

## Headline Article

June 10, 2010

# Formation of Stony-Iron Meteorites in Early Giant Impacts

--- Cosmochemical studies and dynamical models of hit-and-run planetary collisions suggest a new origin for the stony-iron meteorites called pallasites.

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Esquel Pallasite Meteorite



(Photograph by Geoffrey Notkin © Aerolite Meteorites.)

Slice (8.2 cm wide) of a typical pallasite with mm-to-cm-sized fragments of olivine in metallic Fe,Ni (white). Photograph by Geoffrey Notkin © Aerolite Meteorites. Click image for a high-resolution version.

**P**allasites, meteorites composed mainly of olivine ( $\text{Mg-Fe}_2\text{SiO}_4$ ) and metallic Fe-Ni, are widely thought to have formed at the boundary between the metallic core of a melted and [differentiated](#) asteroid and the surrounding [olivine](#) mantle, but their precise origin is controversial. Studies of the thermal histories of 28 members of the largest group of pallasites, called the main group, by Jijin Yang and colleagues at the University of Massachusetts, Amherst and the University of Hawai'i show they cooled at diverse rates of 2.5-20 [K](#) per million years. These rates are much slower than the cooling rates of another group called IIIAB irons (50-350 K/Myr) proving that the IIIAB irons did not cool in the core of the main-group pallasite body, contrary to widespread belief. The tenfold range in the cooling rates of the main-group samples shows these pallasites did not cool at the core-mantle boundary of a single body, otherwise they would have had indistinguishable cooling rates. The main-group pallasites, like several groups of iron meteorites, appear to have cooled in bodies that were formed after the original differentiated bodies were split open by glancing collisions with larger bodies. Pallasites, the iron meteorites, and their parent asteroids are vestiges of a vast population of differentiated bodies with a violent early impact history.

## Reference:

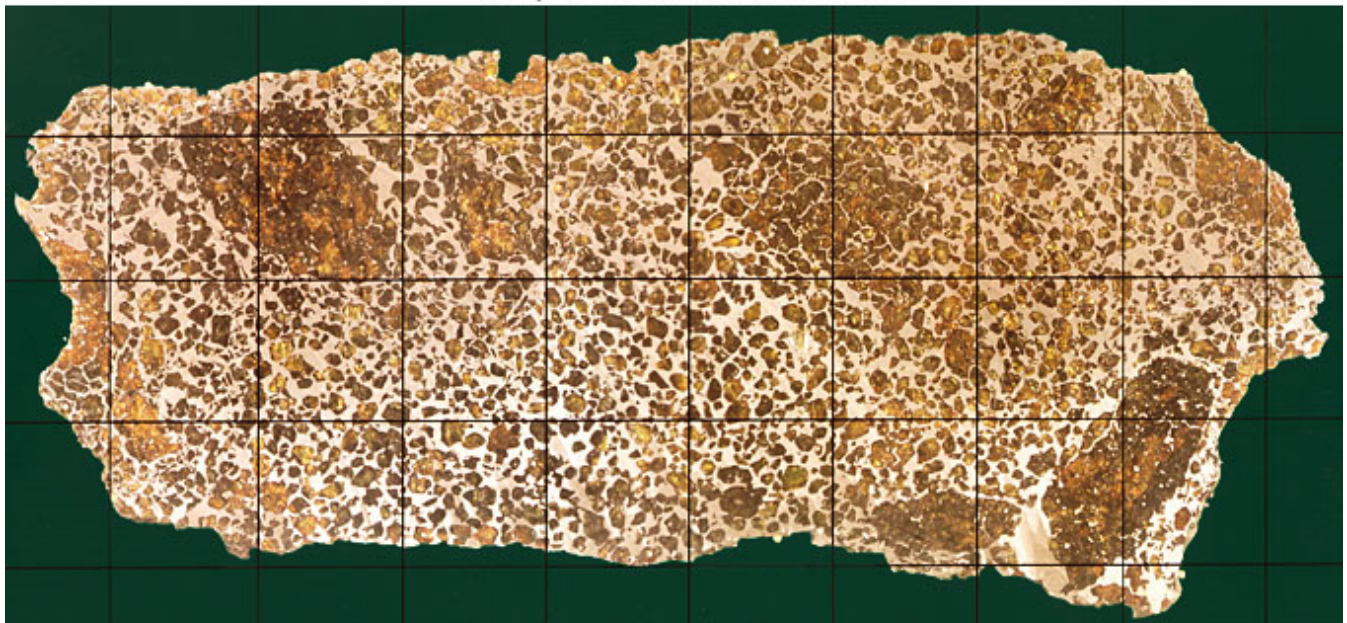
- Yang, J., Goldstein, J. I., and Scott, E. R. D. (2010) Main-group Pallasites: Thermal History, Relationship to IIIAB Irons, and Origin. *Geochimica et Cosmochimica Acta*, v. 74, doi:10.1016/j.gca.2010.04.016.

**PSRDpresents:** Formation of Stony-Iron Meteorites in Early Giant Impacts --[Short Slide Summary](#) (with accompanying notes).

## Exquisite Meteorites

**P**allasites are spectacularly beautiful meteorites made largely of millimeter-to-centimeter-sized crystals of [olivine](#), metallic iron-nickel (Fe-Ni), and troilite (FeS). About 90-95% of the 85 known pallasites, which comprise the main group, have similar compositions and probably come from a single body. The remainder are probably derived from five or six additional asteroids. Since most pallasites are composed of angular fragments of olivine embedded in iron-nickel, it is widely believed that impacts mixed olivine fragments from the mantle with molten metal from the core.

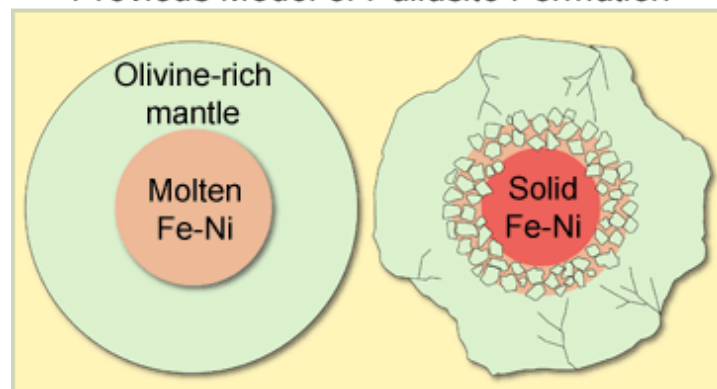
### *Esquel Pallasite Meteorite*



(10-centimeter grid spacing. Photograph supplied by John Wasson, UCLA.)

This 92-centimeter-long slab of the Esquel main-group pallasite was cut from a 680-kilogram specimen by Robert Haag. About 80% of the surface is typical pallasitic material composed of angular olivine fragments in metal. The rest consists of eight 10-15 centimeter-long polycrystalline olivine aggregates that appear to be disintegrating into angular fragments of olivine. A detailed description of the slab is given in a 1998 paper by Ulf-Møller and colleagues; see reference list at the end of the article. Click image for a high-resolution version.

### *Previous Model of Pallasite Formation*



Cartoon showing how pallasites are thought to have formed in differentiated asteroids at the core-mantle boundary by impact-induced mixing of fragments of olivine-rich mantle with molten Fe-Ni metal from the core. For main-group pallasites, the composition of the metal suggests that it was residual melt from a largely solidified core. Our results are incompatible with this model and show that main-group pallasites did not cool at the core-mantle boundary.

The structure and composition of the metal in pallasites resembles that in [iron meteorites](#) so that large regions



free of olivine develop a Widmanstätten pattern of oriented kamacite plates as the single crystal, phosphorus-bearing taenite slowly cools. But in most pallasites the olivines are typically only a few millimeters apart so that the taenite is polycrystalline and oriented kamacite plates are sparsely distributed. The chemical compositions of the metal in pallasites and iron meteorites are also similar except that most main-group pallasites are strongly depleted in iridium (Ir) and other elements that prefer solid metal to liquid metal. This depletion suggests that their metal was derived from the core of an asteroid after ~80% had solidified. Since the metal in main-group pallasites is a good compositional match for the iron meteorites at the low-Ir end of group IIIAB and their oxygen isotopic compositions appear indistinguishable, it is widely believed that they come from the same asteroid.

*Glorieta Mountain Pallasite Meteorite*



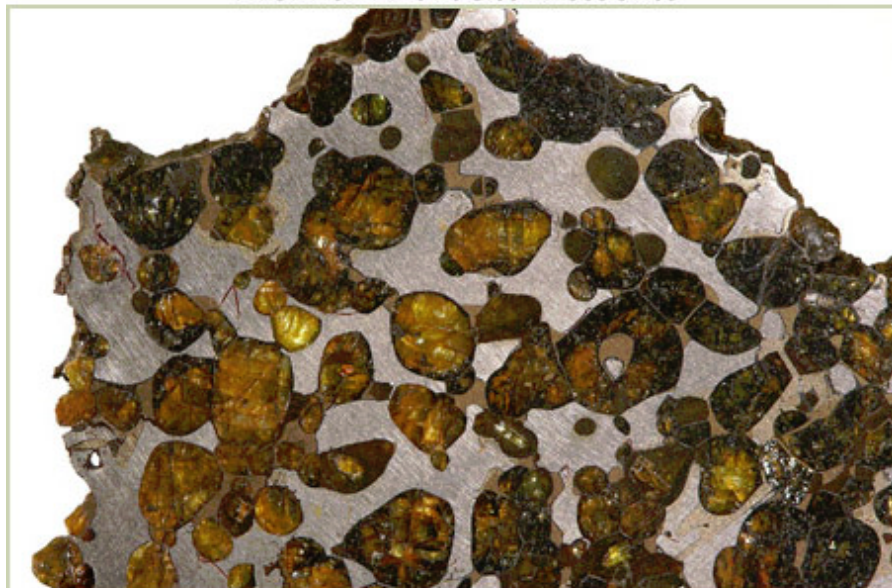
Photo © by the Oscar E. Monnig Meteorite Gallery, Texas Christian University.

*Newport Pallasite Meteorite*



Smithsonian Institution photo and sample (USNM 847)

*Brenham Pallasite Meteorite*



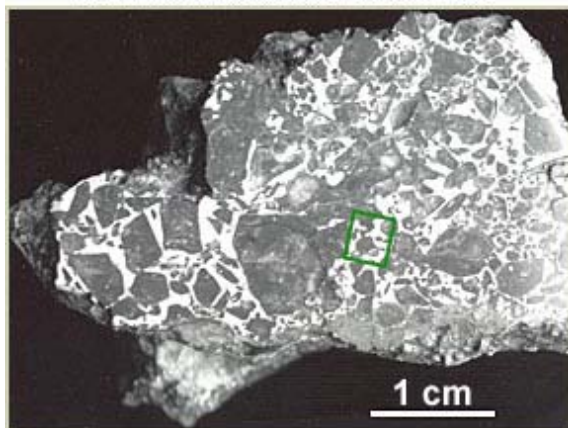
Photograph by Geoffrey Notkin © Aerolite Meteorites. In the Monnig Meteorite Gallery.

Click on the images for high-resolution versions. **Top left:** The Glorieta Mountain pallasite has regions with normal pallasite structure (left slice) and other regions where olivine is absent and the metallic Fe-Ni developed a Widmanstätten pattern of oriented kamacite plates, which is visible on etching in acid (right slice). Photo © by the Oscar E. Monnig Meteorite Gallery, Texas Christian University. **On the right:** Black and white photograph of an etched slice of the Newport pallasite showing that the Widmanstätten pattern of oriented kamacite plates only develops in olivine-free regions of metallic Fe-Ni. By determining the cooling rate of pallasites with oriented kamacite plates, we were able to test possible links between pallasites and iron meteorites and models for pallasite formation. Smithsonian Institution photo and sample (USNM 847). Maximum length is 10.5 centimeters. **Bottom left:** This unetched slice of the Brenham pallasite contains rounded olivines in

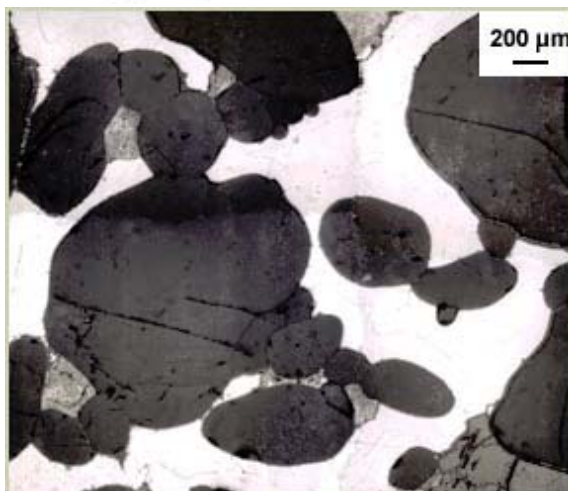
metal, rather than angular ones, and polycrystalline olivine aggregates with equilibrated textures and  $120^\circ$  grain boundary triple points (lower right). Photograph by Geoffrey Notkin © Aerolite Meteorites; 11x10 centimeter slice from the Monnig Meteorite Gallery.

About 15-20% of main-group pallasites, like Brenham, show rather different textures consisting of rounded olivine crystals with mutual grain boundaries that resemble those in metamorphosed rocks. Since aggregates of tiny olivine grains in the pallasites with seemingly angular olivines show Brenham-like textures under the microscope, the rounded textures therefore result from grain boundary migration at high temperatures. Pallasites with large rounded olivines must have spent a longer time at high temperatures when metal was partly molten than the pallasites with large angular olivines.

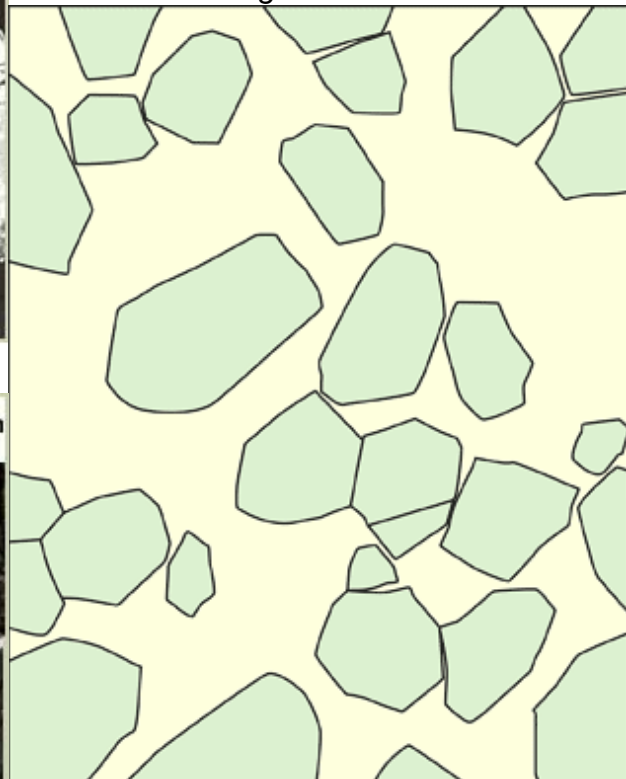
### *Admire Pallasite Meteorite*



Photographs by Ed Scott of U. New Mexico slice.



### *Conversion of Angular to Rounded Olivines*



**Top left:** Slice of the Admire pallasite showing angular fragments of olivine in metallic iron. The green box shows location of magnified image shown in bottom left. **Bottom left:** At higher magnifications, the angular olivines in the Admire pallasite appear rounded and sub-millimeter olivines show textures like those shown by centimeter-sized olivines in Brenham. **On the right** is an animated cartoon showing how the rounded olivines in Brenham were formed at high temperatures. At high temperatures, when metal was partly molten, grain boundaries migrated to minimize the metal-olivine interfacial area and the total surface energy of the grain boundaries.

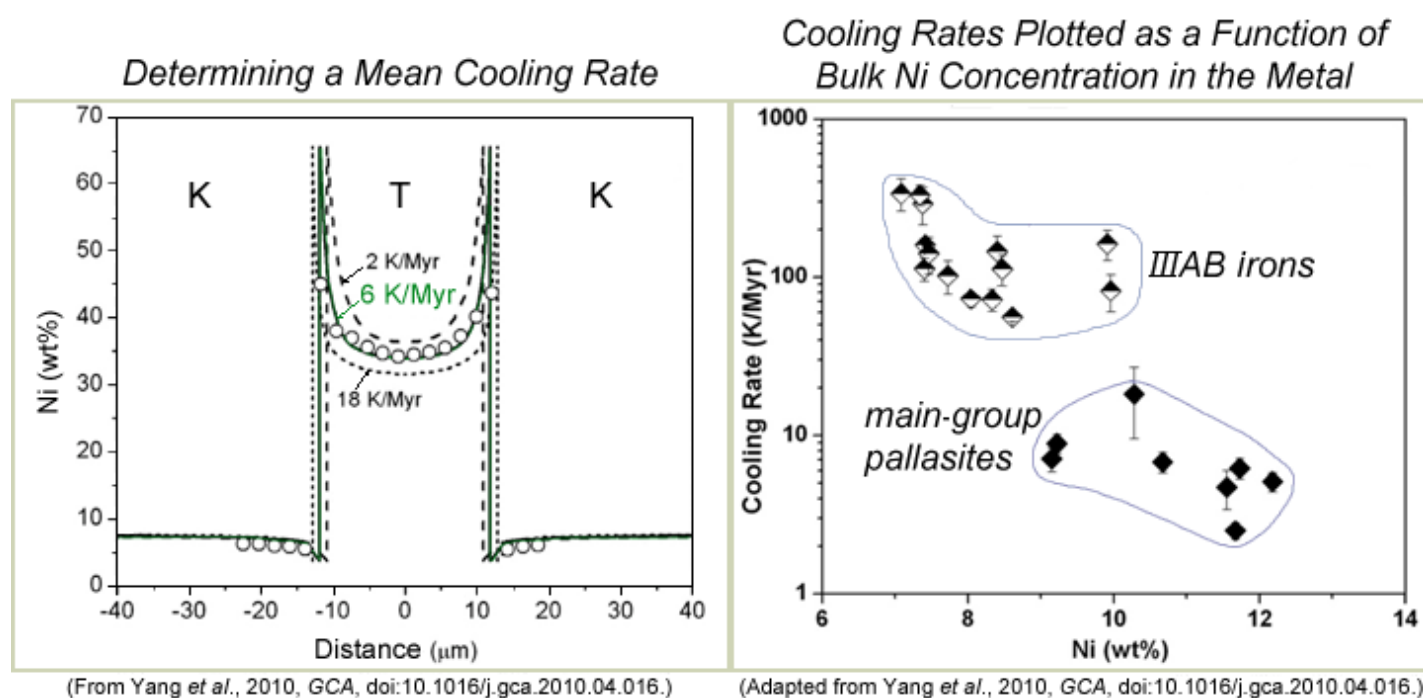
Although this general model explains many properties of pallasites, there are many unsolved problems. For example, a close genetic link between IIIAB irons and main-group pallasites is difficult to reconcile with the higher level of shock in IIIAB irons and their much longer [cosmic-ray exposure ages](#). How could the pallasites with rounded olivines have stayed hotter for longer periods if they all formed at the core-mantle boundary? Since olivine should float up quickly through molten metal, pallasites should be rather rare--but they are not. We have roughly one pallasite for every 12 irons. Where are the meteorites from the olivine mantles? Finally, there is some geochemical evidence that is very difficult to reconcile with a deep-seated origin at the



core-mantle boundary. Some pallasites have high concentrations of [rare-earth elements](#) in their phosphates suggesting they once contained small amounts of residual silicate magma, which should have been concentrated near the crust, not the core.

## Cooling Rates

To test the proposed relationship between IIIAB irons and main-group pallasites and to learn more about the origin of pallasites, we investigated the thermal histories of 28 main-group pallasites using procedures we developed for iron meteorites (see [PSRD article: When Worlds Really Did Collide](#)). In samples of eight main-group pallasites, we found regions large enough to have developed a Widmanstätten pattern of oriented kamacite plates. To determine how fast they were cooling when kamacite formed at  $\sim 500\text{--}700^\circ\text{C}$ , we analyzed the nickel concentration across taenite lamellae of known orientation and compared the observed nickel profile with those calculated for various cooling rates using equilibrium phase compositions and diffusion rates.

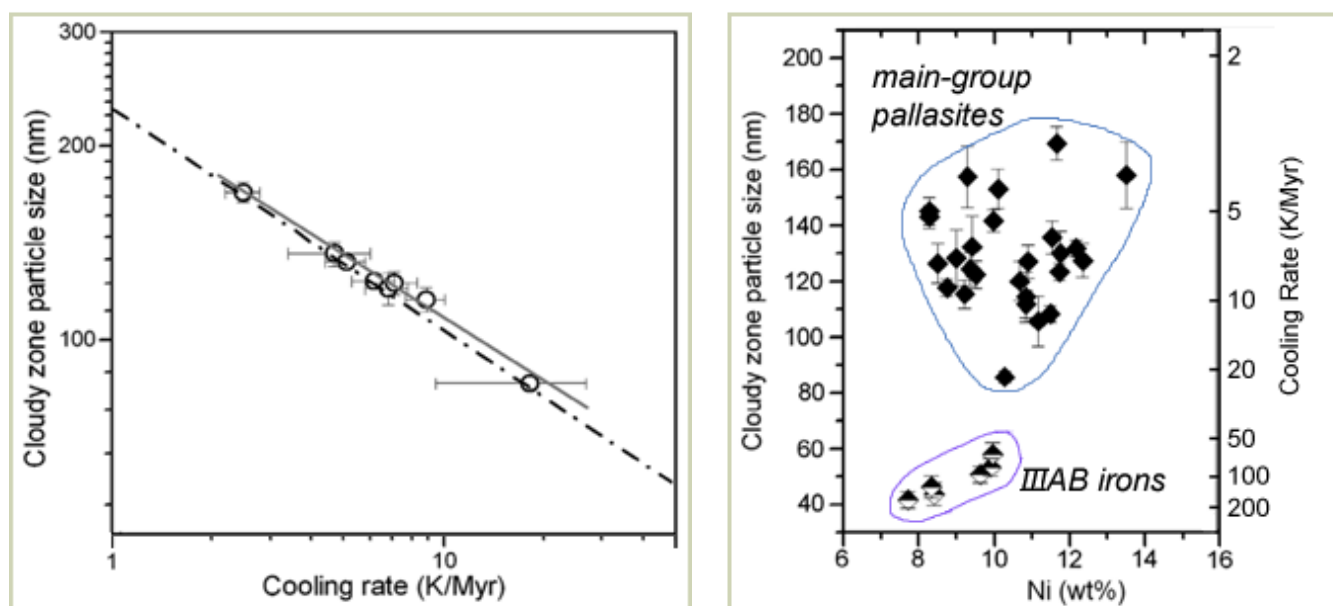


Compositional zoning in metallic minerals allows cosmochemists to determine the rate at which the metal cooled. **Left:** Concentration of Ni measured across a  $25\ \mu\text{m}$  wide lamella of taenite (labeled T) in the Giroux pallasite from [electron microprobe](#) analysis. Distances are measured normal to the boundary between taenite and kamacite (labeled K) from the center of the taenite lamella. The data closely match the Ni profile calculated for a cooling rate of 6 K/Myr (shown in green). Averaging results for 10 taenite lamellae gives a mean cooling rate for Giroux of  $6.8 \pm 1.0$  K/Myr ( $\pm 2\sigma$ ). **Right:** Cooling rates for IIIAB irons and main-group pallasites with Widmanstätten patterns plotted against their bulk Ni concentrations. These main-group pallasites cooled more slowly than the IIIAB irons showing that the IIIAB irons could not have cooled in the core of a body containing the pallasites.

We also determined relative cooling rates of the pallasites at  $\sim 300^\circ\text{C}$  from two features at the edge of the taenite lamellae. The size of the high-nickel particles in a sub-micrometer intergrowth, which is called "cloudy taenite" from its appearance in reflected light after etching in acid, and the width of the rim of tetrataenite (ordered Fe-Ni between kamacite and cloudy taenite) are both controlled by diffusion of Fe and Ni, like the growth of kamacite. Therefore the larger the cloudy zone particles and the wider the tetrataenite rim, the slower the cooling rate.

We were surprised to find that the eight main-group pallasites with Widmanstätten patterns cooled at diverse rates of 2.5 to 20 K/Myr. These cooling rates are closely correlated with the sizes of the cloudy zone particles

and the tetrataenite rims so we can infer reliable cooling rates for pallasite samples that lack Widmanstätten patterns. These data show that all 28 main-group pallasites cooled at 2.5-20 K/Myr, much more slowly than the IIIAB irons, which cooled at 50-350 K/Myr. For the main-group pallasites, cooling rates are not correlated with bulk Ni (unlike the IIIAB, IVA and IVB irons) nor with the shape of the olivine grains.



(From Yang *et al.*, 2010, GCA, doi:10.1016/j.gca.2010.04.016.) (Adapted from Yang *et al.*, 2010, GCA, doi:10.1016/j.gca.2010.04.016.)

**Left:** Cooling rates determined for samples of eight main-group pallasites with Widmanstätten patterns plotted against the particle sizes in the cloudy taenite. The excellent correlation shows that cloudy zone particle size provides a good estimate of cooling rate for samples lacking Widmanstätten patterns. (Solid line is best fit for main-group pallasites; dashed line is best fit to all data for iron and stony-iron meteorites.) **Right:** Cloudy zone particle sizes (left axis) and inferred cooling rates (right axis) for 28 main-group pallasites and six IIIAB iron meteorites plotted against their bulk Ni concentrations. These data confirm that main-group pallasites cooled more slowly than the IIIAB irons. The wide range of cooling rates for the main-group pallasites shows they did not cool at the core-mantle boundary of a single body.

## Pallasites and IIIAB Irons: No Kinship

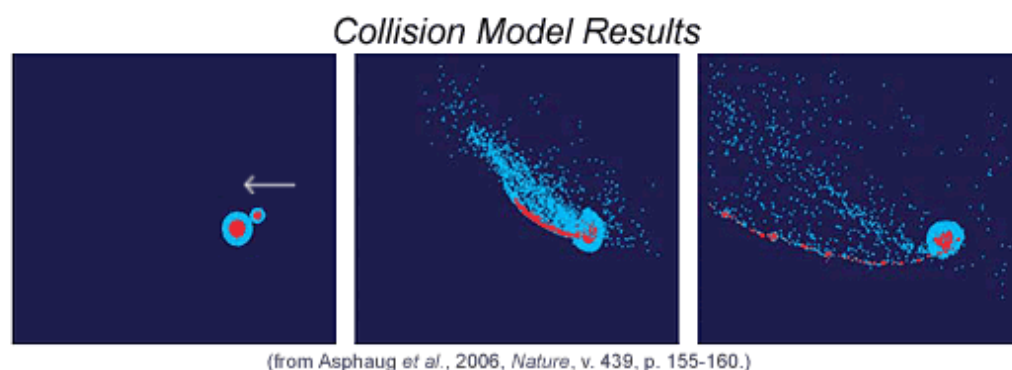
When a body cools by conduction, the interior is hotter and cools more slowly than the outer layers. If the main-group pallasites had cooled at the core-mantle boundary of a differentiated body that supplied the IIIAB irons from its core, we should expect that the IIIAB irons would have cooled marginally slower than the main-group pallasites. (The thermal conductivity of metal is so high relative to silicate that the difference in their cooling rates would be too small to detect.) Since the IIIAB irons cooled faster than the main-group pallasites, they could not have cooled at the center of the main-group pallasite body. The positive correlation between the cooling rates of the IIIAB irons and their bulk Ir concentrations shows they cooled in a core that crystallized inwards--like the IVA irons but unlike the core of the differentiated main-group pallasite body--and was enclosed by only a few kilometers of mantle material. Thus the IIIAB irons were not derived from the core of the differentiated main-group pallasite body.

The diverse cooling rates of the main-group pallasites show they did not cool at the core-mantle boundary of one body. We cannot completely exclude the possibility that the main-group pallasites cooled at the core-mantle boundaries of several differentiated bodies. But given their uniform oxygen isotopic composition and the wide range of oxygen [isotopic](#) compositions shown by all pallasites, it seems much more likely that they cooled at diverse depths in a single body that formed as a result of the destruction of the original differentiated body.

Having excluded the IIIAB irons from the main-group pallasite body, we searched for other groups of irons or ungrouped irons that might be related to the main-group pallasites. Their absence suggests that large metallic regions ( $>1$  meter across) were rare in the source region of the main-group pallasites. Similarly, the absence of related olivine [achondrites](#) in our meteorite collections, the highly fragmented nature of the olivine in pallasites, and the small size of the polycrystalline olivine masses ( $<10$ - $20$  centimeters across) in pallasites suggest that large metal-free olivine masses ( $>1$  meter across) were also rare in the main-group pallasite source region. If the main-group pallasites are representative of the body in which they cooled, it consisted solely of a mixture of fractured mantle olivine and metallic Fe-Ni-S. Until spacecraft visit large olivine-rich asteroids, we probably won't know the size of the pallasitic regions or how they were distributed within their parent bodies. For example, were pallasitic regions separated by fractured olivine in bodies that were coated with thick [regoliths](#) of olivine fragments? Given these uncertainties, we cannot specify precise limits on the size of the main-group pallasitic body, but the radius was probably  $\sim 100$ - $400$  kilometers.

## What Destroyed the Differentiated Parent Body of the Main-Group Pallasites?

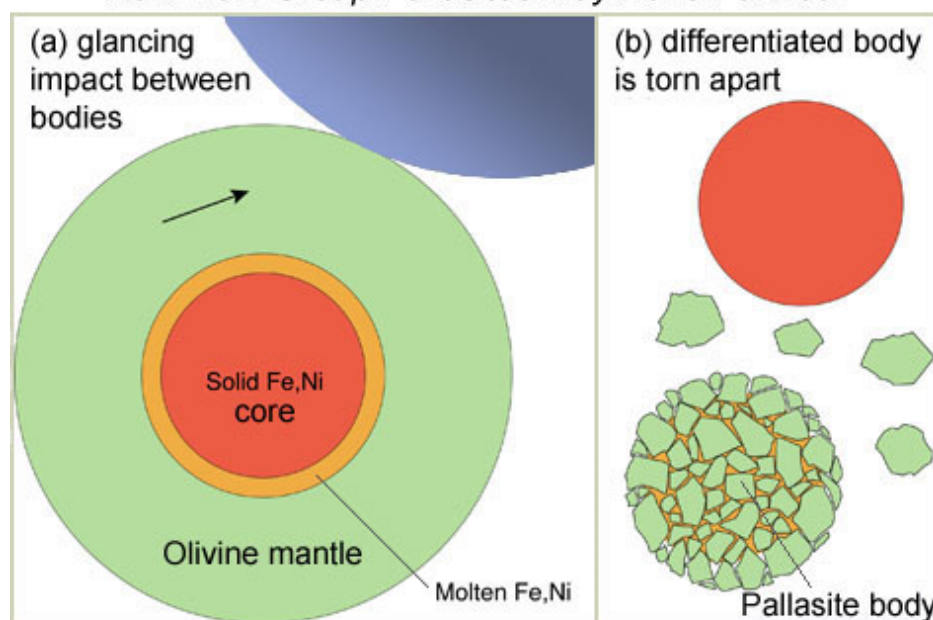
Until very recently, it was thought that metallic meteorites and asteroids resulted from impacts by smaller bodies that smashed differentiated asteroids into fragments over billions of years. However, such impacts do not simply strip mantles from cores, and a projectile capable of removing the mantle from a 500-kilometer asteroid would blow the core to smithereens. Erik Asphaug and colleagues at the University of California, Santa Cruz propose instead that metal-rich asteroids and meteorites were formed in "hit and run" collisions between protoplanets (see [PSRD](#) article: [Hit-and-Run as Planets Formed](#)). They suggest that glancing collisions with larger bodies disemboweled differentiated bodies as large as the Moon generating chains of metal-rich asteroidal bodies.



This illustration shows modeling results, from left to right (before, during, and three hours after impact), of what happens when a smaller projectile has a "hit and run" collision with a protoplanet with the mass of Mars. The arrow shows direction of the projectile with one-tenth the target's mass. Red indicates the metallic cores and blue indicates the rocky mantles of the bodies. The impacting projectile is dispersed leaving a chain of smaller metal-rich bodies.

In hit-and-run planetary collisions, destruction results not solely from the shock wave that radiates outwards from the point of impact in seconds, as in conventional impacts, but predominantly from shear and tidal forces operating over an hour or more that deform and disaggregate the entire smaller body. This could account for the ubiquitous finely-fragmented olivines in pallasites and the complete absence of any shock melted and intensely-deformed olivines, which are characteristic of strong shocks. Total disruption of the differentiated body would help explain why the pallasites are so abundant, how they came to be buried at very diverse depths, and why they acquired traces of residual silicate melt rich in rare earth elements.

### How Main-Group Pallasites May Have Formed



(From Yang *et al.*, 2010, GCA, doi:10.1016/j.gca.2010.04.016.)

Cartoon showing how main-group pallasites with angular olivines may have formed. In (a) a glancing impact occurs between a differentiated body with a core that was largely solidified and a bigger body. In (b) we infer that the solid part of the core was lost and that a new parent body consisting of olivine fragments and molten Fe-Ni was formed from the residual Fe-Ni melt and the mantle of the differentiated body. Main-group pallasites are probably derived from diverse depths of the new parent body.

### How Did the Rounded-Olivine Pallasites Form?

Since the cooling rates of the main-group pallasites with rounded olivines are not systematically lower than those with angular olivines, we infer that the rounded olivine intergrowths formed before the impact that made angular olivine fragments. This conclusion is consistent with what we see in the newly discovered pallasite, Szymchan, which contains both angular olivines and fragmented aggregates of rounded olivine.



### Seymchan Pallasite Meteorite

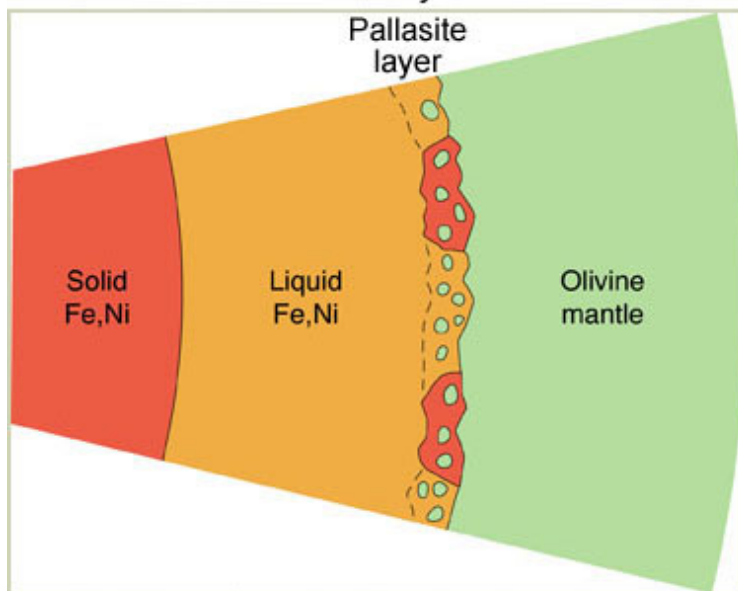


(Photograph by R. A. Langheinrich. Monnig Meteorite Gallery, Texas Christian University.)

Polished and etched slice (48 centimeters wide) of Seymchan, a unique main-group pallasite, showing olivine-free metal regions with Widmanstätten patterns, angular regions with Brenham-like pallasitic material with rounded olivine-metal textures (left and center), and a zone on the right side with mostly angular olivines in metal. The angular olivines appear to have formed by the break-up of Brenham-like olivine material. As with galaxies, the best insights into the collisional history of pallasites come from peculiar specimens! Click on the image for a high-resolution version.

We suggest that olivine crystals at the core-mantle boundary of the original differentiated body were welded into rounded olivine intergrowths as the core crystallized before the impact that created the pallasites with angular olivines. Some of the rounded olivine pallasites, like Brenham, have low-Ir metal consistent with solidification of metal after the impact, but a few have high-Ir metal implying their metal largely solidified before the impact.

### How Main Group Pallasites with Rounded Olivines May Have Formed



(From Yang *et al.*, 2010, GCA, doi:10.1016/j.gca.2010.04.016.)

This cartoon cross-section shows how the main-group pallasites with rounded olivines may have formed from a pallasitic layer of intergrown rounded and metamorphosed olivine grains at the core-mantle boundary of the differentiated body. Pallasites like Pavlodar with high-Ir metal could represent regions where metallic Fe,Ni largely solidified in the pallasitic layer prior to the impact that broke up the differentiated body. Pallasites like Brenham with low-Ir metal may have formed from rounded-olivine intergrowth and molten metal that solidified in the pallasite body after the impact.

## Wandering Planetesimals and Violent Impacts

Irons and stony-iron meteorites were once thought to be the products of numerous collisions between differentiated asteroids 5-200 kilometers across and smaller hypervelocity projectiles that destroyed them over many billions of years. Our study of the main-group pallasites and IIIAB, IVA, and IVB irons suggests that their parent differentiated bodies were larger and were disrupted when their cores were still partly molten during the first 5-20 million years of Solar System history. These collisions created metallic bodies ~100-300 km across with less than a few kilometers of silicate mantle (for the irons), and olivine-metal bodies several hundred km across (for the pallasites). Theoretical studies of planetary accretion suggest that the original differentiated bodies were not destroyed by smaller projectiles but by glancing collisions with larger bodies when Moon-to-Mars-sized bodies were abundant in the Solar System. Thus the differentiated meteorites and asteroids are vestiges of a vast population of bodies with a violent early impact history. These bodies may have originated not in the asteroid belt but at 1-2 AU (see PSRD article: [Iron Meteorites as the Not-So-Distant Cousins of Earth](#)).

## Additional Resources

LINKS OPEN IN A NEW WINDOW.

- **PSRDpresents:** Formation of Stony-Iron Meteorites in Early Giant Impacts --[Short Slide Summary](#) (with accompanying notes).
- Asphaug, E. (2010) Similar-sized Collisions and the Diversity of Planets. *Chemie der Erde*, published online doi:10.1016/j.chemer.2010.01.004.
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- Bottke, W. F. and Martel, L. M. V. (2006) Iron Meteorites as the Not-So-Distant Cousins of Earth. *Planetary Science Research Discoveries*. <http://www.psrld.hawaii.edu/July06/asteroidGatecrashers.html>.
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- Yang, J., Goldstein, J. I., and Scott, E. R. D. (2010) Main-group Pallasites: Thermal History, Relationship to IIIAB Irons, and Origin. *Geochimica et Cosmochimica Acta*, v. 74, doi:10.1016/j.gca.2010.04.016.

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