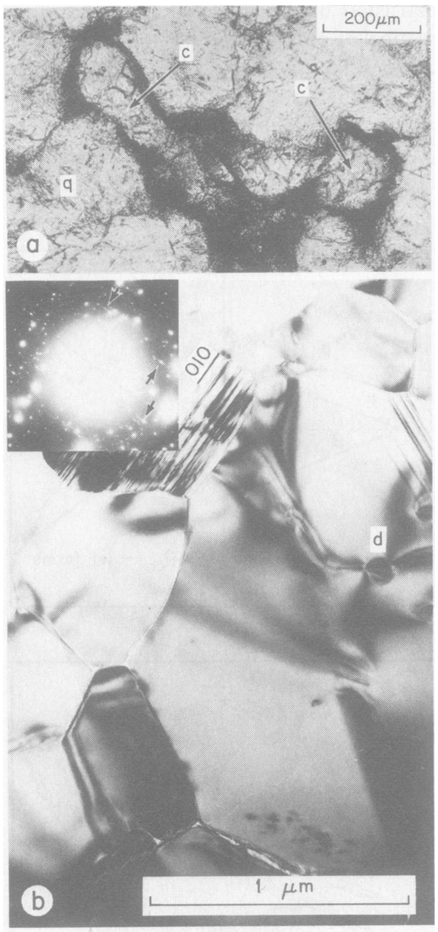


Fig. 4. (a) Two cryptocrystalline coesite cores (*c*) in shocked Coconino Sandstone. These were initially injected into pores as molten jets. The dark rim which surrounds the coesite cores is a thermal aureole (see text) and contains grains of coesite (typically less than 1 μm in diameter) and stishovite. The quartz grains (*q*) are relatively unshocked. Plane polarized light. (b) Electron micrograph showing the characteristic equilibrated texture of coesite in the core. Dislocations (*d*) are present in the coesite; twins parallel to (010) cause streaking on the spots indicated by small arrows on the diffraction pattern. [Micrograph by P. Thakey, S. Kieffer, and J. Christie]

Jetting in the Coconino Sandstone

A particular type of material found in shocked Coconino Sandstone from Meteor Crater appears to be interstitial jecta (*29*); a study of this material, which was formed by the collision of quartz grains 0.1 to 0.2 mm in diameter during shock, provides information about the products formed upon high-velocity collision of roughly equidimensional particles. In moderately shocked Coconino Sandstone [class 3, defined in (*23*)] abundant "cores" of cryptocrystalline coesite occur in regions interpreted to be collapsed pores (Fig. 4a) (*23*). Transmission electron micrographs (*22*) show that these cores have a mosaic texture, with many grain boundaries intersecting at angles of 120° (Fig. 4b). Such a texture is characteristically observed in annealed recrystallized metals and single-phase mineral aggregates. The texture is referred to by metallurgists as a mature polycrystalline structure, and indicates that grain boundary equilibrium was nearly attained in these regions. These cores are the only regions within naturally shocked rocks where textural evidence for equilibrium within shock waves has been found. Since the cores had only 10 to 45 msec to form during the impact event at Meteor Crater (*23*), their equilibrated texture implies that they formed from a very hot precursor phase. Because of the steep slope of the SiO_2 liquidus, it is probable that the temperatures in the cores exceeded 2000°C.

The cores are inferred to be jecta—the cooled residue of jets injected into pores upon impact of quartz grains. The inferred process of formation of the jecta in the Coconino Sandstone is shown in Fig. 3, c to f; detailed discussion of the propagation of shock waves in porous media and the formation of jets is to be presented elsewhere (*22*). The shock wave generated by the impact of the meteorite caused the quartz grains of the Coconino to impact against each other as pores collapsed (Fig. 3c). Molten silica cores were formed as the leading regions of grains were jetted into the pores (Fig. 3, d and e). These cores, which are inferred to have been hot amorphous material or to have short-range order (SRO) only, subsequently crystallized to cryptocrystalline coesite jecta upon release of high pressure (Figs. 3f and 4).

The trailing regions of impacting grains which did not enter the jet were much less strongly shocked. These regions of the grains (plus other quartz grains that were not near pores) form a matrix of fractured quartz which surrounds the jecta (Figs. 3f and 4). This quartz shows no evidence of thermal recovery (*22*) and probably suffered initial heating of only a few hundred degrees. However, as the jets cooled by conduction of heat into this surrounding matrix of quartz, some of the quartz transformed into coesite on the periphery of the core; that is, a thermal aureole about 100 μm thick was formed (Figs. 3f and 4).

Large temperature gradients existed in these rocks, for if it is assumed that the original distance between unjetted, relatively cold fractured quartz and the jetted core was less than the 100-μm thickness of the thermal aureole, the temperature gradients must have been at least 20° per micrometer. It may be concluded that jetting is an efficient mechanism for focusing shock energy into the regions of impacting particles that enter the jet.

Jets are formed from material derived from at least two interacting grains. Therefore, the composition of the jet is determined by the composition of the colliding particles and the degree of mixing attained during the jetting process. The Coconino Sandstone, which is composed almost entirely of quartz, provides no opportunity to study the composition of jecta formed by collision of two grains of different compositions, such as olivine and pyroxene. It is likely that collisions between particles of different compositions would yield jecta of mixed compositions.

The preexisting pores in the regolith impart two textural characteristics to the jecta which reflect their origin within a regolith and which contrast with properties of droplets that solidify in free space. First the size and shape of pores in the regolith determine the size and shape of the jecta. Since most pores are, to first order, ellipsoidal, the jecta are also roughly ellipsoidal, but they do not have the perfect spheroidal form of cooled droplets. Secondly, jets formed by injection into pores cool relatively slowly. In contrast to droplets in free space, which cool primarily by radiative transfer, hot spots in a regolith cool primarily by thermal conduction, and since mineral grains are very poor conductors, the cooling is relatively slow (*23*). Quench textures therefore may not be as likely to develop in jets cooling within a regolith. Furthermore, if the cratering events are of roughly the same duration as the Meteor Crater event (10 to 45 msec), the jets may be at high pressure for much of their cooling cycle (*23*), with the result that the jecta consist of crystalline high-pressure phases, rather than glass or quenched high-temperature phases. It is possible that some irregularly shaped chondrules that are rimmed and have a granular, rather than a quenched, texture were formed by jetting within a porous regolith on a protoplanetary surface, and were subsequently broken free to be reassembled even later into the chondritic meteorites in which they are now found. However, the spheroidal shape and high-temperature phases of droplet chondrules suggest that they were not formed by jetting within a regolith.

Particle-to-Parent Impacts: Processes and Products

Upon high-velocity impact of a projectile against a target, shock waves that compress the material are formed in both the target and the projectile; initial pressures in the shock waves can be several megabars, depending on the velocity of impact. An initial jet may form at the surface of contact. During the first moments of impact the relative size of the two projectiles does not appreciably affect the shock configuration. The shock waves in each particle initially form a roughly hemispherical front as they expand rapidly outward away from the point of impact, and they therefore engulf a continuously increasing mass of material. The energy in the wave system is relatively constant, so that as the shock is propagated through an ever-increasing mass of material, the induced pressure decays quickly (approximately as the inverse third or fourth power of the distance from the impact).

The ratio of particle sizes becomes important as the shock propagates further from the point of impact. If one particle (called here the parent) is so much larger than the other that it is effectively infinite in size, the wave front in the parent encounters no free surfaces and the basic hemispherical shape of the shock front remains undistorted. The compressive wave front decays to a simple seismic disturbance. Hence, an impact crater surrounded by a zone of broken and fractured target material is formed in the parent.

The wide range of pressure and temperature conditions associated with the essentially unlimited expansion of the compressive shock front in the parent gives rise to the association of glasses and shocked and unshocked fragments typically found in crater ejecta from particle-to-parent impacts. In particular, the type 1 melted glass, including shards and spherules, is intermixed with the other types of glasses formed interstitially and intragranularly, and with moderately shocked and unshocked fragments formed in different regions of the crater. Glass spherules comprise only a small fraction (< 1 percent) of typical crater ejecta from particle-to-parent impacts.

Particle-to-Particle Collisions: Model for Processes and Products

In both bodies of a particle-to-particle collision, and in the smaller body of a particle-to-parent impact, the expanding hemispherical compressive wave fronts generated initially are disturbed by reflection from the boundary surfaces of the particles. The reflected waves are rarefaction waves, complex systems of tension and shear waves. In brittle substances, such as rocks and minerals, these rarefaction waves cause extensive spallation and fracture of material near the boundary surfaces (*14*). Hence, the shock history experienced by material at a particular distance from the point of impact in a small particle may be very different from that experienced by material at the same distance from the point of impact in a large particle.

On the basis of these considerations of the shock conditions that exist in small particles during impact, and the description of grain-to-grain collisions given above, I propose the following model for the high-velocity collision of two roughly equidimensional particles of zero porosity (*30*). Upon impact, material near the point of collision is melted by high shock pressures and jetting. A roughly hemispherical compressive shock wave propagates into both particles, but is disturbed by reflection of the shock from boundary surfaces with the result that much of the unmelted material is pulverized by spallation and fracturing initiated at the free surfaces. Very little material experiences a shock history intermediate between the two extremes of melting and fracturing.

It is necessary to consider the amount of melt that might be formed by particle-to-particle collisions, for in order to produce chondrites that are 50 to 70 percent chondrules without a sorting or chondrule-enrichment episode following their formation, the collisions must be relatively efficient in converting the mass of the colliding particles to melt. The amount of melt that is generated will depend on the velocity of impact of the particles. Although we currently do not have laboratory data on the amount of melt produced by particle-to-particle collisions as a function of velocity, it is possible to obtain rough estimates of the amount of melt produced and the velocities of impact of grains in the Coconino Sandstone. The jecta (the cryptocrystalline coesite cores) typically comprise 10 to 20 percent of the shock-metamorphosed class 3 samples, and if every quartz grain of the original rock had been involved in a jet-forming collision, then on the average at least this fraction of quartz was transformed to melt by a typical collision. The average velocity of impact of grains can be estimated from the equation of state of quartz (*31*) and Coconino Sandstone (*32*), and from a model for the behavior of individual grains during shock compression of a porous material (*23*). The average pressure experienced by the class 3 shocked Coconino Sandstone fragments was between 150 and 250 kbar (*23*); the equations of state suggest that the average relative velocity of impact of grains was between 2.0 and 4.5 km/sec at these pressures. At higher relative velocities of impact, a larger fraction of the mass of impacting grains was converted to jecta. In class 4 shocked Coconino Sandstone samples (*23*), which are interpreted to have experienced pressures above 250 kbar, and therefore higher particle velocities, 50 to 60 percent of the quartz was converted to jecta. [The jecta in these rocks are much more difficult to recognize because the jets inverted to vesicular glass on cooling (*23*).]

In summary, the geometric differences between particle-to-parent impacts and particle-to-particle collisions cause two substantial differences in the impact processes: in particle-to-particle collisions (i) initial jetting causes melting of a much larger fraction of the total mass of the particles, and (ii) disturbances of the expanding shocks by the reflected rarefaction waves cause much of the unmelted material to be pulverized by spallation and fracturing. Very little material experiences a shock history intermediate between these two extremes.

Origin of Droplet Chondrules

The texture of ejecta from impact craters made by particle-to-parent impacts does not resemble the texture of chondritic meteorites in detail. The dissimilarity leads to two well-recognized difficulties with the hypothesis that chondrules were formed by impacts of meteorites into protoplanets of asteroidal size: (i) ejecta from impact craters show a wider range of shapes and sizes than the chondrules and chondrule fragments in chondritic meteorites, and (ii) crater ejecta consist of a mixture of shocked and essentially unshocked debris, of which glass spherules that resemble chondrules comprise only a small fraction. Impact theories for the origin of chondrules must account for the unimodal and narrow size distribution and textural characteristics of chondrules by providing either a process of chondrule formation that produces only such particles, or a process that sorts a larger distribution of sizes and textures subsequent to chondrule formation. [For example, Dodd (*6*) proposed that material formed by impact cratering was recycled back into the nebular cloud by the impacts and that subsequent gravitational settling provided sorting.]

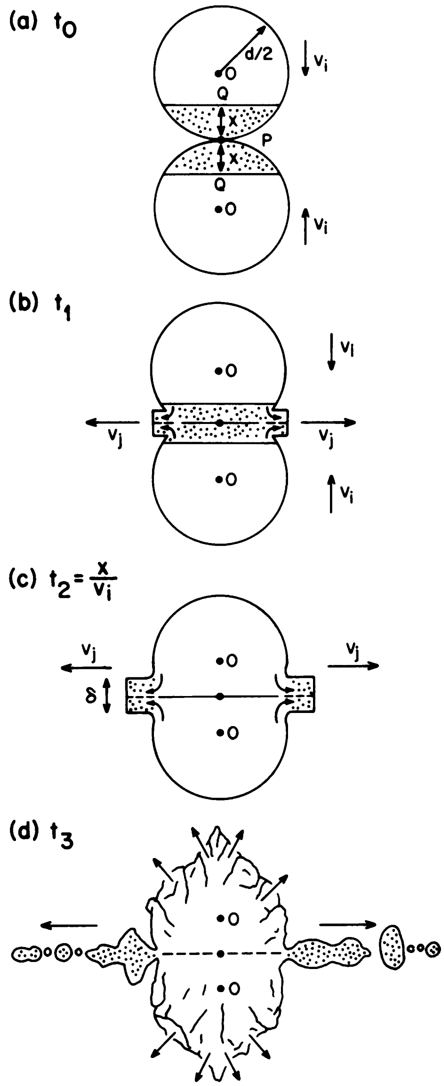


Fig. 5. Schematic drawing of the formation of chondrules. (a) Two spheres of diameter d impact with relative velocity $2v_i$. (b) Material from the segment of height x flows into the central plane of the impact and out into the jet, which is extruded at average velocity v_j. (c) The segments collapse in time $t = x/v_i$, during which the material from the segments has been transferred into an annulus around the collapsed particles. (d) Instabilities develop in the annulus, which breaks down into columns (rays) and droplets. The trailing portions of the spheres are fractured by rarefaction waves. A cone of fractured material erupts from the antipodal point of each sphere (*14*).

These problems associated with the formation of droplet chondrules by impact on protoplanets can be resolved by the following model. It is assumed that the droplet chondrules were formed by collisions between small particles of restricted size ratios—by particle-to-particle collisions rather than particle-to-parent impacts. The collisions were at sufficiently high velocity that molten jets were extruded into space (see Fig. 3b). As these jets broke into small globules because of inherent instabilities in the flow of liquids they cooled to form spherical jecta, which became the droplet chondrules. The fine-grained matrix material observed in chondritic meteorites may be the fraction of the impacting grains which did not enter the jet; it experienced a relatively low-temperature, low-pressure history. (Some matrix material may also consist of particles which never attained sufficiently high velocities to become involved in chondrule-forming collisions, and some might also consist of chondrules crushed by impacts after their formation.)

The following simple model of the particle-to-particle collision process is introduced to estimate the size of impacting particles which could have formed droplet chondrules. Two spherical particles of equal diameter d, volume V_{sph}, and density ρ are assumed to impact with equal and opposite velocities v_i relative to the central point of contact P, as shown in Fig. 5a. A radially symmetric jet begins to form as material flows from the edges of the spheres into the plane of symmetry perpendicular to v_i (Fig. 5b). Let $m = m(v_i)$ denote the mass fraction of each incoming projectile which enters the sheet, and assume that this fraction is derived from the first segment of each colliding sphere to interact, as shown in Fig. 5, b and c. The segment from which the jet is derived has volume V_{seg} and height x, which is related to the mass fraction m as

$$\frac{V_{seg}}{V_{sph}} = m = \frac{x^2(3d - 2x)}{d^3} \qquad (1)$$

If m is small and $x << d$, this gives $x \sim d(m/3)^{1/2}$.

The spheres collapse the distance x in time $t = x/v_i$, during which the sheet forms. A three-dimensional sheet would thin with distance from the point of impact, in order to satisfy conservation of mass, and because of instabilities of fluid flow, the sheet would break into filaments and droplets after a short distance, as illustrated in Figs. 5d and 3b. In this model, however, the mass fraction m is assumed to be completely transferred to an annulus surrounding the colliding spheres before this breakup begins (Fig. 5c). The annulus is assumed to have average thickness δ and average radial velocity v_j at time $t = x/v_i$. The outer radius at this time is then $v_j x/v_i$ and the inner radius is $(xd - x^2)^{1/2}$; hence, the volume is

$$V_{jet} = \pi \delta \left(\frac{v_j^2}{v_i^2} x^2 - dx + x^2 \right) \qquad (2)$$

where, for simplicity, the density of the jet has been taken equal to ρ. Conservation of mass requires that $V_{jet} = 2m V_{sph}$; hence

$$d = \delta \left[\frac{v_j^2}{v_i^2} - \left(\frac{3}{m} \right)^{1/2} + 1 \right] \qquad (3)$$

The diameter d obtained from this equation will be the largest for maximum values of v_j/v_i and δ and a minimum value of m, and is relatively independent of reasonable values for these parameters.

A limit may be placed on the velocity ratio v_j/v_i by considering conservation of energy, which requires that $mv_j^2 \leq v_i^2$. The choice $v_j/v_i = (m)^{-1/2}$, which is equivalent to assuming that all projectile energy is transferred to the jet, maximizes the calculated particle radius r. In fact, because of dissipative processes within the shock (such as heating) and deposition of some shock energy in material of the spheres which does not enter the jet, the velocity of the jet will be substantially less than the value given by this assumption.

In order to relate the thickness δ of the annular sheet (the jet) to the mean diameter of chondrules (the jecta), it is assumed that the sheet breaks into columnar filaments of average diameter δ and that these filaments then break up into droplets (the droplet chondrules). Laboratory data on liquid jets (*33*) demonstrate that such columnar filaments break up into primary, secondary, and even tertiary droplets due to the growth of instabilities. The size of the droplets depends on the initial jet diameter, its velocity, viscosity, and surface tension, and a characteristic wavelength for the initial disturbance. Assuming inviscid flow, the largest droplet formed typically has a diameter 1.8 times that of the jet and the smallest (tertiary) has a diameter 0.2 times that of the jet (*33*). The parameters for viscous breakup are not significantly different for the purpose of this model. In order to maximize the estimated value of d, it is assumed that droplet chondrules are the smallest (tertiary) droplets from jetting events; the average chondrule diameter, 0.4 mm, is then taken to be 0.2 times the sheet thickness; that is, δ is 2 mm.

With the assumptions, then, that $m = 0.1$, $v_j/v_i = 3.3$ and $\delta = 2$ mm, Eq. 3 gives a diameter of 1 cm for the particles from which the droplet chondrules of average diameter were formed.

In order to produce ejecta characteristic of particle-to-particle collisions rather than particle-to-parent impacts, the Gault-Wedekind criterion (*14*) specifies that the ratio of particle sizes involved in the collisions must be fairly small. The maximum ratio of particle sizes depends on the velocity of impact, v_i, which is not specified by this model; however, an estimate of the minimum velocities may be made. It was concluded in the previous section that velocities between 2.0 and 4.5 km/sec were required for the conversion of 10 to 20 percent of impacting quartz grains to jecta in the class 3 Coconino Sandstone. Experiments of Gault and Wedekind (*14*) suggest that very little glass is produced on impact of aluminum spheres into Pyrex spheres at velocities of 1 to 3 km/sec, so it is likely that 3 km/sec is the minimum impact velocity at which an appreciable fraction of quartz (say, 10 percent) can be converted to melt by jetting. Jetting may occur at somewhat lower velocities on impact of bronzite and dunite particles, which are more typical of meteoritic composition than are quartz particles (*34*).

If the average impact velocity was 3 km/sec, the Gault-Wedekind criterion that particle-to-particle collisions have more than 10^7 erg/g delivered to the target mass dictates that the ratio of particle sizes could not exceed 20; if the average velocity was 10 km/sec the limiting ratio is 40. This suggests that, if the average particle diameter was 1 cm, most particles were in the range 0.5 mm to 20 cm diameter. It should not be concluded that particles of larger or smaller size were absent at the time of formation of droplet chondrules. It is suggested, however, that collisions of particles within this size range were the dominant events of the chondrule-forming epoch.

Summary

I have proposed that droplet chondrules were formed by jetting during collision of meteoritic particles with diameters ranging in order of magnitude from 0.5 mm to 20 cm. This conclusion, based on a dynamic model for the collision process, supports the hypotheses of Wasson (*2*) (based on geochemical considerations) and Whipple (*35*) and Cameron (*36*) (based on dynamic model considerations) that chondrules were formed from objects less than 1 m in radius.

In this model, the formation of chondrules is viewed as a textural, but not substantial chemical, change in the material of the early solar system. Droplets of melt produced by jetting are mixtures of material derived from two parent grains. Jets are probably not appreciably fractionated (except in volatile elements) either in the short duration of the shock events (several microseconds) or in subsequent cooling.

This model for the formation of droplet chondrules implies that they were formed at a time in the history of the solar system when particle sizes were small. The most likely time for this condition is early in the process of accretion of nebular dust to planetary matter. Since velocities less than approximately 1.5 km/sec are required for the agglomeration and accretion of particles (*37*), the relatively higher velocities indicated for droplet chondrule-forming collisions indicate an early high-velocity destructive epoch amidst the general trend toward accretion of material.

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Compartments and Polyclones in Insect Development

Clones made in early development keep within certain fixed boundaries in the insect epithelium.

F. H. C. Crick and P. A. Lawrence

In this article our aim is to describe recent work on the development of intact epithelia and in particular the important results and ideas of Professor Antonio Garcia-Bellido (*1*) and his group in Madrid which are not yet widely known. We try to explain as clearly as possible what these ideas are and what sort of experiments have been done to support them. Some of the more obvious questions arising from the results and how the new concepts may relate to other ideas such as "gradients" are listed.

Development of *Drosophila*

The development of an adult *Drosophila* is a complex process. The nucleus of the fertilized egg divides a number of times to form a compact mass of about 250 nuclei, near the center of the egg, without cell walls. These nuclei then migrate outward to the inner surface of the egg where for the first time cell membranes are formed. The cells divide several more times to form a single layer of cells, about 4000 in all, lining the inside of the egg. This is called the blastoderm. Behaving as a sheet of cells, the blastoderm undergoes complex folding movements generating a multilayered germ band, which soon becomes visibly segmented. The egg hatches after 24 hours and the animal then goes through three larval stages each separated by a molt. After these larval stages, lasting in all about 96 hours, the animal then pupates and metamorphoses into the adult fly.

This adult is formed mainly from special groups of cells in the larva which themselves take little or no part in larval development or function. These are the histoblasts and the imaginal discs. There are 19 of the latter (nine pairs of discs plus the single genital disc). We shall concentrate mainly on one pair of these, the so-called wing disc. The left wing disc, within the left side of the larva, produces the left wing of the insect and that part of the dorsal left side of the thorax next to the wing.

The wing disc is seen in the first larval stage as a small patch of embryonic epidermal cells (*2*). These cells remain diploid, while the surrounding larval epidermal cells become polyploid (*3*). There are probably only about 15 to 30 cells forming the wing disc at this early stage (*4–6*). During the course of larval growth these disc cells divide in all about 10 or 11 times (on average) to give a total of some 50,000 cells (*5*). Shortly after puparium formation cell division of the disc stops. The disc has now a characteristic size and shape, being somewhat like a flattened and heavily folded balloon (*7*).

At metamorphosis a complicated set of cell movements occurs, and these result in the disc being turned inside out so that it can form the adult structure. The wing itself, for example, is first formed as a bag. The bag is then collapsed to form the adult wing, which thus becomes a single sheet of epithelial cells folded and collapsed to form a double layer of epithelial cells.

Basic Ideas of Clonal Analysis

For the purposes of exposition we now temporarily leave the wing and describe a hypothetical sheet of "white" epithelial cells on the adult fly. We imagine that we have at our disposal a special technique that enables us to mark (say black), at random, a single cell in a developing disc. The mark is such that it does not interfere in any way with the normal development of the animal. Moreover, all the descendants of this marked cell retain the mark and can be recognized in the adult. The method of marking has the advantage that we can choose fairly precisely when, in development, we mark the cell; but it has the disadvantage that we cannot mark a particular cell at that time, but only one chosen at random, and in early stages we usually mark only one cell in any one individual. If we assume that the significant features of the process are effectively the same in all individuals, we can piece together what is happening in development by combining experiments on many different individuals.

What do we find? Naturally, we see a set of black cells in the adult, but how many of them are there, and how are they arranged?

The first observation is what might be

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