

Hot Idea

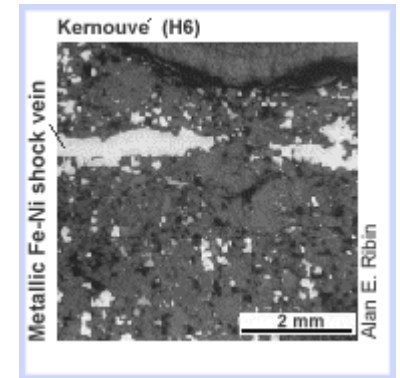
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Asteroid Heating: A Shocking View

--- Mineral intergrowths in chondritic meteorites may indicate that some asteroids were heated by impact.

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Almost all meteorites are chips of asteroids. Their mineralogical and chemical properties show that they have been heated to varying amounts, from a little (only 25 °C or so) to melting at more than 1100 °C. Isotopic dating shows that meteorites formed near the beginning of the solar system 4.55 billion years ago. What was the source of energy to heat them? The leading candidate is the decay of short-lived radioactive isotopes such as aluminum-26 (²⁶Al). This isotope has a short half-life, only 700 thousand years. It decays rapidly, releasing heat as it does so. Studies of chondritic meteorites prove that ²⁶Al was present when the solar system formed, so it is the logical source of heat to warm up and even melt asteroids.

Parts of asteroids have also been heated by the impact of other asteroids. Alan Rubin (UCLA) has been studying the effects of shock in chondrites for a long time. He has documented what this generally messy process does to chondrites and other stony meteorites whose ages show that they were affected by impacts long after ²⁶Al had decayed completely away. He now reports that some of the features common to shocked chondrites (those clearly affected by impact) are also abundant in apparently unshocked chondrites. This leads him to suggest that impacts played an important role in heating chondrites. If correct, this conclusion has great implications for the early history of the asteroid belt. The idea is controversial, however, and will be debated by meteoriticists.

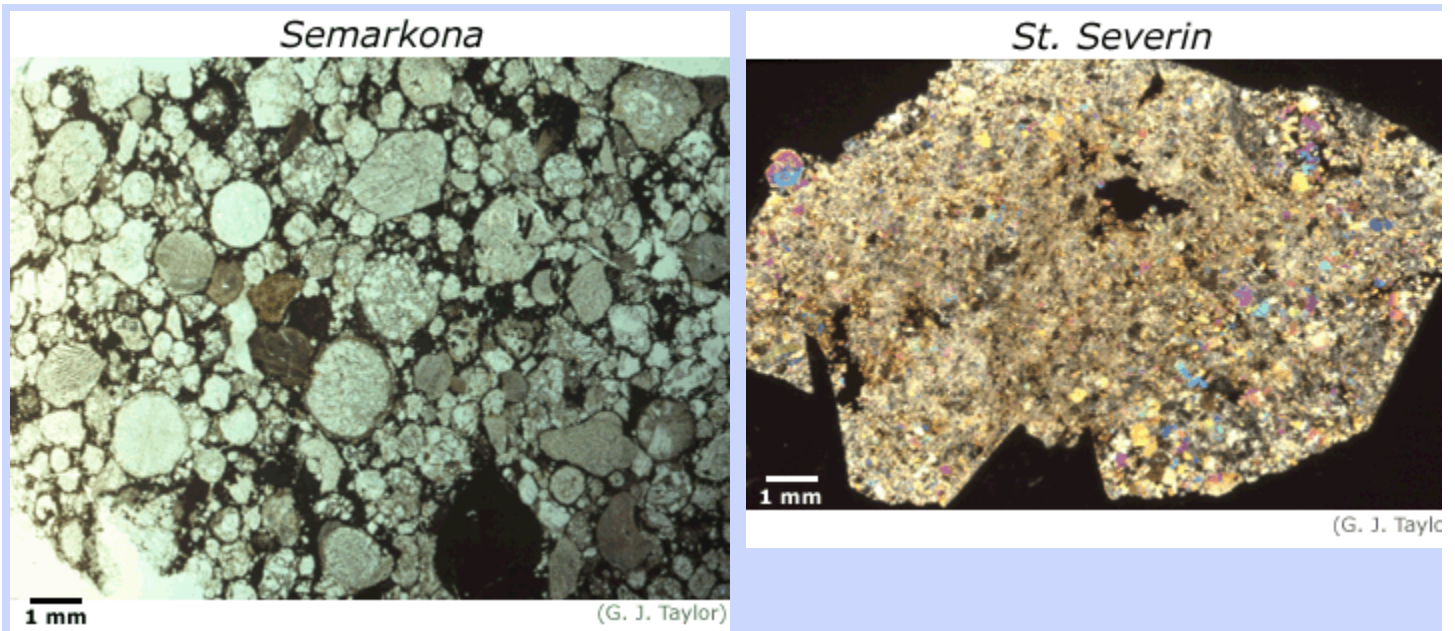
References:

Rubin, Alan E. (2003) Chromite-plagioclase assemblages as a new shock indicator; implications for the shock and thermal histories of ordinary chondrites. *Geochimica et Cosmochimica Acta*, v. 67, p. 2695-2709.

Rubin, Alan E. (2004) Postshock annealing and postannealing shock in equilibrated ordinary chondrites: Implications for the thermal and shock histories of chondritic asteroids. *Geochimica et Cosmochimica Acta*, v. 68, p. 673-689.

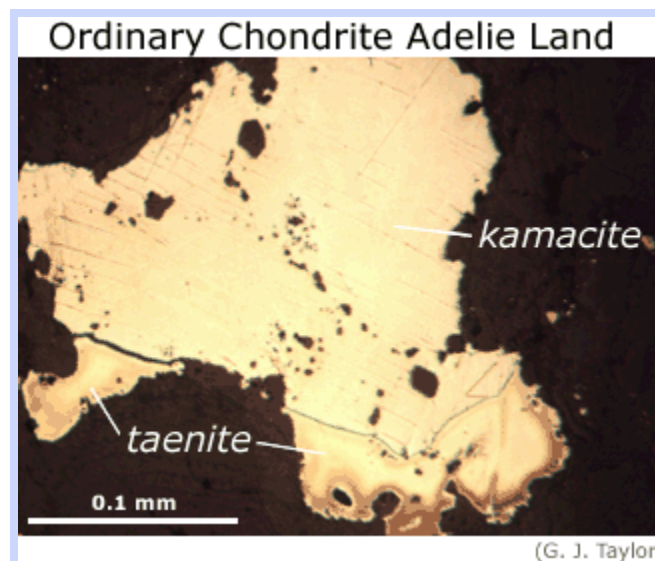
The Heating and Cooling of Ordinary Chondrites

Ordinary chondrites never melted, although some of their constituents did. Chondrites are named for the millimeter-sized spherules in them, chondrules, which formed as molten droplets in the gas and dust cloud surrounding the still-forming Sun. Nobody really knows how chondrules were made, but the consensus is that they formed before the asteroids and planets. Chondrules aggregated along with unmelted dust and metallic particles to form the parent asteroids of chondrites. The compositions and intergrowths of minerals in chondrites show that the amount of heating varied considerably inside the chondritic asteroids. Some were barely heated. Others were heated to 900 °C, causing mineral compositions to become uniform throughout and the boundaries between chondrules to become vague. Studies of thousands of chondrites show that there is a sequence of thermal effects, from unheated to strongly heated, forming a metamorphic sequence from type 3 chondrites, through types 4 and 5, to type 6, the most severely modified. Mineral compositions indicate that the highest temperature reached during metamorphism ranged from about 400-500 °C (for type 4) to 900 °C (type 6).



Photomicrographs of ordinary chondrites, showing an unmetamorphosed type 3 chondrite (Semarkona) on the left and a thoroughly metamorphosed type 6 chondrite (St. Severin) on the right. Chondrules (round objects clearly visible in the photograph on the left) become progressively less visible with metamorphic grade.

The metallic minerals in ordinary chondrites reliably record the rates at which chondrites cooled after they were heated. The cooling rate is recorded in variations in the concentrations of nickel and iron in metallic iron-nickel minerals. Cooling rates are quantified by knowledge of the rate of movement of iron and nickel in solid metal and of the way the compositions of two iron-nickel minerals (kamacite and taenite) vary with temperature. Numerous measurements indicate that most chondrites cooled at rates between 1 and 100 °C per million years. These rates are generally consistent with rates derived from precise determinations of the isotopic ages of chondrites: the older the chondrite, the faster the cooling rate. Rates between 1 and 100 °C/million years imply burial beneath several tens of kilometers of rock.



Photomicrograph of a polished slab of a chondrite (Adelie Land) showing kamacite and taenite grains. The slab was polished and then lightly etched in a solution of 1% nitric acid in ethanol, revealing microscopic properties. The color variation in taenite reflects variation in the concentration of nickel, which allows us to quantify the cooling rate of the chondrite.

Aluminum-26 and Asteroid Heating

²⁶Al was present when meteorites were forming (see **PSRD** article [Using Aluminum-26 as a Clock for Early Solar System Events](#)). It is a radioactive isotope with a half-life of only 700 thousand years, so its presence means that the solar system formed within a few half-lives of the formation of ²⁶Al in an exploding star. It decayed by emitting a beta particle (an electron), creating ²⁶Mg (magnesium-26) and releasing energy. The energy released is considerable. If ²⁶Al made up only 5×10^{-5} (0.005%) of all the aluminum in a chondrite (most is aluminum-27, which is not radioactive), it would release enough energy to melt asteroids a few kilometers across and larger. Lower amounts of ²⁶Al cause less melting.

Because aluminum was probably distributed uniformly throughout the asteroid, the body would have been heated uniformly, except for a temperature gradient in the regions near the surface where heat radiated into space. Once ²⁶Al had decayed for five or ten half-lives it was not abundant enough to heat an asteroid, so continuous cooling began.

Other heat sources have been proposed to explain asteroid heating. Floyd Herbert and Charles Sonnett (University of Arizona) suggested that huge outflows from the Sun could have caused induction heating of entire asteroids. It would be like zapping asteroids in a gigantic microwave oven. Heating would have been heterogeneous inside the body, dependent on variations in electrical conductivity. However, this heat source does not leave behind a specific fingerprint, unlike ²⁶Al which leaves behind extra ²⁶Mg, so it is hard to prove or disprove. Conventional wisdom is that asteroids were heated by the decay of ²⁶Al.

The Effects of Impact

High-velocity impacts leave impressive fingerprints. Impacts do more than make craters. They break up, mix, heat, and melt the target rocks. Individual mineral grains are damaged, leaving telltale signs visible in an optical microscope. Meteoriticists have been studying those effects for many years and this work contributed to development of a scheme for classifying the effects of shock (the rapid, temporary rise in pressure resulting from a high-velocity impact) in chondrites. The classification was devised by Dieter Stöffler (Institute of Mineralogy at the Museum of Natural History, Berlin, Germany), and Ed Scott and Klaus Keil (University of Hawai'i). It uses the effects seen in experimentally shocked samples and rocks found in terrestrial impact craters to classify ordinary chondrites from unshocked (S1) to heavily shocked (S6). The table below summarizes the classification scheme and links the shock effects to shock pressure and the increase in temperature caused by the shock.

Stages of shock effects in ordinary chondrites (from Stöffler *et al.*, 1991). S1 shows no effects of shock; S6 shows the most. The most important criteria are listed in **bold red**. The classification is based on changes in the properties of the minerals olivine and plagioclase feldspar as viewed in thin sections using an optical microscope. Shock pressure is listed in Giga Pascals (Gpa); 1 GPa is equal to 10,000 times the atmospheric pressure at the surface of the Earth.

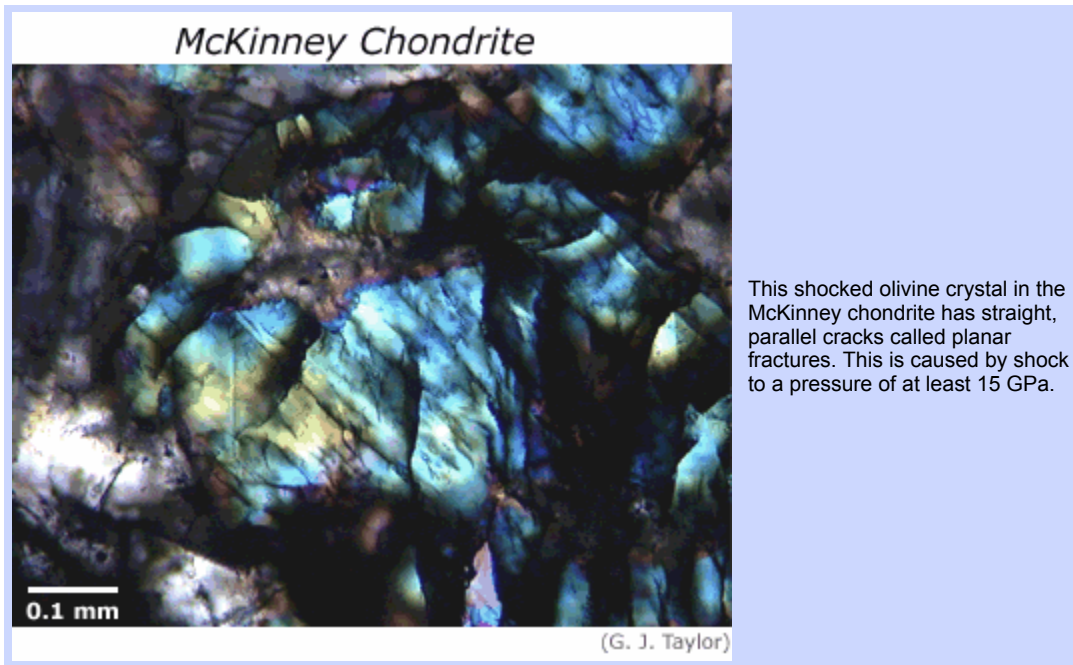
Shock Stage	Effects resulting from general shock pressure	Effects resulting from local P-T excursions	Shock Pressure (Gpa)	Minimum temp. increase (°C)
S1 unshocked	Sharp optical extinction as viewed in microscope. Small number of irregular fractures (cracks).	None	< 5	10
S2 very weakly shocked	Undulatory (wavy) extinction, irregular fractures	None	5-10	20
S3 weakly shocked	Olivine: Planar fractures , undulatory extinction, irregular fractures Plagioclase: Undulatory extinction	Opaque shock veins; melt pockets, sometimes interconnected	15-20	100
S4 moderately shocked	Olivine: Mosaicism (weak), planar fractures Plagioclase: Undulatory extinction, isotropic in places, planar deformation features	Melt pockets; interconnected melt veins; opaque shock veins	30-35	300
S5 strongly shocked	Olivine: Mosaicism (strong); planar fractures and planar deformation features Plagioclase: Maskelynite (isotropic feldspar)	Pervasive occurrence of melt pockets and veins; opaque shock veins	45-55	600
S6 very strongly shocked	Olivine: Solid state recrystallization and staining, presence of ringwoodite, local melting Plagioclase: Shock melted	Same as in stage 5	75-90	1500
Shock melted	Entire rock is melted	---	> 90	> 1500

The shock effects are visible using an optical microscope (some effects are visible in hand samples). Geologists have been using optical microscopy since the middle of the 1800s, especially after H. C. Sorby began to examine thin slices of rocks in the microscope. Thin sections are mounted on glass slides and ground to a thickness of only 30 micrometers (about one ten-thousandth of an inch). Most minerals are transparent when ground so thin, but some are still opaque. In chondrites metallic iron-nickel, iron sulfide, and assorted oxide minerals are opaque.

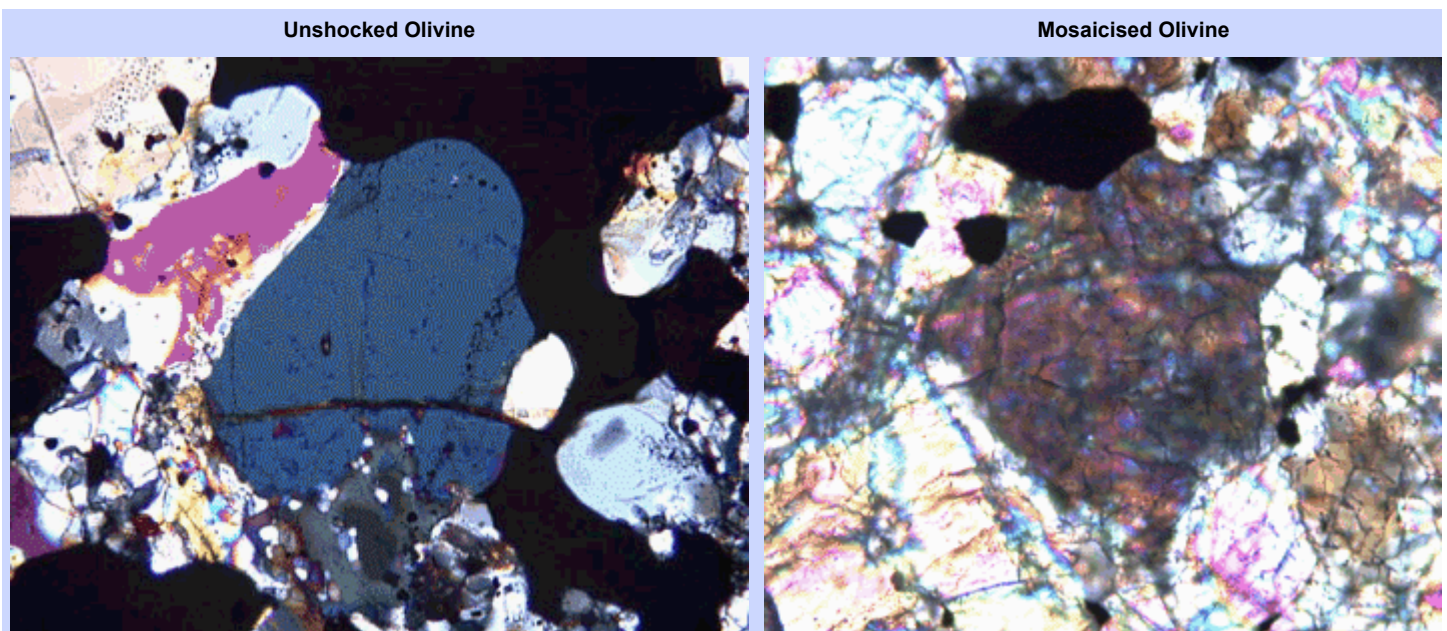
Petrographic microscopes come equipped with polarizing filters, one below the thin section and another above it. The filters are polarized in opposite directions, so if no mineral is in the light beam, no light gets through to the eyepiece—the first filter polarizes the light in one direction, blocking other directions of polarization, and the second filter does the opposite, thus blocking all the light. Minerals also polarize the light, so when a mineral is placed in the beam of light it changes the polarization direction so the light does not become completely blocked by the second filter. Instead, an interference color is produced. The colors are one of the diagnostic tools used to identify a mineral.

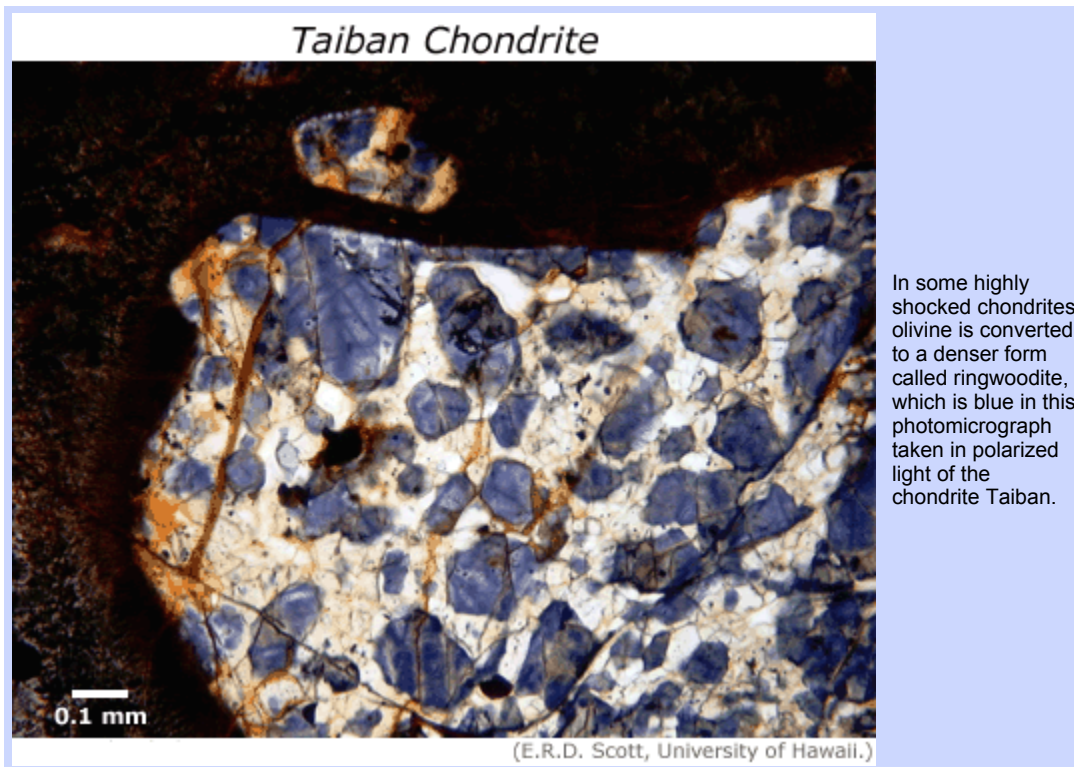
In this era of high-tech, high-cost laboratory equipment, we sometimes forget how useful a microscope can be. The shock classification summarized in the table above is based entirely on optical microscopy of thin sections. It uses several features in chondrites. At the lowest shock category, olivine and plagioclase crystals have irregular fractures (cracks). With increasing shock pressure, the grains develop planar fractures, which are simply cracks lined up in one direction. There is often more than one direction of fracturing in a single mineral crystal, and the cracks are oriented along crystallographic planes.

In polarized light, minerals blank out the light every 90 degrees when the stage of the microscope is rotated. This is called "extinction." (Minerals with cubic structures and uncrystallized glass are isotropic, so do not further polarize the light, thus making them appear dark at all orientations.) Unshocked olivine and plagioclase have crisp extinction—each crystal becomes dark quite suddenly and evenly when rotated. If shocked somewhat, the crystal structure is deformed and the extinction is wavy, a feature called "undulatory extinction." At higher shock pressure, the olivine crystal structure is messed up even further, forming small (only a few micrometers) domains that differ in their extinction positions. This causes a characteristic appearance called mosaicism. With increasing shock pressure, plagioclase shows increasing undulatory extinction, until at a critical pressure it simply transforms to a disordered, isotropic glass called maskelynite. Maskelynite is not melted. The shock wave rearranges the atoms in a crystal so it no longer has a long-range order to it. It is effectively a glass.



When an unshocked olivine grain is rotated in polarized light using a petrographic microscope, it becomes extinct (dark) evenly, like this one in Kernouvé (**see movie, below, on the left**). When shocked to a pressure exceeding about 45 Gpa, however, olivine is severely damaged and the extinction is spotty and irregular. This is called mosaicism as in the movie of the chondrite Alfianello, **below, on the right**. The field of view in each movie is 0.9 mm. Images by G. J. Taylor.

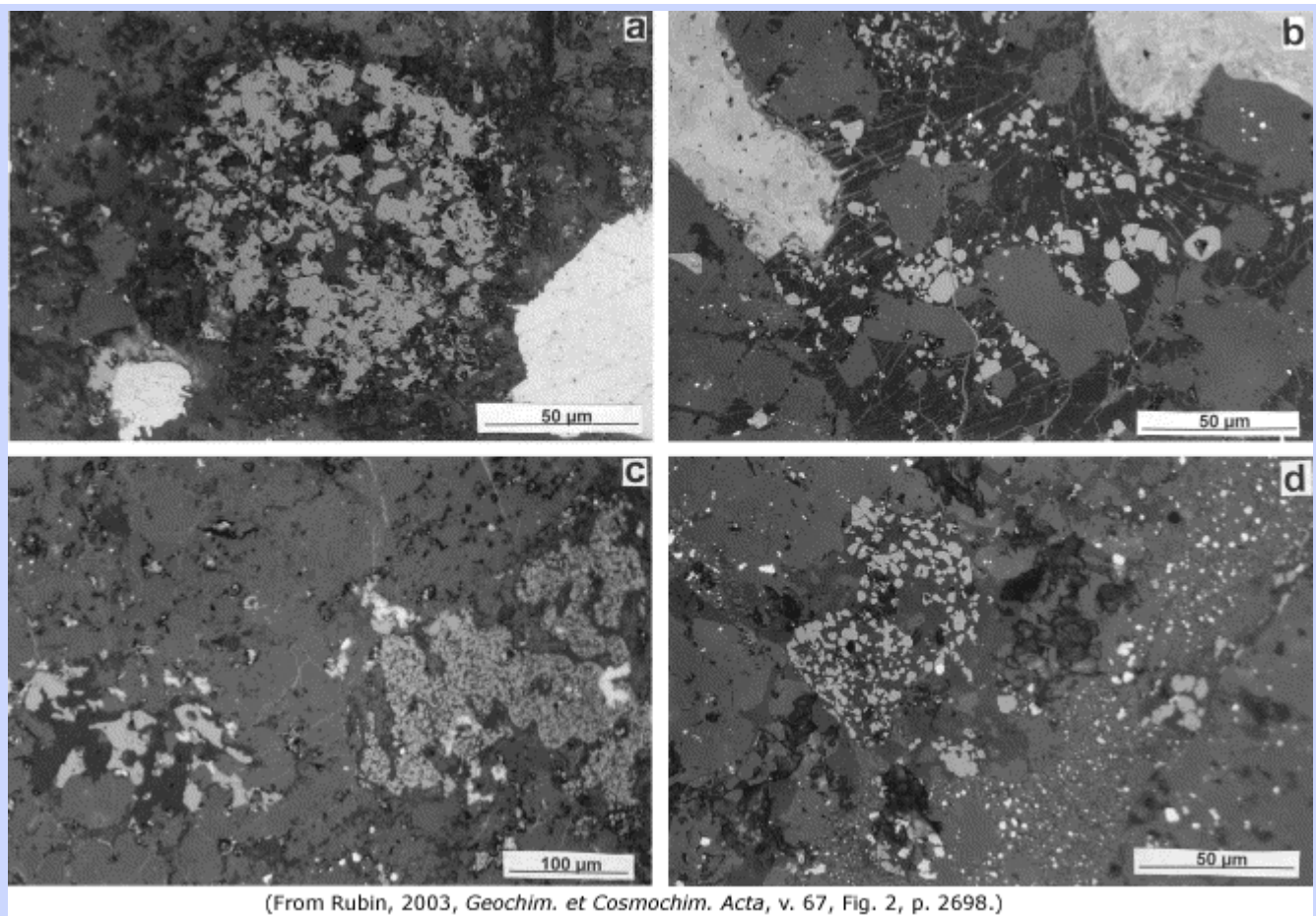




A shock wave does not pass uniformly through a rock, so some regions might be shocked more than others because of reinforcement by reflected shock waves. This can create local pockets of and veins of melted rock. Robert Dodd (State University of New York at Stony Brook) and Eugene Jarosewich (Smithsonian Institution) showed in 1982 that melt pockets tend to have higher aluminum than average in a chondrite, reflecting the fact that plagioclase is easier to melt by shock than other major minerals in chondrites. At high shock pressures large portions of the rock begin to melt, starting with small veins, then dike-like structures, and at the highest pressures almost total melting of the rock occurs.

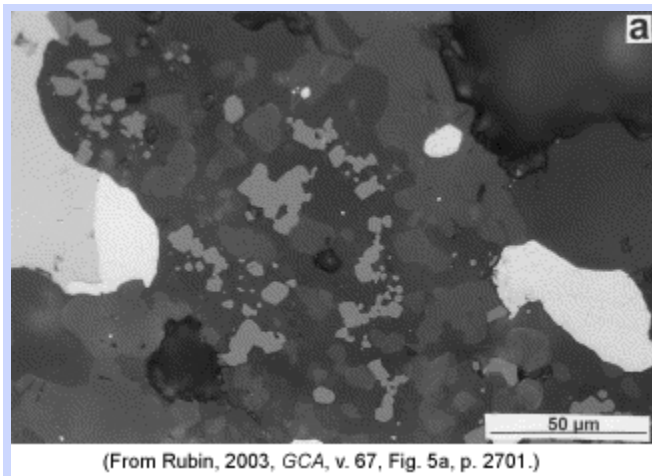
Impact Effects in Unshocked Chondrites?

AI Rubin has developed additional criteria to discern shock effects in ordinary chondrites. The most important one to us here is the presence of mixtures of the minerals plagioclase feldspar and chromite. In most cases chromite grains are surrounded by plagioclase. These chromite-plagioclase assemblages, as Rubin calls them, vary in size (20 to 300 micrometers across), size of the chromite crystals in them (0.2 to 20 micrometers), and abundance of chromite (10 to 70 volume %). Rubin reports that chromite-plagioclase assemblages occur in almost every chondrite shocked to shock stage S3 or above.

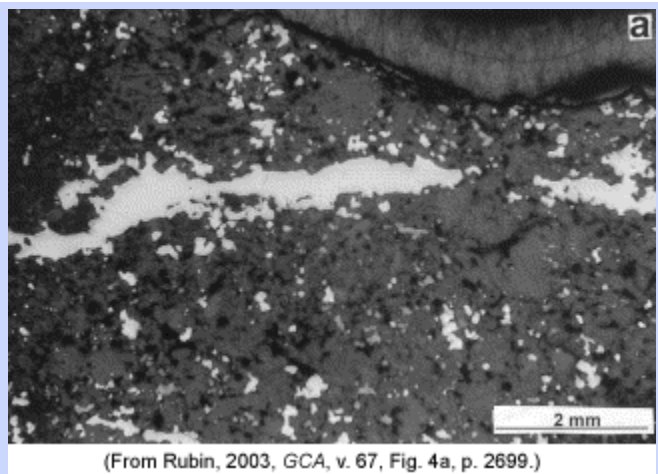


Examples of chromite-plagioclase assemblages in chondrites shocked to stages S3 and higher. These photomicrographs of polished thin section were taken in reflected light. Chromite is light gray, plagioclase is dark gray. Olivine and pyroxene grains are medium gray. The size and abundance of chromite varies in the assemblages. As Rubin suggests that the assemblages formed by preferential shock melting of plagioclase, with the melt incorporating nearby chromite. (Recall that Dodd and Jarosewich showed that melt pockets are enriched in aluminum, hence incorporated more of the easily-melted plagioclase.)

Rubin reports that chromite-plagioclase assemblages also occur in unshocked (stage S1) and lightly shocked (S2) chondrites. In fact, they occur in all 210 unshocked and lightly shocked petrographic type 4-6 chondrites he examined. Assuming that chromite-plagioclase assemblages result from shock, Rubin reasons that type 5 and 6 chondrites, even those apparently unshocked, were shocked to stage S3 or higher. In support of this, he notes that the chondrite Kernouvé contains both chromite-plagioclase assemblages and veins filled with metallic iron-nickel. It would appear that Kernouvé, a classic unshocked type 6 chondrite with an old age (4.45 by the Ar-Ar method) was shocked, heated, and then annealed to remove the effects of shock. Rubin cites other convincing examples as well, including annealing followed by a shock event. A particularly interesting case is the MIL99301 chondrite, which has an age of 4.26 billion years. (The age has been determined by Eleanor Dixon, Donald Bogard, and D. H. Garrison at the Johnson Space Center.) Unless the parent asteroid for ordinary chondrites was very large, it would have been cooled long before 4.26 billion years ago and the ^{26}Al would have been long gone. The heat for annealing MIL99301 must have been provided by impact. Rubin uses these observations to conclude that shock events provided the heat needed to metamorphose Kernouvé and other metamorphosed chondrites.



(From Rubin, 2003, *GCA*, v. 67, Fig. 5a, p. 2701.)



(From Rubin, 2003, *GCA*, v. 67, Fig. 4a, p. 2699.)

Photomicrograph in reflected light of chromite-plagioclase assemblage in shock stage S1 chondrite Kernouvé (**left**). Silicate is dark gray, metallic Fe-Ni is white, and troilite is light gray. Al Rubin argues that shock Kernouvé was shocked long ago, but then annealed to remove almost all evidence for the event. As supporting evidence, he shows a prominent vein of metallic iron-nickel (white) with silicate grains (dark gray) in Kernouvé (**right**). Such veins occur in heavily shocked chondrites.

Some loose ends-unraveling the story?

Rubin uses his detailed microscopic observations of numerous chondrites to make a good case for apparently unshocked type 5 and 6 chondrites having been shocked very early in their histories. Such shock events might have left chondrite parent asteroids hot and thus caused the metamorphism they clearly experienced. However, there are some loose ends that need to be tied up before the idea is embraced by meteoriticists.

One loose end is that Rubin's story requires that the shock heats portions of an asteroid to the metamorphic temperature experienced by type 6 chondrites, about 900 °C. If the initial temperature was 0 °C, from the table above we see that such a temperature increase would require shocking to between stages 5 and 6. This would result in widespread veins, which are not observed in many unshocked type 5 and 6 chondrites, Rubin's excellent example from Kernouvé notwithstanding. More important, the olivine grains would be almost totally mosaicized after the shock event. Rubin's interpretation is that slow cooling after shock heating would have removed the mosaicism through a process called annealing. Kernouvé and other type 5 and 6 chondrites cooled at rates of around 10 °C/million years. This would seem to be plenty of time to remove the effects of shock. However, it is not clear that large mosaicized olivine grains would convert back to large single crystals. Annealing removes damage from crystals by growing new, smaller, undamaged crystals, but the process is slow and it has not been shown quantitatively that the process would result in large, unshocked olivine crystals, even if cooling takes millions of years.

Another loose end is the physical setting for the metamorphism and slow cooling after the monumental shock event that Al Ruben envisages. Most material in an impact is moved around, but not greatly heated or shocked. Most of the shocked materials occur inside the crater produced by an impact. Such craters cannot be too large or deep on an asteroid because the bodies are only a few hundred kilometers across to begin with. Even if we assume that an impact makes a crater 50 kilometers in diameter, the melted and heated zone on the crater floor is no more than one kilometer deep. (This can be calculated using equations in a book by Jay Melosh, University of Arizona). A depth of 1 kilometer sounds like a lot, but cooling rates of 1-10 °C/million years require burial of tens of kilometers. Thus, an open question is how a large volume of chondritic asteroid could be shocked and heated, then buried deeply and cooled slowly. Rubin countered in an email to PSRD that the situation might be different for asteroid heating. If asteroids are porous rubble piles, as many meteoriticists and astronomers think, impact energy is distributed differently, concentrating in the walls and floor of a crater. If there were enough impacts into such rubble piles, he argues, perhaps a significant volume of an asteroid could be heated by impact. We clearly need a better theoretical understanding of the effects of multiple impacts on asteroids.

There is strong evidence that ^{26}Al was present in the early solar system. Surely it must have affected chondrites to some extent. If ^{26}Al was the heat source, perhaps it could cause melting of plagioclase when it was close to chromite, causing formation of the chromite-plagioclase assemblages. Such assemblages form during shock events, however, as Ruben shows in his paper, so it is not clear that another mechanism is needed. If ^{26}Al contributed to heating an asteroid, how would that heat change the way shock damaged the rock? It seems that more work is needed before we understand the relative roles of shock and ^{26}Al heating in the early solar system.

Widespread Smashing in the Early Asteroid Belt?

Almost all shocked chondrites are much younger than unshocked chondrites. Meteoriticists have interpreted this to mean that chondrites were not shocked severely when they formed or shortly thereafter, but were affected later on. However, Rubin and other meteoriticists have shown that some very old meteorites, the enstatite chondrites, were shocked, even melted by shock, 4.5 billion years ago (though they cooled very rapidly afterwards). During the Lunar and Planetary Science Conference in March 2004, my colleague Ed Scott summarized meteorite evidence for collisions early in the history of the solar system, showing evidence from 10 different meteorite parent asteroids. High velocity impacts clearly happened early in solar system history. In many cases the impacting bodies were already molten. What was the heat source for this melting? ^{26}Al ? Impact? In the early solar system, both might play important roles. Thus, Al Rubin's ideas about impact heating do not focus on a narrow question concerning the metamorphism of chondrites. It is part of the larger puzzle of the role of impact and the earliest evolution of the asteroid belt. We better tie up those loose ends!

Additional Resources

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[Web site](#) about Henry Clifton Sorby, the man who pioneered "Microscopical Petrography" in 1849.

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