PRESS ABSTRACTS

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The Program Committee for the Twelfth Lunar and Planetary Science Conference has chosen these contributions as having the greatest potential interest for the general public. The papers in this collection have been written for general presentation, avoiding jargon and unnecessarily complex terms. More technical abstracts will be found in Lunar and Planetary Science XII.

For assistance during the conference, call the NASA Johnson Space Center News Center at (713)483-5111. Telephone numbers of the first author of each contribution will be found on page ii. Feel free to call for more information.

The following abstracts were also thought to deserve widespread attention, but could not be rewritten in time to appear in this volume (page numbers denote location in Lunar and Planetary Science XII):

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This abstract volume was prepared by P. R. Criswell, Technical Editor, Lunar and Planetary Institute.
Since the early 1800's, when it was first realized that meteorites came from outer space, scientists have wondered which bodies they come from. Presumably many come from the asteroids, the small rocky planets that are concentrated between the orbits of Mars and Jupiter. Perhaps some come from comets that occasionally visit the inner solar system after aeons of cold-storage on the outer fringes of the solar system. But the properties of these rocky and metallic missiles from the sky have long proved rather bewildering to meteoriticists, the scientists that dissect and analyze them. It is hard to imagine in what sort of parent bodies they formed or how they formed there.

Most meteorites appear to have been heated to rather high temperatures, at least to the point of metamorphism. Others are clearly the product of even more extreme conditions: they appear to have solidified from molten lavas, or from the molten interiors of planetary bodies. Some, the iron meteorites, even appear to be chunks from the metallic cores of planetary bodies, analogous to the iron core at the center of the Earth. But the asteroids and comets have always seemed too small to provide the "ovens" needed to "cook" these meteorites. Comets are conventionally believed to be icy bodies that were never heated. Asteroids are too small to be heated by the radioactive decay processes responsible for heating the interior of the Earth. Even if they were heated by the much more powerful radioactivity that some astrophysicists believe may have been present during primordial epochs, the heat would be radiated away from asteroid-
sized bodies too rapidly to account for the properties of many meteorites, according to calculations made by several scientists during the past fifteen years.

Clark Chapman, an expert on asteroids, and Richard Greenberg, whose specialty is celestial mechanics, are re-examining these problems by taking as their key the need to model the origin of two particularly strange types of stony-iron meteorites called pallasites and mesosiderites. Pallasites look like fruit cakes: they are made of nickel-iron with raisin-sized crystals of green olivine embedded in the metal. Mesosiderites look like lumps of volcanic soil whose pores have been filled with an interconnected network of iron.

Calculations by Greenberg and Chapman have helped save a conventional hypothesis for the origin of pallasites that had been running into trouble. These objects plausibly formed at the outer edge of a parent body's liquid iron core, where the olivine crystals once floated. But the researchers became convinced that the accepted models for the origin of mesosiderites cannot be correct. The accepted models have mesosiderites forming entirely near a parent body's surface, while Chapman and Greenberg wonder whether the iron may have entered after the soil sunk down to meet the core.

In developing these new ideas about how mesosiderites formed, they have been forced to re-think the whole question of how asteroids have evolved and how meteorites are derived from them. They now believe they have a general model of these processes that seems consistent not only with the properties of meteorites, which have been the chief constraints on previous hypotheses for meteorite origins, but also with geophysical calculations concerning asteroid collisions and fragmentation and with telescopic evidence concerning the surface compositions of the larger asteroids. This synthesis is based on the work of many other scientists: the disagreements with previous work are rare compared with the agreements. There remain gaps in the model where detailed research will be required to demonstrate the validity of "best guesses" about certain poorly understood processes. The Lunar and Planetary Conference seems an appropriate forum
to lay out these ideas so that others may criticize them and help develop them further.

Chapman and Greenberg believe that the stony meteorites have been derived mainly from the larger asteroids, those larger than about 100 km (e.g., to 60 miles) in diameter. The iron and stony-iron meteorites, on the other hand, are derived from metallic asteroids -- now between 15 and 50 km in diameter -- that were originally the cores of melted asteroids several times as large. It appears that approximately 10% of the original population of asteroids larger than about 25 km diameter were somehow heated to the point of at least partial melting. They are the parent bodies for those meteorites (principally irons, stony-irons, and basalts) that are the products of high-temperature processing. Other asteroids were heated less and are the parent bodies for many of the types of meteorites, called chondrites, that preserve primordial textures from the time they first accreted.

In this model, the asteroids that have melted are believed to have been smaller than many researchers previously calculated. Such bodies were thought to cool too rapidly to account for evidence that many meteorites cooled slowly over a long duration. But recent studies of asteroid collisions have shown that large asteroids collide rather frequently. These collisions break the bodies into small fragments. Even in such explosive events, the velocities of the fragments usually fail to reach "escape" velocity, so the fragments reaccumulate, leaving an asteroidal body covered with layers of broken-up rock. Such layers of rubble are insulators and can keep even small bodies hot for long periods of time.

Over the 4.5 billion year age of the solar system, about half of the melted asteroids around 35 km in diameter have suffered such energetic collisions that their rubbly crusts and mantles have been blasted off into space, leaving behind their relatively intact, strong, metallic cores. From the surfaces of such cores, later impacts chipped off metal-rich fragments, some of which find their way into Earth-crossing orbits and eventually plummet through our atmosphere to be
recovered as the iron and stony-iron meteorites, including mesosiderites.

Mesosiderites are roughly half metal, half rock. The rocky portions are similar to some of the basaltic meteorites that must form near the surfaces of parent bodies. This material is similar to volcanic lava. Furthermore, mesosiderite rocks show evidence of brecciation, a process of fracturing and recementing of rock minerals by violent cratering impacts, presumably near the surface. Yet the metallic portions of mesosiderites have a crystalline pattern suggesting they cooled more slowly than any other type of meteorite; so mesosiderites resided for hundreds of millions of years at depths of hundreds of kilometers inside a very large parent body. How can mesosiderites have been found both at the surface of a body and in its deep interior?

The conventional model suggested that an iron asteroid impacted on the surface of a basaltic asteroid, creating the mesosiderite breccia, which was thereupon buried at great depths only to be later re-excavated with sizable quantities ejected onto Earth-crossing orbits. Greenberg and Chapman think that hypothesis involves a succession of implausibilities. It is difficult to form a large quantity of metal-rock breccia in an impact; once the material is somehow buried inside the huge asteroid, it is highly improbable that it could be re-excavated and ejected at escape velocities towards Earth.

The new idea may jar the preconceptions of some specialists, but Greenberg and Chapman believe that it can account for the major properties of most mesosiderites. They believe that a basaltic crust that had formed on the surface of a substantially molten body foundered; that is, it sank through the largely molten mantle until it floated on the surface of the molten metal core. The molten metal invaded the rock, forming the metallic network in mesosiderites, and melted the edges of some of the rock minerals, just as observed. But the core metal quickly solidified, quenched to warm but sub-molten temperatures by the relatively cold crustal blocks. As the parent body cooled, its rocky upper layers were smashed by collisions into rubble piles, insulating the warm interior to produce the
slow cooling histories inferred for mesosiderites. Eventually the body suffered a supercatastrophic collision, blasting away the mantle rocks and exposing the core to space. Since the zone where the relatively weak mantle grades into the strong, pure metallic core is just at the interface where the mesosiderites were formed, they are ideally located at the surface of the remnant core for subsequent impacts to liberate them into Earth-crossing trajectories.

Although in this model the mesosiderite parent-body is one of the largest melted parent-bodies from which we get meteorites, it is not nearly so large as the parent body others have hypothesized in the past. The original body need be only about 150 km in diameter. Chapman and Greenberg calculate that several dozen asteroids that large have probably been destroyed by impact over the age of the solar system, of which several might be once-melted bodies capable of leaving intact cores.

For more information, call Clark Chapman or Richard Greenberg at (602) 881-0332.
AN IO THERMAL MODEL WITH INTERMITTENT VOLCANISM

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In March of 1979, a theoretical paper by Stan Peale, Peter Cassen, and Ray Reynolds from the NASA Ames Research Center, predicted that tidal stresses inside Jupiter's innermost major moon, Io, would give rise to intense heating of Io's interior, with the possibility that "widespread and recurrent surface volcanism would occur." Within weeks after this paper appeared, the Voyager I flyby of Jupiter gave dramatic confirmation to this prediction with the spectacular photographs of Io and its volcanic plumes.

Inspired by the excitement of Voyager, a number of other scientists (the first in print were Dennis Matson, Gary Ransford, and Torrence Johnson of JPL) used a number of techniques to measure the heat coming out of Io. They measured a heat flow of 1000-2000 ergs/cm²s—an incredibly high figure, compared to the 10-20 ergs/cm²s measured for the earth and the moon. In fact, it was much higher than the Peale et al theory predicted. They had said that, even under the best of conditions, tidal heating could provide a heat flow of absolutely no more than 800 ergs/cm²s, and they felt that 400, or less, was a more reasonable number. Getting any more heat than this out of tidal heating would require Jupiter or Io to dissipate tidal stresses in a way quite incompatible with what we know about their internal makeup, and (as Charles Yoder of JPL pointed out) it could rob too much energy from Io's orbit—the ultimate source of the energy for tidal heating—to allow the orbital configuration of the Galilean satellites which we see today to be stable over the lifetime of the solar system.
There was another problem. All the volcanoes seen on Io were near Io's equator. But the tidal heating theory predicted that the poles would be heated more than the equator. Of course, this might just reflect the fact that the tidal heating theory was oversimplified, compared to what's really going on in Io.

The Peale et al heat flow was based on a simple, homogeneous, steady-state model for Io. I decided to attempt a more complex, time-dependent thermal evolution model for Io, which would include differences in how heat was input, and how it flowed through the planet as a function of latitude and time.

I started with a thermal evolution computer model which I had originally written, before the Pioneer mission, to predict the interior evolution of the icy satellites Europa, Ganymede, and Callisto. This program was changed to accommodate tidal heating and heat flow in two dimensions (which increased the computer time needed by a factor of 10 over the old models), and also included solid state convection in the hot interior and the melting behavior of rock.

The first surprising, and somewhat controversial, result was that tidal heating alone could not maintain a molten interior in a simple rocky planet. The initial melting does occur in our model, but as the molten region moves out toward the surface of the planet, the resulting steep thermal gradient in the crust plus the efficient transport of heat in the interior by solid state convection combine to move heat out of the planet rapidly enough to refreeze the body. (However, this involved modelling heat transport processes inside Io which are still not understood completely, and some other workers in the field have disputed this conclusion.)
But as Io heats up, it will also undergo a chemical evolution, covering its surface with a layer of sulfur which acts as an insulating blanket to keep the planet's interior warm. When this blanket is added to the model, temperatures close to the surface become hot enough to melt rock within the top 10 km of the planet.

This melting would result in the explosive eruption of sulfur (as I had discussed in a paper on the chemistry of Io's volcanoes soon after Peale et al's prediction of them). Furthermore, this eruption and the molten rock accompanying it would carry heat very efficiently from the interior to the surface of the planet, where it could radiate to space.

When these eruptions were added to the model, it became clear that the volcanoes did not occur continuously, but turned themselves on and off. After a volcano was started, the region of the planet immediately below the volcano would cool off due to the efficient transport of heat by the molten rock, and soon conditions needed to melt the surface layer at that latitude no longer existed and the volcano would stop. Volcanoes would be least likely to occur again there immediately; rather, subsurface layers at some distant latitude would be warmer and thus more likely to be the site of the next eruption. Thus the volcanoes might occur anywhere on the planet at any given time, despite the fact that the heating was greatest at the pole.

While the volcanoes were erupting, the extra outpouring of heat would raise the total heat flow out of the planet to roughly 1000 ergs/cm²s. But after they had stopped, during the 90% of the time that there were no active volcanoes, the heat flow was only a little
over 100 ergs/cm\(^2\)s. The average heat flow, taken over all time, was only 150 ergs/cm\(^2\)s, easily within the range allowed by the tidal heating theory.

So, to summarize, this computer model for Io served to illustrate a theory of intermittent volcanism on Io. Most of the time, tidal stresses serve to add heat to Io's interior, but there are no volcanoes. About 10% of the time, enough heat will have built up inside Io to trigger volcanoes somewhere on the surface. These volcanoes serve to expel in a short time (our guess is less than 15,000 years) the heat that had been building up over a period ten times as long—hence the high heat flows actually observed today on Io, during a period of active volcanism. After this heat has been expelled, the part of Io with the volcanoes has cooled down enough to stop the eruptions; the next eruptions are likely to occur at some other part of Io that hasn't had volcanoes for a while. Thus every part of Io's surface will likely have volcanoes, sooner or later.

It was a matter of good luck—the odds were about 10 to 1—that we happened to see active volcanoes the first time we got a close view of Io.
HYPERVELOCITY IMPACT CRATERS IN Icy MEDIA, S.K. Croft, Lunar and Planetary Institute 3303 NASA Road 1, Houston, TX 77058

Large-scale impact cratering is an enormously effective geologic process that sculpted the surface of every solid planet and satellite in the Solar System at the time when the planets gravitationally accreted from the debris orbiting the primitive Sun. These ancient battered surfaces dominate the appearance of all planets too small to retain an atmosphere or internal heat sufficient to obliterate the craters through subsequent atmospheric weathering or volcanism. Most planetary crusts in the inner Solar System consist of silicate rocks and soils. Because the rocky surfaces of the Earth, the Moon and Mercury were investigated first, most laboratory impact experiments performed to study the nature of impact cratering were done in targets of rock or sand. However, the Viking and Voyager missions to Mars and the satellites of Jupiter and Saturn have now given us close-up views of the surfaces of planets whose crusts consist primarily of pure water ice and/or ice-rock mixtures. The physical properties of ice are significantly different from the properties of rock: ice is weaker and is more easily melted and vaporized than rock. Ice is also less dense than liquid water, whereas solid rock is more dense than liquid rock. Conceivably, the unusual properties of ice could significantly alter certain aspects of crater formation and produce the differences in appearance found between craters on the Moon and craters on Mars and the icy satellites of Jupiter and Saturn. To evaluate the influence of the presence of ice on cratering processes, a series of impact experiments were performed in targets consisting of solid blocks of frozen ice/sand mixtures (ice-saturated sand), pure ice, and thin ice plates over liquid water. These targets simulate a variety of crustal conditions and are considered separately:

Solid ice and ice-saturated sand: These targets are thought to be characteristic, respectively, of the icy satellites (e.g. Ganymede and Mimas) and Mars. The experimental craters formed range from a few inches to about a foot in diameter. The shapes and visual appearances of the craters in both the ice and ice-saturated sand are similar to the shapes of similar-sized craters in rock. However, for craters formed at the same impact energy, the craters in the ice-saturated sand are about twice as large as the craters in rock. The craters in ice about three times larger than the craters in rock. The ice targets were also significantly more fractured beyond the crater rim than either the ice-saturated sand or rock targets. No significant effects due to either melting or vaporization of the ice were observed. Thus ice appears to act simply as a very weak rock during an impact.

Direct comparison between craters a few inches in diameter and craters a few miles in diameter cannot be made. However, one important application of the enlargement of craters formed in weak icy targets compared to craters formed in rock that can be made involves age estimates of planetary surfaces made by counting craters. In general, the larger the number of craters at a given diameter found on a given surface, the older the surface is. The diameters of craters used in age determinations are frequently smaller than a mile in diameter, the largest diameter at which crater enlargement due to ice in the crust is still important. Consequently, icy surfaces will have more large craters, and thus appear older, than rocky surface that are really the same age. Therefore, impact experiments like these can be used to obtain more accurate crater-count ages, and thereby improve understanding of planetary geologic histories.
Thin ice plates: Extremely large craters characterized by a "bull's-eye" pattern of concentric rings of cliffs or mountains are called multiring basins. They are found on the Earth, the Moon, Mercury, Mars, Ganymede and Callisto. Multiring basins typically have two to five well-defined concentric rings. The basins on Callisto, however, have dozens of concentric rings and ring segments, and should probably be called "multi-multiring basins". Figure 1 is a sketch map of Valhalla, the largest basin on Callisto. The central region is a bright, featureless patch surrounded by many concentric segments of ridges. The zone around the central patch has relatively few craters, implying the existence of an ejecta blanket, but few other characteristic features of ejecta blankets are present. For example, only a handful of radial secondary crater chains, which extend away from the basin center like the spokes of a wheel, have been found. Secondary crater chains are usually found in great numbers around basins on the other planets. The concentric ridges extend much farther from the basin center than the ejecta blanket. It is thought that at the time of basin formation, the solid icy crust overlying the weak (liquid?) mantle on Callisto was very thin and easily broken. It has been suggested that the rings formed very late in the cratering event, when soft mantle materials flowed back to fill the immense central crater, dragging along the thin, brittle crust and fracturing it in the process. Another possibility is that the cracks formed very early in the cratering event when the primary shock wave from the impact traveled outward, fracturing the ice in radial and concentric patterns similar to those formed in a glass window around a bullet hole. The impact experiments into thin ice plates over water, which simulates impacts in the ancient crust of Callisto, were specifically designed to examine the type of cracks formed by the primary shock wave. A sketch drawing of one of the thin-plate impact craters is shown in Figure 2. The central crater is slightly irregular in shape and is filled with slush. Both the crater and the concentric and radial cracks shown by heavy solid lines in Fig. 2 extend through the plate. An extensive pattern of radial and concentric fractures that did not go completely through the plate are indicated by the dashed lines. The fractures represent zones of weakness in the plate that extend to great distances beyond the crater rim. High speed films confirm that the cracks and fractures were formed by the initial shock wave.

With the exception of the prominent radial cracks, which are due in part to the finite size of the plate, the overall appearance of the experimental crater and fracture pattern in Fig. 2 is not unlike the appearance of the Valhalla basin in Fig. 1. Based on the sequence of events seen on the high-speed films and the observed final crater, a possible scenario of the formation of Valhalla (and similar) basins can be constructed: The crater begins with the penetration of the thin ice crust of Callisto by an icy moonlet possibly 30 miles across. The crater formed by the impact punches through the crust, ejecting large amounts of liquid water from the mantle along with crushed fragments of the crust. The primary shock wave forms concentric and radial cracks and fractures far beyond the crater's edge, weakening at least half the entire planet's crust. The liquid crater walls begin to collapse before most of the ejected material returns to the surface, converting the concentric fractures generated by the shock into a concentric ridge system either by inward drag or simple collapse (the radial fractures are not affected). The crater floor rebounds to fill the crater. The rebounding material originates primarily from the liquid mantle, so the original crater becomes a large, slush-filled lake. The slushy ejecta lands in the inner fracture
zone, rounding contours, filling low spots, and obliterating older craters. Relatively few recognizable chains of secondary craters are expected because of the lack of large solid blocks in the ejecta, consistent with the observed paucity of secondary craters around Valhalla. The concentric ridge pattern extends far beyond the recognizable ejecta blanket because of the very extensive fracture network generated by the shock, and the virtually planet-wide fluid response of the mantle. Eventually the slush-filled lake at the center re-freezes to form the featureless central plain. The central plain will be brighter than the surrounding crust because it is fresh ice lacking the darkening admixture of rock present elsewhere.

As with the ice-block impact experiments, extrapolation of the ice-plate impacts to basin sizes is fraught with uncertainty, but the scenario of basin formation motivated by the experiments is consistent with the observed structure of Valhalla and similar basins, and provides a viable framework for further study of these fascinating and beautiful geologic features.
HYPERVELOCITY IMPACT CRATERS IN ICY MEDIA

Croft S. K.

Figure 1. Sketch map of the Vallaha Basin, Callisto. The central bright patch marking the central crater and the concentric ridge system are shown in outline. The zone around the central patch which has few small craters is where ejecta from the central crater fell. Note that the concentric ridge system extends at least twice as far from the central patch as the ejecta, affecting nearly half of Callisto's crust. (This figure is taken from B. A. Smith et al.(1979) The Jupiter System through the Eyes of Voyager I. Science vol. 204, pp. 951-972. Used by permission of Am. Assoc. for the Advancement of Science.) Central bright patch is about 190 miles in diameter.

Figure 2. Sketch map of impact crater in thin ice plate over liquid water. Central crater is filled with slush. Solid lines are cracks splitting plate completely. Dashed lines are shock-induced fractures within the plate that did not split completely open. Note the similarity of the concentric fracture pattern around this experimental crater compared to the concentric ridge pattern around Valhalla in fig. 1. Central crater is about three inches in diameter.
Basalt fragments from howardite meteorites and the multitude of planet-like bodies in the early solar system.

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Among the stony meteorites, the group known as basaltic achondrites is of particular importance because it is more like terrestrial and lunar basaltic rocks than any other group. The basaltic achondrites are a rare and useful source of information about planetary processes in a part of the solar system remote from the earth and moon. These meteorites are believed to have formed by processes which can occur only on, or slightly beneath, the surface of a planet-like body. For example, the subgroup of basaltic achondrites called howardites look like the soil, or regolith, on the surface of the moon and are interpreted to have formed by similar volcanic and impact-controlled processes, to those known to have created the lunar surface. Chemically, however, the howardites are very different from the moon and cannot be lunar fragments.

These howardite meteorites are described as breccias. This means that they contain fragments of different rock types that were mixed and bound together to form a new rock type. The fragments of the different rock types can be studied to discover the variety of rock types that were present on the parent planet and also for comparison with other groups of meteorites. Until the present study was begun, the howardite meteorites were thought to be breccias containing essentially two rock types. These are calcium, aluminum, iron rich fragments
similar, or identical, to the eucrite group of basaltic achondrites, and magnesium rich rock fragments made up almost entirely of a single mineral (pyroxene) and very like the diogenite group of achondritic meteorites. The presence of these two types of fragments, in the howardites, suggests that three groups of achondritic meteorites: the howardites, the eucrites and the diogenites all formed on the same planet, or in very similar planetary environments. If this is true, then it should be possible to relate the chemistry and geology of these meteorite groups to one another. An accurate model relating these groups is essential for further understanding of the original environment in which these achondritic meteorites evolved and great progress has been made in recent years toward developing appropriate models. However, the great chemical differences between the eucrite and diogenite meteorites (and their equivalents in the howardites) and the mechanism by which they may be derived from a common source have not yet been adequately explained.

Because the howardite meteorites contain fragments of both eucritic and diogenitic material, further study was initiated in the hope of finding fragments of other rock types that would provide more evidence about the evolution of the parent body. In particular, the presence of rock fragments with compositions intermediate to calcium, aluminum, iron rich eucrites and the magnesium rich diogenites was expected. The research reported at the 12th Lunar and Planetary Science Conference (1981) provides data for a new group of rock fragments in howardites that are similar to the expected fragments but, in addition, suggests new possibilities for the interpretation of basaltic achondrite meteorites.

These fragments make up a sequence of basaltic rocks that vary in composition from very magnesium rich (having affinities with the diogenite meteorites that are characterized by a magnesium rich pyroxene mineral) to calcium, iron,
aluminum rich like the basaltic eucrite meteorites. The calcium iron, aluminum rich members of this group differ from other fragments in the howardites which are very like the eucrite meteorites, because they contain more sodium. The existence of this group of variable composition in the howardites, together with the two previously recognized groups, is persuasive evidence that the various types of rock fragments are closely related to one another. The close compositional relationships between the rock fragments in the newly recognized group, are readily explained by the process known as igneous fractionation. This process is characteristic of rocks that formed on planets, rather than in the pre-planetary nebula. Knowledge of fractionation can be used to predict how the compositions of the minerals making up these rocks will change as a mass of molten rock (or magma) cools and crystallizes. The new basaltic rock fragments from howardites contain minerals that have compositions fairly similar to the compositions that are predicted by igneous fractionation theory.

In detail, however, the compositional differences between the three groups of rock fragments present in howardites suggest that several different, but related, processes may be necessary to produce the observed diversity of rock types. When these rock fragments are compared to other basaltic achondrites which contain similar rock types (eucrites, diogenites and the stony fraction of the mesosiderite meteorites) a single unique process for evolution from a single common source is not reasonable. Although many of the basaltic fragments in these meteorites are similar, their differences are sufficient to require that different processes operated on different portions of the original starting material. If all this material was on a single planet, then it was probably fairly large since research reported at a recent Lunar and Planetary Science Conference suggests the variability of the basalt types present on a planet decreases as the size of the planet decreases. For example, basalts on the moon
are much less diverse than those on earth. Since most models for the origin of basaltic achondrites derive them from small asteroid like bodies (about 500 km in diameter) which are very much smaller than either the moon or the earth, the amount of diversity among the basalt types on such a body must be small. If all the basaltic achondrites were formed on a single planet, then it must have been significantly larger than the known asteroids. Alternatively the different achondritic meteorites probably evolved independently on several small bodies that formed from very similar material in the same general part of the solar system. One parent body has been tentatively identified as the asteroid Vesta but this asteroid cannot be the parent body of all the basaltic achondrites and others have yet to be found, if, indeed, they have not been destroyed by the event that sent fragments of them flying toward earth.

In summary, the identification of a new group of basaltic rocks in howardite meteorites provides new constraints on the evolution of the howardite parent body, and in conjunction with results from other basaltic achondrites, suggests that this important group of stony meteorites were originally fragments of several planet-like bodies remote from the earth and moon. These samples, which reveal the considerable differences between various bodies in the early solar system are of great significance, since they provide constraints that allow us to determine the early history, and evolution, of the solar system more accurately.
Comparison of spectral reflectance properties of terrestrial and martian surfaces determined from Landsat and Viking Orbiter Multispectral Images. Diane L. Evans and John B. Adams, Department of Geological Sciences, University of Washington, Seattle, Washington 98195.

A technique developed to study images of Mars has now been applied to satellite images of the Earth. The images used are multispectral images obtained through filters that are only sensitive to certain energies or wavelengths of light. When these images are combined, it is possible to determine a spectral signature for the area covered in the images. In studies of Mars, we have developed a technique of comparing spectral signatures of rocks and minerals determined in the laboratory to spectral signatures of a surface determined from multispectral images. This makes it possible to extract compositional information from images directly.

This new technique involves determining the spectral signature of a material of interest ahead of time and searching a stack of multispectral images for areas in the image that have that spectral signature. When these areas are found, a map of materials with a desired composition can be made.

In our most recent study we compared laboratory spectral signatures of rocks and minerals with satellite multispectral images of the Earth. Our purpose in this study was to see if we could apply the same technique developed for our Mars studies to Earth, where we could compare actual surface samples with images of the sampled area. Not only would this be a breakthrough for geologic remote sensing of the Earth but it would also help us better understand what the spectral information in images can tell us about surface composition. This would make it possible to put further constraints on the composition of the martian surface where we cannot obtain samples at this time.
Color and near-infrared pictures of the Earth have been acquired for the last 10 or 15 years from the NASA satellites called Landsat 1, 2 and the recently launched Landsat 3. Landsat sends back two visible and two near-infrared images. We obtained a set of Landsat images of the big island of Hawaii in order to test our technique on a set of satellite pictures of the Earth. From a remote sensing standpoint, the biggest difference between the Earth and Mars is that the Earth has a much thicker atmosphere which strongly affects satellite images. The blue of far-off mountains tells us that we're not seeing true colors when we look through our thick atmosphere, even on a clear day. Fortunately, many scientists have been working on ways to correct for this problem, and we used a set of corrections published last year.

We visited Hawaii and collected about fifty samples from the surfaces of lava flows of various ages. We then went through the procedure of 1) measuring the spectral response at visible and near-infrared wavelengths, 2) calculating the signals that would be produced in the Landsat bands, 3) correcting those signals for atmospheric effects, and 4) mapping out that signature in the Landsat image. The maps produced from these signatures showed that our technique works very well, even for the Earth.

We found that what we were seeing in the Hawaii data was that changes in spectral signatures of rocks were directly related to the ages of the samples. Fresh, unoxidized basalts have a very flat spectral signature. All wavelengths of light are absorbed equally and the rock appears black. As the rocks get older, they develop iron-rich coatings that make the rock appear redder. (Due to the presence of oxidized iron, the rocks absorb blue light and reflect red light.)
In the Hawaii Landsat image, we have been able to map flows that range in age from 60 to 1840 years old. By comparison, there do not appear to be any rocks that are completely unoxidized on Mars. That is to say, we did not find any areas that had flat spectral signatures. We did, however, find that laboratory and Landsat measurements of partially weathered, prehistoric flows on Mauna Loa were in good agreement with a regional unit seen in the Viking Orbiter images.

In a previous study we found that only a basaltic tephra (ash) from Hawaii that was weathering to an oxidized iron-rich gel had a counterpart in the Viking Lander and Orbiter images where it reasonably accounted for units of surface dust. Our analyses of the prehistoric Mauna Loa flows in this study show that they are characterized by mm-scale surface coatings of the same kinds of gels overlying relatively unoxidized basalt. These observations correspond well to another study in which some telescopic spectral signatures were modeled with fresh basalt overlain with a coating of iron rich gel. Our results therefore add further support to the idea that terrestrial weathering processes of basalts in arid to semi-arid regions (such as high altitudes in Hawaii) provide good analogs for the surface of Mars.
INFRARED SPECTROSCOPY OF INTERPLANETARY DUST IN THE LABORATORY.
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Tiny stratospheric dust particles weighing only billionths of a gram have recently been identified as a third type of extraterrestrial material available for laboratory study: interplanetary dust. These particles are different from meteorites and moon rocks, and some of them are probably from comets, which are in turn a most promising source for unaltered material from the early solar system. Techniques are now available for determining which colors of infrared light are absorbed by these microscopic particles. The results can be compared with those obtained by telescopic observation of dust in our solar system and elsewhere in the universe. Preliminary results show that these dust particles, which are black when viewed with visible light, show patterns of infrared light absorption which can help identify the visibly transparent silicate minerals in them.

Dust is a major constituent of the universe. In interstellar space, dust occurs as grains less than 10 millionths of a meter in size, and causes reddening of starlight in the same way that dust and gas in the earth's atmosphere causes reddening of the sun as seen at sunrise and sunset. Interactions with light in the visible and infrared are a major vehicle for our information about interstellar dust, and about dust in our own solar system. Dust between the planets gives rise to the phenomenon known as the zodiacal light, which is a glow in the sky seen after sunset. And anyone who has looked at the night sky has seen the arrival of interplanetary debris in the form of meteors or shooting stars. Outside of effects due to its physical presence, information on interplanetary dust may help our understanding of comets, meteorites, the early solar system, and the origin of interstellar dust.

Unfortunately, direct collection of interplanetary dust is difficult in space because the particles are traveling at very high velocities (often greater than 15 kilometers per second). At such velocities, impact onto a solid collection surface results in partial-to-total destruction of the particle, and the formation of a micrometeoroid crater - a miniature of the meteor crater in Arizona. Rather remarkably, the earth's atmosphere is a much better collector of interplanetary dust (e.g. ref. 1). First of all, the slowing-down process is much gentler because grains can be gradually slowed down by the atmosphere over distances of 40 kilometers or more. Although most particles larger than 100 millionths of a meter in size probably melt or vaporize, many particles which are around 10 millionths of a meter in size survive without severe heating (e.g. ref. 2). Secondly, the slowing down process and low settling velocity for such tiny particles (At 30 kilometers they fall at the rate of only 0.03 meters per second) concentrate the particles to volume densities a million times greater than would be found in space. Although over a billion particles (greater than 10 millionths of a meter in size) are collected by the earth's atmosphere each second, they are so widely dispersed that a stationary collector one meter on a side would on the average collect only one particle every 4 days by settling.
The most successful method so far for collecting these particles from the stratosphere was initiated by Brownlee et al (3) in 1974. A piece of plexiglass 4.5 cm on a side, coated with a thin film of high viscosity silicone oil, is mounted under the wing of a NASA U-2 aircraft. The collector, protected from contamination near the ground, is opened out into the airstream at an altitude of 20 kilometers. Particles down to a few millionths of a meter in size stick on the collector and can be removed later for laboratory study. Although most of the particles are transparent aluminum oxide spheres from solid fuel rocket exhaust, a sizeable fraction of the remaining particles are black aggregates with compositions similar to those of "carbonaceous chondrite" meteorites (4,5) which for a variety of reasons are thought to be among the least altered of available materials left over from the formation of our solar system. Because of the small size of the collection program over the last 5 years, the total weight of collected "chondritic" particles to date can still be measured in millionths of a gram.

The extraterrestrial nature of the "chondritic" particles has been confirmed by measurements of elemental and isotopic noble gas abundances (6,7) which indicate a direct exposure in space for at least tens of years to the solar wind. In spite of strong compositional similarities to primitive meteorites, these interplanetary dust particles (IDPs) exhibit some systematic differences in structure and mineralogy in comparison to meteorites. Although these differences may in part result from heating on atmospheric entry, some of the particles are distinctly different from known meteorites, and consist of collections of even tinier particles (e.g. 10 to 100 quadrillionths of a gram in mass) of a sort predicted from astrophysical observations to exist between and around other stars (8).

The recent availability in the laboratory of interplanetary dust, albeit in small quantities, represents an important opportunity to relate the optical properties of such dust to knowledge of composition and structure only obtainable by "hands on" examination. In this paper, we report results on the colors (or frequencies, measured in "wavenumbers") of light between 2000 and 400 wavenumbers which are absorbed by the IDPs when they are illuminated by a broad spectrum of infrared colors.

First, "absorption spectra" were obtained for some commonly occurring minerals in these IDPs using "large" (typically thousandth gram) quantities of material, to provide a point of reference in interpreting spectra from microscopic samples (weighing only billionths of a gram). Figure 1 shows such spectra of the minerals olivine, pyroxene, magnetite, and pyrrhotite. The deep features (or "valleys") near 1000 and 500 wavenumbers in these graphs of the percent of light transmitted through the sample for olivine and pyroxene (the two silicate minerals) are signatures of the stretching and bending vibrations characteristic of their silicate structures. There are no such strong features in the nonsilicate minerals magnetite and pyrrhotite. Two other common constituents of the IDPs, a poorly crystallized silicate and a carbonaceous material, are not yet well enough understood to allow easy selection of comparison materials.

Secondly, data from samples weighing between 1 and 10 billionths of a gram have been obtained. Figure 2 shows such spectra from olivine, pyroxene, and from a mount of 3 crushed IDPs (9). This and subsequent IDP spectra demonstrate that diagnostic spectra of these particles can now be obtained, and they indicate that the dominant spectral features (in the neighborhood of 1000 and 500 wavenumbers) are probably due to the silicate minerals contained in the particles. In this particular IDP, the dominant absorption is clearly distinct from that of olivine.
Finally, some attempt has been made to invoke the diagnostic potential of such measurements. Two of eleven particles which were examined in the transmission electron microscope (8,10) consisted mostly of a noncrystalline silicate material, with large amounts of sulfur and iron apparently mixed in. These were of special interest because astrophysical observations of the interstellar feature near 1000 wavenumbers suggests that a noncrystalline silicate may be common in dust outside the solar system. Two mounts from one of these "noncrystalline" particles were available for spectroscopic work. Unfortunately, each contained less than a billionth of a gram of material. Nevertheless, both of their spectra (Fig. 3) did show a feature near 1000 wavenumbers which we believe to be due to absorption by the particle. A spectrum for a similarly mounted olivine is also shown. We hope to have considerably better, and hence more diagnostic, spectra of these and other particles in the near future.

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(d) Magnetite
0.79

(c) Pyrrhotite
0.69

(b) Pyroxene
0.68

(a) Olivine
0.79

Figure 1
Figure 2

(a) Olivine

(b) Pyroxene

(c) Three IDPs.

Figure 3

(a) Olivine TEM Mount

(b) IDP 13-06-05A Mount 1

(c) IDP 13-06-05A Mount 2
Field studies in the Dry Valleys of Antarctica have shown the presence of numerous surface features and processes operating which are analogous to those observed on the surface of Mars. The environment of the Dry Valleys has been recognized as very unique since their discovery during the International Geophysical Year (1956-57), and only reconnaissance studies were carried out at that time. Since then, only limited studies have been carried out in the valleys. The Dry Valleys are the Earth's coldest and driest desert and were previously believed to have implications for the Mars biological program. The Dry Valley system of southern Victoria Land comprises an area of several thousand square kilometers that is blocked by the Transantarctic Mountains from the flow of glaciers from the polar plateau (Figure 1). The mean annual air temperature is -20 to -25°C, although the surface may reach temperatures above zero for short periods of time in the late summer. The ground is underlain by permafrost which is found at depths from a few centimeters to over a meter, depending on the elevation, proximity to lakes and glacial melt, valley orientation, and other factors determining the overall degree of desiccation of the location. During the summer months diurnal cycles of freezing-thawing occur, depending upon the amount of radiation the area receives. The meager annual precipitation is in the form of snowfall (mean of 15 gm/cm²/yr). No rainfall has ever been recorded or observed in the Dry Valleys. Because of the low relative humidity of the valleys, the snow sublimes without visibly wetting the ground. The low relative humidity is caused by the katabatic winds that blow from the polar plateau down the valleys. Surfaces are covered with ventifacts and wind-sculptured pebbles, rocks, and ridges, which attest to the strength of the winds.

The Dry Valleys of Antarctica are believed to be the best terrestrial analog of the surface of Mars. The weathering processes operating in the Dry
Valleys are related to the Martian surface in the following manner: low temperatures (mean temperature of \(-17^\circ\)C in Wright Valley), low absolute humidities, diurnal freeze-thaw cycles (even during daylight hours), low annual precipitations, desiccating winds, low magnetic fields, and oxidizing environment. In the Dry Valleys physical or mechanical weathering predominates over chemical weathering processes. Even though chemical alteration is a secondary weathering process in the Dry Valleys, it is still present and plays an important role in regolith processes. In order to better understand the formation and modification processes operating on the Martian surface, a suite of systematically sampled soils, rocks, and cores from the valleys and brine ponds of Taylor and Wright Dry Valleys in Antarctica were collected during the 1979-80 austral summer. The samples have been returned and stored at temperatures below \(-10^\circ\)C since their time of collection to prevent alteration. We have been studying the abundances of the carbon, sulfur, and water, along with water soluble cations and anions (e.g. Ca\(^{2+}\), Na\(^{+}\), K\(^{+}\), NO\(_3\)^\(-\), SO\(_4\)^{2-}\), and Cl\(^{-}\)) in addition to the mineralogy of the soils in order to understand the relationships of the regolith forming processes obtained from the samples collected in the Dry Valleys.

Evidence exists that the Dry Valleys have been drying out for thousands of years. Numerous evaporite ponds along with saline ponds and lakes are present throughout the region and are believed to be fed by glacial meltwater. These bodies have no drainage and water-loss is by evaporation or sublimation. Lakes and ponds are generally frozen year-round except for melting around their edges and inlets during late summer. The only exception is Don Juan Pond in South Fork, Wright Valley, which remains unfrozen because of its high salt content. Salt crusts are found throughout the valley system. The most common ions are sodium, calcium, magnesium, chloride, sulfate and nitrate.

Viking data from Mars shows features which are similar to those observed in the Dry Valleys. The flanks of Don Juan Pond are similar in appearance to the Viking 2 landing site (Figures 2 and 3). A boulder field with evaporite regions between the rocks is present at each location. However, the source of the rocks are different in the two cases. At the Viking 2 site, the boulders represent ejecta from Mie crater, whereas at Don Juan Pond they result from mass-wasting from the surrounding valley walls. Duricrust as seen by Viking has been observed in the Dry Valleys. The Dry Valley duricrust is only 1 to 5 mm thick and results from the cementation of surface soil layers by salts which have been
deposited by percolating water as it moves toward the surface prior to evaporation. Salts remain after evaporation and act as a sealant to the tops of the soils. Aeolian action produces the abrasion and removal of the salts at the edges of the duricrust. Often, beneath the surfaces, larger salt deposits are present as seen from trenches dug near evaporite ponds.

Soils from the Prospect Mesa Formation in Wright Valley are among the oldest, if not the oldest soil present in Antarctica. Ages for the Prospect Mesa Soil ranges between 7 and 10 million years old. Soil samples were collected from a one-meter deep soil pit and these soils sampled the aeolian zone, salt formation zone, active zone, seasonally frozen zone, and permanently frozen zones. Soils were chemically and mineralogically analyzed. The aeolian zone (top 2 cm) represents an area of deflation and showed slight depletions in total water, sulfur, chloride, sodium, potassium, and sulfate concentrations as compared to the salt layer immediately below this surface. Concentrations of sodium, chloride, nitrate, sulfate, potassium, and total sulfur were the highest in the salt or evaporite-rich zone. Sulfur concentrations as high as 2.21% were found. Concentrations of water soluble ions (K\textsuperscript{+}, Ca\textsuperscript{2+}, SO\textsubscript{4}\textsuperscript{2-}, NO\textsubscript{3}\textsuperscript{-}, Na\textsuperscript{+}, and Cl\textsuperscript{-}) systematically decreased in the zones above the permanently frozen ground (depth 35 to 40 cm) and remained essentially constant below the permanently frozen ground. This suggests that essentially no exchange or transport of these cations or anions is occurring and the major geochemical changes are occurring above the permafrost level. It is interesting to note that the molar concentration ratio of Na\textsuperscript{+} to Cl\textsuperscript{-} was almost identical. The presence of halite is suggested by these results which agree with the mineralogical analysis. Secondary minerals previously identified in the Dry Valley soils include the following: halite, mirabilite, bloedite, gypsum, calcite, aragonite, monohydro-calcite, soda niter, therardite, antarcticite, bishovite, sylvite, trona, and limonite. The sulfur enrichments and water soluble cations and anions near the surface represent addition of these components from lateral transport and not from upward movement through the soils.

A comparison of the total sulfur and water soluble chloride concentrations present in the Dry Valley soils and those measured at the Viking 1 and 2 sites on Mars has been made. The chloride concentrations in the Dry Valley soils from below the permafrost level are almost identical to the 15 Martian soils analyzed by the x-ray fluorescence experiment aboard the Viking lander. The sulfur
concentrations from the salt-rich regions are almost identical to those reported for the Martian regolith. From the normal weathering processes operating in the cold environment of Antarctica on the source rocks-Beacon sandstone and Ferrar dolerite-the enriched sulfur and chloride concentrations are similar to the soils analyzed on Mars. Thus, such enrichment can be produced by normal weathering processes, and no "exotic" sulfur- or chloride-rich source rocks are necessary.

A soil profile for the regolith present in the Dry Valleys of Antarctica has been developed which may be similar to the soil profiles expected for the Martian surface. The major difference between the situation in the Dry Valleys and Martian regolith would be the depth of the permafrost layer. For the Antarctic soils studied, the upper 40 cm (soil above the permafrost zone) may represent an expanded version of the Martian regolith where the permafrost layer is expected to be closer to the surface. From the initial studies of the Dry Valley soils, it is obvious that the detailed study of these samples will provide critical information to the understanding of processes operating within the Martian regolith.
Figure 2. Viking 2 landing site surface photography. Note the large number of boulders and evaporite regions between boulders.

Figure 3. Don Juan Pond, Wright Valley, Antarctica. Note the similarity to the Viking 2 surface morphology.
MODELING EQUILIBRIUM PARTIAL MELTING: IMPLICATIONS FOR EARLY LUNAR DIFFERENTIATION. John Longhi, Dept. of Geology and Geophysics, Yale Univ., P. O. Box 6666, New Haven, CT. 06511.

After years of experimental study - namely melting lunar rocks and their synthetic analogs at various pressures - there is now sufficient information on the compositions of minerals and coexisting silicate melt that the compositions of magmas produced by partial melting of the lunar interior can be calculated, if the bulk composition of the moon and the depth of melting are specified. There are limits to the bulk compositions and depths of melting permissible in the calculations, but these limits encompass all of the currently popular compositions - those based upon accretion of the moon from meteoritic material as well as those based upon a moon fissioned off the earth - and depths of melting to 400 km.

By first calculating the compositions of magmas produced at depth and then reversing the calculations to simulate crystallization within the crust, it is possible to test proposed bulk compositions of the moon to see if they are capable of producing magmas and, ultimately, rocks with the characteristic chemical and mineralogical features observed in the ancient or "pristine" igneous rocks that were the original constituents of the lunar crust some 4.2 to 4.5 billion years ago.

All of the proposed lunar compositions tested give roughly similar results and all fail the test. At all depths small degrees of partial melting (<10%) will produce magmas with fractionated patterns of incompatible elements such as Sc, Ti and the rare earths, which mimic in some respects the patterns expected from the pristine rocks. However, they also possess crystallization sequences in which olivine is first, followed by plagioclase, high-Ca pyroxene and then low-Ca pyroxene, whereas the crystallization sequence displayed by the pristine rocks is low-Ca pyroxene before high-Ca pyroxene; furthermore, high-Ca pyroxene does not crystallize until fairly late in the natural, lunar sequence. At relatively large degrees of partial melting (>40%) the low-pressure crystallization sequence changes over to low-Ca pyroxene before high-Ca pyroxene, but the incompatible elements have relatively unfractonated patterns that do not match the patterns expected of the parent magmas of the pristine rocks.

These results suggest that either the moon possesses an unexpectedly low Ca concentration and fractionated concentrations of incompatible elements or that crustal formation was a physically and chemically complex process that involved much more than simple transport of hot magma from the interior to the outer, cooler layers of the moon where the magma solidified. In order for the moon to have accreted from material in which Ca, Al, Ti, Sc and the rare earth elements were not fractionated relative to one another, the growing crust must have exchanged material with the lunar interior and some of this material must have been mixed and remelted several times in such a way so as to change the chemical character and crystallization sequence of the magmas that solidified to form the crust. This process has been modeled previously by the author (1,2) and has been linked to the solidification of a magma ocean some 300-500 km. deep. The large body of melt would have made an ideal
physical regime in which portions of the floating crust composed of dense minerals rich in Ca, Sc and Ti broke off and sank while less dense feldspar and differentiated liquid remained in the crust to be assimilated by magma rising convectively to the base of the crust.

Recent models of celestial mechanics and crater dynamics (3,4) have suggested that the moon accreted too slowly to have melted completely to depths of 300-500 km. Rather the impact of large projectiles is thought to have generated relatively small "puddles" of total melt overlying a much deeper zone of partial melt. Large impacts also cause a rebound in the mantle. If the portion of the mantle under the impact were already partially molten then the decompression caused by the rebound would increase the partial melting. Some of this melt would likely coalesce, rise to the surface and mix with the melt generated by direct impact, producing a puddle only tens rather than hundreds of kilometers deep. Repetition of such a process coupled with partial crystallization and fractionation of the melt zone during the interval between successive impacts may have produced a physical and chemical regime with material transport and mixing properties previously ascribed to a magma ocean.

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LATE-STAGE SUMMIT ACTIVITY OF MARTIAN VOLCANOES. P.J. Mougins-Mark,
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Several very large volcanoes have been known to exist on Mars since the
mission of Mariner 9 in the early 1970's. Individual examples, such as
Olympus Mons, reach heights of more than 25 km above the mean datum of the
planet and may have basal diameters in excess of 600 km. In comparison, the
largest volcano on Earth (Mauna Loa, Hawaii) is only 9 km high and 200 km
in diameter, making the martian volcanoes the largest positively identified
volcanic features in the Solar System.

From the lack of appreciable numbers of meteorite craters upon their
flanks, these martian volcanoes are considered to be relatively young in
comparison to other landforms on Mars. Relatively recent volcanism such as
this requires that Mars remained internally active for significantly longer
periods of time than did the Moon and Mercury.

Two major volcanic regions, Tharsis and Elysium, exist on Mars and
together they have seven volcanoes larger than any on Earth, as well as
numerous smaller examples. A basic simplification in earlier investigations
of these large Tharsis and Elysium volcanoes has been the assumption that
most of them had the same style of volcanic activity. For example, it has
been productive to compare the general characteristics of the four Tharsis
volcanoes (Olympus, Arsia, Pavonis and Ascalaeus Montes) to the "shield"
volcanoes on Earth, such as Mauna Loa in Hawaii. As recognized for some time,
however, volcanoes on Earth are very diversified in their eruption character­
istics: volcanoes in Hawaii usually erupt lava every 3 - 5 years, Mount
St. Helens produces several large explosive eruptions every 100 - 150 years,
while Stromboli (Italy) has erupted nearly continuously for over 2,000 years.
It therefore seems reasonable to expect that martian volcanoes also showed
some variation in the degree of violence and the amount of lava that was
erupted in any single event.

An appreciation of the diversity of martian volcanoes, and the spatial
relationships of flank activity to the summit craters, consequently forms an
integral component of the analysis of martian surface geology and, indirectly,
the evolution of the martian lithosphere. In particular, the use of volcano
morphology and the areal distribution of lava flows and/or ash deposits to
recognize explosive vs. effusive (i.e., lava flows) activity holds important
ramifications for magma evolution and martian geochemistry. This analysis has
therefore utilized the highest resolution Viking Orbiter images (which permit
objects less than 50 meters in diameter to be seen) to determine the most
recent styles of volcanic activity on Olympus Mons, Ascraeus Mons, Elysium
Mons and Hecates Tholus.

It has been found that the following differences in activity are
evident between the individual volcanoes on Mars and their terrestrial counter­
parts:

1) Martian volcanoes typically possess multiple summit craters (caldera). An
excellent example is shown in Figure 1, which illustrates three nested
caldera at the summit of Olympus Mons. There is, however, no consistent
Figure 1: Mosaic of the summit area of Olympus Mons, showing the nested caldera and the complex system of ridges on the relatively old portions of the caldera floor. Note that subsequent collapse episodes of the wall material failed to exploit pre-existing fracture systems in the older caldera floor, suggesting that caldera collapse was a very violent process. Part of JPL photomosaic number 211-5930. Width of image is equivalent to about 70 km.

sequence in size for successive periods of caldera collapse (i.e., the largest crater may either have been the first or last to form). On the Earth, caldera are produced by the collapse of the summit due to a large eruption of ash or lava, and the size of each caldera indicates the approximate magnitude of each eruption. Since there is no consistent trend in caldera sizes on Mars, it appears that each volcano investigated evolved in a slightly different manner. In addition, unlike terrestrial volcanoes such as Piton del Teide (Tenerife) and Piton de la Fournaise (Reunion Island), in no instance is a subsequent volcanic cone constructed within a martian volcano. This indicates that not only was the long-term activity of each volcano highly variable, this activity was also non-cyclic, in that no volcano followed the sequence of cone construction – caldera collapse – new cone construction.

2) The morphology of features close to each volcano's summit are highly diverse for the four examples investigated. Lava flows can be recognized on the caldera rim of Ascraeus Mons and, more significantly, also on segments of the collapsed caldera walls. This implies that caldera collapse was associated with eruptions of lava, rather than ash, which would have buried the same near-summit lava flows that can now be observed. Consequently, eruptions like those of Mount St. Helens were probably rare (if not non-existent) on Ascraeus Mons. In contrast to this effusive style of volcanism in the Tharsis Region, the absence of lava flows around the summit caldera and the subdued summit morphology of Elysium Mons and Hecates Tholus are consistent with explosive eruptions on Mars.
3) Unlike terrestrial shield volcanoes (e.g., Kilauea, Hawaii), the caldera floors of the martian volcanoes lack recognizable individual lava flows. This suggests that the last eruption of each volcano created a molten lava lake over the entire caldera floor. Terraces within the caldera of Ascraeus Mons, possibly produced by the withdrawal of magma from a lava lake, support this interpretation.

4) Volcanic/tectonic features can be recognized on all four volcanoes investigated. In the case of Olympus Mons, a very complex pattern of wrinkle ridges extends across much of the caldera floor (Figure 1). High resolution images of these ridges (Figure 2) reveal a morphology almost identical to that of lunar mare ridges. This indicates that not only were ridges formed in obviously volcanic rocks on Mars, but also that (by analogy with lunar mare ridges) considerable tectonic deformation of the caldera floor occurred after the lava lake solidified. This in turn indicates that Olympus Mons continued to evolve even after the last summit eruptions, possibly in response to flank eruptions of lava.

Figure 2: A complex series of ridges, morphologically similar to lunar mare ridges, occurs on the floor of Olympus Mons caldera. The absence of recognizable lava flows in this image suggests that a molten lava lake once covered this area, while the ridges indicate that tectonic deformation took place after the lava solidified. Viking Orbiter image 360A34. Image width is equivalent to about 18 km.
The present analysis suggests that martian volcanoes were appreciably more diverse in their styles of activity than previously supposed. Large explosive eruptions are considered unlikely for Ascraeus Mons and Olympus Mons, but may have occurred on Elysium Mons and Hecates Tholus. The existence of ridges on the caldera floors and the lack of individual lava flows suggest that volcanic eruptions in the Tharsis Region were none-the-less spectacular, with the possibility of molten lava lakes tens of kilometers wide constituting the final period of activity within each caldera.

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by

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For the last 40 years since the application of radioactive decay methods to determining the absolute age of rocks geologists and biologists interested in the evolution of life, have been presented with an astonishing problem. Remnants of life, that is fossils, were found in rocks which were at least 500 million years old, evidence of dinosaurs, their footprints and bones, are found in sedimentary rocks which only represent a small fraction of the life record 65 to 225 million years ago. At the end of the 65 to 225 million year old Mesozoic epoch, not only did all the vestiges of dinosaurs and other reptiles, representing some 66% of the total number of species, disappear but major disruptions in the oceanic food chains occurred. Some 85% of the floating marine micro-organisms were destroyed in a very short time interval at the end of the Cretaceous period. Some 90% of marine reptiles and the entire population of the multichambered marine organisms, the ammonites, suddenly disappeared. At this time also, the epoch of mammals or Tertiary epoch began.

What happened 65 million years ago at the end of the Cretaceous period and the beginning of the Tertiary has puzzled geologists since 1859 when many began
to accept the theory of Charles Darwin who suggested that life had evolved slowly while different species struggled for existence and only the fittest species survived. The sudden disappearance of many life forms in, geologically speaking, an instant of time, contrasts sharply with Darwin's gradualist philosophy of evolution. During the last 20 years the Cretaceous-Tertiary boundary has become the subject of intense scrutiny by not only the paleontologists, that is, geologists who study ancient life, but scientists studying ancient climates and oceanic circulation systems using the data specifying the positions of the continental land masses on the earth at that time provided by plate tectonics.

The theory of plate-tectonics, or continental drift in providing these data gives a very differing geography some 65 million years ago at the time of Cretaceous-Tertiary boundary. North and South American were just beginning to break away from Europe and Africa, respectively. Moreover, in what is now the Pacific basin there was a very large mass of land which also was breaking-up. Different portions of this land area is now speculated to have been added onto Asia and North America and make up respectively the mass of mainland China and most of the Alaska rocks. Slivers of this land mass in the Pacific are thought also to exist and comprise the areas of coastal Oregon and Washington as well as give rise to large submarine plateaus in the southwest Pacific Oceans. Small pieces are believed to comprise portions of Central America as well as the exotic Falkland Islands of the southernmost Atlantic Ocean.

Not only have the environmental causes of the Cretaceous-Tertiary extinction sought, but geophysicists have also carefully studied the magnetism of rocks deposited before, during, and after, the Cretaceous-Tertiary boundary to determine if the earths magnetic field, which provides an invisible shield against charged particles impinging from outer space and the sun, could have been absent at the time of the extinction of these many life forms. Neither a coincidence with a "turning-off" of the earths magnetic field or even its reversal was found.
In June, 1980, the father and son team of Luis and Walter Alvarez and coworkers Frank Asaro and Helen Michel, of the University of California (Berkeley) published a scientific paper which, for the first time, provided a physical basis for understanding the extinction of the dinosaurs and a multitude of other life forms 65 million years ago. Although this group was searching for evidence of an explosion of a nearby star, or super-nova, at the end of the Cretaceous what in fact they discovered was that a clay layer from 1 to 150 cm thick demarking the Cretaceous-Tertiary boundary was enriched in noble metals such as iridium, osmium, gold, platinum, rhenium, ruthenium, palladium, nickel and cobalt by factors of 5 to 1000 relative to the earth's crust. More recent geochemical analyses have demonstrated that this layer is worldwide in extent having now been detected at the Cretaceous-Tertiary boundary in marine sediments in Italy, Denmark, Spain, New Zealand, Morocco, and recently in sediments cored from the floor of the Pacific Ocean as well as in stream (land) deposits in Montana.

The pattern of occurrence of these mostly noble metals such as iridium, osmium, gold, platinum, nickel, palladium and ruthenium is similar to that found in certain stony and iron meteorites and are completely different from the ratio of these elements, as for example seen, in conventional gold or platinum deposits on the earth. Alvarez and coworkers thus proposed that a very large meteorite hit the earth, 65 million years ago and produced a dust cloud which obliterated the sun for a period of time and this was the cause of the extinction of dinosaurs and other life forms. The dimensions of the meteorite may be calculated from the worldwide noble metal abundance in the Cretaceous-Tertiary boundary layer. A diameter of 8 to 12 miles and a mass of about 1 trillion tons, or about one billionith the entire mass of the earth is obtained for the meteorite.

We have examined the impact mechanics which would result from the interaction
of the Cretaceous-Tertiary extinction bolide (or presumed fire-ball) in order to understand exactly how the impact of such an object, with the earth, which could have had an energy equivalent of a million megatons of TNT will interact with the atmosphere, ocean and the earth beneath the oceans (the last is the most likely target). By means of computer calculations, we have modeled the distribution of impact energy between heat and kinetic energy of the fragments of the meteorite and the earth's surface. We have also studied the depth of penetration of meteorites into the atmosphere, ocean and earth for various likely meteorite compositions such as solid silicate, iron or ice. The latter would correspond to a comet-like object which are believed to comprise one-third of the meteorites which hit the earth. Finally, we have calculated the trajectories and energy contents of the debris or ejecta cloud produced upon impact at speeds which could vary from 5 to 72 km/sec.

We have determined what the direct effect of a 10 mile diameter meteorite upon impact on first the atmosphere, and then the ocean. The maximum amount of energy which can be imparted to the atmosphere by a rocky or icy comet (so large that ablation is unimportant) was examined for 1, 0.1 and 0.01 specific gravity objects. The most efficient energy transfer, not surprisingly, is for a very porous meteorite or cometary object. As an extreme case, an object having one hundredth the density of water impacting the atmosphere at 72 km/sec requires some 80 projectile diameters to deliver its energy to the atmosphere. The largest such meteorite which would stop in the air before hitting the earth would have a mass of ten million tons and an energy equivalent of the explosion of about 10 million tons of TNT. This is just equal to the energy determined for the famous Tunguska fireball which was observed on June 30, 1908 by seismographs and recording barometers in Europe and Central Asia. The effects of this fireball flattened trees over an area of two thousand square kilometers but it is generally agreed that the object did not hit the ground. We conclude that the energy of
the 65 million year old Cretaceous-Tertiary extinction bolide was more energetic by a factor of about 1 billion than the Tunguska meteorite and that it did not lose an appreciable amount of energy via direct interaction with the atmosphere. Furthermore we infer that it definitely interacted strongly with the ocean and the rocks beneath the ocean or just the rocks of the earth in the case of impact on continents.

We then investigated the energy balance which occurred when such objects impact the sea, we concluded that at least 10 projectile diameters of ocean are required to stop the projectile and surprisingly this distance is nearly independent of impact velocity when the impact velocity is strongly supersonic. Therefore for a 10 mile diameter projectile, impacting an average ocean which is merely two miles deep, it is clear that the ocean is not sufficiently deep enough to stop the Cretaceous-Tertiary bolide. We therefore concluded that this object must have hit solid rock either on land or beneath the ocean.

How can we explain the extraordinarily high worldwide concentration of extraterrestrial meteoritical material, up to 21% in the mid-Pacific core material, containing platinum group elements in the Cretaceous-Tertiary boundary layer? Normal debris, or ejecta, from impact craters on the earth and the moon contain from 0.1 to at most 2% of material which can be attributed to the projectile (the meteorite) material. In order to address this question we have carried out detailed computer calculations of the ratio of meteoritical versus earth (terrestrial) impact ejecta as a function of velocity and ejection angle. We have discovered that although it may take a minute or more to excavate the expected 100 mile diameter crater which would result from such a massive meteorite it is within the first one or two seconds after impact of a 10 mile diameter meteorite with the earth that intensely shocked material is lofted to altitudes of 10 to 100 miles and contains from 1 to 30% meteoritical debris. We conclude that the fine material found worldwide at the Cretaceous-Tertiary boundary was in fact distributed after
being lofted to great altitudes and represents perhaps a total of 10% of the actual meteorite mass.

We have also calculated how much of the meteorite energy can be transferred to ejecta which is lofted to great elevations and found that less than 10% is ejected to an altitude of 5 miles or greater. Thus although most of what we see of the physical evidence of the Cretaceous-Tertiary bolide came from a very fine dust layer which settled out of the upper atmosphere, we found that most of the energy of the impact goes into heating the ejecta which interacts with the atmosphere at largely lower elevations. We conclude that although the direct penetration of a meteorite in the atmosphere is not an effective mechanism for transferring its energy to the oceans or atmosphere, the energy in the ejecta is significant and could be a source of worldwide heating, which is likely to have had a profound effect on especially large animals. We note that all land animals weighing more than 50 pounds did not survive the Cretaceous-Tertiary extinction event. We conclude that the interaction of ejecta from a 10 mile diameter asteroidal or cometary bolide impacting the earth could raise the average air temperature by ten degrees and/or raise the temperature of the upper 100 meters of the ocean by several degrees. Such a temperature increase will destroy all large reptiles and many other species as well have drastic consequences on the marine food chain according to Cesare Emiliani of the University of Miami. These heating effects will be superimposed on the more complex effects of the high altitude dust cloud, which has been proposed. The latter may have affected the climate on a longer time scale.
NEW COMPONENTS DISCOVERED IN METEORITES: CLUES TO THE EARLY HISTORY OF THE SOLAR SYSTEM. Edward R.D. Scott, G. Jeffrey Taylor, Alan E. Rubin, Susan McKinley, Akihiko Okada and Klaus Keil, Institute of Meteoritics and Department of Geology, University of New Mexico, Albuquerque, New Mexico 87131, and B. Hudson and C.M. Hohenberg, McDonnell Center for Space Sciences, Washington University, St. Louis, Missouri 63130

Meteorites were once pieces of asteroids (or perhaps comets) which were broken off by collisions and eventually hit the earth. Apart from lunar rocks, they are the only extraterrestrial rocks that can be studied in the laboratory. What makes the meteorites so interesting is that they contain a record of the very earliest stages in the formation of the solar system. At this time, 4½ billion years ago, planets, moons and asteroids were forming from the solar nebula—a cloud of gas and dust which surrounded the sun. Because the earth and moon were melted soon after they formed, existing rocks from these bodies do not preserve a record of the formation of the solar system.

We have been studying a common variety of meteorite called ordinary chondrites which are largely composed of silicate spherules ('chondrules') surrounded by finer-grained metallic iron, silicate and iron sulfide minerals. In certain types of these meteorites we have discovered a new component consisting of a very fine-grained mixture of graphite and iron oxide. Although these minerals are composed of very abundant elements (carbon, iron and oxygen), such a mixture has not been observed before. The mixture looks black or dark grey under the microscope, and exists as lumps up to one millimeter (1/20 of an inch) in size.

We first observed this graphite mixture in meteorite breccias, rocks consisting largely of fragments of other meteorites stuck together. From studies of analogous lunar rocks, it is known that these meteorite breccias formed on the surface of asteroids as a result of continuous bombardment by smaller bodies. In searching for more lumps of the graphite mixture we found three meteorite fragments composed almost entirely of silicate spherules embedded in a similar mixture of graphite and iron oxide. These fragments, which do not exceed five millimeters (¼ of an inch) in size, are richer in carbon than any other type of meteorite. We believe that colliding asteroids made of this material were the source of these fragments and the isolated lumps of the graphite mixture.
We have also found smaller amounts of the graphite mixture in several unequilibrated ordinary chondrites. These meteorites were examined because like the three fragments described above they contain silicate minerals which vary widely in composition. The heterogeneity of these meteorites indicates that they experienced very little heating in their parent planets. We therefore believe that the graphite mixture, like the other ingredients of these meteorites, existed in the cloud of gas and dust from which the planets formed. Our microscopic studies indicate that much of the metallic iron in these meteorites formed from the mixture of graphite and iron oxide. When heated, such a mixture will react to form metallic iron and carbon monoxide. We therefore suggest that the graphite mixture may have been the source of much of the metallic iron in these meteorites.

How the mixture of graphite and iron oxide formed is not known. Either it condensed from the solar nebula before the planets and asteroids formed, or it formed before the solar system. Exciting work on meteorites during the past five years indicates that some grains in meteorites may have existed as interstellar grains, which formed even earlier than the solar nebula. In view of astronomical evidence for the existence of graphite in interstellar
grains, we speculate that the graphite mixture may contain such grains.

Very little is known for certain about the formation of asteroids and planets from the solar nebula, but it is believed that tiny dust grains somehow stuck together, gradually forming larger and larger bodies. Some of these bodies were preferentially enriched in the graphite mixture. We hope that future studies in our search for primitive components of the early solar system will help to elucidate these processes.

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New type of meteorite consisting of silicate spherules (grey) in a mixture of graphite and iron oxide (black). Width - 1.7 mm.
THE EVOLUTION OF IMPACT BASINS

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The impact of a large object onto the solid surface of a planet produces a circular basin generally exceeding 200 km in diameter and often displaying two or more concentric rings. These multi-ringed basins formed in the first billion years of planetary history and can be seen on the surfaces of the Moon, Mars, Mercury, and the Galilean satellites. Their presence on these bodies makes it a virtual certainty that they also formed on the early surfaces of Venus and the Earth. Our knowledge of the Venus surface is not sufficiently detailed for us to decide whether such basins are currently present. On the Earth, the time of basin formation occurred prior to the time when stable nuclei of continental lithosphere could persist unmodified to the present, so no such basins have been preserved. Nonetheless, basin formation was clearly an important process in the early, formative years of planetary crustal evolution.

The formation of a basin concentrates a substantial amount of heat into a small volume near the surface of a planet. One estimate for the energy of the Imbrium basin impact on the Moon, for instance, is one million times greater than the annual heat loss from the Earth and would be roughly equivalent to one billion simultaneous nuclear explosions each of 100 Mton size. In addition to the influence of the impact itself, impact basins become a focus for other planetary processes, such as volcanism and tectonism, long after the impact event.
The volcanic and tectonic processes can modify the structure and form of the impact basin, and the timing and character of such modification processes can tell us much about the nature and evolution of the interior of the planet. We have identified three major processes that act to modify impact basins over geologically long time scales (millions to billions of years): (1) volcanic filling and lithospheric loading, (2) viscoelastic relaxation of topographic relief, and (3) thermal contraction and associated thermal stress. Each of the presently observed basins on the planets has been subjected to these modification processes to a greater or lesser degree; the extent of such modification is sensitive to the thermal state and evolution of the planet at and after the time of basin formation.

Most of the large impact basins on the Moon, Mars and Mercury have been at least partially flooded by basaltic lavas. These basalt units, rich in iron and of high density, often exert a large load on the underlying lithosphere. The anomalous mass excess is visible in the planetary gravity field as a "mascon," or a large positive gravity anomaly. As a result of the load, regional subsidence of the lithosphere gives rise to stresses large enough to fracture the crust. The rilles or graben surrounding many large basins on the Moon and Mars, and the ridges on the flooded basin floors, are the result of such fracturing. The spacing and position of such tectonic features permits a direct measure of the lithosphere thickness at the time the fractures occurred.

While the rugged ring mountains of comparatively young basins are often strikingly evident on the present surfaces of the Moon, Mars and Mercury, the ring structures on older basins on these planets are often incomplete and much more poorly preserved. There are also circular basins,
possibly of impact origin, on Venus and on the icy Galilean satellites with
at most very modest topographic relief. The most likely mechanism responsible for such very different degrees of preservation of impact basins in the solar system is viscoelastic relaxation, or plastic flow, to relieve the topographic stresses. Such relaxation occurred only in impact basins formed early enough in the history of a planet so that near-surface temperatures were high and plastic creep could readily occur.

The large amount of heat deposited in the interior of a planet during the formation of an impact basin is eventually lost to space by conduction and surface radiation. As a result of such cooling, there is a sizable contraction of the lithosphere beneath a basin on a time scale of millions to hundreds of millions of years. This contraction contributes to the topographic profiles of basins seen today. Along with this differential contraction, large thermal stresses accumulate during basin cooling. These thermal stresses are often large enough to fracture the surface rocks and thus can contribute to the tectonic features formed in basin regions.

Thus for many of the planets, the formation and evolution of large impact basins occupy central positions in the overall planetary history. In terms of the planetary energy budget, in terms of volcanic activity, and in terms of faulting and tectonic activity, the detailed characteristics of each major basin tells us much about how the interiors of planets evolve.
## STAGES IN BASIN FORMATION AND EVOLUTION

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→ ———— LOSS OF INITIAL HEAT ———— ←

(melt) (deeply buried heat)

**TIME** —— seconds to hours ——— thousands to millions ——— millions to billions of years

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**Figure 1:** Stages in basin formation and evolution

Are there water oceans in any of the giant planets? The answer provided by the research reported here seems to be a qualified yes for Uranus and Neptune and an almost certain no for Jupiter and Saturn. In any event, these "oceans" are very different from the earth's ocean because they occur below a very dense hydrogen-helium atmosphere where the temperature is perhaps 2000°C (about 3600°F) and the pressure is about 200,000 times that at sea level on earth.

In order to understand even the meaning of the question posed above, let alone the answer, I need first to provide some background on what we know about the giant planets and the behavior of water. The four giant planets differ fundamentally from the terrestrial planets because they managed to incorporate the very abundant volatile materials (those with low freezing and boiling points) which make up most of the material in the Sun and in the Universe. These materials are loosely characterized as the "gases" (hydrogen and helium) and the "ices" (water, methane and ammonia). In each ten thousand atoms of the gas and dust cloud out of which the planets are believed to have formed, on average there would have been about 9200 atoms of hydrogen, 780 of helium, 8 of oxygen, 4 of carbon, 1 of nitrogen, and one atom of "rock" forming material (mostly magnesium, silicon or iron). The terrestrial planets (Mercury, Venus, Earth, Mars) incorporated only that last one atom in ten thousand, the part which could condense out from the cloud at the high temperatures prevailing near the Sun.

Jupiter is mostly hydrogen and helium, and apparently incorporated almost all of the material in its region of formation; this is the reason why it is so massive. Saturn is also mostly hydrogen and helium but models that
have been calculated of its interior indicate that it is enriched in heavier elements, the most important of which is oxygen, incorporated in the form of water. Uranus and Neptune are significantly different: they have far less hydrogen and helium and over half of their mass is in the form of "ices" (primarily water). The "mixing ratio" of water to hydrogen is important in determining how water will behave in these bodies. In Jupiter, the mixing ratio is very low (for each molecule of water, there are perhaps two or three hundred molecules of hydrogen); in Saturn it is still low (perhaps 1:50) whilst in Uranus and Neptune, the ratio is about 1:1.

Internal temperatures also differ substantially between the giant planets. These planets probably formed by the collapse of gas onto a rock and ice nucleus of perhaps ten times the mass of the earth. Just as the air-gasoline mixture in the cylinders of your automobile is heated when the piston compresses it, so the gas and other constituents of a giant planet are heated by the collapse produced by gravity. The larger the planet, the greater the temperature rise produced. The internal temperature is also affected by the distance from the Sun. The present day temperatures at the level at which the pressure is 200,000 times that at the earth's surface have been estimated by theoretical models to be around 5300°C (9500°F) in Jupiter, 4000°C (7200°F) in Saturn, and 2000°C (3600°F) in Uranus and Neptune. In each case the material is fluid, which means that it is too hot to be solid and also so dense that there is no meaningful distinction between a gas and a liquid. (Physicists call this state "supercritical." It is this property which explains why none of the giant planets have a surface in the conventional sense.)

Let us now consider how water and water-hydrogen mixtures behave in the environments appropriate to these planets. We are accustomed to thinking
of water as consisting of well defined molecules, each of which contains one atom of oxygen and two atoms of hydrogen. However, this simple picture no longer applies at the temperatures and pressures of interest. It has been known for many years that when water is compressed and heated, its electrical conductivity rises dramatically. Eventually, at a pressure of around 150,000 atmospheres and a temperature of around 1500°C (2700°F), the conductivity saturates at about one billion times the value that it has at 1 atmosphere and 20°C (68°F). In fact, the conductivity is then similar to that of a molten salt (e.g., molten sodium chloride), excellent electrolyte. These measurements on water have been made during the passage of a shock wave, but there are good reasons to believe that the same results would be obtained if the high pressure and temperature were sustained for a long period.

Many experiments on water compressed by shock waves have been carried out, including recent experiments at the Lawrence Livermore Laboratory by Nellis and co-workers and at the California Institute of Technology by Lyzenga and Ahrens. These and earlier results form the basis for some theoretical models which we have developed for the behavior of water. Motivated by a suggestion made about ten years ago by Sefton Hamann (of CSIRO in Australia), we have modeled water as an "ionic melt" (analogous to molten sodium chloride) consisting of H3O+ and OH− ions. In other words, we consider the water to be dissociated, with no neutral H2O molecules remaining. We find that this model can explain the shock wave data for the density and temperature at high pressures. It is also consistent with the measured electrical conductivity and with estimates of energy required to dissociate water. There are a number of uses for such a model, in particular it can be used to predict other high pressure thermodynamic properties which have not yet been measured in the laboratory. For example, we can estimate the solubility
of water in hydrogen (or hydrogen in water) at the conditions of interest. Since the hydrogen molecule is still essentially neutral and non-polar (which means that its distribution of electronic charge is not biased towards one of the hydrogen atoms), we expect from the well-known empirical evidence of elementary chemistry that the ability to mix with a strong electrolyte such as $\text{H}_3\text{O}^+\text{OH}^-$ is severely limited. However, the detailed calculations indicate that for the low mixing ratios and very high temperatures prevailing in the interiors of Jupiter and Saturn, the water and hydrogen will remain uniformly mixed and there will be no tendency to form raindrops of water. (This should not be confused with the formation of raindrops or snowflakes higher up where the pressure is only a few atmospheres. In that region, raindrop formation occurs for exactly the same reason that it occurs in the earth's atmosphere).

By contrast, the high mixing ratios and lower temperatures in Uranus and Neptune lead to the prediction that a uniform mixture is not possible. Instead, most of the water must settle out to form an ocean. The surface of this ocean is perhaps 6000 km (3800 miles) below the observable atmosphere, and the depth of the ocean is perhaps about 10,000 km (6000 miles). Ammonia and minor constituents are likely to be dissolved in the ocean, but methane is likely to be in the hydrogen-helium atmosphere (because of its non-polar character).

This may all seem to be in the realm of speculation, but it is consistent with other information and has some important implications for these planets. First, it is consistent with some very recent estimates of the moment of inertia of Uranus obtained by observations of the Uranian rings. (The moment of inertia of a body is a measure of how the material within the body is distributed. A low moment of inertia means that the central regions of the planet are much more dense than the outer regions. The moment of inertia determines the extent to which the planet changes its shape from
that of a sphere because of its rotation. This in turn changes the gravity field that is exerted on the ring particles, changing their orbits in a detectable way). The moment of inertia implied by these and other observations is consistent with most of the water being separated from the hydrogen and helium as an ocean.

Second, the ocean hypothesis provides an obvious reservoir for ammonia and thereby may help explain why no ammonia has been detected in the atmosphere of Uranus. This surprising lack of ammonia in the Uranian atmosphere (it has been detected in the atmospheres of Jupiter and Saturn) becomes less surprising when we allow for the fact that the $\text{NH}_4^+$ ion can be very readily incorporated in an "ionic melt" ocean of $\text{H}_3\text{O}^+\text{OH}$. There may be other explanations for the absence of $\text{NH}_3$ in the atmosphere, involving reactions with sulfur so this is not an unequivocal test of the ocean hypothesis.

Third, the ocean hypothesis is consistent with the observed enhancement of methane in the atmospheres of Uranus and Neptune, since methane is expected to have low solubility in the ocean.

The ability of water to mix with hydrogen in Jupiter and Saturn may have important implications, especially for Saturn. One possible consequence is that the deep atmosphere of Saturn may be enriched in water (relative to Jupiter). The large latent heat of water may play an important role in the large scale atmospheric dynamics. The striking difference in the jet streams between Jupiter and Saturn observed by Voyager may be related to the behavior of water deeper down.

Future work will be directed at understanding the implications of these ideas for the evolution of the giant planets. It is also hoped that an improved data base for the behavior of water and hydrogen-water mixtures will eventuate because of experiments which are in progress or planned.

After more than a decade of intensive study, the refractory inclusions of the Allende carbonaceous chondrite continue to provide a focus for many aspects of ongoing research into the early history of the solar system. These tiny objects have provided important insights into the conditions and processes that shaped the early history of the solar system and its planets. Yet a seemingly crucial question about the origin of the Allende inclusions has not yet been settled: Did the solid inclusions we now see crystallize from liquids or did they originate as solids? This question is important for several reasons. If the inclusions originated as solids, perhaps condensed from the gas of the solar nebula at its inception, this would imply certain temperatures and pressures in the nebula. But suppose the inclusions condensed as liquids or were later melted by a secondary process; this might imply substantially different temperatures and pressures for their origin, possibly but not necessarily much higher for both, and might necessitate a rethinking of the conditions that are currently believed to have prevailed in the early solar system.

How can an object that has always been solid be distinguished from one that was once molten? Why is this important question so hard to answer? A variety of tests have been proposed but unfortunately none are entirely free from ambiguity. Two simple approaches are based on observations of the textures of the inclusions; that is, of the microscopic intergrowths between the mineral grains that comprise the inclusions. When a liquid cools and crystallizes, the mineral grains that form become intergrown in patterns that have come to be recognized through a century of geological study by earth scientists as characteristic of rocks that have crystallized from a molten or partially molten state. These patterns are functions of the composition of the liquid and the rate at which it is cooled. Some of the inclusions in Allende have textures that indicate that they crystallized from liquids, so there is general agreement that at least some of the inclusions were once molten. In others, however, the textures are ambiguous or have been obscured by secondary processes. A second approach to this question also involves microscopic study of the inclusions, but rather than overall textural patterns, the order of crystallization of the minerals is examined. If one mineral grain is contained within another mineral grain, one can usually conclude that the first mineral crystallized prior to the second (just as one can be reasonably certain that the string within a piece of rock candy was there before the sugar crystallized around it). How does knowing the order of crystallization of different minerals help to distinguish between a liquid or solid origin of an inclusion? This is possible since the order in which minerals condense as solids from the gas of the solar nebula would typically differ from the order in which they would crystalize from a liquid inclusion.

The focus of this study was to determine by experiment the order in which minerals would crystalize from liquids similar in chemical composition to the Allende inclusions and the temperatures at which these inclusions would melt. The relationships between the order of crystallization and the chemical composition of the inclusion and between the textures of crystallized inclusions and the rate at which these inclusions might have cooled and crystallized were also examined. These data provide a framework for addressing the questions raised above that concern the origin of the Allende inclusions and what they imply for the conditions and evolutions the early solar system.
The experiments consisted of bringing samples of a synthetic rock with a chemical composition similar to that of a typical Allende inclusion to high temperatures (1200-1600°C), and allowing them to partially crystallize at these temperatures or cooling them at variable rates until they were fully crystallized. The samples were then examined microscopically in order to determine the order of crystallization and to characterize the textures produced in the experiments. These textures and crystallization sequences were then compared with those of actual Allende inclusions.

The conclusions can be summarized as follows:
(1) Very high temperatures (~1550°C) are needed to melt some Allende inclusions.
(2) The crystallization sequences observed experimentally are similar to those observed in Allende inclusions, but there are some differences. These differences, and the textures of the inclusions, suggest that the inclusions cooled and crystallized rapidly from a liquid state at high temperatures.
(3) Allende inclusions differ from each other in chemical composition. The experimental results show that not all inclusions will have the same order of crystallization and provide a framework for understanding the relationship between inclusion composition and crystallization sequence.
(4) Most of the inclusions differ in chemical composition from the solid condensates that are predicted to condense from the gas of the solar nebula. These differences and the variations in chemical composition between Allende inclusions are, however, consistent with an origin of the inclusions as molten or partially molten condensates. If the inclusions were solid condensates, it is likely that they were melted at some point after condensation.
(5) Conditions must have existed in the region of the solar nebula in which the Allende inclusions formed, though perhaps only locally and for short times, that could produce molten droplets of the composition of the Allende inclusions.
A MODEL FOR SYNTHESIS OF METHANE IN LUNAR SOIL

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Studies of lunar samples have often suggested clues for an understanding of phenomena which are not confined to the moon. Observations on methane are likely to be a case in point. Small amounts of methane—of the order of a few parts per million—have been detected in lunar soil. This methane is inferred to be of indigenous origin. It was extracted by Abell et al. using deuterated acids like DF and DCl to eliminate the possibility of synthesis during the extraction process. Experiments of Holland et al. have indicated the association of this methane with solar wind implanted rare gases like neon and argon. It was suggested by Bibring et al. that the methane was synthesised by an ion implantation synthesis process and that this process was perhaps also responsible for the synthesis of methane observed in interstellar space. It is, however, not yet clear what exactly this synthesis mechanism is. Two problems associated with the synthesis of methane in the surface layers of soil grains are:

i) stability of methane to ionization, in layers accessible to solar wind radiation; and

ii) absence of comparable quantities of ammonia.

In the present model we suggest a possible mechanism and a specific site at which this methane could be synthesised and which explains the two features mentioned above.
When solids are bombarded with high fluence of low energy ions of hydrogen or helium, the diffusing ions coalesce in the form of bubbles of gas. The solids react to this influx of large number of foreign atoms by confining them to small volumes which are seen as bubbles (a kind of ghetto for alien immigrants). Such bubbles have previously been observed in metals, semiconductors, and minerals like olivine. The grains of lunar soil are exposed to the low energy hydrogen and helium ion flux of the solar wind and bubbles have been observed in these grains by Hutcheon et al. In this model we propose these bubbles as reaction cells in which the methane is synthesised.

The bubbles serve as a trap for the diffusing atoms, and the atoms captured in the bubbles cannot leave it easily. Solar wind consists mostly of hydrogen ions with about 5% of helium and heavier nuclei. Most of the gas in the bubbles in lunar grains would therefore consist of hydrogen and helium. However, the bubbles would also trap atoms of other elements which diffuse through the lattice. Experiments of Bibring et al. on minerals implanted with carbon ions indicate that a significant fraction of carbon atoms diffuse and is redistributed in the top layer of the grains.

For nitrogen there is no such direct experimental evidence to indicate whether it is mobile in the grains of lunar soil. On the other hand, it is known that it is trapped efficiently in the soil grains. The ratio of carbon to nitrogen in soil samples is also found to be lower than in the solar wind. And it has been suggested that due to the
reactivity of atomic nitrogen and the stability of its bonds with lunar cations, the efficiency of retention of nitrogen in the soil grains may approach hundred percent. Even if it is not hundred percent, it is clear that its mobility is small compared to carbon atoms. Hence, the probability of their capture in the bubbles would also be small compared to carbon atoms. Ammonia, therefore, cannot be synthesised in bubbles by a similar mechanism, in quantities comparable to methane.

Since a large number of atoms are confined in the bubbles, the gas pressures are very high—of the order of a few thousand atmospheres. They are also situated within ~500 Angstroms of the surface and hence receive some ultraviolet irradiation. Methane would be synthesised in these bubbles by a process similar to the Bergius process of synthesis of hydrocarbons from coal. In this process coal is hydrogenated at 400-450°C in the presence of iron oxide—which acts as a catalyst—at 200 atmosphere pressure of hydrogen. In the case of bubbles, the temperature is lower (maximum temperature on lunar surface is about 117°C), but this is compensated by the higher gas pressure. Though there is no catalyst present, the activation energy could be provided by the ultraviolet irradiation, and the time scales involved are much larger.

The synthesis of methane in bubbles would also account for its stability against ionization. A methane molecule in the bubbles cannot be effectively destroyed by ionization, since it would recombine with the abundant hydrogen atoms present in the bubbles.
The ion implantation experiments carried out so far are not conclusive enough either to support or rule out the mechanism outlined above. Experiments with low fluxes of carbon and hydrogen ions on samples preirradiated with helium ions to produce helium bubbles could serve as a test for the model suggested here.
The Earth and the Moon are differentiated planets. At one stage of their evolution they were completely or at least partially molten. On Earth there is still magmatic activity. Partial melts (basalts) from the interior penetrate the crust and come to the surface of the Earth. These basalts often carry with them more or less unaltered fragments of the Earth's mantle. These mantle nodules come from depths of some 50 km. (The largest depth reached by drilling a hole into the Earth is about 10 km). They are prime sources of information on the composition of the Earth (e.g. 1, 2, 3).

Recently, we have analyzed several carefully selected mantle nodules for the concentrations of more than 60 elements. One group of elements is an especially good indicator for primitive, unaltered mantle material: the refractory elements (these elements form compounds which are stable at high temperatures and have high condensation or evaporation temperatures). In some nodules concentration ratios among refractory elements are the same as those found in primitive meteorites, which were never molten and, therefore, resemble the composition of the solar nebula, from which the Sun, planets and meteorites formed. (Undifferentiated meteorites are called chondrites).

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![Diagram](image)

**Fig. 1:** Chemical composition of the Earth's mantle normalized to the composition of carbonaceous chondrites Typ 1 (composition of the condensable portion of the solar nebula) and to silicon (Si = 1). All other non-metallic refractory elements not plotted in this diagram have abundances very similar to those of Sc, Al and Yb.
Some of the refractory elements partition very effectively into any melt formed, they are incompatible with the major minerals. Lack of fractionation among refractory elements in some mantle nodules means that there are regions in the Earth's mantle which have never been affected by magmatic processes, besides removal of metallic NiFe for the formation of the core.

Carbonaceous chondrites of type 1 are the most primitive meteorites. Their composition is, except for the most volatile elements, equal to the composition of the Sun. It is therefore common to normalize the chemical composition of planetary objects to that of carbonaceous chondrites of type 1, and to use silicon as reference element.

When comparing the elemental abundances of the Earth's mantle with that of carbonaceous chondrites of type 1 we found (see also Fig. 1):

1.) All refractory elements, with under normal conditions, non-metallic character (lithophile elements) as well as magnesium - after oxygen and silicon the most abundant element in the mantle - are enriched by the same factor of about 1.3.

2.) The transition elements vanadium, chromium and manganese are depleted by a factor between 2 and 4.

3.) Iron and all moderately siderophile (siderophile = iron loving) elements i.e. Ga, Cu, W, Co, Ni are depleted by a relatively small but similar factor of about 7.

4.) The moderately volatile elements potassium, sodium, rubidium and fluorine have abundances similar to those of moderately siderophile elements.

5.) Highly siderophile elements (iridium, osmium, rhenium, gold, etc.) although highly depleted are found in approximately C1 abundances ratios.

6.) The halogens chlorine and bromine are depleted by about a factor of 100. Today they reside predominantly (85 %) in the Earth's crust. About two thirds of chlorine is in the oceans in form of ordinary kitchen salt (sodium chloride).

7.) Carbon, sulphur and water also seem to be highly depleted in the bulk Earth, but strongly concentrated in the Earth's crust.

The relatively small and similar depletion factors for moderately siderophile elements seem to exclude that the Earth's mantle was ever in complete chemical equilibrium with a pure iron-nickel phase. Laboratory measurements of metal/silicate partition coefficients of these elements would predict variable, and for nickel and cobalt considerably lower concentrations.

To explain these trends in the elemental abundance pattern of the Earth's mantle, we have set up an inhomogeneous accretion model with the following sequence:

1.) Accretion started with highly reduced material, free of volatiles and almost free of moderately volatile elements. All siderophile elements down to the only weakly siderophile elements were in metallic state, even silicon was partly present as metal; chromium, manganese and vanadium as metals or sulfides.

2.) After the Earth had reached about two thirds of its present mass and after the metals were concentrated in the core, further material, accumulated by the growing Earth, became more and more oxidized. The last 20 % of the accreting mass of the Earth consisted of highly oxidized material, which contained Fe, Ni, Co, Cu, W in oxidized form. All elements down to the moderately volatile elements Na, K, Rb, F, etc. were present in C1 abundances. Only very small amounts of metallic iron (less than 1 %) were present at this stage but this was sufficient to extract highly siderophile elements (Ir, Os, Re, Au, etc.) into the Earth's core.
3.) The abundance of metal decreased further and the accreting material became richer in volatiles like Cl, Br, I, S, C, H2O. Therefore only the last fraction of the accreting material was responsible for the Earth's supply of highly volatile elements. This veneer hypothesis was first suggested by Anders (4). After the Earth reached about 99.9 % of its present mass, metallic Fe became unstable and extraction of siderophiles was no longer possible and hence highly siderophile elements of the last 0.1 % of the Earth's mass remained in the mantle in their primordial (C 1) abundance ratios.

The uniform enrichment of magnesium and all refractory lithophile elements relative to silicon can also be interpreted in terms of a silicon deficiency. It was suggested that the silicon, missing in the Earth's mantle went into the core in metallic form. From our data we estimate a silicon concentration of 14.5 % in the core. This would be sufficient to reduce the density of the core by the 10 % required according to current theories. From seismic data it is known, that except for a small central part, the Earth's core is liquid. The presence of silicon in the molten outer core might lead to the precipitation of solid Ni2Si to form the solid inner core as suggested by Herndon (5).

This model has the advantage that the relative abundances of non-volatile elements in the bulk Earth are the same as in C 1 chondrites. This is especially true for iron, silicon and magnesium.

One might further speculate that planets closer to the Sun accreted from material even more reduced than that of the first two thirds of the Earth's mass. In that case silicon may be totally concentrated in the metal phase. The high density of planet Mercury could be explained by an extremely high degree of reduction instead of a five-fold increase of the Fe/Si ratio which is required in most other models.

From our data for the bulk composition of the Earth, earlier estimates of the composition of the Moon and the eucrite parent asteroid (parent body of meteoritic basalts) as well as from rough estimates of the K/U ratio of the planets Venus and Mars, we conclude that the Earth, the Moon and probably all inner planets as well as the eucrite parent asteroid are not only depleted in highly volatile elements but also in moderately volatile elements like K, Na, etc.

Fractionation of moderately volatile elements requires temperatures in the order of 800 °Celsius which exceeds presently estimated temperatures for the primitive solar nebula in the regions where the inner planets formed (6). Break-up of the primitive solar nebula in rings and/or large gas spheres may have provided conditions to reach the required temperatures for the observed fractionation of chemical elements in the Earth and the other objects of the inner solar system. Another possible heat source is the extinct radioisotope aluminum-26 (half-life 700 000 years), which could not only have been the heat source required to melt small asteroids soon after their accretion (eucrite parent asteroid), but could also have lead to fractionation of the more volatile elements.

Aluminum-26 was indeed identified in certain meteorites in amounts sufficient to melt even objects as small as a few kilometers (7). However, the question arises why only a small fraction of asteroids were molten and those which are the parent bodies of the most abundant meteorites, the ordinary chondrites, were not.

Already in 1959 Urey (8) introduced the idea of primary and secondary objects. In context with our present knowledge it could well be that objects subjected to melting and differentiation processes are primary objects and undifferentiated ordinary chondrites are secondary objects. If the time
scale of accretion of kilometer sized objects was in the order of the half-life of $^{40}$Al, all early formed objects became molten before they reached their final (present) size. Inside these rather loosely compacted objects volatile and moderately volatile elements will move from hot interior into cool surface layers. During accretion loss (impacts) and gain of material will almost balance each other. The volatile rich surface layer of these objects will therefore, to a large extent, be continuously replaced by newly accreted material and fine grained volatile-rich material dispersed in space.

Collisions of objects will frequently lead to total disruption and if they contain molten material millimeter sized droplets will be produced in large quantities. Such a model could explain the origin of the chondrules (millimeter sized spherules), one of the major components of ordinary chondrites. A similar model for the origin of chondrules was proposed by Zook (9).

Material not yet accreted as well as material dispersed from collisions of objects of the first generation continuously formed new objects. However, objects which accreted at a later time when aluminum-26 had decayed were not heated enough to mobilize volatile elements. Therefore, the last generation of objects (secondary objects) made in this scheme will have the highest concentrations of volatile elements. At the time of formation of objects of later generations, the ambient gas of the solar nebula may be more oxidized, because of preferential loss of hydrogen from the median plane of the nebula, while escape of water (the main oxygen carrying species) might be prevented by formation of ice grains. The material of the objects of later generations will have had time to react and equilibrate with the gas before accretion.

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**Fig. 2:** Oxygen isotope diagram of R.N. Clayton et al. (10). Differentiated meteorites: Eucrites (eu), howardites (how), diogenites (di), pallasites (pall) aubrites, and Shergottite, Nakhla and La Fayette. Undifferentiated meteorites: Enstatite chondrites (E) and ordinary chondrites (H, L and LL chondrites).
and thus will become more and more oxidized. If the isotopic composition of oxygen in the gas is different from that of the solids, later formed objects would have a different oxygen isotope composition. A correlation between degree of oxidation and oxygen isotope composition is indeed observed for enstatite chondrites and the various groups of ordinary chondrites (Fig. 2).

Most of the early formed, molten and differentiated, primary objects will be destroyed by collisions or will end up in larger planets, only a few of them will survive. These are the parent asteroids of eucrites and other differentiated meteorites. In the regions of the inner planets, off-streaming gas may have been responsible for fractional removal of the fine volatile-rich material. Hence, the major portion of the mass of the inner planets would be derived from material of primary objects depleted in volatile elements. Such a scenario could also explain the striking parallelism between the depletion of moderately volatile elements and the oxygen isotope ratios of the objects in question. In the oxygen isotope diagram of R.N. Clayton (10) all objects depleted in moderately volatile elements, i.e. Earth, Moon and all differentiated meteorites plot close to the same oxygen isotope fractionation line but ordinary chondrites (H, L, and LL group meteorites), which are not depleted in moderately volatile elements, plot differently.

Accretion of interstellar dust will form highly reduced primary objects. Removal of hydrogen from the region of planet formation will gradually produce more oxidized material. This is exactly the sequence we have postulated above to explain the elemental abundance patterns of the Earth's mantle.

Literature:

Dear Aunt Hattie:

I'm writing you about the absolutely titillating idea that there was once some place else in the solar system besides Earth where liquid water could be found. From your earth-centered point of view this may seem like a trivial matter, but if you look around the solar system you won't find much flowing, or even stagnant, water. Oh, rumor has it that there is some water underneath the icy crusts of Europa, Ganymede, and Callisto. But that's only theory, and anyway it doesn't help out in the particular dilemma I'm mixed up in. The dilemma arises because there are certain meteorites, called carbonaceous chondrites, which seem to have soaked in water for some considerable amount of time, at least a few months, maybe thousands of years. (No one is quite certain about that.) So the question is where did these meteorites take their baths.

In thinking about this question it seems natural to consider as prime locations for liquid water those places from which meteorites are thought (for other reasons) to have come. Since no one knows for sure where meteorites come from: this unknown place is called the "meteorite parent body". This is a nice inoffensive phrase that doesn't favor anyone place over another. OK, so the prime candidates for the meteorite parent bodies are asteroids and comets. Right now asteroids seem more prime than comets, but this seems to be a matter of fashion which changes from decade to decade. So it appears safest to cover our bets by considering both possibilities. Besides it turns out that it's not too easy to imagine either comets or asteroids as a place where there was ever any water. Here's the problem: Today asteroids are in a place (between Mars and Jupiter, you recall) where water on their surfaces would actually be ice and it would evaporate away fairly rapidly. Ice cubes would last on an asteroid only a year or two at the most. And they wouldn't melt. They would just evaporate. Comets are also much too cold at present to have any liquid water in them. Most comets spend their lives in the freezing outer solar system. Those that stay inside the orbit of Jupiter are in the same boat as the asteroids.

Now I have been talking about ice on asteroids as though there might actually have been some, but most scientists wouldn't give this idea two seconds. Oh yes, for comets it's a different story, everyone seems to agree that comets are made of ice or at least are half ice. But the idea of ice on the asteroids doesn't really fit in with our idea about the inner solar system. After all, look around at Mercury, Venus, the moon and Mars. You don't see alot of water or ice on those planets. Sure Earth has oceans and Mars might have a layer of ice under its top soil, but the
amounts are peanuts compared to the amount of water potentially available from the ice that formed the satellites of Jupiter and Saturn. Conventional wisdom (due mostly to a scientist named John S. Lewis) has it that the water on the inner planets was acquired (by the planets during their growth) in the form of minerals which contained water in their structures. (It was too warm for ice to form in the inner solar system. Examples of such minerals are clay minerals, as in potter's clays. Then what happened was that the water got cooked out of the clays - as in baking the pots. So why couldn't the water in asteroids have come from clay minerals? Why not, indeed. It is just this idea that I am trying to defend against the wicked attack on it made by Drs. Bunch and Chang. They wrote a beautiful paper about the soaking of carbonaceous chondrites in water on the meteorite parent body, but they also launched an attack on the clay minerals as sources of water. Horror of horrors, they suggested that water from ice acted upon the original minerals in the meteorites to form the clay minerals they see there now. They think that it is too difficult to form the clay minerals in the dust and gas clouds which are thought to have preceded the formation of the planets. Well, I wasn't there during the building of the planets and neither were they, but I want to remind Bunch and Chang that astronomers who have been studying the dust elsewhere in our galaxy think that clay minerals are a pretty good match for what they see there. So if clay minerals can form there, why couldn't they be present in our early solar system. Furthermore, their suggestion that clay minerals could be formed by soaking ordinary rocks in cold water for a few months or so is pretty naive. They've obviously never tried it. Well, it is clear that I think there is a pretty strong case for keeping the clay mineral idea alive.

But Nature is never simple, so I have to honestly admit that I can't rule out their icy idea entirely if the carbonaceous chondrites actually come from comets rather than asteroids. I think it's really unlikely that comets were ever melted, especially since they seem to have dust and small rocks mixed in with the ice and if comets were ever melted you would think that the dust and rocky stuff would have separated from the water. But maybe not. Maybe it was stirred up. The problem is we don't know enough about comets now to rule out the idea. But I'm not betting on slushy comets. I sure wish I could get my hands on a comet though.

I'm sorry to have leave these loose ends dangling. I know you like neat and tidy stories, but this is the best I can do for now. I just want to leave you with the thought that the clay minerals can't be ruled out as a source of water - not by a long shot.

Your niece,

Laurel