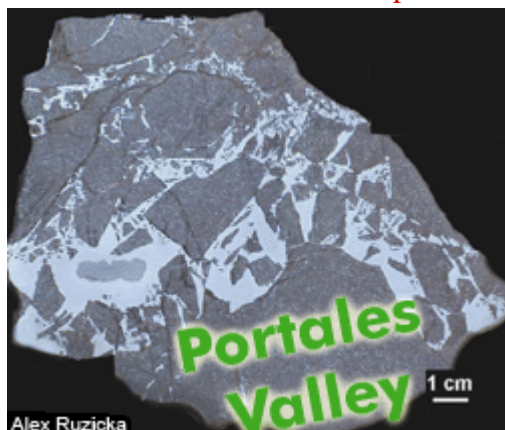


Hot Idea

posted September 30, 2005



Portales Valley: Not Just Another Ordinary Chondrite

--- A melted meteorite gives a snapshot of the heat and shock that wracked an asteroid during the first stages of differentiation.

Written by [Alex Ruzicka](#) and [Melinda Hutson](#)

Department of Geology, Portland State University

Soon after the Portales Valley meteorite fell in 1998, it was classified as one of the most common types of meteorites, an H6 ordinary [chondrite](#). Although researchers quickly recognized that Portales Valley is not a typical H6 chondrite, there was little agreement about how the meteorite formed. A recent study of Portales Valley by Ruzicka and colleagues suggests that the textures, mineralogy, and chemistry of the meteorite are best explained as the first good example of a metallic melt [breccia](#). This meteorite represents a transitional stage between chondrites and various classes of differentiated meteorites, and offers clues as to how [differentiation](#) occurred in early-formed planetary bodies.

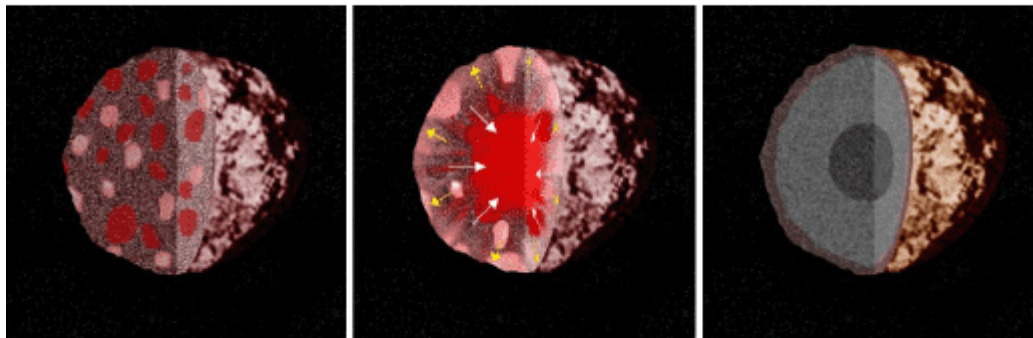
Reference:

- Ruzicka, A., Killgore, M., Mittlefehldt, D.W. and Fries, M.D (2005) Portales Valley: Petrology of a metallic-melt meteorite breccia. *Meteoritics & Planetary Science*, v. 40, p. 261-295.

Differentiation: a widespread but poorly-understood process

Most solar system material underwent differentiation, a process involving melting and separation of liquids and solids of varying density and chemical composition. However, chondritic meteorites escaped this process and are believed to be pieces of undifferentiated asteroids. All other meteorites, and probably all rocks from planets and large moons, melted when the parent bodies differentiated to form cores, mantles, and crusts. The heat source for differentiation is uncertain, as are the exact physical processes and conditions that allowed differentiation to proceed in small planetary bodies with weak gravity. Proposed sources of heat include internally-generated heat from short-lived radioactive materials such as aluminum-26 (^{26}Al), external heating from our young active Sun, and heating resulting from collisions between planetary bodies (shock heating). A detailed study of the Portales Valley meteorite suggests that differentiation of small planetary bodies involved a combination of an internal heat source and shock. Shock heating was not the major heat source involved in differentiation, but the stress waves associated with even modest shock events played a critical role in helping materials to separate and reconfigure during differentiation.

Differentiation of a Planetesimal



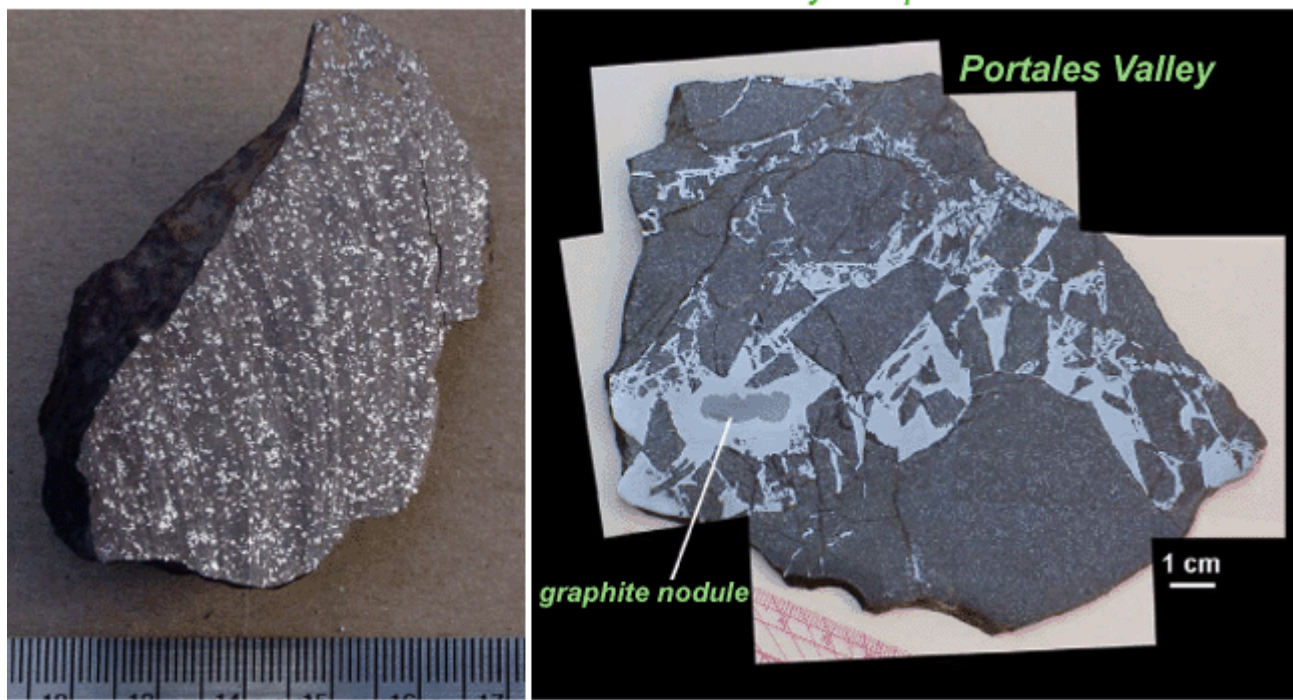
(Frank Granshaw, Artemis Software)

A sequence of images showing stages in the differentiation of a planetesimal, an early-formed planetary body. The image in the left hand side shows a chondritic planetesimal becoming hot enough for melting to begin. The middle image shows that the heavier metallic liquid sinks toward the center, while the less dense rocky material rises toward the surface. The result is a differentiated object with a crust, mantle and core, as shown in the image in the right hand side. (Images created by Frank Granshaw of Artemis Software for the Cascadia Meteorite Laboratory, Portland State University.)

Not an ordinary H6 ordinary chondrite

Three features link Portales Valley to H-group [ordinary chondrites](#). These are (1) the presence of rare chondrules with a rather typical chondritic texture present in silicate-rich areas, (2) the compositions of most minerals, and (3) the bulk oxygen isotopic composition of the meteorite. Nonetheless, Portales Valley contains unusual features that distinguish it from any other ordinary chondrite. Even in a cut section, the differences between Portales Valley and a typical H-chondrite are readily apparent (see figures below).

H chondrite and Portales Valley comparison



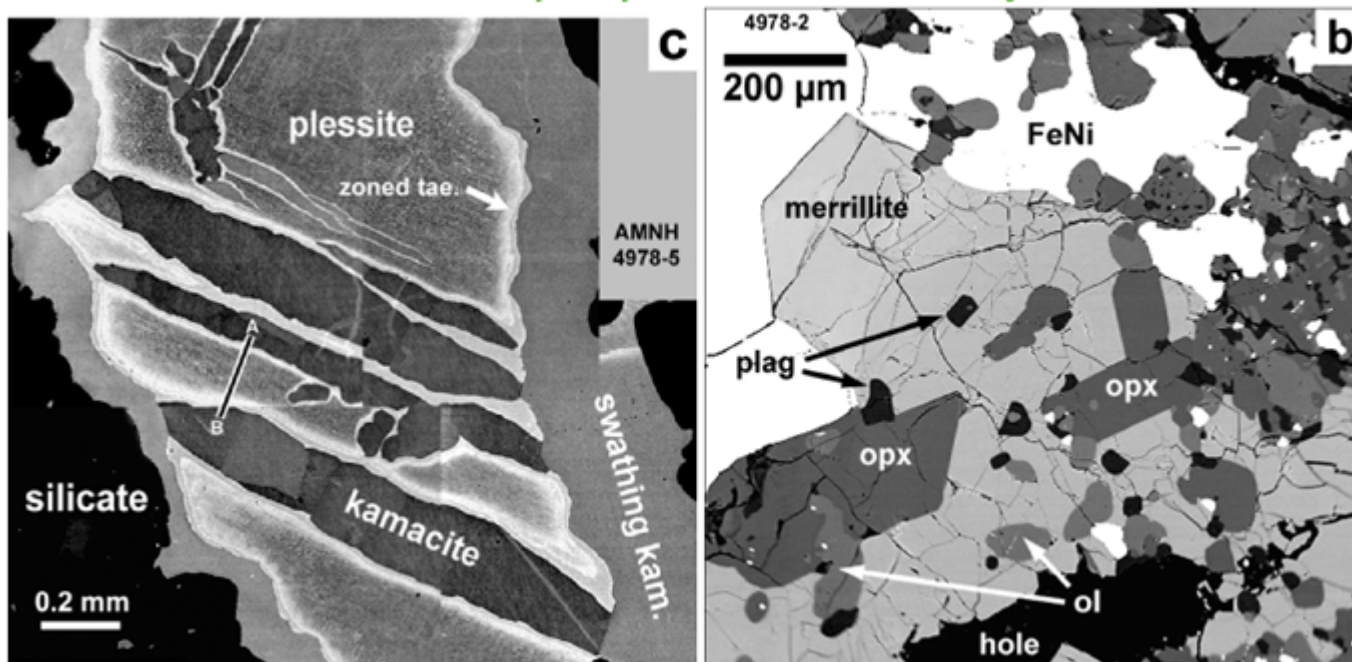
(Photographs by Alex Ruzicka)

A comparison of a typical H-chondrite and Portales Valley. Bright areas are mainly metallic; dark areas are mainly silicates. Left: A slice of a meteorite that is paired with the Franconia (H5) chondritic meteorite. The

small lines on the ruler are one millimeter apart. Right: A slice of the Portales Valley meteorite showing that the chondritic, silicate-rich material occurs as angular clasts floating in metallic veins. Tiny bright spots in silicate-rich clasts consist of troilite (FeS) and smaller amounts of fine-grained metal. A large graphite nodule is visible.

Besides the obvious differences between Portales Valley and a typical H chondrite, Portales Valley is also unusual in several other ways. It is the only known ordinary chondrite that contains coarse (cm-sized) graphite nodules as well as metal that shows a Widmanstätten texture (an intergrowth of high- and low-Ni metal, see left image below), both of which are common in iron meteorites. Another notable feature is that different sections of Portales Valley vary widely in their proportion of metal, ranging from silicate-rich areas almost devoid of metal to areas that are almost entirely metal. Finally, Portales Valley is also unusual in having coarse (0.5-1 mm across) and abundant phosphate minerals, which are usually found at the contact between metal and silicate-rich areas (see right image below).

Metal and phosphate in Portales Valley



(Photographs by Alex Ruzicka)

These are back-scattered electron images of areas in Portales Valley. Left: Metal vein showing parallel kamacite (low-Ni metal) lamellae surrounded by higher Ni-metal (zoned taenite and plessite), representing a Widmanstätten texture similar to that found in iron meteorites. The entire metal grain is swathed by kamacite. Right: Coarse phosphate (merrillite) intergrown with silicates (plagioclase, orthopyroxene, olivine) next to coarse FeNi-metal (white).

Varied interpretations of Portales Valley

Portales Valley has been alternately interpreted as an annealed (heated) impact breccia, a primitive [achondrite](#), or a meteorite transitional between chondrites and silicate-bearing iron meteorites. It is important to determine which, if any, of these ideas is correct, as each implies a different heat source and formation mechanism for the meteorite. We will consider each of these ideas below.

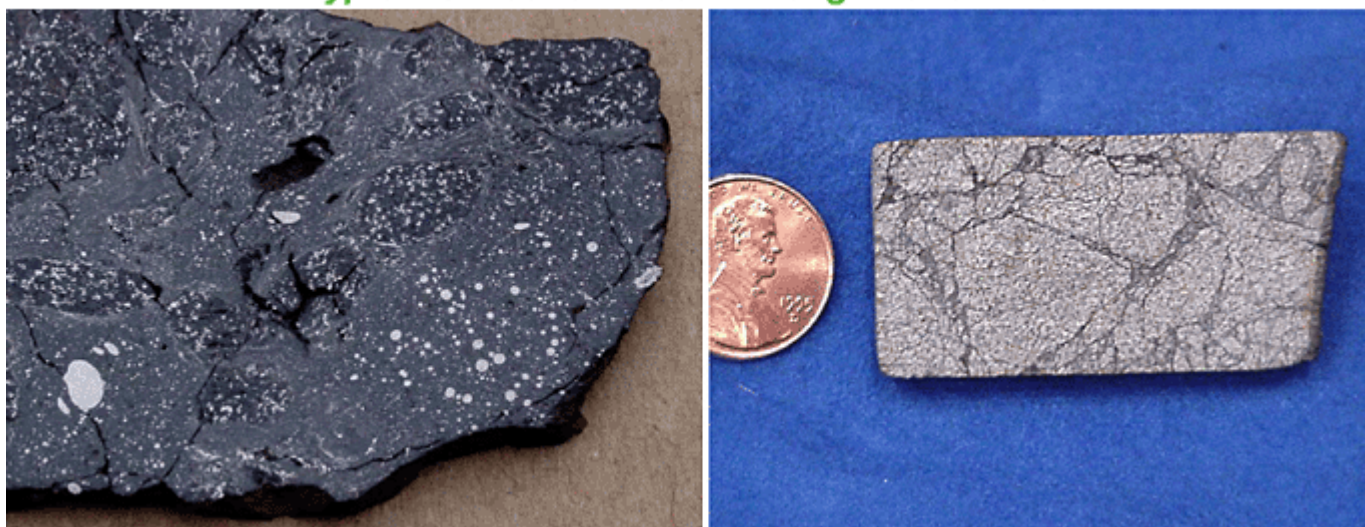


Annealed impact melt breccia?

One possibility is that Portales Valley represents an impact melt breccia that has undergone slow cooling

from high temperatures (annealing). When two objects collide, they may generate enough heat to create a melt, which can form veins that cut through unmelted portions of the meteorite. One model for Portales Valley is that the metal veins were produced by this type of shock melting process. There are some problems with this model. Studies show that shock deforms minerals in a characteristic fashion producing features such as planar fractures and mosaic extinction in olivine and structural changes in feldspars (see [PSRD article: Asteroid Heating: A Shocking View](#).) None of these deformation features are observed in Portales Valley. It has been proposed that deformation features were present originally but were removed by annealing. Even so, there are other problems with this model. Typically when a chondrite is partially melted, glassy silicate veins are produced which cut through unmelted material (see right image below). With more extensive shock melting, larger areas of melt are produced, with metal and troilite forming globules embedded in silicate melts (see left image below). In neither case are large metallic veins produced. Another problem is that in order to produce the large metal veins observed in Portales Valley, temperatures would have to have been so high that the silicates would be substantially melted and there would be no visible chondritic texture left.

Typical effects of shock melting in chondrites



(Photographs by Alex Ruzicka)

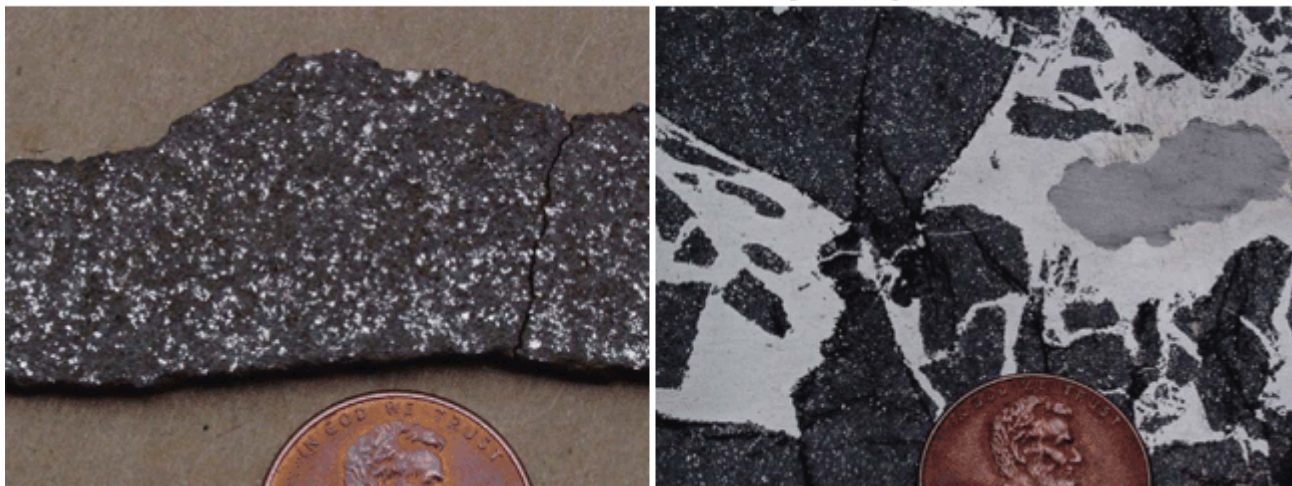
These meteorites show features not seen in Portales Valley. The bright areas are mainly metallic; the dark areas are mainly silicates. Left: "Gao melt" showing clasts of H6 material surrounded by metal-bearing silicate shock melt. The metal in the melted portion forms droplets instead of veins (field of view is ~4.5 cm wide). Right: Peekskill (H6) chondrite, which consists of angular clasts surrounded by thin, dark glassy melt veins.



Primitive achondrite?

Another possibility is that Portales Valley is a primitive achondrite, such as an acapulcoite, lodranite, or winonaite. These are meteorites that are approximately chondritic in chemical composition, but which have been raised to high enough temperatures to be melted. The primitive achondrites are believed to have been heated solely or primarily by internal heating. They generally do not have any significant vein structure, although one acapulcoite (Monument Draw) contains a coarse phosphate vein and a thin metal vein. Neither of these closely resemble the large vein structure in Portales Valley. Additionally, experiments show that melting chondrites by internal heat alone generally produces isolated patches or globules of metallic melt, not veins.

Achondrite and Portales Valley comparison



(Photographs by Alex Ruzicka)

Bright regions in these meteorites are mainly metallic; dark areas are mainly silicates. Note that the textures of the two meteorites are completely different. Left: NWA 1058, an ungrouped primitive achondrite. Right: Portales Valley. The medium gray object inside the bright metal is one of two graphite nodules found in the meteorite.



Silicate-bearing iron meteorite?

Yet another possibility is that Portales Valley represents a silicate-bearing iron meteorite. Some iron meteorites, such as Campo del Cielo (IAB iron), contain regions that are texturally similar to Portales Valley, as shown in the pictures below. The silicate regions in IAB iron meteorites are often approximately chondritic in composition and mineralogy, but it is clear that Portales Valley is not simply another IAB iron as its oxygen isotope composition is completely different.

Silicate-bearing iron meteorite and Portales Valley comparison

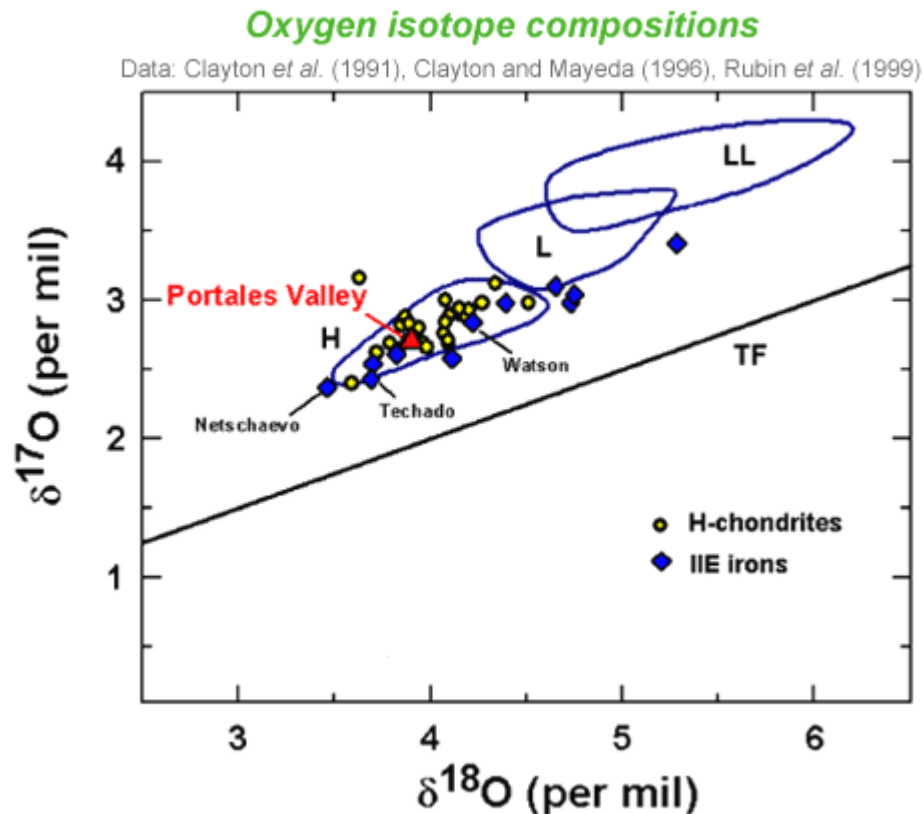


(Photographs by Alex Ruzicka)

This comparison between a silicate-bearing iron meteorite and Portales Valley shows that they are texturally similar. Bright areas are mainly metallic; dark areas are mainly silicates. Left: Campo del Cielo - IAB silicate-bearing iron. Right: Portales Valley.

On the other hand, the oxygen isotope composition of Portales Valley is the same as that of H-group ordinary chondrites and resembles the IIE group of silicate-bearing iron meteorites, as shown in the diagram below. The silicate-bearing IIE iron meteorites are a diverse group. Some contain silicates that are not similar to chondrites in composition at all. Three others (Netschaëvo, Techado, and Watson) contain silicates that are approximately

chondritic in mineralogy and bulk chemical composition. Two of these (Netschaëvo and Techado) also contain a few recognizable chondrules, similar to Portales Valley. Despite these similarities, there are significant differences in mineral compositions and abundances between Portales Valley and IIE irons such as Netschaëvo. These differences suggest that Portales Valley is not simply another silicate-bearing IIE iron meteorite.



Standard three-isotope oxygen diagram showing the compositions of Portales Valley, H-, L-, and LL-group ordinary chondrite, and IIE iron meteorites. TF is the terrestrial fractionation line. The y-axis plots the ratio of oxygen-17 to oxygen-16 compared to mean sea water. The x-axis is the ratio of oxygen-18 to oxygen-16, also normalized to sea water. This figure shows that there is an overall resemblance between Portales Valley, H-group chondrites, and IIE iron meteorites.

So how did Portales Valley form?

The best model for producing Portales Valley involves a blend of the three possibilities described above. A shock process was probably responsible for producing the obvious coarse vein structure, as experiments show that such veins cannot be produced easily by static heating. However, such a shock event could not have been very intense, as the minerals in the meteorite are not significantly deformed. On the other hand, as with primitive achondrites and iron meteorites, there is clear evidence that portions of Portales Valley melted, probably by an internal heating mechanism unrelated to shock. The reason that Portales Valley is difficult to pigeonhole is that it is transitional between primitive H-chondrite-like material and more evolved (achondrite, iron) meteorite types. Because it is transitional, Portales Valley provides a snapshot of the first stages of differentiation in asteroids.

Many unusual features of Portales Valley provide clues as to how it formed, and any story of its formation has to explain them. These features include:

1. the coarse metal veins that appear to have formed when molten metal flowed around silicate clasts
2. composition of the metal in Portales Valley is different from that found in H-chondrites and differs between the coarse-veined and silicate-rich areas
3. troilite (sulfide phase) is not present in the coarse metal veins, but is concentrated in the silicate areas
4. the presence of large graphite nodules in the coarse metal veins
5. the presence of coarse phosphate preferentially located at the contact between the metal-rich and silicate-rich areas
6. the amount of high-calcium pyroxene (clinopyroxene) in Portales Valley is less than half the amount expected in an H-group ordinary chondrite
7. ratio of olivine to low-calcium pyroxene (orthopyroxene) is lower than that found in H-group ordinary chondrites

Ruzicka and his colleagues have proposed a model for the formation of Portales Valley to explain the features listed above.

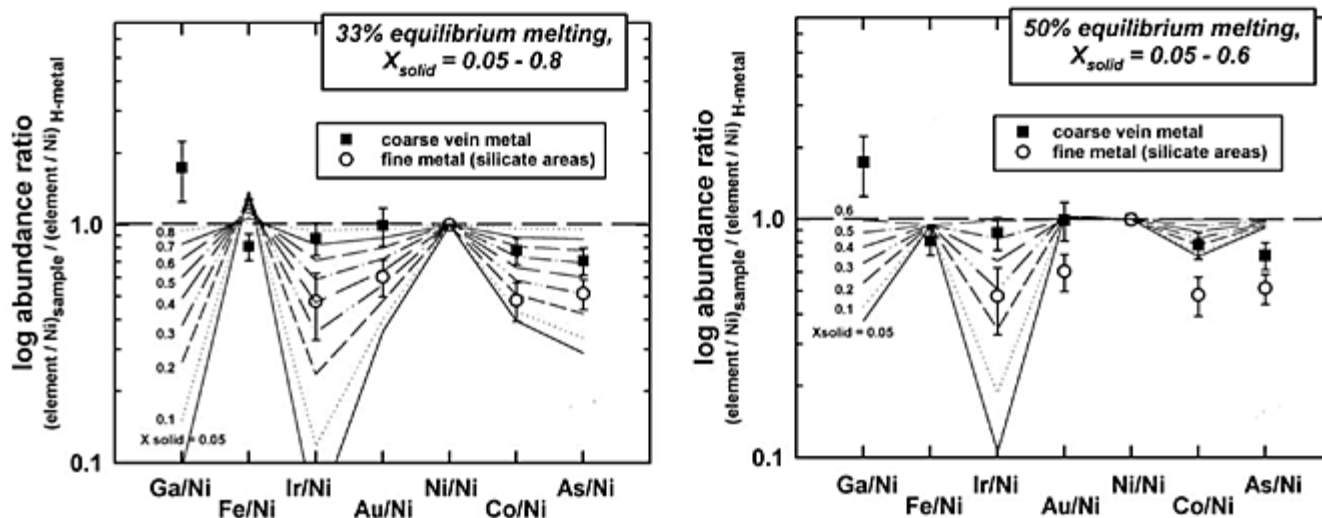


Melted and mobilized metal and sulfide

There is good evidence that at least some of the metal and troilite in Portales Valley was molten. The prominent metal-veining textures imply that metal was substantially molten and that it sometimes entrained silicate fragments (clasts) that floated in the metal. Moreover, the composition of the metal is somewhat different than that found in H-chondrites, and this difference can be explained by a partial melting process.

The trace-element composition of the metal in Portales Valley varies between the metal present in the coarse veins, and that found as finer grains in silicate-rich areas. A model involving partial melting of metal and sulfide with incomplete separation of melted and solid portions can explain this variation and also provides constraints on the maximum temperature during melting. The graphs below compare the composition of metal in coarse veins and silicate areas (filled squares and open circles, respectively) to model compositions (lines) produced by melting either 33% or 50% of the metal and sulfide in an H-chondrite, while keeping the melt in chemical equilibrium with the solid. Shock processes cause the melt to move through the meteorite, relative to the solid. Solid and liquid metal can be mixed in different proportions in various places in the meteorite. In the figure below, the different lines indicate various proportions of solid metal fractions (given by X_{solid} , where X_{solid} can be as low as zero or as high as one) relative to the total amount of metal (liquid or solid). The compositions are normalized to the abundance of nickel and to H-chondrites. With 33% melting, a solid-liquid metal mixture containing ~20-40% solid agrees with the observed composition of fine metal in Portales Valley, and a mixture containing ~40-80% solid substantially agrees with the composition of the coarse vein metal. The Ga/Ni ratio of the latter is too high to be explained by the model, but the concentration of Ga is known to be affected by shock, which could account for this discrepancy. In contrast, with 50% melting, the models clearly fail to match the observed compositions. The model results imply that metallic melt fractions of less than or equal to 40% provide acceptable matches to the chemistry of Portales Valley. This amount of melting corresponds to temperatures of ~940-1150 °C. With these temperatures, as much as 13% of the silicates could have melted as well.

Metal compositions in Portales Valley compared to theoretical calculations



(From Ruzicka *et al.*, (2005) *MAPS*, v. 40, p. 261-295.)

These complicated, but informative, diagrams combine data from the Portales Valley meteorite (symbols) with theoretical calculations. The graph on the left shows how the ratios of the concentrations of several elements in the metallic iron vary with the amount of solid and liquid metal present. The data match reasonably well for 20-80% solid metal if the amount of melting was 33% (as shown in the left graph). The data do not match at all if 50% of the metal was molten (as shown in the right graph).

The inferred temperatures of ~940-1150 °C for Portales Valley are somewhat higher than the maximum temperatures of ~800-960 °C reached by H-chondrites (type 6 metamorphic grade) due to internal heating. The most likely explanation for the features seen in Portales Valley is that it experienced a shock event while it was already warm from internal heating. The shock would have provided only a small temperature increase. More importantly, the shock wave was necessary for moving melt through the meteorite. Portales Valley probably formed at depth in the parent body below an impact crater in a slowly-cooling environment, enabling the Widmanstätten structure to form in metal and allowing other mineralogical reactions to proceed.

When a chondrite is partially melted, all of the sulfide phases will melt and the sulfur will be concentrated in the metallic melt. The modeling results shown in the graphs above indicate that the metallic regions in the silicate-rich areas had a higher proportion of liquid metal, and thus should have incorporated more sulfur than the coarse metal veins. In agreement with this, troilite, the major sulfur-bearing phase in Portales Valley, is indeed concentrated in silicate-rich areas and not found in coarse metal vein areas. However, the models imply that at least some sulfur should have been present in the coarse veins initially, when metallic liquid was still present. The absence of troilite in the coarse veins implies that sulfur-bearing metallic liquid must have been expelled from the coarse veins, and moved into the silicate-rich areas, before Portales Valley finished solidifying.

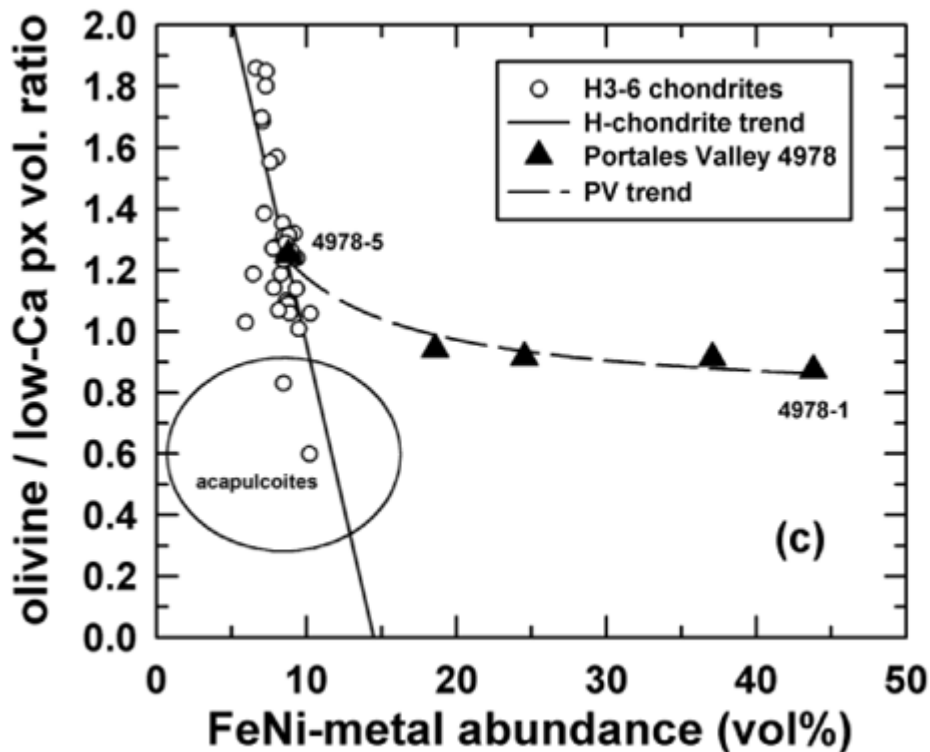


Changes in mineralogy due to mobilization of metal and sulfide

The presence of metallic liquids and the transport of this liquid through the Portales Valley source region had a dramatic effect on the distribution and amount of minerals in the remaining rock. For example, carbon, like sulfur, will dissolve in metallic liquids during partial melting. In order to account for the centimeter-sized graphite nodules found in the meteorite, carbon must have been scavenged from large volumes and concentrated locally in the metallic liquid, where it crystallized to form the nodules. A similar crystallization process was probably responsible for making graphite nodules in iron meteorites. The scavenging effect inferred for Portales Valley would have been facilitated by the presence of moving metallic liquids, which passed through large volumes of the rock, picking up carbon along the way.

Moreover, at the high temperatures inferred for Portales Valley, phosphorus would have dissolved in metallic alloy. Upon cooling, phosphorus-bearing metal will react with high-calcium pyroxene in the silicates to produce phosphates such as merrillite and apatite. This reaction can explain why phosphate minerals are preferentially concentrated at metal-silicate interfaces in Portales Valley, and why phosphate is enriched and clinopyroxene is depleted in Portales Valley compared to ordinary chondrites. Thermodynamic analysis suggests that the phosphate would have been produced between temperatures of 975-725 °C as the meteorite cooled slowly from high temperatures. Finally, the phosphate-forming reactions redistributed oxygen, which changed the proportions of the major silicate minerals (olivine and pyroxene) in the meteorite. The figure below shows the olivine-to-pyroxene ratio and metal content in Portales Valley compared to other meteorites. Typically the olivine/pyroxene ratio in Portales Valley is lower than that found in H-chondrites. As shown by the dashed line, there is a relationship between metal content and olivine/pyroxene ratio in Portales Valley, forming a trend which is unlike that found in H-chondrites and acapulcoites (a primitive achondrite). Areas in Portales Valley that contain more metal are areas in which there was a greater amount of phosphorus available for reaction, resulting in lower olivine contents.

Olivine/pyroxene ratio and metal content comparison



(From Ruzicka *et al.*, (2005) *MAPS*, v. 40, p. 261-295.)

This diagram shows that the ratio of olivine to low-calcium pyroxene is lower in Portales Valley than that found in H-chondrites.

This table summarizes the major features of the Portales Valley meteorite and how Ruzicka and coauthors explain them.

Feature in Portales Valley	Proposed Formation
silicates trapped in metallic veins	metal melted and flowed because of shock heating
metal composition different from H-chondrites	metal compositions were modified by partial melting
FeS concentrated in silicate areas	sulfur-bearing metal was expelled from coarse metal veins
large graphite nodules in metallic veins	carbon was scavenged from wide area and concentrated in metal
big phosphate grains next to metal	phosphorus in the metal moved to the contact between the metal and silicate and was oxidized
low content of high-calcium pyroxene	formation of calcium phosphate occurred by reaction with high-calcium pyroxene
low ratio of olivine to low-calcium pyroxene	formation of phosphate minerals redistributed oxygen in the silicates, leading to the destruction of olivine and the formation of low-calcium pyroxene

The complexities of planet formation

Portales Valley is transitional between primitive (chondrite) and evolved (achondrite and iron) meteorites. It formed by a shock event while the parent body was being heated internally. Portales Valley can be considered an achondrite in the sense that it was partially melted. It also bears striking resemblances to silicate-bearing iron meteorites, which formed by differentiation. The main importance of Portales Valley may ultimately lie in what the meteorite has to tell us about the formation of other kinds of meteorites and the parent bodies from which they were derived. Portales Valley may be telling us that simultaneous impact and internal heating events could have been important in the overall process of differentiation. The meteorite gives us a glimpse at the nature of the complex processes that operated in even small bodies as the planets were forming.

Additional Resources

LINKS OPEN IN A NEW WINDOW.

- [Cascadia Meteorite Laboratory](#)
- Rubin, A. E. (2004) Postshock annealing and postannealing shock in equilibrated ordinary chondrites: implications for the thermal and shock histories of chondritic asteroids 1. *Geochimica et Cosmochimica Acta*, v. 68, p.673-689.
- Ruzicka, A., Killgore, M., Mittlefehldt, D.W. and Fries, M.D (2005) Portales Valley: Petrology of a metallic-melt meteorite breccia. *Meteoritics & Planetary Science*, v. 40, p. 261-295.
- Taylor, G. J. (2004) Asteroid Heating: A Shocking View. *Planetary Science Research Discoveries*. <http://www.psr.d.hawaii.edu/April04/asteroidHeating.html>