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PRESS ABSTRACTS

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Evolution of an Impact-Generated H_2O-CO_2 Atmosphere and Formation of a Hot Proto-Ocean on Earth

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Background

Among four terrestrial planets, Mercury, Venus, Earth, and Mars, the Earth is the only planet which has the ocean. How were the atmospheres of terrestrial planets formed and why does only the Earth have the ocean? This is one of the most fundamental questions on origin and evolution of the terrestrial planets.

According to the recent planetray formation theory, the terrestrial planets have been thought to be formed by accretion of planetesimals. During middle stage of accretion, planetesimals impact into a proto-planet with very high velocity (more than several km/sec). High-velocity impact of planetesimals results in degassing of volatiles contained in planetesimals because of increase in temperature by shock heating. Due to such an impact-degassing, a proto-atmosphere should be formed and covers entire surface of a growing proto-planet (e.g., Lange and Ahrens, 1982). H_2O and CO_2 are the most abundant volatiles in carbonaceous chondrites and terrestrial planets. Therefore, we may consider that the impact-generated proto-atmosphere are composed mainly of H_2O and CO_2.

If such H_2O-CO_2-rich atmosphere was formed, the gravitational energy released by impacts of planetesimals during accretion cannot escape directly into interplanetary space. This is because both H_2O and CO_2 absorb the infrared radiation efficiently. Thus the surface of the growing proto-planet is heated up. We have shown that the surface of the growing Earth melts, and thus a magma ocean is formed during accretion (Abe and Matsui, 1985, 1986; Matsui and Abe, 1986a, 1986b). Once a magma ocean covered the entire surface of the growing Earth, the surface temperature and mass of H_2O in the atmosphere are shown to be kept nearly constant. This is because the mass of H_2O in the atmosphere is controlled by dissolution of H_2O in silicate melt. The total mass of H_2O in such an impact-induced atmosphere at the end of accretion is shown to be about $\sim 10^{21}$kg, which is very close to the mass of the present hydrosphere of the Earth

($\sim 1.4\times 10^{21}$kg) (Abe and Matsui, 1986; Matsui and Abe, 1986b) Final mass of the atmosphere is also shown to be insensitive to variations in the input parameter values, such as accretion time, initial water content of planetesimals and efficiency of impact-degassing at low temperature. Therefore, these results seem to suggest an impact-origin of the Earth's hydrosphere during accretion.

Evolution of the Proto-Atmosphere

As mentioned above, the proto-Earth is considered to have an impact-generated (H_2O-CO_2-rich) proto-atmosphere. Then, the next question is whether or not H_2O in the atmosphere can be condensed into oceans. In this paper, we investigate the evolution of an impact-generated H_2O-CO_2 atmosphere of the Earth and formation process of a proto-ocean at the final stage of accretion by using one-dimensional radiative-convective atmosphere model. Based on the previous results and the present CO_2 inventory in the near surface layers of the Earth, the total H_2O and CO_2 masses in the atmosphere and ocean are fixed to be about 10^{21}kg and about 2.5×10^{20}kg, respectively.

Since the atmospheric pressure and temperature is high (200bar and 400~1500K), which is close to the critical point of water vapor (220bar, 647K), we need to take into account non-ideal behaviors of gases. Thus we use the Peng and Robinson's equation of state (Peng and Robinson, 1976). We also take into account the following effects: 1. condensation of H_2O, 2. wavelength-, pressure-, temperature- and pathlength-dependence of the absorption coefficient, 3. greenhouse effect, and geometrical effect (sphericity) of the atmosphere on the radiative transfer. We assume that the temperature gradient in a convective layer is equal to the adiabatic temperature gradient. However, the effect of cloud on the radiative transfer is neglected.

Evolution of Proto-Atmosphere on the Earth

We can summarize an early evolution of the proto-atmosphere on the Earth as follows:

1. During the middle stage of accretion, the impact energy flux, F_0, released by accretion of planetesimals, which is the main heat source of the proto-atmosphere, is larger than about 150W/m^2. In this stage the surface temperature of an accreting Earth is kept to be about melting

temperature of rocks (~1500K) and the atmospheric pressure is about 200bar. The thickness of such an atmosphere is larger than about 300km and cloud can exist only in the region higher than about 260km (Fig.1). Though the proto-atmosphere is mainly composed of H_2O, the lower atmosphere is dry; rain drop evapolates before it reaches the surface of the proto-Earth and thus no liquid water can exist in the lower atmosphere. Since the atmosphere is very thick, the direct sun light can not reach the surface of the proto-Earth.

2. As the growing Earth approaches its final size, the number of accreting planetesimals decreases, because most of planetesimals are already swept up by the proto-Earth. It results in decrease in the impact energy flux and the surface temperature decreases. The magma ocean becomes to solidify. Being associated with cooling of the lower atmosphere, the thickness of the atmosphere decreases and the height of the cloud layer becomes lower (Fig. 1).

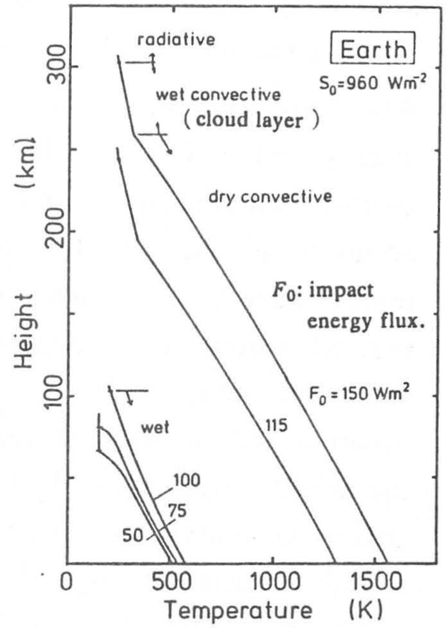

Figure 1.

3. When the impact energy flux decreases to about $100W/m^2$, the height of the cloud layer becomes low enough for rain drops to reach the surface of the proto-Earth (Figs. 1 and 2). It implies that a proto-ocean is formed on the growing Earth. The temperature of the proto-ocean is still very high (about 650K) and thickness of the atmosphere is about 100km. Being associated with the proto-ocean formation, H_2O concentration in the upper atmosphere decreases (Fig. 2), which prevents the photo-dissociation of H_2O and subsequent escape of hydrogen.

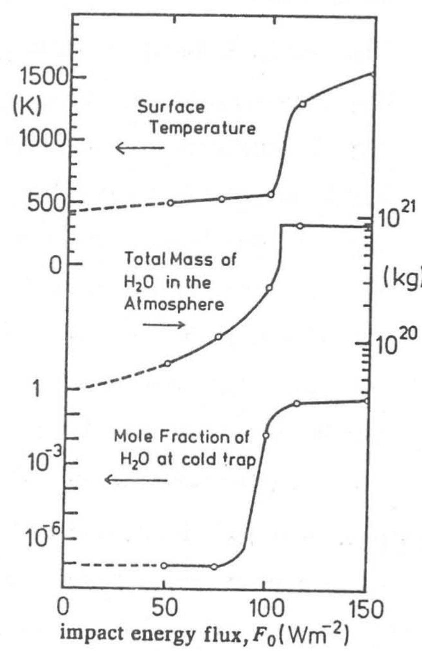

Figure 2.

4. As the impact energy flux decreases, the surface temperature goes down and most

of H_2O in the proto-atmosphere is condensed into oceans (Fig. 2). The mass of proto-ocean approaches to the present mass of the terrestrial ocean. In this stage the atmosphere is composed mainly of CO_2 and the atmospheric pressure is about 50bar, which is determined by the total CO_2 inventory in the near surface layer of the Earth.

5. After the end of accretion the impact energy flux is $0W/m^2$. In this stage the surface temperature is estimated to be about 400K (Fig. 2). Though the surface temperature is still much higher than the present value, it is consistent with the estimated temperature of an archaean ocean based on oxygen isotope data of the oldest crustal rock (3.8×10^9 years old chert) (Oskvarek and Perry, 1976). Such a high temperature is maintained by the greenhouse effect of very thick CO_2 rich atmosphere.

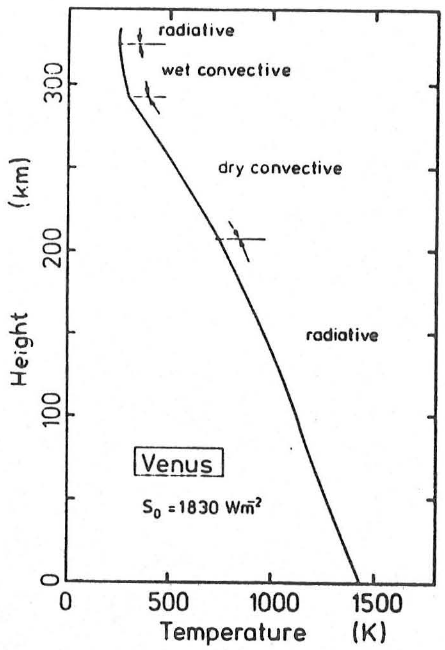

Figure 3.

6. The surface temperature goes down gradually with decreasing CO_2 in the atmosphere due to geochemical reaction in a proto-ocean, for example, formation and precipitation of carbonates such as $CaCO_3$. It has been pointed out that the Earth should have been frozen in its early history, if the Earth has had the present atmosphere (Sagan and Mullen, 1972). This is because the solar flux at 4.6×10^9years ago is estimated to be about 30% lower than the present value. However, our results indicate that, without any ad hoc assumption, the freezing of the proto-Earth is automatically avoided as a consequence of the formation of an impact-generated atmosphere during accretion.

Implications for Evolution of the Proto-Venusian Atmosphere

In the previous paper (Matsui and Abe, 1986c), we have shown that a magma ocean was also formed on the proto-Venus during accretion and the final mass of an impact-induced H_2O-rich proto-atmosphere was about

10^{21}kg. However, if we apply our new model to a proto-Venusian atmosphere, the mass of H_2O in the impact-generated atmosphere is shown to be smaller than that of the Earth.

During accretion the proto-atmosphere of Venus may be similar to that of the Earth shown in the previous section; thick atmosphere and dry lower atmosphere in spite of high H_2O concentration. However, unlikely to the Earth, the surface temperature of proto-Venus is kept very high even after the end of accretion because of higher solar flux (about twice of the terrestrial value). The lower atmosphere is kept to be dry and no water ocean may be formed on Venus (Fig. 3). Since the H_2O concentration in the upper atmosphere is also kept to be high, H_2O is considered to be lost by the photo-dissociation and subsequent escape of hydrogen (e.g., Kasting and Pollack, 1983). It may result in the hot CO_2 atmosphere as seen for the present Venus.

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SPECTRAL ALTERATION EFFECTS IN CHONDRITIC GAS-RICH BRECCIAS: IMPLICATIONS FOR S-CLASS AND Q-CLASS ASTEROIDS.

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The asteroids are of fundamental importance to understanding the origin and evolution of the solar system for several reasons: 1) They probably represent remnants of the population of small bodies which accumulated to form the planets, and preserve an otherwise lost intermediate stage in the formation of planetary systems, between dust and planets; 2) The asteroid belt is located between the rocky inner planets and the icy outer solar system and should preserve the compositional transition between these radically different classes of bodies; 3) Some of them have escaped the melting processes which have destroyed evidence of the original geochemistry in planetary rocks; 4) Study of meteorites has provides a vast body of geochemical, mineralogical, and isotopic data which probably refers to some asteroids.

Studies of the spectral distribution ("color") of reflected sunlight provides the best means of determining asteroidal surface compositions, and relating meteorite classes to their parent bodies. Data obtained in the visible spectral region (0.3 to 1.1 microns wavelength) indicate that a majority of the objects in the inner portion of the asteroid belt belong to spectral class "S". The exhibit strongly reddened spectral curves with shallow absorption bands diagnostic of the silicate minerals olivine and pyroxene. Among the 14 asteroid spectral classes identified in the most recent taxonomic analysis (by David J. Tholen, based on the University of Arizona 8-color asteroid survey), the S-types are the only abundant class with such complex spectra. Unfortunately, this class is also the most controversial, with two opposing schools of thought supporting contradictory interpretations of the spectral data. The conventional method of interpreting asteroid spectra is to pulverize meteorite samples to approximately the texture of asteroid regoliths (as indicated by the polarization data), obtain spectra in the laboratory, and compare them with asteroid spectra. This is an imperfect technique, because some meteorite classes are very rare and museum curators dislike having them destroyed, and because many common types contain large masses or networks of nickle-rich iron alloy (with mechanical properties similar to man-made stainless steel) which makes them difficult to pulverize. In face, none of the meteorite spectra obtained to date match the S-type asteroid spectra closely. This fact is explained in two ways: A) The most common meteorites (ordinary chondrites) also contain shallow olivine and pyroxene absorption bands, but lack the steep red slope also present in S asteroids. Since the red slope appears in pure iron meteorites, slope should be correlated with metal abundance. Increasing the metal abundance in an S-type regolith would tend to increase the spectral slope. Therefore, the S-type asteroids are undifferentiated ordinary chondrites covered with a regolith whose apparent metal abundance is enhanced by some unknown "space weathering" effect which occurs during regolith formation. The simulated regoliths prepared from ordinary chondrites found on Earth do not spectrally resemble the natural regoliths on asteroids because their pulverization is an inadequate simulation of the real regolith-altering processes. B) The spectral differences between S-type asteroids and ordinary-chondrite meteorites represent a real compositional difference. The lack of spectral matches for S-asteroids in the meteorite spectral collection is an artifact of the incomplete nature of that data set. S-asteroids are composed of differentiated stony-iron material similar to two rare classes of meterorites (the pallasites and lodranites), for which no lab spectra have been obtained due to the extreme difficulty of pulverizing the samples.

These two opposing schools of thought have radically different implications in many areas. If interpretation A is correct, 1) the most common meteorites correspond to the most common asteroids; 2) asteroid spectra refer only to a highly altered regolith and tell us nothing about the bedrock beneath; 3) most inner-belt asteroids were only slightly heated and metamorphosed. If interpretation B is correct, 1) the most common meteorites have no known parent body in the asteroid belt, and the most common asteroid type is the source of some of the rarest meteorite types; 2) asteroid regoliths are merely pulverized bedrock and asteroid spectra are easily interpretable; 3) most inner-belt asteroids were strongly heated and melted, but the segregation of silicate and metal components was still incomplete when the heat source decayed and the melt solidified. This controversy thus cuts to the very heart of asteroid and meteorite research.

Several lines of research over the past several years have converged to suggest that interpretation B is the correct one. D. J. Tholen has defined a new spectral class "Q" of which asteroid #1862 Apollo is the prototype. Spectra of this object are nearly identical with that of some pulverized ordinary chondrites. About 10-20% of the asteroids of Earth-crossing orbits appear to belong to this class; but it is totally absent in the main belt. M. J. Gaffey has produced simulated ordinary chondrite regoliths in which the metal abundance is enhanced by magnetic separation. Surprisingly, even very metal-rich simulations show no increase in the red slope thought to be characteristic of nickel-iron metal. Apparently the spectral signature of metal in undifferentiated meteorites differs from that in differentiated meteorites, for reasons which remain obscure. Gaffey also has made observations of asteroid #8 Flora (which has been nominated by promoters of interpretation A as the best match for ordinary chondrites) to search for mineralogic variations across its surface. Such variations were found and exhibit trends not found in chondritic meteorites. J.F. Bell and B.R. Hawke have conducted the first comprehensive asteroid spectral survey in the near-infrared spectral region, which indicates that in general S-type asteroids exhibit wide variations in mineralogy inconsistent with known chondrites. Finally, some S-type spectra have been shown to correspond closely to spectra of simulated stony-iron regoliths created by dispersing olivine grains on a metal substrate. This method avoids the problems of pulverizing metal-rich meteorites; with the addition of pyroxene it should be possible to simulate all S-type spectra. Despite these developments, several prominent and vocal supporters of interpretation A remain active; discussions between the two factions continue to enliven coffee breaks at scientific meetings.

The key question is: Does the uppermost few millimeters of an asteroid regolith have the same spectral curve as the bedrock underneath? A small subset of meteorites, the solar-gas-rich breccias, apparently preserve portions of the uppermost regolith complete with alteration effects characteristic of long exposure to the space environment. Typically, areas of fine-grained matrix in these meteorites are rich in implanted solar wind gases, particle than even the most primitive meteorites (the so-called carbonaceous chondrites). Indeed, it is likely that most of the micrometeoroids (and consequently their daughter micrometeorites collected on the Earth) originate from comets (supposed to be the most primitive matter). This important inference is suggested by the work of astronomers who determine the orbits of "meteors" that represent the ion trails formed during the ablation of micrometeoroids in the atmosphere. It has been shown from the statistics of such orbits that at least 90% of micrometeoroids with mass larger than 0.1 mg have cometary orbits quite distinct from those of meteorites.

Today, teaspoons of well preserved cosmic dust grains (representative of the whole micrometeoroid flux) can be readily retrieved from terrestrial sediments. Moreover, they may represent a sample of the dark sand scooped from the astonishly dark surface of a cometary nuclei, such as that of comet P. Halley, observed instrumentaly in March 1986 from the Vega and Giotto satellites. There are, however, two difficulties concerning the relationship between cosmic dust on Earth and micrometeoroids in space. Firstly, in all previous studies, including our recent analyses of Greenland cosmic dust grains, at least 99% of the grains were described as spherules, resulting from the melting of their parent bodies in the atmosphere. This melting blurred to an unknown extend the "primitive" characteristics of their parent bodies. Secondly, the corrosion of the cosmic dust grains in their host sediments (i.e. "terrestrial weathering") produces further modification of these characteristics. Our paper offers new ways of tackling these severe limitations.

In July 1984, samples of dark sediment were collected at 6 distinct locations on the melt zone of the West Greenland ice cap, at the latitude of Søndrestrømfjord and Jakobson. The cosmic dust grains trapped in these sediments were released by simple mechanical disaggregation of the sediments. This technique avoids any artefacts related to the magnetic extraction procedure, which had to be used to extract large numbers of grains from deep-sea sediments. In addition, we already showed that these dark sediments constitute the richest and best preserved mine of cosmic dust grains found to date on the Earth. This minimizes difficulties related to terrestrial weathering.

Two unexpected discoveries were made, while running the sample of sediment collected at the largest distance (abcut 50 km) from the margin of the Jakobson ice field, by K. Eichelmein and W. Harrison during a seismic sounding investigation on the ice cap. We first found a very high enrichment of the cosmic dust component in this sample, as at least 50% of grains with a size in excess of 0.1 mm showed an extraterrestrial origin. This astonishing purity of the cosmic dust component is probably related to a favorable circulation of very clean mid-tropospheric wind, blowing from the interior to the margin of the ice cap. This wind pattern transforms the melt zone in a gigantic dust free hood.

Thanks to this high enrichment we discovered a new population of cosmic dust grains, showing both irregular shapes of "fragments" and measurable contents of volatile elements (such as sulfur). This indicates that these grains have not "burned" upon atmospheric entry. Moreover, we found that the abundance of these unmelted fragments was much higher (about 25% to 30%) than previous estimates of "less than 1%". Typically, a 100 gramme aliquot of wet sediment will yield about 25 unmelted grains with sizes greater than 0.1 mm (most of the mass of sediment is composed of filamentary bacteria colonies in which both terrestrial and cosmic dust grains have been firmly "cocooniced"). These unmelted fragments represent a corner stone in the study of cosmic dust grain accreted by the Earth.

This high abundance of unmelted fragments related to other important results : trace elemental contents, mineralogical and chemical compositions, peculiar mass distribution, demonstrates that micrometeorites survive amazingly well upon ablation in the atmosphere. However, reliable computations indicate that compact chunks of meteorites with sizes in excess of 0.1 mm are "completely" destroyed upon ablation, as their surface to volume ratio becomes too small to radiate away the frictional heat released during their hypervelocity impact with the atmosphere. This differs from our preliminary observation on a random set of about 100 unmelted fragments with sizes ranging from 0.1 mm up to 0.5 mm. Thus a very efficient cooling mechanism is probably needed to prevent the melting of about 1/4 of the micrometeoroids. This mechanism may be related to their composite pyrolisable structure. In such a structure, now very different from the compact structure of meteorite, a component of volatile material would permeate a "fluffy" aggregate of nonvolatile grains. Upon frictional heating the volatile compounds could generate a flux of gas providing a very efficient cooling mechanism, as long as the pore structure of the aggregates stay opened.

Using these unmelted fragments, we hope to circumvent the difficulty previously encountered with the spherules while trying to reconstruct the initial characteristics of their parent bodies. In fact, some unmelted grains should directly yield the characteristics of the nonvolatile component of the dark sand found on the surface of cometary nuclei, without requiring the complex corrections, that must be developed for the spherules.

In summary, our preliminary investigations of about 100 unmelted fragments further confirm that micrometeoroids are very different from the parent bodies of meteorites. Most stony fragments have a chemical composition compatible with that of the most primitive stony meteorite, that are very rare in terrestrial collections. Thus, the abundance of primitive objects is much higher in the collection of cosmic dust grains than in the collection of meteorites. The ablation constraints indicate that the best preserved Greenland micrometeorites constitute new families of extraterrestrial objects that might be more representative of the meteoroid complex in space than conventional meteorites. The detailed analyses of 26 unmelted fragments, reveal that they are very different from each other. This unexpected variability adds a further constraint on the origin of the solar system, that we have still to fully understand.

Finally the unexpected abundance of the unmelted cosmic dust grains indicates that we can extract a sufficient number of them by melting 100 tons of very old blue ice in Antarctica. An examination for possible changes in the composition of the fragments extracted from blue ice of different ages, may allow us to detect changes in the past activity of the micrometeorite flux, which is generally considered as being dominated by the contributions of the few "most dusty" comets over time scales of a few thousand years.

MIRANDA GEOLOGY: EXOTIC ICES ON THE ROCKS

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Study of the varied geologic features on Uranus' bizarre moon Miranda has provided circumstantial evidence for large quantities of ices of exotic composition including mixtures of ammonia and water ice and ice clathrates, an unusual form of water ice containing large amounts of trapped gases. The numerous craters on Miranda appear to have been formed primarily by debris originating within Uranus' satellite system rather than by objects common to the entire Solar System such as comets. The local origin of crater-forming objects greatly lessens the probability that spectacular collisions literally blasting Miranda apart ever occurred, or that crater densities can be used to relate absolute ages of geologic events on Miranda to the established chronology of events on the Earth and Moon, but does promise information concerning conditions under which the satellites formed in the first place.

One of the major questions concerning the icy satellites of Jupiter, Saturn, and Uranus is: what are they made of? Theories of formation of the planets and satellites have predicted that in the cold parts of the Solar System distant from the Sun, objects like comets and planets should have formed containing not only the rock, metal, and water ice found on Earth, but also ices of compounds that are gases on Earth: ammonia, methane, carbon monoxide, argon, and others. Methane has been found by spectral analysis in the atmosphere of Titan, and on the surfaces of Triton and Pluto. Spectral evidence for the other ices is poor to non-existent, and not likely to be obtained. For instance, if ammonia-water ice were formed on the surface of a satellite, the action of sunlight would quickly remove the ammonia, leaving behind only the water ice which we do detect on virtually all the icy satellites.

Geologic analysis, however, provides an alternate approach for investigating the presence of exotic ices. A basic idea in planetary studies is that the occurrence of volcanism and tectonics (surface fracturing and folding) on a planet or satellite is related to its size: small planets form cold and are small enough to remain cold in spite of internal radioactive heating so that melting and rock movement in the interior never occur, precluding the occurrence of volcanism and distortion of surface rocks. On the other hand, large planets form hot and retain enough radioactive heat that extensive melting, volcanism, movement, and surface distortions are produced. This relation holds for the rocky terrestrial planets: the Moon's surface is dominated by impact craters and exhibits only minor volcanic flooding, while the surface of the much larger Earth consists almost entirely of young rocks constantly being broken and remelted. The icy satellites generally follow a similar pattern, with small satellites like Mimas (of Saturn) exhibiting only craters while large satellites like Ganymede show extensive volcanism. The icy satellites, however, repeat the sequence at smaller absolute sizes than the rocky terrestrial planets (Ganymede is only slightly larger than the Moon) because the "magma" on the icy satellites is water, which melts at much lower temperatures than the rocky magmas of the terrestrial planets. Thus, though the internal temperatures in the icy satellites are generally less than in the larger terrestrial planets and too low to melt rock, they are still high enough to melt water. Miranda is a small icy satellite similar to Mimas in size. Consequently, prior to Voyager 2's arrival at Uranus, Miranda was expected to be simply a cratered snowball, yet it shows extensive fractures and undeniable evidence of volcanism.

One possibility for explaining the evident activity on Miranda is the presence of tidal stretching which causes additional internal heating, as is the case for icy Enceladus (of Saturn) and rocky Io (of Jupiter), but this appears not to be the case for Miranda. Another possibility is the presence of some of the exotic ices. In particular, if ammonia is present, the melting point of ammonia-water ice is lowered nearly 100^{o}C below the melting point of pure water ice. By itself, this is still not enough because the thermal conductivity (the ability to conduct heat) of ammonia and water ices is high enough to keep the interior of Miranda well below the melting point of even ammonia-water ice. But if Miranda's interior also contains large amounts of methane clathrate, an exotic form of water ice containing methane found in terrestrial arctic sediments and natural gas pipelines in polar regions, then the interior of Miranda can heat enough to melt moderate amounts of ammonia-water ice in the deep interior. This is because the thermal conductivity of clathrate is much smaller than that of ordinary ice, forcing the interior to get quite warm before heat can escape to the surface. This extra internal heating will lead to moderate internal melting and some surface volcanism as is observed, and will also produce about the right amount of internal heat expansion to produce the fractures and canyons seen on the surface.

If one assumes ammonia and clathrate are present in Miranda, they are probably also present in Uranus' other satellites. How about them? Since they are all larger than Miranda, their interiors should get warmer, melting should be more complete, and surface volcanism more extensive. This appears true for Ariel, which shows more extensive fractures and surface volcanic flows than Miranda. Giant Titania, which should be covered with volcanic deposits, appears instead to be covered by impact craters. However, careful study of the sizes and areal distributions of craters on the Uranian satellites reveals a correlation between the age of a surface (measured by the number of craters per unit area) and the sizes of craters: old surfaces such as the heavily cratered sections of Miranda have relatively more large craters than younger surfaces such as those on Ariel which have relatively few large craters. The craters on Titania represent an intermediate case, but they are enough different from the old crater population (which by any theory had to occur on all of Uranus' satellites) that Titania's original surface must have been completely buried by volcanic flows. Thus, Titania did in fact experience massive melting very early in its history, supporting the inference of exotic ices in its interior.

A final piece of evidence for exotic ices on the Uranian satellites comes from the characteristic widths of the canyons on Miranda, Ariel and Titania. The widths of canyons formed by expansion and cracking are related to the thickness of the surface brittle layer in which they occur. The thickness of the brittle layer depends on the rate of flow of heat from the interior, which increases with satellite size, and on the thermal conductivity of the layer, which depends on composition. Comparison of canyon widths on Titania and Ariel with those on Jupiter's satellite Ganymede indicate surface layers of similar thermal conductivity, probably water ice or ammonia-water ice. Relative canyon widths on Miranda are substantially wider, indicating a much lower thermal conductivity characteristic of ice clathrates. Thus, the outermost layers of Ariel and Titania apparently consist of ammonia-water ices erupted from an extensively melted interior that covered the original surfaces to depths of several tens of kilometers, while the outer layer of Miranda apparently consists of an original ice clathrate composition covered in only a few restricted areas by thin layers of erupted ammonia-water ice.

Another question related to the formation as well as the geology of Miranda concerns the origin of the crater forming objects. One hypothesis is that the objects are external to the Uranian system and thus related to a presumed early Solar System wide population of objects whose remnants include comets. If this hypothesis is true, then at least one crater population should be common to all the solid objects in the Solar System which, in principle, would allow extension of the radiometrically determined age sequence of different crater densities on the Moon to every planet and satellite in the Solar System. Another consequence of the external origin of crater-forming objects is a high concentration of objects with high relative velocities near the giant planets that could totally disrupt small satellites such as Miranda. The second hypothesis is that the craters were largely formed by objects internal to the Uranian system: debris leftover from the actual formation or assemblage of the satellites or blocks ejected from the satellites after formation by moderately large impacts. This hypothesis implies separate crater density chronologies unrelated to any other within each satellite system, and much lower local concentrations and velocities of impacting objects, greatly reducing the probability of impact disruption.

Geologic evidence concerning the origin of the crater-forming objects is as follows. Miranda's surface consists of three volcanically flooded areas within pre-existing depressions in an otherwise continuous, old, heavily cratered surface. The old cratered surface shows no evidence of a major disruption of Miranda into small pieces that subsequently re-assembled (as pictured in the popular literature). Disruptions may have occurred, but if so, they must have occurred long enough before the formation of the present surface to have allowed re-cratering of the entire surface to a uniform extent. Thus, Miranda presents no direct evidence of a disruption which might be indicative of an external origin for crater forming objects.

In addition, the crater populations on the Uranian satellites are not only distinct from each other, as noted above, but also from crater populations elsewhere in the Solar System. This implies that most of the crater forming objects are internal to the Uranian system, rather than external. There are, of course, craters formed by external objects such as comets, but they are apparently too few relative to the internally formed craters to be identified as a separate population. In addition, the correlation between crater density (and hence age) and the relative number of large craters implies that the population of crater-forming objects within the Uranian system changed with time by breaking up into smaller pieces via mutual collisions. If, as is apparently the case, the crater forming objects did originate within the Uranian system, they will provide information about conditions that prevailed during the formation of the satellites and thus aid in understanding how all the planets formed.

THE D/H AND $^{18}O/^{16}O$ ISOTOPIC RATIOS IN COMET HALLEY

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Of the five spacecraft that encountered comet Halley in March, 1986, the closest approach to the nucleus was made by the Giotto spacecraft of the European Space Agency when, on March 14, it flew past comet Halley at a distance of 605 km from the nucleus. The relative speed of the spacecraft and the comet at the time of the encounter was 68.4 kilometers per second (km/s), which is more than three times the nominal speed of meteors entering the earth's atmosphere. Gases evaporating from the nucleus of the comet, and the dust particles carried by the gases, flow outward at speeds less than 1 km/s with respect to the comet. To an instrument on the spacecraft with an orifice facing in the direction of the comet these particles appeared to be almost stationary with respect to the comet, so that the instrument collected the constituents of the coma just as a night hawk, flying with its mouth open, gathers insects.

Measurements essential to determining the composition of the gases of the coma and the rates of release of volatiles from the comet were made on the Giotto spacecraft by an integrated package of instruments called the neutral mass spectrometer (NMS). The NMS measurements included mass and energy spectra of neutral and ion constituents of the coma beginning 900,000 km from the nucleus. At 893 km from the nucleus the operation of the NMS was interrupted by a severe electrical impulse, probably the result of plasma created by a dust particle impact, which disabled all of the 384 detectors of the two analyzers of the NMS.

The NMS had two independent particle analyzers. One, called the M-analyzer, was a double focussing, magnetic deflection mass spectrometer which separated particles according to molecular mass and measured their rates of collection by the instrument at various mass numbers. The other device, the E-analyzer, used electrostatic fields to sort particles according to energy and measured rates of influx over a wide range of energies. Both analyzers were designed to make constructive use of the nominal ram energy of the coma sample to separate cometary species from residual contaminants, and both had multi-channel, focal plane detectors to facilitate simultaneous accumulation and readout of entire spectra. During the encounter the analyzers sequenced through various modes that sampled coma neutral and ion constituents. Periodic measurements were also made in background modes to determine the effects of cometary ions and neutrals bombarding residual gas in the analyzer inlet. In neutral modes, electron beams traversing the inflowing gas stream were used to ionize incoming molecules without modifying their velocities. Two electron bombardment energies were provided: electrons accelerated to an energy of 90 volts were used for efficient ionization but with significant fragmentation of molecular species; and 17 volt electrons were used for spectra with minimal fractionation of the dominant parent molecules.

The data set gathered by the NMS during the Giotto encounter with comet Halley is rich in information on the composition of the cometary coma and the rates of loss of volatiles from the comet. For example, we have shown that water, the dominant volatile released from the comet, was escaping at a rate of 5.5×10^{29} molecules per second (i.e. about 17 tons per second) at the time of the encounter. The second most plentiful gas in the Halley coma was carbon monoxide (CO) with an abundance, relative to water, in the range 5-15%. Curiously, most of the CO is not produced by evaporation in the comet nucleus. Instead it is produced by a source that extends throughout the inner coma, to distances of 20,000 km from the nucleus. Owing to the absence of viable parent molecules for CO in the coma, we have proposed that CO is either released from cometary dust grains or it is formed by dissociation of a short lived, volatile constituent of dust grains. It is unlikely that temperatures of the protosolar nebula would have been low enough to allow condensation of CO in dust grains. Hence the presence of CO in Halley dust grains suggests that some cometary dust may be accreted interstellar dust, and that Halley may be the most primitive body that has been investigated.

While absolute abundance measurements of water and other molecules indicate the present state of the comet, a complimentary view of its origin and evolution can be obtained by isotopic analysis, i.e. the determination of the relative abundances of atoms of the same element but differing nuclear mass. In natural systems where selective escape due to mass differentiation has occurred, excesses of the heavier isotopes of volatile elements tend to remain. Of all stable elements, the isotope pair of normal hydrogen (H) and heavy hydrogen, or deuterium (D), with atomic masses of 1 and 2, respectively, have the greatest relative mass difference and hence the greatest likelihood of variation in their abundance ratio. This is borne out by measurements of D/H ratios in such varied objects as interstellar molecules, meteorites, and planetary atmospheres. Significant variations in relative isotopic abundances of helium, carbon, nitrogen, and oxygen have also been found in extraterrestrial matter.

Measurements of the relative abundances of isotopes by in situ mass spectrometry is made very difficult by the weight restrictions of spaceflight, which generally preclude the use of instruments with sufficient mass resolution to detect the small nuclear mass defects that distinguish molecules of similar atomic mass number but differing elemental composition. With limited mass resolution the problem of isotope measurements centers on the fact that for light elements the low abundance isotope is always heavier than the major isotope, and molecules formed by the addition of hydrogen to the lighter isotope interfere with measurements of the heavier isotope. For example, the position in the mass spectrum of the deuterium ion, D^+, at 2 atomic mass units (amu) is coincident with the more abundant molecular hydrogen ion, H_2^+, and $^{18}O^+$ is coincident with normal water vapor, $H_2{}^{16}O^+$, at 18 amu.

By associating identifiable molecular and and atomic ions with ion spectra from the inner coma, we have been able make a preliminary evaluation of the relative abundances of the isotopes of oxygen and hydrogen in cometary water ice. For oxygen the ratio of ^{18}O to ^{16}O, is $0.0023 \pm .0006$, which is, within experimental errors, identical with the terrestrial $^{18}O/^{16}O$ ratio of 0.00205. Further refinement of the comet Halley data is needed, including, if possible, an independent determination of the oxygen isotope ratio for the CO evolving from dust grains, before meaningful comparisons can be made of cometary, meteoritic, and terrestrial oxygen.

The deuterium to hydrogen ratio for Halley water ice is of greater interest. Preliminary analyses of data from the Giotto NMS indicate that the D/H ratio lies between 0.6×10^{-4} and 4.8×10^{-4}, implying that cometary deuterium is enriched by at least a factor of 3 (and perhaps more) with respect to protosolar hydrogen and with the hydrogen accreted in gaseous form from the protosolar nebula by Jupiter and Saturn. Deuterium enrichments comparable to that in comet Halley occur in hydrogen in interplanetary dust, meteors, Titan, and terrestrial water, suggesting a common source of hydrogen, perhaps as the result of accretion of volatile molecules like water vapor or methane. Alternatively, these bodies may have acquired their hydrogen from the same region of the protosolar nebula. The NMS measurements strengthen a common hypothesis of several theories, that the water on the terrestrial planets is of cometary origin. Cometary origins of carbonaceous chondrites and interplanetary dust are also allowed by the Halley D/H ratio.

THE GEOLOGY OF PAVONIS MONS, MARS. Ken Edgett, Department of Geology, Earlham College, Richmond, IN 47374; James R. Zimbelman, Lunar and Planetary Institute, 3303 NASA Rd. 1, Houston, TX 77058; and Jon W. Branstrator, Department of Geology, Earlham College, Richmond, IN 47374.

Geologic mapping of a locality provides a picture of the distribution of geologic formations and structures in a form that is easily seen and interpreted (1). Such maps are useful in providing a framework for further study of a region.

A geologic map of Pavonis Mons (6^{o}N to 5^{o}S, 107^{o}W to 118^{o}W) has been compiled using Viking low to medium resolution images and Mariner 9 B-frame images as a data base. (There are no high-resolution images of Pavonis Mons.)

Pavonis Mons is one of the four largest volcanoes on Mars, and it is one of the Tharsis Montes, a three-volcano chain on the great Tharsis Bulge, to the west of the canyon Valles Marineris and to the southeast of Olympus Mons, the giant volcano (see Map 1). Pavonis Mons, like its counterparts Arsia Mons and Ascraeus Mons, is thought to be a basaltic shield volcano (2), intermediate in age between the other two (3).

This work represents the first to focus specifically on the geology of Pavonis Mons. Much has been done on the geology of Olympus Mons, the Tharsis Plains, Arsia Mons, and Ascraeus Mons. As yet, there has not been a geologic map of Arsia Mons, but Ascraeus Mons was mapped and studied in detail by Zimbelman, 1984 (4).

The Pavonis Mons region, mapped in this study, exhibits three major units: the shield, the plains, and the landslide terrains (see Map 2). The term "landslide" refers to a roughly circular lobe which extends northwestward from the northwest flank of the volcano. Its origin is uncertain, but thought to be related to mass-wasting (land-sliding) processes (1,4,5,6).

At the shield summit is a circular, 45-kilometer (28 miles) wide caldera (cf, cw, cws), which is younger than an adjacent 100-km (62.5 mi.) volcano-tectonic depression (d) (a circular feature related to the collapse of the summit due to volcanic and tectonic forces) (3). The oldest shield surfaces (ps1) are on the south and east slopes. It is characterized by numerous and distinct arcuate (curved) grabens (down-dropped fault blocks) which are concentric to the volcano-tectonic depression; rille-like channels (related to volcanic eruption), many of which run down the flanks of the volcano; and two embayments, one on the northeast flank and the other on the southwest flank. The embayments were sites of lava eruption, and they lie on a buried fault system that trends northeast-southwest through the Tharsis Montes (3). The old shield surface is buried on the north/northwest slope by younger volcanic material (ps2). The younger unit is characterized by an apparent burial of old grabens, and a lack of grabens on the young surface. Some grabens on the older surface are truncated (cut off) at the contact between the old and new surface, and traces of some older grabens are visible in the younger unit. The western slope (ps3) has a ragged or jumbled surface, characterized by old grabens that appear degraded relative to their counterparts on the south and east slopes. Grabens on the southwest flanks tend to be less degraded. The western slope is probably a zone of detachment, or, rather, the source for the debris which makes up the landslide lobe to the west and northwest. A similar surface was described by Carr, et al., 1977, on the west slope of Arsia Mons, in association with a similar landslide lobe (5).

The plains surrounding Pavonis are younger than the shield. The plains consist of extensive lava flows (arp, asp, thp, ?thp, pthp, athp) and flows from the southwest shield embayment (pes1, pes2) are among the youngest. The flows from the northeast shield embayment (pen1, pen2) may be older, as this unit is cut-off by younger lava plains to the east and north (thp), and it is fractured by 3 to 5 kilometer (2-3 mi.) wide, closely spaced, arcuate and parallel grabens. This unit, and the grabens within it, are partially buried to the west by debris from the landslide.

The landslide (plm, pls) is a roughly circular lobe which extends up to 250 km (156 mi.) from the base of the north/northwest flank of the shield. Similar lobes are located on the west sides of Arsia Mons and Ascraeus Mons (1, 6, 7, 8). The outer margin is a ridge and, in some areas to the northwest, a series of parallel ridges. The interior of the lobe varies from mountainous (plm) to knobby (plm, pls) to smooth (pls) in texture. The origin of the lobe is difficult to determine at available image resolutions. It has been interpreted as ancient terrain (5), a landslide or debris flow (1,4,5,7), and as a blanket of debris left behind by a melted or sublimated ice cap (8).

The ridge on the eastern margin of the landslide lobe is interesting, as it appears to run down the lower flanks of the north side of Pavonis, and then continues across the north-flank grabens. It would seem that this material either rode over the top of the grabens (if it was indeed a landslide or debris flow), or it was deposited by an ice cap, because this ridge and landslide material does not seem to have been affected by the presence of the grabens. However, an ice-deposit interpretation is complicated by the fact that Pavonis Mons lies on the equator.

Volcanism at Pavonis Mons was dominated by lava eruption and flow, both from the summit and from vents on the shield, and at the base, from the northeast and southwest embayments. We found no evidence of pyroclastic volcanism, that is, explosive eruptions associated with ash deposition. However, pyroclastic material (ash, tuff) may be buried or simply invisible at available image resolutions.

In addition, we did not find any evidence of recent volcanism. Most geologic units bear visible impact craters, suggesting that these surfaces are relatively old. Estimates suggest an age of around 0.1 to 1.4 billion years (2).

Variations in lightness and darkness of surface dust deposits (albedo variations) during the Viking missions suggest that aeolian (wind-blown) transport and redistribution of fine-grained (6,9,10) materials is occuring on the shield (11).

The geologic map of Pavonis Mons will aid further studies of the Tharsis Montes. It can be used as a framework for the evaluation of other remote sensing data on Pavonis, much as Zimbelman did for Ascraeus Mons (4). Eventually, a detailed study of the geologic history of Pavonis Mons can be compared with the geology of Ascraeus and Arsia Montes, and these can be evaluated in the context of the volcanic and tectonic history of the Tharsis region, which is considered to have been very important in shaping the history of Mars over the past few billion years.

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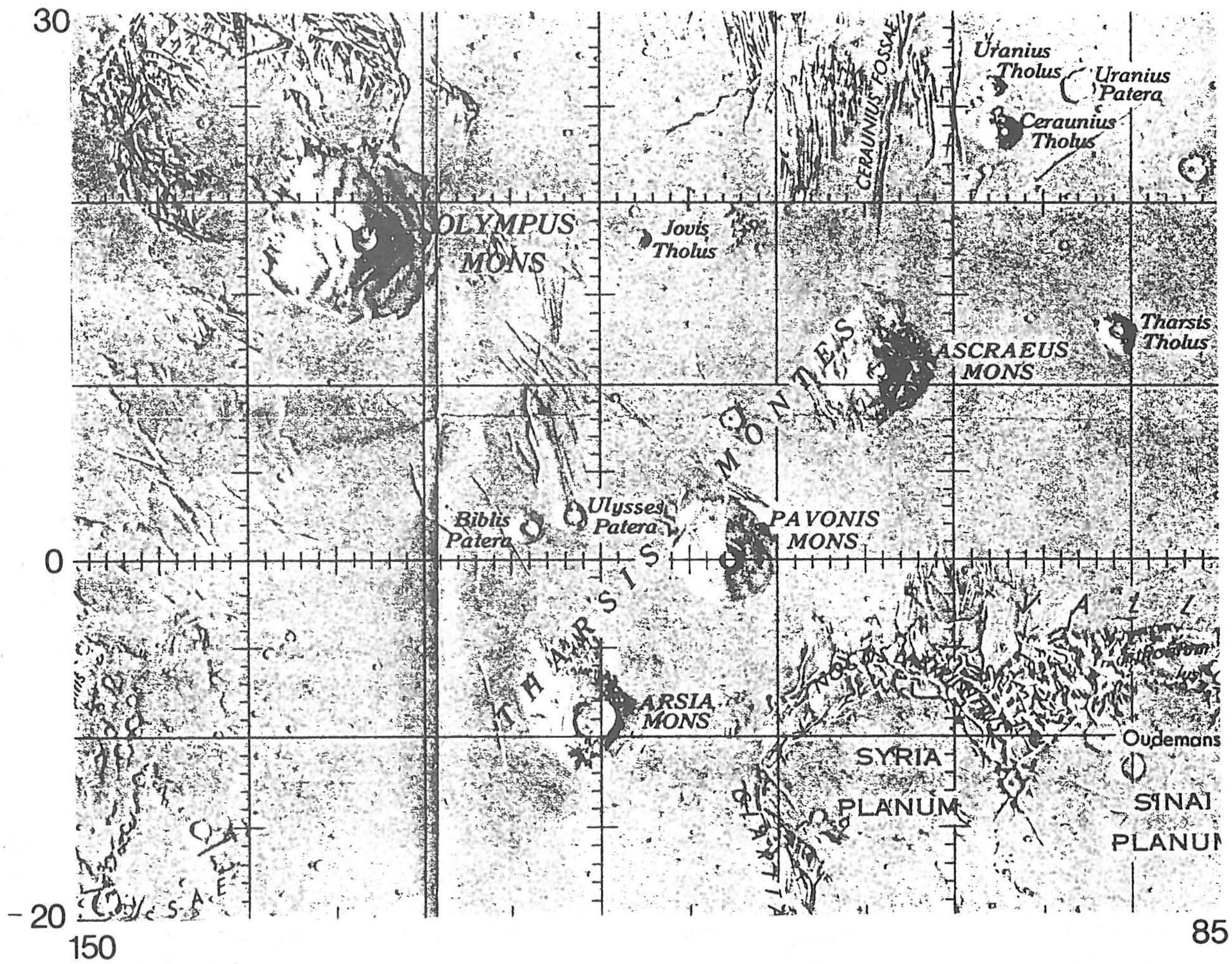
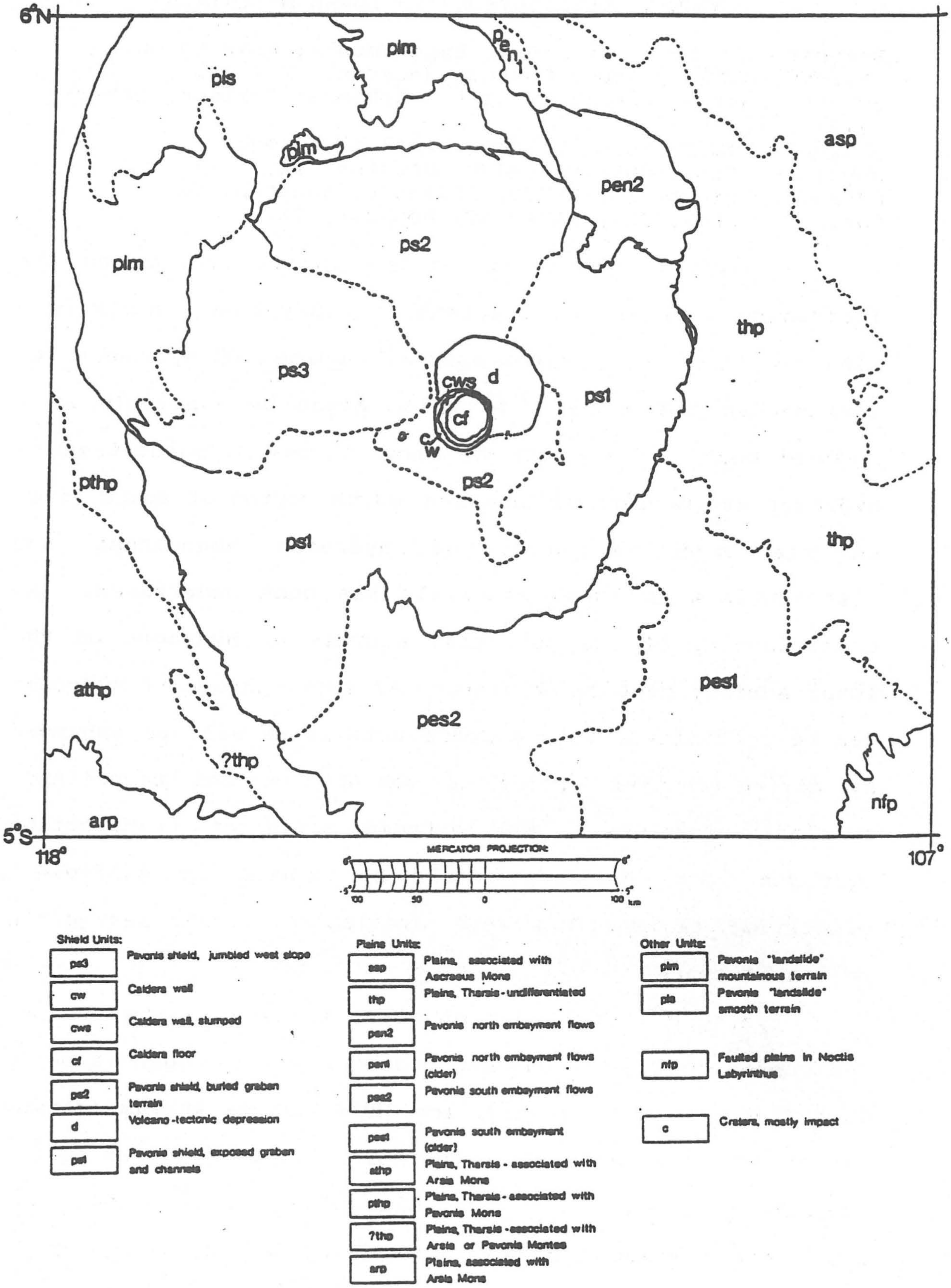
MAP 1: Tharsis Region. Pavonis Mons is at the center.



FOLLOWING PAGE: MAP 2: Geologic Units of Pavonis Mons.


6°N
5°S
118°
107°
pls
plm
plm
plm
pen1
asp
pen2
ps2
thp
ps3
cws
d
ps1
cf
c
w
ps2
pthp
ps1
thp
?
?
athp
pes1
pes2
?thp
nfp
arp
MERCATOR PROJECTION
6°
-5°
100
50
0
100 km
Shield Units:
ps3 Pavonis shield, jumbled west slope
cw Caldera wall
cws Caldera wall, slumped
cf Caldera floor
ps2 Pavonis shield, buried graben terrain
d Volcano-tectonic depression
ps1 Pavonis shield, exposed graben and channels
Plains Units:
asp Plains, associated with Ascraeus Mons
thp Plains, Tharsis-undifferentiated
pen2 Pavonis north embayment flows
pen1 Pavonis north embayment flows (older)
pes2 Pavonis south embayment flows
pes1 Pavonis south embayment (older)
athp Plains, Tharsis - associated with Arsia Mons
pthp Plains, Tharsis - associated with Pavonis Mons
?thp Plains, Tharsis - associated with Arsia or Pavonis Montes
arp Plains, associated with Arsia Mons
Other Units:
plm Pavonis "landslide" mountainous terrain
pls Pavonis "landslide" smooth terrain
nfp Faulted plains in Noctis Labyrinthus
c Craters, mostly impact

HYDROGEN DISTRIBUTIONS IN LUNAR MATERIALS

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With a commitment to the Space Station and the increasing interest in a potential lunar base, there is a need to find an extraterrestrial source of hydrogen for consumables and propellents which might be available at a reduced cost. In order to know if usable quantities of hydrogen are present in the near-earth region of space (i.e. on the moon) a study of hydrogen abundances and distributions in lunar materials has been undertaken. An understanding of the potential sources of hydrogen on the lunar surface must be obtained. If such sources of hydrogen can be identified, future space activities will be enhanced by having another source of consumibles and propellants available for use. The extreme costs of transporting hydrogen from the earth would be reduced if sufficient quantities of hydrogen were available in the near-earth region of space.

Hydrogen is the most abundant element in the cosmos. The sun is constantly burning hydrogen and hydrogen is being lost from our sun. In addition, hydrogen is streaming away from the sun in the form of the solar wind. Hydrogen is the most abundant element in the solar wind. It is known that the lunar surface has been irradiated by the solar wind.

Hydrogen has been implanted in the lunar surface through the solar wind activity. From the detailed studies of lunar materials it has been shown that selected volatile element present in the solar wind (i.e. H, He, C, N, Ne, Ar, etc) are enriched on the surfaces of the materials exposed to the solar wind. The longer the surfaces of the samples are exposed to the solar wind the greater the amounts of solar wind species trapped in the lunar materials. It is now generally accepted that the majority of the hydrogen present in lunar materials is derived from the solar wind.

Our research group has been carrying out a program of measuring hydrogen abundances and distributions in lunar soils, breccias and crystalling rocks in order to provide baseline information for the engineering models undergoing study at the present time. A microanalysis technique utilizing helium ionization equipped gas chromatography was employed for measuring hydrogen released by pyrolysis of milligram quantities of lunar soils. We have analyzed sieved size fractions from five soil samples and one regolith breccia. In addition, we have analyzed 12 breccias and 16 basalts for bulk hydrogen contents.

Hydrogen abundances measured in the five bulk soils range from 26 to 54 μgH/g, the lowest abundance found being that of a submature soil. The hydrogen abundances calculated from the mass fractions of the sieved soils are in excellent agreement with those found experimentally for the bulk samples. An Apollo 15 soil breccia was

disaggregated by freeze-thaw and ultrasonic methods into its different size fractions. Mass balance calculations for the hydrogen content of the breccia were in excellent agreement with the experimentally determined value for the bulk samples. For the five soils studied, over 80 percent of the hydrogen is found in the sub-45 micron size fraction. In the case of the soil breccia, 95 percent of the hydrogen is in the sub-45 micron size fraction. A comparison with the maturity indicator I_s/FeO and hydrogen abundance value for the Apollo 15 soil breccia shows the soil breccia is enriched in hydrogen as compared to lunar soils of similar maturity. It appears that whatever process formed the soil breccia caused it to be enriched in hydrogen. Additional hydrogen abundance measurements along with grain size information for additional lunar soil breccias is required to know precisely why the soil breccias are enriched in hydrogen.

From our studies it appears that there is sufficient hydrogen present in selected lunar materials which could be recovered to support future space activities. It is well-known that hydrogen can be removed from lunar materials by heating between 400 and 800^{o}C. Recovery of hydrogen from these regolith materials on the lunar surface would involving heating with solar mirrors and collecting the released hydrogen. In order to have a feel for the magnitude or size of the hydrogen recovery process required to recover sufficient hydrogen for space operations, the

Space Shuttle requires around 102,000 kg hydrogen for liftoff from its launch pad on earth. Extraction of hydrogen from a mature lunar soil typical of some of those at the Apollo 11 or 17 landing sites, would require processing a quantity of soil equal to that found from 28 football fields mined 10 feet deep. In comparison to mining operations found on the earth, such mining operations are considered quite small.

MARTIAN (?) CALCITE AND GYPSUM IN SHERGOTTITE EETA79001

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POSSIBLE NEW ANSWERS TO AN OLD QUESTION ABOUT MARS. Do the soils of Mars contain hidden reserves of water and the remnants of an ancient, dense atmosphere? The first tangible evidence that the answer to those questions is 'yes' was recently discovered in a meteorite that is believed to have originated on Mars. The meteorite was found to contain traces of calcite (calcium carbonate) and gypsum (calcium sulfate dihydrate), two minerals that form almost exclusively in environments containing condensed water. On Earth, calcite is the major mineral in limestones whereas gypsum is a common constituent in briny evaporites, including cap rocks on salt domes. Preliminary tests indicate that the salts in the meteorite did not form after the meteorite arrived on Earth but must have formed on the meteorite's parent planet, which is believed by some scientists to be Mars.

SALT MINERALS AS CLUES TO MARTIAN HISTORY. Although many researchers have conjectured that residues of ancient Martian atmospheres or oceans might be found as carbonate or hydrate minerals in the Martian soil, the predicted minerals have yet to be identified on Mars. The highly successful Viking missions, which landed two unmanned spacecraft on Mars in 1976, found water, sulfur, and chlorine in Martian soils but were not equipped to identify specific minerals. Consequently, this new discovery may provide the first direct revelations about the potential of Martian soils as a reservoir of water and carbon dioxide.

Although Earth's modern atmosphere contains only a fraction of one percent of carbon dioxide, tremendous amounts of carbon dioxide have been removed from circulation by formation of limestones throughout geologic history. The present Martian atmosphere is 100 times thinner than that of Earth but, if Mars experienced an Earth-like removal of carbon dioxide into storage as carbonates, then finding substantial deposits of carbonate minerals on Mars might support the hypothesis that more Earth-like atmospheric pressures existed on ancient Mars. Identification of hydrous minerals might also support speculation that free water was more abundant on ancient Mars than it is today.

CASE FOR MARTIAN ORIGIN. The meteorite at the center of the Mars story is classified as a shergottite (after the first such meteorite that fell in Shergotty, India in 1865) and was found near the Elephant Moraine in Victoria Land, Antarctica in 1979. Previous laboratory analyses at the Johnson Space Center and at the University of Minnesota showed that this meteorite, given the abbreviated name EETA79001, contains trapped gases that are nearly identical in composition to those in the Martian atmosphere, as determined by the Viking landers. The clear but controversial implication is that EETA79001 and three other shergottite meteorites (and possibly four additional meteorites of related types) are Martian rocks that were catapulted to Earth by one or more cataclysmic impacts of asteroid-like objects on the surface of Mars. Apparently, Martian atmospheric gases in EETA79001 were implanted by the shock wave of the impact during "launch" from Mars. The recently discovered grains of calcite and gypsum are associated with the partially melted areas of the meteorite that contain the highest concentrations of trapped gases, implying that the salt grains and the trapped gases formed on the same planet -- Mars. Among meteorites, calcite and gypsum have been previously known only from carbonaceous chondrites that apparently formed on wet, possibly comet-like bodies in the asteroid belt.

Discovery of coexisting calcite and gypsum grains in EETA79001 came after arduous searching of many small pieces of shock-melted glass using a scanning electron microscope. The work is tedious because numerous samples must be meticulously examined; the mineral grains of interest are few in number and are typically only a few ten-thousandths of an inch in size. Independently, an exploratory saw cut revealed haloes of calcite around shock-produced voids near the center of the meteorite. Elemental compositions of the salts were determined by an energy-dispersive X-ray spectrometer attached to the electron microscope and confirmation of calcite in the largest deposit was made by an X-ray diffraction camera. Although identification of the salt minerals is very important, their detailed analysis is limited by the rarity of the material. The proven deposits of calcite, for example, comprise less than one one-hundred-thousandth of an ounce. Nevertheless, techniques first developed by scientists during the Apollo program to analyze small amounts of lunar samples are being improved and applied to EETA79001 to maximize the harvest of possible information about Mars.

Because calcite and gypsum are common minerals on Earth and it is believed that EETA79001 landed in Antarctica at least one hundred thousand years ago, the possibility of an Antarctic origin for the salts in EETA79001 must be eliminated before their origin on Mars can be argued with certainty. The evidence accumulated to date, though, supports the pre-terrestrial origin for at least some of the salts. The interior glass samples of EETA79001 that contain the calcite and gypsum contain none of the other tell-tale products of Antarctic weathering that occur in the exterior of the meteorite. Although the relative time (and planet) of origin of the diffuse calcite haloes remains ambiguous, physical characteristics of the calcite and gypsum grains in the glass imply that the salt crystals existed prior to (and were trapped by) the shock-produced melting that accompanied "launch" of the rock from its home planet. The intimate association of salt grains with glass suggests that shock melting might have preferentially occurred in salt-rich areas of the rock and that the traces of salt are relics that survived decrepitation because the melting occurred too rapidly to be complete. Such 'disequilibrium' effects are well known to geologists and, in fact, form much of the basis for deciphering sequences of events in ancient geologic processes. Perhaps, the parent rock of EETA79001 occurred originally in a rubbly mixture of rocks and soils prior to explosive ejection from Mars, thereby accounting for the remaining traces of soil-forming materials in the meteorite.

MARTIAN GYPSUM AS A SOURCE OF WATER FOR FUTURE EXPLORERS ?

The search for additional evidence of salt and other water-bearing minerals of pre-terrestrial origin will continue for EETA79001 and other "Martian" meteorites. Such work cannot be expected to yield complete information about Martian soils but should help in planning future Martian exploration, especially missions to collect samples on Mars and return them to Earth for detailed laboratory studies. At least a few potential ramifications are already apparent.

If gypsum is an important mineral in Martian soils, as results from EETA79001 might indicate, then estimates can be made for at least one possible source of near-surface water on Mars. If all of the sulfur in Martian soils, as measured by the Viking landers, is contained in gypsum, then average surface soils on Mars would contain an equivalent of 15-16 % gypsum by weight. Because gypsum contains 21 % water that can be retrieved by heating the mineral to 400° F, appropriate baking of Martian soil might yield 1 gallon of water from every 3 cubic feet of soil (255 pounds on Earth or 96 pounds on Mars), given an energy input of approximately 9 kilowatt-hours.

Eventual manned exploration of Mars will rely heavily on advanced knowledge of the Martian surface environment -- the kind of information that can be obtained only by direct analyses of pieces of the red planet.

Meteorites from the Planets

by

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As recently as ten to fifteen years ago, meteoriticists and planetary scientists believed that the parent bodies of most meteorites were asteroids or comets. Asteroids and comets are small compared to the terrestrial planets. They are mostly less than 500 km in diameter, whereas Mercury is 4876 km in diameter, Venus is 12,100 km in diameter, Earth is 12,756 km in diameter, the Moon is 3476 km in diameter, and Mars is 6796 km in diameter. Also, compared to the terrestrial planets, asteroids and comets have undergone relatively little geologic processing. That is, they have not separated into zones of different composition through melting and remelting. Even basaltic meteorites -- rocks that resemble volcanic rocks on Earth -- were thought to come from parent bodies with simple geologic histories. For example, the most abundant basaltic meteorites (eucrites, and similar meteorites) are thought to be the products of only one major episode of melting on their parent body. Eucrites solidified from melts about 4.6 billion years ago, not long after the formation of the solar system. This means that melting on the eucrite parent body (EPB) began soon after its formation and continued only for a short time. On larger planets melting also began about 4.6 billion years ago, but continued for much longer times. We know from studies of lunar rocks that two major episodes of melting occurred on the Moon. One episode was a global event around 4.6 billion years ago. The second consisted of local melting events about 3 - 4 billion years ago. Volcanic activity has occurred on Mars more recently than the last volcanic activity on the Moon. And, of course, volcanic activity continues on Earth today. Thus, there appears to be a relationship between the size of a planetary body and the duration of volcanic activity on that body. Hence, the EPB is certainly smaller than the Moon, and probably much smaller. Studies of the light reflected from asteroids can give information about the composition of their surfaces. Such studies have shown that there is at least one asteroid (Vesta,

~400 km in diameter) that is a promising candidate for the EPB. The theory that Vesta is the eucrite parent body is now popular, though not universally believed, among planetary scientists. By analogy with eucrites, it has also been generally believed that the other groups of basaltic meteorites were derived from asteroids with geologic histories similar to that of the EPB.

In the last decade, however, the idea that all meteorites are derived from comets or asteroids has been shown to be untrue. In the late 1970's and early 1980's, meteoriticists began to realize that one group of basaltic meteorites (collectively referred to as SNC's) must have been derived from a body of larger than asteroidal size. These meteorites crystallized less than 1.3 billion years ago, which means that their parent body has been geologically active for much of the history of the solar system. Mars was proposed as the most likely candidate for the SNC parent body (SPB), based on compositional arguments. The discovery that two of the SNC meteorites contain trapped rare gases very similar in composition to those in the Martian atmosphere (as analyzed by the Viking landers) strengthened the identification of Mars as the SPB. This is now a popular, though unproven, view.

Also, in 1982 a small meteorite discovered in Antarctica by the U.S. Antarctic Meteorite Collecting Team, was quickly recognized as being more similar to lunar rocks returned to Earth by the Apollo missions, than to any other type of meteorite. Extensive study of this rock by teams of scientists all over the world has proven this meteorite to be from the Moon. It is doubtful whether such a certain identification could have been made if we had not had the Apollo samples for comparison. Subsequently, three more meteorites from the Moon have been identified in the Antarctic collections.

One of the major objections that was put forth to the idea that meteorites could be derived from Mars and the Moon was that meteor impact events energetic enough to eject rocks out of the gravity fields of large planets would leave the rocks strongly deformed or melted by the shock of the impact. However, the SNC's and the lunar meteorites are not highly shocked. Subsequently, Jay Melosh and Ann Vickery at the University of Arizona were able to dispel this objection. Their calculations showed that some of the ejected material should be relatively unshocked.

Ureilites form another group of basaltic meteorites. Until recently these meteorites have been relatively rare. In 1970 only five ureilites were known. Since then, largely due to the

Antarctic meteorite collection program, the number of ureilites has increased to about thirty. Ureilites are now the second most abundant class of basaltic meteorites, next to the eucrites and their kin. This increase in the number of ureilites has sparked a renewed interest in trying to understand how ureilites formed and how they might be related to other meteorite types. Cyrena Goodrich and John Jones at the University of Arizona have been trying to determine the overall volcanic history of the ureilite parent body (UPB) from the mineralogy and chemical composition of ureilites, and will present the results of their work at the Eighteenth Lunar and Planetary Science Conference. They think that the UPB must be large by asteroidal standards -- at least 500 km in diameter --and that it has undergone at least two major melting events, similar to the Moon. If this hypothesis is correct, "**Where is the ureilite parent body?**"-- Goodrich and Jones ask. None of the observed asteroids (which include most asteroids greater than about 50 km in diameter) appear to have surface compositions similar to ureilites. One possibility is that the UPB has been completely smashed to bits and its remains are too small to recognize as ureilitic material. Another possibility is that the surface composition of the ureilite parent body is significantly different from that of ureilites, and so scientists have not looked for the correct compositional signature among asteroidal spectra. If Goodrich and Jones are correct, the UPB may have a crust which resembles the crust of the Moon or the eucrite parent body, rather than resembling ureilites themselves.

The third and most intriguing possibility suggested by Goodrich and Jones is that ureilites might come from Venus. These authors have noticed that trapped rare gases in ureilites are very similar to those in the Venusian atmosphere (as measured by Venus atmospheric probes), which is distinct from the atmospheres of all other terrestrial planets. This observation may be significant. After all, it was the similarity of rare gases in SNC's to those in the Martian atmosphere that provided the first *concrete* evidence that SNC's are from Mars. Some other aspects of what we know about Venus are consistent with the Goodrich and Jones model for the UPB. For example, the model predicts that the UPB does not have a metallic core. Although it has not been proven that Venus does not have a core, there is no geophysical evidence that it does, unlike the other terrestrial planets. Also, Venus is large enough to have had at least two major episodes of melting. On the other hand, the compositions of the Venusian atmosphere and surface suggest that ureilites would not be chemically stable on the surface of Venus.

Goodrich and Jones hope that by presenting their ideas at the Lunar and Planetary Science Conference they will stimulate specialists in a number of fields -- among them, physicists, chemists, and geologists -- to consider the possibility that ureilites come from Venus. Jay Melosh has already begun to study the physics of getting rocks from Venus. He has shown that large meteor impacts can make a "hole" in a planet's atmosphere, so that Venus' thick atmosphere is not necessarily a problem to knocking rocks off Venus.

In summary, Goodrich and Jones think that ureilites come from a parent body of significant size, which has had a complex geologic history. We do not know if that parent body is Venus, but it is no longer unthinkable for meteorites to be derived from the terrestrial planets. This is an exciting area for continuing research. Hopefully, useful ideas about ureilites and, possibly, Venus will emerge from discussions at the Conference.

1986 DA AND 1986 EB: IRON OBJECTS IN NEAR-EARTH ORBITS - A BONANZA FOR SCIENCE AND SPACE INDUSTRIALIZATION; Jonathan Gradie, Planetary Geosciences Division, HIG, Univ. of Hawaii, Honolulu, HI 96822 and Edward F. Tedesco, Jet Propulsion Laboratory, Pasadena, CA 91109

The estimated 1500 asteroids, with diameters larger than a few hundred meters, which cross or closely approach the Earth's orbit, are divided into three orbital classes: the Aten asteroids, with semi-major axes (a measure of the size of the orbit) less than 1 astronomical unit (AU, the mean distance between the earth and the sun) and which cross the Earth's orbit near aphelia (point furthest from the sun in the asteroid's orbit); the Apollo asteroids, with semi-major axes greater than or equal to 1 AU and with perihelia (point in orbit closet to the sun) greater than 1.17 AU; and the Amor asteroids, with perihelia between 1.17 and 1.3 AU (1). Ultimately, most of these objects collide with, or are ejected from the solar system by one of the major planets in a few million to at most a few hundred million years. This time is short compared to the age (4.5 billion years) of the solar system. A significant fraction eventually collide with the Earth. We refer to asteroids in the Aten, Apollo, and Amor orbits as "near-Earth" or "earth-approaching" asteroids.

The short lifetime of these objects means that their number must be constantly replenished from an outside source. Likely sources include the main asteroid belt between Mars and Jupiter and the short-period comets population, found throughout the inner solar system, that results from gravitational and non-gravitational perturbations of long-period comets.

Near-Earth asteroids are interesting for a number of diverse reasons: they represent a group of objects from which at least some of the meteorites in our museums are derived; they may harbor extinct cometary nuclei which may contain some of the most pristine and primitive material from the beginning of the solar system; they may harbor pieces of main-belt asteroids which have been perturbed into planet-crossing orbits; they occasionally collide with the Earth, sometimes causing a disastrous mass biological extinction; and they are among the most accessible object in our solar system, some requiring less energy to reach than the Moon.

This last fact, the accessibility of the near-Earth asteroid population, makes this group of objects particularly attractive for scientific study such as sample return missions, and space industrialization, i.e., a source for easily accessible raw materials. Their potential as sources for raw materials will become increasingly important in the next century as mankind establishes a permanent presence in space. The reason for this lies in the fact that some asteroids in the main belt are known to contain, among other things, significant amounts of water, metals (such as iron and nickel), and, possibly, hydrocarbons. Hence, it is important to determine not only the compositions of the near-Earth asteroids themselves but also the source or sources of this population.

We have identified from ground-based observations two objects from the near-Earth population, 1986 DA and 1986 EB, which appear to be composed mostly, if not entirely, of iron-nickel metal. These two objects not only represent a potential source of raw materials for space industrialization but, also, provide important clues as to the origin of the near-Earth asteroid population.

IRON OBJECTS IN NEAR-EARTH ORBITS
Gradie, J. and Tedesco, E. F.

Study of the physical properties of the Earth-approaching asteroids is constrained both by the generally long time between close approaches and by their poorly known orbits. Of the 88 Aten, Apollo, and Amor class asteroids discovered through 1985 only 47 have orbital elements sufficiently reliable to permit their routine re-observation. Therefore, the timely announcement of the discovery of 1986 DA, an Amor asteroid, by M. Kizawa (IAU Circ. 4181) and of 1986 EB, an Aten asteroid, by E. Shoemaker and C. Shoemaker (IAU Circ. 4191) allowed for quick follow-up physical observations of the size (using 10 and 20 micron infrared radiometry at the NASA Infrared Telescope Facility at Mauna Kea Observatory, Hawaii) and spectral reflectance properties in the visible and near-infrared wavelengths (using spectrophotometric observations made at Kitt Peak National Observatory, Tucson, Arizona). These observations showed that these two objects, each slightly more than 2 kilometers in diameter, were most likely entirely metallic in composition. Confirming evidence of the metallic compositions of one of the objects, 1986 DA, was obtained by Dr. Steven Ostro of the Jet Propulsion Laboratory who used the Arecibo radio telescope to measure the radar reflectivity. The high radar reflectivity of 1986 DA measured by Dr. Ostro rules out anything but a metallic-rich if not entirely metallic body. The close similarity between the infrared and visible wavelength properties of 1986 DA and 1986 EB strongly suggests that 1986 EB is entirely metallic, also.

Iron meteorites are the closest analogies to these metallic asteroids. Iron meteorites, thought to have formed about 4.5 billion years ago in asteroidal bodies 100 kilometers or larger in size, are composed predominantly of iron and nickel metal. Catastrophic collisions between asteroids have broken apart some of these asteroids and fragmented their metallic cores. Subsequent gravitational perturbations by Jupiter have moved some of these metallic fragments into Earth-approaching orbits, where they can collide with the Earth. The smaller centimeter- to meter-sized fragments are called meteorites; the larger 100 meter- to kilometer-sized fragments produce craters such as Meteor Crater (one kilometer in diameter) in Arizona.

The idea that metallic (iron meteorite-like) objects in Earth-approaching orbits could have great economic value is not new. However, considerable attention has been focused on space resources in recent years. The Solar System Exploration Committee of the NASA Advisory Council's 1986 report entitled "Planetary Exploration Through the Year 2000: An Augmented Program" notes that, "Iron meteorites are actually chunks of iron-nickel alloy. They are predominantly iron (about 90% by weight), nickel (5% to 10%), and cobalt (0.6%) with trace amounts of other elements including gold and platinum group metals (0.001% to 0.01%). Such objects are potential sources of large amounts of metals. A metal asteroid one kilometer in diameter (if such a thing exists) could be worth more than $1 trillion at current market prices." Either one of these newly discovered asteroids would be worth more than $10 trillion dollars.

The economic value of these objects becomes greatest in the region near the Earth where the large space structures of the future will be built. High launch costs associated with lifting material from the surface of the Earth into space can be avoided by bringing material in from those parts of the solar system where gravitational penalties are smaller, i.e., asteroids in near-Earth orbits. However, the economic and strategic value of metals such as cobalt for use on Earth as well as in space cannot be overlooked.

IRON OBJECTS IN NEAR-EARTH ORBITS
Gradie, J. and Tedesco, E. F.

1986 DA and 1986 EB represent objects of great scientific value and curiosity. Their presence in near-Earth orbits provides us with a clue about the origin of all near-Earth asteroids, some insight into the production and delivery of iron meteorites to the surface of the Earth, and a source for speculation about the physical state of a comet nucleus.

The origin of the Aten, Apollo, and Amor asteroids has come under considerable study and considerable dispute. The total number, 1500 or so, of the near-Earth asteroids was originally explained as a by-product of the of the short period comets. Calculations showed that a sufficient number of comets were being perturbed by Jupiter into Aten-, Apollo-, and Amor-like orbits to offset the removal of these near-Earth objects by collision or ejection from the solar system. On the basis of this calculation, it was predicted that most of the Aten, Apollo, and Amor objects would be composed of whatever material composed the conjectured rocky core of a comet.

Subsequent studies of the dynamical interaction between Jupiter and the main belt asteroids have shown that about half the near-Earth asteroids should come from the main belt. Occasional collisions between main belt asteroids produce large (and small) fragments that are eventually perturbed into the inner solar system. These recent theories predict that specific regions of the belt should be more active at producing and injecting these objects into the inner solar system than other regions. In particular, those regions where the orbital period of the asteroid is related to the orbital period of Jupiter by the integer ratio (or resonance) 3:1 (at about 2.06 AU) and 5:2 (at about 2.82 AU) are predicted to be the most active. On the basis of this model we would expect the compositions of at least some near-Earth asteroids, namely those which come from the main belt, to reflect the composition of the main belt asteroids.

In principle, it should be a simple matter to compare the compositions of the near-Earth asteroid population with the compositions of the asteroids in the 3:1 and 5:2 resonance and the composition of a comet nucleus. One needs simply to ratio the number of comet-like compositions to asteroidal-like compositions to find the dynamical efficiencies at which short period comets and main belt asteroids are turned into near-Earth objects.

The compositions of the asteroids in the main belt is fairly well known, at least in a relative sense. The 3:1 and 5:2 resonances contain asteroids mostly of type C (spectrally neutral, low albedo material), type S (spectrally reddened, moderate albedo material generally with the spectral signature of the silicates pyroxene and olivine), and type M (spectrally reddened, high albedo material of either metal or metal-silicate composition). The composition of the nucleus of a comet is not well determined, but based upon the observations of comet Halley and several other short period comets, the non-volatile component of the nucleus appears to be spectrally reddened with a very low albedo, i.e., unlike asteroid types C, S, and M.

Near-Earth asteroids are difficult to observe. They are faint and are available for observation for only a few months. For this reason many are "lost", i.e., their orbits are so poorly determined that it is unlikely that they will be observed during the next close approach to the Earth. Also, the compositions are poorly determined for many near-Earth asteroids because quick reaction to discovery news is not always possible. In spite of these problems, significant progress toward observing near-Earth asteroids has been made in the last decade. We have compiled observations from a variety of observers to determine the compositional characteristics of the near-Earth asteroid population. The results show that the compositional characteristics of the near-Earth population is nearly identical to the asteroidal population in the 3:1 and 5:2 resonances, i.e., C, S, and M asteroids. Of the nearly 30 near-Earth asteroids examined, nearly all have asteroid-like, not comet-like, compositions. Various interpretations are possible. However, we feel that the most likely explanation is that the majority of the near-Earth asteroids come from the main asteroid belt, in particular, the 3:1 and the 5:2 resonances.

If the near-Earth asteroids come from the asteroid belt but there are enough short period comets to account for more than half of these asteroids, then where are those near-Earth asteroids that are extinct comet nuclei? One possibility, and the one that we favor, is the comet nucleus is so fragile that it disintegrates into "dust balls" and meteor streams without leaving behind a solid core. If this explanation is correct, then the nucleus could be thought of as chunks of non-volatile material, perhaps as large as meters in diameter, held together by a volatile or icy "glue". Once the icy glue sublimes, the non-volatile material disperses.

Models of meteorite production predict that most of the meteorites come from the asteroid belt as chunks of asteroids knocked off during occasional collisions. Some meteorites are produced from the near-Earth asteroids, the source is the same, the asteroid belt, but the orbital evolution is different. Meteorites that come directly from the asteroid belt tend to have long "cosmic-ray exposure ages", that is, they have remained as meter-sized objects exposed to solar and galactic cosmic rays for a long period. These long exposure ages indicate that evolution of the meteorite orbit from the asteroid belt to the Earth took a long time. Most iron meteorites have cosmic ray exposure ages between 100 million and a billion years. These ages have been interpreted to mean that iron meteorites spend a long time in the asteroid belt before developing Earth-approaching orbits.

The presence of two, kilometer-sized iron objects in near-Earth orbit suggests at least some of the iron meteorites that fall on the Earth should have come from a near-Earth source. These meteorites would have very short cosmic ray exposure ages, perhaps as short as a few million years. We predict about half of the iron meteorites that fall should have very short cosmic-ray exposure ages. The lack of iron meteorites with such short exposure ages remains unclear. Perhaps the answer is hidden in the large number of meteorites returned from Antarctica. Perhaps we will have to travel to and gather samples from either 1986 DA or 1986 EB to find out.

THE BETA PICTORIS CIRCUMSTELLAR DISK: A FORMING SOLAR SYSTEM?; J. Gradie and J. Hayashi, Planetary Geosciences Division, HIG, Univ. Hawaii, Honolulu, HI 96822, B. Zuckerman and H. Epps, Dept. Astronomy, UCLA, Los Angeles, CA 90024, and R. Howell, Dept. Phys. Astron., University of Wyoming, Laramie, WY 82071.

The gravitational collapse of giant molecular clouds leads to the formation of stars. Mathematical models of the hydrodynamics of this collapsing process suggest that the formation of a flattened, proto-stellar disk is a necessary stage of star formation. Given certain initial conditions of mass and angular momentum, this cloud may bifurcate, or split, to form a multiple star system. Given other initial conditions planets may accrete from the material in the proto-stellar disk. The common occurrence of binary and multiple star systems provides ample evidence that bifurcation of proto-stellar disks occurs. However, our solar system provides the only example for the accretion of planets and the formation of a planetary system.

Observational evidence for planetary systems around other stars is scarce if not altogether non-existent. Direct imaging of other planetary systems is nearly impossible with current telescopes and instrumentation. Indirect techniques which look for the slight wobble of a star's path across the sky indicative of the presence of an unseen companion, or companions, have not demonstrated fully the existence of other planetary systems. The most promising technique is to look at young, forming stars to see if the proto-stellar or circumstellar disk shows any evidence of the accretion of planet-sized objects.

Disk-like structures associated with the formation of stars are found in a variety of forms: (1) elongated structures of dimensions ranging from 1000 to 10,000 astronomical units (AU, the distance between the Earth and the sun), (2) far-infrared emission disks of dimensions ranging from 100 to 1000 AU where the infrared emission comes from cool, T = 50K, dust, (3) far infrared emission disks of cool dust identified by the Infrared Astronomical Satellite (IRAS) of dimensions ranging from 10 to 300 AU, (4) near-infrared scattering disks of dimensions $<$ 300 AU that contain a hot imbedded source, i.e., a proto-star, and (5) visible and near-infrared scattering disks of dimensions $<$ 1000 AU surrounding young main-sequence stars, e.g., the Beta Pictoris circumstellar disk.

These disk-like structures represent various stages of the proto-stellar nebula during the collapse and formation of a star. Although it is not possible to determine if the material in the disk structure is accreting into planet-sized objects, it is possible from certain observations to determine some of those physical parameters of the forming solar system which prohibit or enhance the formation of planets.

Most observations by infrared and spectroscopic techniques, although they provide the essential physical parameters of the system, do not produce direct images of the circumstellar disk. Instead the shape is inferred from the observations since most of the emitted infrared radiation comes from a region obscured by dust and gas. Circumstellar disks around young but fully formed main sequence stars were not expected until IRAS observations began to identify a significant number of stars as having long wavelength (60 to 100 microns) infrared excesses (an anomalous amount of infrared radiation that would not be expected from an otherwise normal star) indicative of clouds of cool dust. Beta Pictoris, the second brightest star in the southern constellation Pictoris (the Painter's Easel), was identified as a prime candidate for star with a possible circumstellar disk.

Looking for a cloud of dust around a star is equivalent to looking for the sun's corona during the day since the bright, direct light from the star obscures or hides the fainter light from the surrounding material. The first successful attempt to image circumstellar material was done by Bradford Smith of the University of Arizona and Richard Terrile of the Jet Propulsion Laboratory. They borrowed a technique from solar astronomers and applied the "coronagraphic technique" to image the circumstellar disk around the star Beta Pictoris. This technique, used by the authors of this report for their study of the Beta Pictoris circumstellar disk, allows the observer not only to blot out the light from the star with an occulting spot, but also to remove the excess light scattered and diffracted by the telescope structure with a device called a Lyot stop. This simple optical device developed by the French astronomer Bernard Lyot in the 1930's for the first coronagraph allows the astronomer to improve immensely the photometric contrast in the image.

Direct imaging of faint sources next to extremely bright sources becomes possible once the scattered light is removed. Contrast enhancements of 100,000 or more a few arcseconds from the star are possible. One drawback to the technique is that regions obscured by the occulting spot cannot be observed. Groundbased observations are limited by atmospheric seeing which when combined with guiding and other errors limits the the smallest size of the occulting spot to several arcseconds radius. The smaller the occulting spot the closer to the star one can observe. The Hubble Space Telescope will be able to improve greatly on this lower limit. However, observations of regions greater than several arcseconds away from the star will still be feasible, if not easier, from the ground. In any case, groundbased observations of stars suspected of having circumstellar disks will always be useful as reconnaissance for space telescope observations.

The coronagraphic technique is the most suitable technique for direct imaging circumstellar disks. By removing the direct and scattered light from the star, the light from the circumstellar disk itself can be studied. A variety of tests can be applied to study the disk. One of the simplest is to observe the disk at a variety of different wavelengths since the wavelength dependent scattering properties of the disk are determined by the particle size. If the particles that scatter light in the disk are small compared to the wavelength of light such as would be the case for molecules of gas, then the disk would scatter blue light preferentially and the disk would appear blue relative to the direct starlight. This effect, called Rayleigh scattering, causes the Earth's sky to be blue. If, on the other hand, the particles that scatter light are large compared to the wavelength of light as in the case of dust or sand grains (or larger) particles, then the disk will take on the color of the scattering particles. The actual color of the disk will depend upon the spectral and photometric properties (i.e., composition, size, and shape) of the scattering particles themselves.

Another important property of the disk that can be determined by the coronagraphic technique is the spatial distribution of scattering particles. This property, determined from the absolute intensity of the disk as a function of distance from the star, can be used to estimate the number density of particles. The number density gives an indication of the total mass of the material in the disk as well as the probability of the formation of larger particles by accretion.

The absolute intensity from the disk can be combined with the infrared emission observed by IRAS to obtain a model reflectivity of the particles. The method works as follows: the amount of light reflected is determined by the particle's reflectivity. The amount of infrared radiation emitted is determined by the the amount of light absorbed by the particle since the amount of light absorbed must be reradiated as heat. Measurements of the light scattered and the thermal radiation emitted permit us to solve, within certain limits, for the reflectivity of the particles.

The first observations of the Beta Pictoris circumstellar shell by Smith and Terrile were designed to test the feasibility of direct imaging of a circumstellar disk. Additionally, if the disk could be detected, the absolute distribution of light as a function of distance away from the star could be measured, also. Their observations not only detected and imaged the disk but identified the edge-on characteristics of the disk as well. Unfortunately, they were not able to observe the disk at several wavelengths.

These results inspired the construction of a "stellar" coronagraph for use at the University of Hawaii's 2.2 meter telescope situated at Mauna Kea Observatory, Hawaii. This coronagraph has been used in our study of the Beta Pictoris circumstellar disk, a search for circumstellar disks around other nearby stars identified by IRAS as having infrared excesses associated with circumstellar material, an on-going search for "brown dwarf companions" to late-type, low luminosity stars, and an on-going program to search for material (satellites or dust clouds) around asteroids in our solar system.

Our observations of Beta Pictoris were designed to observe the disk in a variety of wavelengths (blue or 0.45 microns, yellow or 0.55 microns and the near-infrared or 0.9 microns) and to determine spatial extent of the disk structure. The large southern declination (-51 degrees) means that this star does not get more than 20 degrees above the horizon and that the useful observing time is limited to about 60 minutes. However, careful planning of the observations in combination with the excellent atmospheric conditions at Mauna Kea Observatory allowed us to obtain images through B (blue) and I (near-infrared) filters on October 7, 1985 (UT) and through the V (yellow) filter on February 4, 1986 (UT).

We have concluded from our analysis of these images that the color of the disk is slightly redder than the light from Beta Pictoris which means the majority of the material is in the form of dust particles larger than 1 to 10 microns in size. This rules out a dominant Rayleigh, i.e., gas, component. The model dependent reflectivity of the particles was determined to be between 20% to 30%.

The reflectivity and color of the Beta Pictoris disk can be compared directly to similarly sized materials found in our own solar system, namely asteroidal material, cometary material, and the zodiacal dust. The size range implied for the circumstellar dust suggests that zodiacal dust and cometary dust are probably the best candidates. In fact, the V-I color (0.6 mag) and reflectivity (20% to 30%) of the Beta Pictoris dust is consistent with zodiacal dust.

The similarity in color between the zodiacal light dust and the Beta Pictoris dust suggests a similarity in composition. Whether this implied similarity in composition means a similarity in origin is not clear. Zodiacal dust is composed of cometary and asteroid dust created during collisions of asteroids and the sublimation of comets. However, given the young age of the Beta Pictoris system, a few million years, it is just as likely that the accretional processes which can take 10 to 100 million years to complete may still be active. Since spectrally neutral water-ice is stable at the low temperatures dominant in the observable regions of the disk, accretional processes active in this region would be producing volatile-rich, cometary material.

It is not clear whether the material in the circumstellar disk is accreting to form cometary-like objects or planets or is leftover from an accretion process occurring closer to the star. Since groundbased coronagraphic techniques cannot see extremely close to the star (due to the size of the occulting spot and atmospheric seeing), we cannot tell whether planets have formed in the innermost region of the disk. Future observations of the Beta Pictoris circumstellar shell may help answer this and other questions about the formation of planetary systems and will certainly shed new light on the processes which formed the planets, satellites, asteroids, and comets in our own solar system.

VENUS VARNISH: MODIFICATION OF THE SURFACE BY WINDBLOWN PARTICLES

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Simulations of Venus to study the interaction of sand and bedrock show that chemical and physical changes occur, even in slow-moving winds. The edges of grains become worn and shed debris which collects on bedrock surfaces. Thus, material can be transferred from loose grains to rocks (and vice-versa) which could yield misleading results on rock compositions. Moreover, the generation of such debris would enhance chemical reactions that could affect the composition of the atmosphere.

Wind erosion on Venus is a topic of speculation. Although particle-moving winds were measured by Soviet Venera spacecraft, the efficiency of wind erosion is open to question. To address this problem, the *Venus Simulator* was fabricated to run experiments using sand blown against rock targets under Venus conditions. Particle hit targets at controlled speeds and periodicity in a carbon dioxide atmosphere at temperatures up to 800 K 980°F and pressures more than 114 greater than on Earth, as appropriate for Venus. Activity is viewed through a thick quartz window. Physical and chemical changes of the grains and the target are assessed with a scanning electron microscope.

A series of tests was run in which basalt (a common lava on planetary surfaces) and olivine grains 3 mm in diameter were blown against basalt targets at speeds of about 60 cm/sec. The conditions tested are appropriate for particle motion by gentle venusian winds at elevations ranging from the mid-level plains to the summits of mountains on Venus.

Experiments were also run using the same materials with Earth conditions for comparison. Each run consisted of blowing a single grain against the target 100,000 times. The rate of impact was about twice per second. Thus, if a single particle on Venus were to move about at the same rate, the experiments would represent about 14 hours and a transport distance of about 3 km.

Despite the very low impact velocities, the edges of all the impacting grains became rounded in the experiments. The basalt targets impacted by the grains showed no apparent erosion in the experiments, although the surfaces were noticeably modified by the accretion of debris shed from the grains.

Results have implications for several aspects of venusian surface evolution. Perhaps most important is the potential effect on surface compositions. Rocks and exposed to windblown sand on Venus may be veneered with debris derived from the grains, forming a deposit similar to desert "varnish" which is common on Earth. Thus, remote sensing and other instruments that obtain measurements of surface compositions may not be assessing "bedrock" materials. Although planetologists have long been aware of similar problems arising from mantles of windblown dust settled from the atmosphere, the mechanics described here suggest that foreign material can be plastered on vertical surfaces. Thus, even measurements from surfaces that might be expected to be free of dust mantles have no guarantee against compositional mixing.

Experiment results also have implications for chemical weathering on Venus. The generation of fine debris from windblown grains greatly increases the surface area of material for exposure and reaction in the atmosphere. Thus, chemical weathering processes may be accelerated. Moreover, it has been proposed that windblown grains would "buffer" the composition of the atmosphere; the generation of fine material by impact would also enhance this process. On the other hand, rocks and surfaces that have been veneered may be partly shielded from abrasion by more energetic impacts of windblown grains and be partly protected from chemical weathering.

In conclusion, simulations of Venus show that windblown particles can produce fine debris which, in turn can be transferred to rock surfaces. Caution must be exercised in using measurements of surface compositions which may involve a mixture of "bedrock" and accretionary layers resulting from the impact of windblown material. Finally, some aspects of chemical weathering and atmospheric compositional "buffering" effects may be enhanced.

ORIGIN AND EVOLUTION OF VALLEYS ON MARTIAN VOLCANOES: THE HAWAIIAN ANALOG; V.C. Gulick and V.R. Baker, Department of Geosciences, University of Arizona, Tucson, Arizona 85721

We have used high-resolution Viking photographs to study the origin and evolution of valley and channel forms on six Martian volcanoes: Ceraunius Tholus, Hecates Tholus , Alba Patera, Apollinaris Patera, Hadriaca Patera, and Tyrrhena Patera. Several theories have been proposed for the formation of these valleys and channels including: lava, fluvial processes (surface water runoff), sapping (undermining of overlying rock and sediment by groundwater outflow), and volcanic density currents. However by evaluating the characteristics of these valleys and channels and comparing them with valley/channel features of a known origin, we have determined that most valleys on Ceraunius, Hecates, and Alba are fluvial, while valleys on Tyrrhena, Hadriaca, and Apollinaris are of mixed lava and fluvial origin. The presence of these water eroded volcano valleys has important implications for Mars' past climate and fluvial history.

Our mapping studies of Alba Patera reveal that this volcano contains the highest density (number of streams per unit area) and the best developed fluvial valleys on the surface of Mars (Figure 1). This volcano also contains the youngest water formed valleys yet detected on the planet. Most researchers believed that valley development was coincident with heavy bombardment (a time of intense asteroidal and meteoric impacts on all planets in the solar system, approximately 3.8 billion years ago), and subsequently ceased near the end of this phase. Relative age dating[1] of Martian volcanoes indicate that Alba Patera formed well after this period. Thus we conclude that fluvial valleys continued to form more recently than previously thought. The formation of fluvial valleys on Alba also has important implications for Mars' climatic history. Valleys of this nature on Earth (Figure 2) could only be formed by surface water runoff (ie. from rain) suggesting that similar processes must have existed on Mars in the past.

Similarities also exist between Martian and Hawaiian volcano valley development. Valleys initially formed on the Hawaiian islands by water flowing down the flanks of volcanoes and concentrating in low regions (i.e. fractures, folds or joints in rocks) which radiate out from the summits. Water runoff collects and concentrates in these low regions and erodes a channel. With continued erosion, surface water will downcut into the channel until the channel bottom intersects the groundwater table. At this point, groundwater outflow can contribute significantly to the erosion process by undermining channel walls, thus removing the support for overlying rocks. These rocks will eventually collapse into the channel, thereby enlarging it. This process of erosion by groundwater outflow is called "sapping", and is characterized by unusually wide valleys and theater-headed tributaries. As groundwater systems become less energetic, valley

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[1] A method used to date planetary surfaces based on the assumption that the density of craters on a given surface reflects the age of that surface.

enlargement ceases. Valleys on the western flank of the Martian volcano, Hecates, seem to have entered into and subsequently "froze" in the sapping stage. Alba Patera is much younger and apparently never reached this stage of valley evolution.

However, based on our studies of Hawaiian valleys, in order for valleys to form, water must initially be able to flow on the surface. On Hawaii island, surface water quickly soaks into the highly permeable basalt flows except in regions containing surface or near surface ash deposits. These fine-grained deposits have a permeability that is low enough to allow water to flow on the surface. Ash is also easily eroded and thus provides a favorable surface which is amenable to valley formation. Our studies of the Martian volcano valleys suggest a similar phenomenon. On Alba Patera fluvial valleys are formed in regions where lava flows are subdued. Since this volcano contains areas of prominent lava flows, regions of subdued lava features may be mantled by ash deposits. The presence of ash on some volcanoes may explain why valleys are present on these volcanoes, but not on others of the same age.

The results of this research provide significant insights into our understanding of Mars' fluvial history. The presence of fluvial (water formed) valleys on volcanoes of all ages requires that water must have existed on the surface of Mars for a prolonged period. The detection of fluvial valleys on Alba Patera implies that water was present much more recently than previously thought, perhaps extending the fluvial period of Mars by a billion years or more. Additionally, based on our studies of both Martian

and Hawaiian valley development, valley forming processes and stages in valley evolution on volcanic landscapes are remarkably similar for both Earth and Mars.

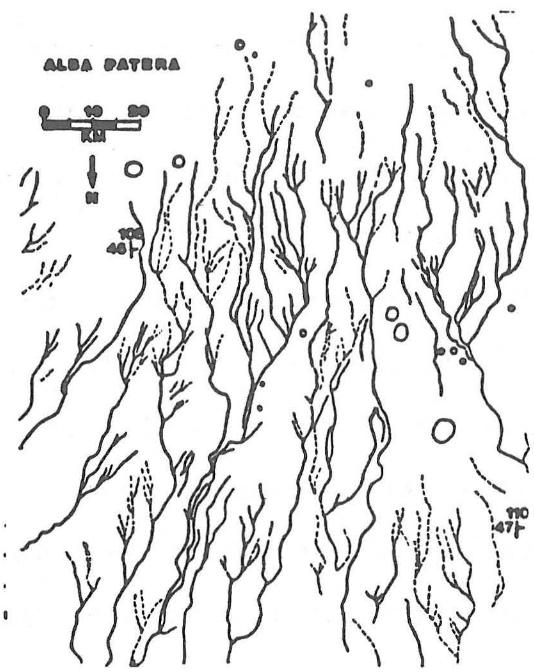

Figure 1: Map illustrating fluvial valleys on Alba Patera. Flow direction is from top to bottom. Note the similarity in valley morphologic (shape) pattern with valleys on Mauna Kea.

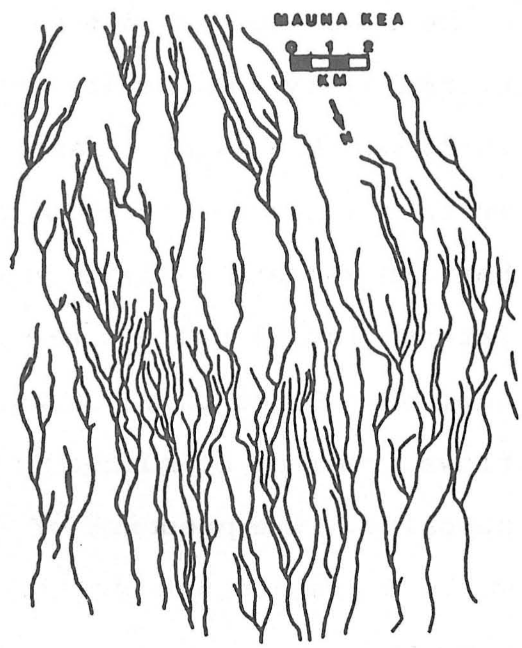

Figure 2: Map illustrating fluvial valleys on Mauna Kea, Hawaii. Flow direction is from top to bottom.

EVIDENCE FOR TOPOGRAPHIC RISES, FRACTURE ZONES, TOPOGRAPHIC SYMMETRY, CENTRAL RIFT ZONES, TRANSFORM FAULTS, AND CRUSTAL SPREADING: APHRODITE TERRA, VENUS

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Geologists at Brown University have found evidence for crustal spreading on Venus. Dr. James W. Head and Dr. Larry S. Crumpler interpret their recent analysis of radar data, collected by the Pioneer–Venus spacecraft and the Arecibo radio telescope, to indicate that the surface of Venus has been shaped by dynamic planet–wide processes similar to those of plate tectonics on the Earth.

Venus has been called Earth's sister planet because it is similar in size to the Earth and occupies a similar position in our solar system. However, early analysis of Pioneer–Venus radar data seemed to indicate that surface geology was very different on the two planets and that Venus lacked any evidence of crustal spreading or plate re–cycling. The new data and interpretations imply that Venus may be more similar to Earth than any other planet we have examined so far, and that, although it may not be an identical twin, it may indeed be accurately called "Earth's sister".

This new view of Venus has important implications for understanding the internal structure and surface evolution of the planet, but it can also help us to better understand plate tectonics on Earth. With Earth as our only example, we could not determine whether the process we call plate tectonics on the Earth is a common planetary process or an anomaly; or, if it is a common planetary process, how it begins, evolves and differs under different planetary conditions. Examining a similar process on Venus, may help us to answer many existing questions about our own planet.

According to plate tectonic theory, new material is created at spreading centers and then moves laterally for thousands of kilometers in the form of rigid plates. On Earth, mid–oceanic ridges are the spreading centers and the rigid plates carry the continents with them. As plates converge or slide past each other, mountain belts such as the Andes or Himalayas, or large fault zones such as the San Andreas in California are formed. Symmetrical patterns of magnetic stripes in the sea floor basalt on either side of the mid–oceanic ridges initially confirmed the existence of crustal spreading on Earth.

On Venus, however, we do not have magnetic profile information. The new evidence comes from analysis of the topography of a linear highland region named Aphrodite Terra, which extends for 21,000 km (13,000 miles) along the equatorial region of Venus. As revealed in Pioneer–Venus topographic maps, this highland is divided into a series of segments of roughly rectangular shape, each of which is offset from the others. Where these offsets occur, Arecibo radar data has shown a series of troughs and slopes which cut across the trend of the highland and extend several thousand kilometers into adjacent lowlands on either side of Aphrodite Terra. These troughs resemble oceanic fracture zones, or transform faults, on Earth which occur at right angles to mid–oceanic ridges where new crust is being formed and rifted apart.

Because of the continuous formation and divergence of new material, spreading ridges on Earth have a strong bilateral symmetry of topography in directions parallel to fracture zones. When the topography of the Aphrodite Terra highland is examined parallel to the linear fracture zone–like features, a very strong bilateral symmetry is apparent. In addition, many smaller topographic features are symmetrically arrayed on either side and at equal distances from Aphrodite Terra, as though they were initially formed at the ridge–like highland and rifted laterally apart during crustal spreading. A similar process is responsible on Earth for those symmetrical magnetic stripes.

The existence of fracture zones and topographic symmetry, as well as other pieces of evidence related to this highland, imply that Aphrodite Terra can be interpreted to be a spreading center where new crust is being formed at the surface of Venus.

On Earth, the rigid plates formed at spreading centers are eventually re–cycled by subduction. Although there is strong evidence for the creation and divergence of new crust at spreading centers on Venus, Earth–type subduction has not been identified. Either a different type of plate tectonics operates on Venus, possibly because of its lack of oceans, or subduction zone topography may not be visible with currently available radar imagery. However, other puzzling features on Venus may be related to the process of crustal spreading. Recent radar images of the northern latitudes of Venus by Soviet Venera radar mapper spacecraft revealed extensive areas of what appear to be belts of compressional mountains. If crustal spreading occurs in the equatorial regions of Venus, then mountain belts in the northern latitudes may result when material moving away from the equator converges near the poles and experiences compression.

The discovery of plate tectonics on the Earth revolutionized our understanding of the geology of our planet. The discovery of a similar process on another planet may revolutionize our understanding of the way planets operate and evolve as total systems.

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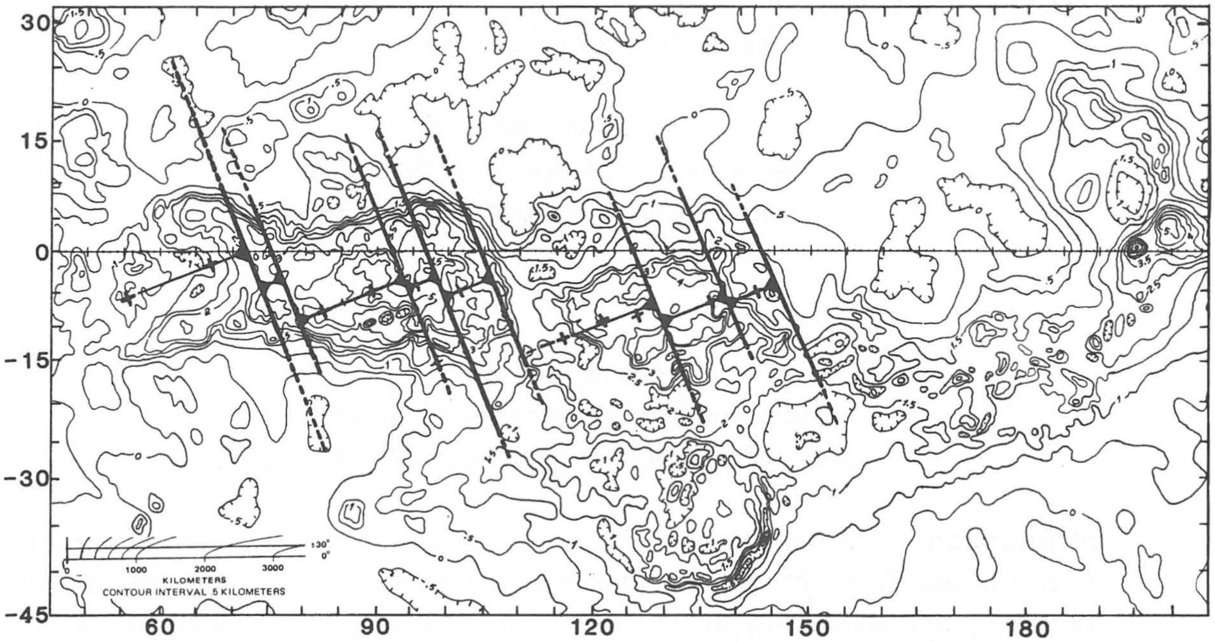
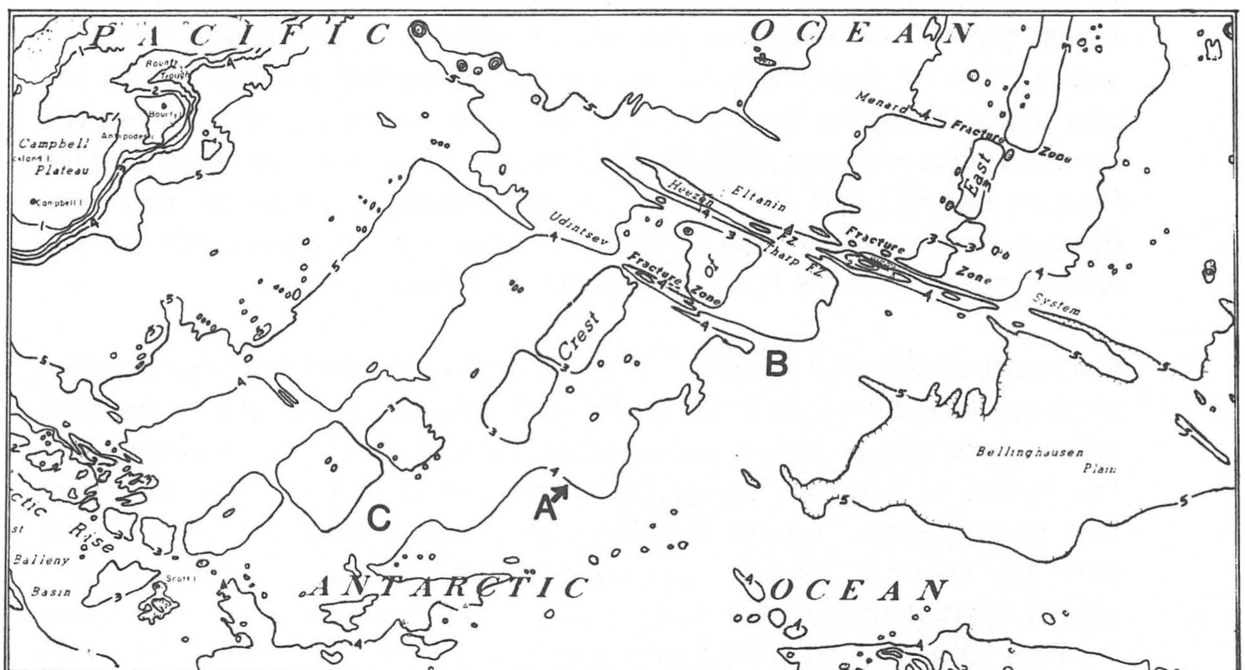
APHRODITE TERRA





TOP. Topographic contour map of the Aphrodite Terra highland area of Venus based on data returned by the Pioneer-Venus orbiter spacecraft in 1979. The heavy parallel lines mark zones on Venus which Head and Crumpler think may be analogous to ocean floor fracture zones and transform faults on the Earth. The lines drawn through crosses along the crest of Aphrodite represent zones about which Aphrodite Terra shows symmetry in topographic profiles similar to the symmetry seen across mid-oceanic spreading ridges on Earth.

BOTTOM. Topographic contour map of the Earth's ocean floor. This example is from the South Pacific mid-ocean ridge. Features analogous to the topography on Venus include linear offsets of ridge crests (A) often accompanied by trough-like fracture zones and transform faults (B) and rectangular segmentation of mid-ocean spreading ridges (C).

MAGMA MIGRATION AND HAWAIIAN–STYLE ERUPTIONS IN SHIELD VOLCANO RIFT ZONES; THE PU'U 'O'O ERUPTIVE EPISODES, KILAUEA EAST RIFT, HAWAII

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Introduction – The sequence of eruptions associated with the activity at Pu'u 'O'o, Kilauea East Rift, Hawaii, over the last several years, and the careful monitoring and analysis by the USGS Hawaiian Volcanological Observatory (1, 2) has provided important data and interpretations which permit the general assessment of the integrated process of magma ascent, lateral migration, and eruption. In this contribution we discuss the geometry of the conduit and dike systems feeding the Pu'u 'O'o vent, and the nature of the observed Hawaiian–style eruptions, including the influence of magma gas content on fire fountain heights, and the control of gas release patterns on near–vent dynamic morphology and the subsequent formation of deposits (cinder cones, spatter cones, rootless flows, lava ponds, and lava flows).

Geometry of the dike system – Analysis of the expected patterns of cooling of dikes injected into Kilauea's East Rift during the few years prior to the 1983 onset of the current activity suggest that pods of partly cooled magma with thicknesses of a few to several meters and vertical and horizontal extents of tens to hundreds of meters may have accumulated at depths of a few km along the rift zone. The major dike injection immediately prior to the episode 1 activity created another such magma body at shallow depth under what is now the Pu'u 'O'o vent. Eruptive events from episode 2 onwards are due to dikes propagating from the summit reservoir system and connecting with the near–vent body and probably some of the earlier–emplaced bodies.

Magma flow speeds in dikes (and hence eruption rates at the surface) are a function of the driving pressure gradient, the magma rheology and the dike width and cross–sectional area. However, dike geometry at the onset of an eruption is itself determined by the magnitudes of the pressure in the magma and the regional stress gradient. The geometry of various parts of the currently–active dike system can be estimated by requiring that the typical maximum mass fluxes during Pu'u 'O'o eruptions (3 to 5 x 10^5 kg/s, i.e., 100 to 200 m^3/s of dense rock equivalent) are driven by stress fields which are also consistent with the dike geometry.

Geometry of the conduit – For largely vertical magma motion through the episode 1 dike, flow speeds for a magma with viscosity 100 Pa s would typically be 0.2 m/s (below the level where significant gas exsolution occurs) through a dike about 0.5 m thick extending for 1000 m horizontally. This dike would converge upwards into a roughly 4 meter diameter conduit at shallow levels below the vent and would contain about 10^6 m^3 of magma between the surface and a depth of 2 km. At greater depths, magma flow would be largely horizontal and driven at a similar speed by a 1 to 1.5 MPa excess magma pressure in the summit reservoir through a 1.5 meter thick dike extending vertically for about 500 meters.

Magma movement – The rapidly accelerating magma discharge rate at the start of eruptive episodes, the duration of eruptions, the abrupt cessation of activity and the length of the repose period can all be understood in terms of the response of magma with a finite yield strength and a strain–rate–dependent viscosity to the stresses imposed on it. The driving stress due to summit inflation increases steadily between eruptions. The retarding stress component imposed by the yield strength increases at all times in a non–linear fashion as magma cools. The retarding component due to dike width increases between episodes as dikes are narrowed by magma chilling against the walls and may decrease locally during eruptions as some of this material is removed again; it also decreases as dikes are inflated by increasing summit pressures. These interactions can be modelled quantitatively to provide estimates of typical magma viscosity(30 to 300 Pa s) and yield strength (3 to 30 Pa) within the plumbing system.

Influence of magma gas content on fire fountain heights – Hawaiian–style volcanic activity is defined as the relatively steady discharge of magma, which is disrupted below or at the surface into a mixture of released gas and pyroclasts. The resulting fire fountains have a range of grain sizes sufficiently coarse so that little of the pyroclastic material is entrained into a convecting cloud over the vent and most of the material returns to the surface to form a variety of features in the vicinity of the vent. Theoretical treatments of the relative roles of **effusion rate** (M) and **gas content** (n) in determining fountain height predict that gas content is the dominant factor under almost all conditions, and that fountain height can be directly related to gas content if the conduit geometry is known. Gasless magmas erupted at rates typical for Pu'u 'O'o (100 m^3/s) produce fountains only centimeters high, far below the typically observed fountain height of 200 m. Theoretical predictions relating magma gas content to fountain height suggest that a 200 m fountain height corresponds to a gas content of about 0.4 wt%, very similar to values measured at Pu'u 'O'o (P. Greenland, personal communication). Confirmation of theoretical analyses by the Pu'u 'O'o observations and measurements indicates that variations in fountain heights can be used as a tool to understand the variability of magma gas content within an eruptive episode and for longer–term trends in the eruption sequence.

Control of gas release patterns on near–vent dynamic morphology and the formation of deposits – These two variables (magma gas content and effusion rate) determine the detailed structure (dynamic morphology) of the fire fountain and the nature of the near–vent pyroclastic deposits. The two main manifestations of variations in M and n are **clast size** and **fountain structure**. Although the detailed relationships between gas content and clast size are not fully understood from a physical point of view, sufficient empirical data are available for basaltic magmas. Fountain structure (dynamic morphology) is determined by the **velocity profile** at any given pressure level and the **maximum spread angle** of the fountain from the vertical. These two parameters completely determine the paths of pyroclasts in the fountain. The combination of the pyroclast size and spatial distribution determines the clast number density and thus the opacity of the fountain and the ability of the pyroclasts to cool in their local fountain environment. For a given set of conditions, two factors thus become important in determining the structure and morphology of pyroclastic deposits: **local temperature** and **accumulation rate**. For example, in typical eruptions at Pu'u 'O'o, the majority of pyroclasts remain inside the optically thick central part of the fountain, undergo minimal cooling, and return to the surface to feed lava ponds and lava flows. A very small percentage of the material occurs at the margins of the fountain, undergoes correspondingly more cooling in the optically thin part of the fountain, and returns to the surface to contribute to the building of the pyroclastic cone (if the accumulation rate is low) or to form rootless flows (if the accumulation rate is high and minimal further cooling occurs). The relationships between these various parameters are being investigated for Hawaiian–style eruptions in general, and Pu'u 'O'o in particular.

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A MODEL FOR THE FORMATION OF MAGNETIC ANOMALIES ANTIPODAL TO LUNAR IMPACT BASINS

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Background

The Moon and the Earth are the only two solar system bodies whose paleomagnetic properties have been measured in any detail. On the Earth, paleomagnetism is typically carried by minerals containing iron oxides (such as magnetite) which usually acquired magnetization by cooling in the Earth's global magnetic field. Terrestrial paleomagnetic measurements have proved to be extremely useful for such applications as determining the ancient orientations of continental blocks and proving the existence of seafloor spreading and (hence) continental drift. On the Moon, paleomagnetism is typically carried by metallic iron grains that are generated as a result of shock and heating during meteoroid impacts. Since the days of the Apollo lunar landings, several possible origins of the magnetic fields responsible for producing the magnetization have been proposed.

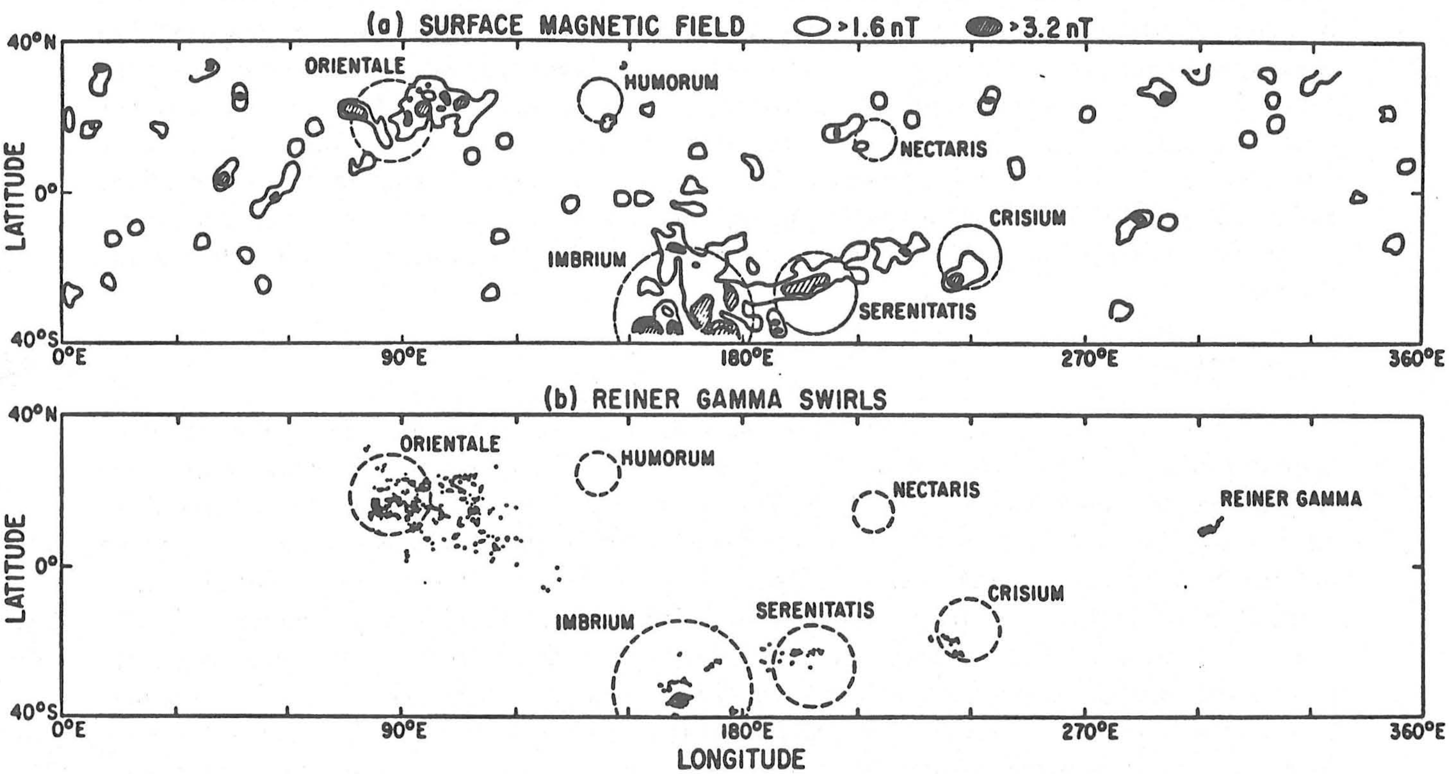
The most well-known hypothesis supposes that a former global lunar magnetic field existed, generated in a small iron core by analogy with the terrestrial case. In support of this hypothesis, sample studies have shown that some mare basalts (igneous rocks produced by magma eruptions that formed the lunar 'seas' or maria) may have acquired their magnetizations by cooling in the presence of a steady magnetic field. Also, some attempts to infer the ancient intensities of magnetizing fields from the magnetization properties of the samples suggest evidence for relatively strong magnetizing fields during a specific period of time, 3.9–3.6 billion years ago. However, other observations have pointed to the importance of impact processes in producing both the materials that are magnetized and, possibly, the magnetizing fields as well. Sample studies show that the strongest magnetizations are carried by impact-produced breccias and soils that contain more of the metallic iron remanence carriers. At least one young (less than 200 million year old) impact glass sample has been inferred to have been magnetized in a relatively strong field. It is unlikely that a global lunar field existed during this time period. Consequently, these studies have suggested that impact processes themselves may result in transient magnetic fields that could have been preserved in rapidly forming lunar materials.

Measurements of lunar crustal magnetic fields obtained by the low orbiting Apollo 15 and 16 subsatellites showed that several specific magnetic anomalies correlated with exposures of the Fra Mauro Formation (Imbrium basin ejecta) peripheral to the Imbrium basin. The strongest single anomaly detected by the subsatellite magnetometers correlated with an enigmatic swirl-like albedo marking on western Oceanus Procellarum known as Reiner Gamma. Suggested origins for Reiner Gamma include (a) residues from a recent cometary impact on the Moon; and (b) unusually strongly magnetized ray-like secondary crater ejecta. In the latter case, preservation of the relatively high albedo of the ejecta was hypothesized to be the result of deflection of the solar wind ion bombardment by the strong local magnetic field. Other strong anomalies detected by the subsatellite magnetometers were found to occur in areas where albedo markings in the same category as Reiner Gamma also occurred. One such area was the Van de Graaff-Aitken-Ingenii region on the lunar far side. Another area was located near the crater Gerasimovich on the far side.

Direct magnetometer measurements of lunar crustal magnetic fields were limited in coverage by the low inclinations of the subsatellite orbital planes to the lunar equator and by the need for nearly ideal plasma-free ambient conditions. Fortunately, it was found that other indirect methods for mapping lunar crustal magnetic anomalies existed which could be used to extend coverage with a nominal reduction in accuracy. The most successful of these was the electron reflection method in which a charged-particle detector measured the ratio of the flux of electrons returning from the lunar surface to the flux incident onto the lunar surface. The ratio increases with the strength of crustal magnetic fields which cause the electrons to 'bounce' back from the Moon by the magnetic mirror effect. Associations of local magnetic anomalies mapped via the electron reflection method have been found in several instances, notably with a graben-like feature on the lunar near side called Rima Sirsalis.

Current Work

Within the past several years, the available electron reflection measurements have been compiled by R. P. Lin and K. A. Anderson of the University of California at Berkeley to produce an approximate map of the large-scale distribution of lunar crustal magnetic anomalies (Figure 1a). This map shows at least four concentrations of anomalies for which independent measurements may be cited to corroborate their existence. For example, several concentrations occur in regions where direct magnetometer measurements showed strong anomalies. These anomaly concentrations presumably reflect corresponding magnetization concentrations in the lunar crust and have therefore been termed 'magcons'. The magcons do not generally coincide with major surface features such as impact basins, maria, etc. but occur in geologically complex regions ranging from the farside highlands to the mare-filled Ingenii basin. However, there are two geologic properties that distinguish each of these zones from the remainder of the lunar surface and therefore provide clues as to the sources of the observed anomalies. First, each zone occurs nearly antipodal (diametrically opposite) to a relatively young large impact basin in regions marked in several cases by unusual grooved and pitted terrain. The latter has been attributed by most geologists to convergence at the antipode of seismic body and surface waves produced by the basin-forming events. Similar terrain is observed antipodal to the Caloris basin on Mercury. Antipodal zones of six basins including the four youngest and largest (Orientale, Imbrium, Serenitatis, and Crisium) are indicated in Figure 1a by dashed circles centered on the respective basin antipodes. The diameter of each circle was chosen to be the same as that of the respective basin. Second, each of these zones contains swirl-like surface albedo markings of the Reiner Gamma class as shown in Figure 1b. (Figure 1b was reconstructed from a map of the distribution of swirls published by P. H. Schultz and L. J. Srnka, *Nature,* *284*, p. 22, 1980.) This result is consistent with the correlation of a single strong anomaly detected by the Apollo 16 subsatellite magnetometer with the prototypical swirl marking, Reiner Gamma.



Since the magcons represent a major fraction of the crustal magnetization detectable from lunar orbit, their interpretation may have important implications for the origin of lunar paleomagnetism. In a paper submitted to this conference, an interpretational model for the formation of the magcons is presented that considers the basin formation process, antipodal seismic modification effects, and the interaction of a thermally expanding impact-produced plasma cloud with an ambient magnetic field. The model shows that a transient concentration of magnetic flux can occur at the antipode of a basin-forming impact event as a consequence of the basin-formation process. Specifically, a high-velocity impact results in partial vaporization of target and projectile material producing a partially ionized vapor cloud at the time of the impact. As the ionized gas expands around the Moon, a weak ambient magnetic field (assumed to be supplied by the solar wind) is forced away from the impact point. The ambient field is embedded in the highly electrically conducting lunar interior and so cannot be forced away from the Moon entirely. The result is that a strong concentration of magnetic flux builds up temporarily at the basin antipode until the ionized cloud dissipates. Calculations indicate that maximum field amplification in the antipodal zone should begin after a time of about 200 seconds after a basin-forming impact and may persist for as long as a day after the impact. Estimates of the field amplification factor are as large as 300 for a circular zone at the antipode with radius 100 km (comparable in size to the magcons). For comparison, arrival times of compressional seismic waves in the antipodal zone would be about 8 minutes and the arrivals of secondary impactors from the basin-forming impact would occur during a period of 30–50 minutes after the impact. According to the model, magnetization is acquired during the period of compressed field amplification as a result of shock and heat produced by the secondary impactors and/or seismic waves in the antipodal zone.

The potential significance of the model is that it shows that much of the observed distribution of lunar crustal magnetization may be explicable as a natural consequence of impact processes. The model does not require the former existence of an intrinsic magnetic field originating in a lunar core. If no lunar field existed, then interplanetary fields could be amplified to intensities of 0.01 to 0.1 G for brief periods in the antipodal zones. (For comparison, the Earth's field near the equator is about 0.3 G.) On the other hand, the model also does not exclude the possible presence of a former global lunar field. If an intrinsic lunar field were present during the basin-forming era, then even stronger fields would be expected in the antipodal zones leading to stronger crustal magnetization there. In either case, the lack of strong anomalies antipodal to older basins is understandable as a result of later impact 'gardening' of magnetized crustal materials. The model does not directly seek to explain the nature of the Reiner Gamma swirls. However, the existence of the swirls in the antipodal zones suggests that they are a secondary product of the same processes involved in production of the magcons. A recent cometary impact origin for the swirls, as has been suggested by some workers, may therefore prove to be an unviable hypothesis. Later more detailed mapping of magnetic anomalies in these antipodal zones and their correlation with local geologic units including the swirls may further elucidate the nature of both the magcons and the swirls. The Lunar Geoscience Orbiter mission, planned for the 1990's, may provide the necessary measurements.

SUBLIMATION AND TRANSPORT OF WATER FROM THE RESIDUAL NORTH POLAR CAP ON MARS; B. M. Jakosky (Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO 80309), and R. M. Haberle (NASA/Ames Research Center, MS 245-3, Moffett Field, CA 94035).

The polar caps on Mars are an important influence on the climate of the planet due to their ability to retain volatiles and to release them into the atmosphere. Any understanding of the long-term behavior of the martian climate will, of necessity, involve a detailed understanding of the behavior of the polar caps on a seasonal timescale and on the longer timescale of the changing orbital elements of Mars. We have been investigating the seasonal behavior of water in the polar caps and in the atmosphere, with an emphasis on understanding the processes which are responsible for the observed atmospheric water vapor behavior. Once the current seasonal water cycle is understood, we may extrapolate the processes to other epochs and thereby gain an understanding of the past climate behavior.

Previous efforts at understanding the seasonal water cycle on Mars have noted the importance of the polar caps in driving the global water behavior. Much of the analysis, however, involved examining the exchange of water between the atmosphere and the global regolith, the vertical distribution of water vapor in the atmosphere and the role of atmospheric aerosols in obscuring the water from view, and the saturation state of atmospheric water and the resulting role of water-ice clouds. In the current analyses, we examine the behavior of the polar cap and atmospheric water vapor during summer, when a large amount of water appears to sublime from the residual water-ice cap into the atmosphere and to be transported away from the immediate vicinity of the pole.

We have calculated the amount of water that would sublime from the residual polar cap into the atmosphere. This calculation is based on measured polar cap surface temperatures and mild assumptions regarding the physical conditions near the surface. For reasonable assumptions, the amount of water placed into the atmosphere is about equal to the amount of water which is observed to appear at these seasons. In fact, about half of the seasonal increase of water seems to come from this source. The calculation not only confirms our previous estimates of the importance of the residual polar cap, but it also places constraints on possible additional sources of water. For example, although there has been much discussion of possible near-surface ground ice at high latitudes, the so-called "high-latitude permafrost region", there is no evidence to suggest that such surface ice is capable of exchanging with the atmosphere on a seasonal timescale. In fact, a large contribution from this source appears to be ruled out.

Observations of the seasonal cycle of atmospheric water suggest that the water sublimed into the polar atmosphere is transported globally by the atmospheric circulation. We have also calculated the role of the atmosphere in transporting water vapor away from the polar region during the summer season. These calculations were done using a previously-developed model of the circulation of the martian atmosphere. Winds computed by this model are used to track the movement of water vapor within the atmosphere, with the residual polar cap supplying water to the atmosphere, as above, and saturation and condensation within the atmosphere removing water or redistributing it as an aerosol. We find that in the absence of a significant eddy mixing, for which there is little evidence, water sublimed from the north residual cap during summer tends to remain at high latitudes throughout the summer. That is, the circulation in the vicinity of the cap lacks the required latitudinal extent to move water out of the polar region. There is a suggestion that the low-latitude circulation at this season is capable of transporting water northward into the mid-latitudes, contributing to the seasonal increase of water in the northern hemisphere. Understanding the relative roles of the polar circulation and of the low-latitude Hadley cell in driving the transport of water vapor will be a key to understanding the current water cycle.

The current analyses provide important constraints in our understanding of the seasonal cycle of water on Mars. The importance of the polar caps in driving the water behavior is reiterated. Additionally, the role of the atmospheric circulation in transporting water vapor throughout the atmosphere cannot be understated. The behavior of water on Mars is certainly much more complicated than has been previously described.

Models of the past climate on Mars depend very strongly on our understanding of the current cycle. As in the Earth sciences, the present is certainly the key to the past; our ability to understand the variations of the martian climate depend strongly on our ability to explain the present-day cycles within the atmosphere. Although we have concentrated on the cycle of water, the other atmospheric and climate-related cycles of carbon dioxide and airborne dust are equally important in driving the movement of species within the atmosphere and in driving changes in the climate. The upcoming Mars Observer mission has as one of its goals the understanding of these atmospheric cycles. Its observations will be of great importance in refining, or even drastically changing, our understanding of the current martian climate.

SINKER INDUCED TECTONICS: APPLICATION TO MIRANDA

by

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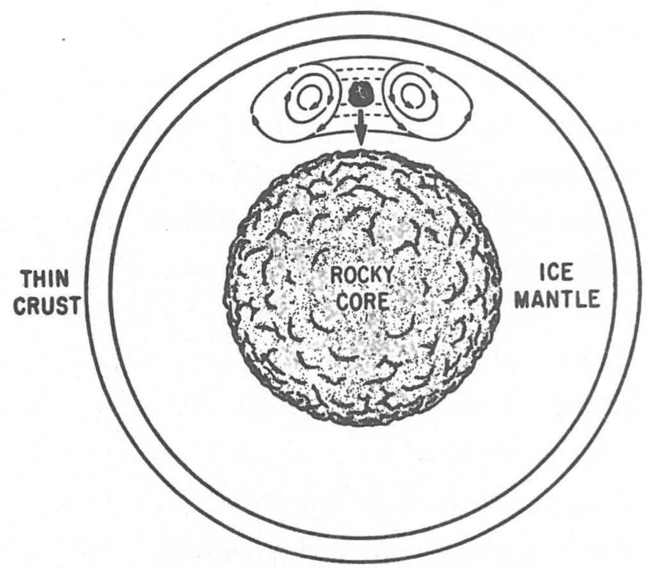
The images of Miranda returned by Voyager 2 in January, 1986 caused perhaps the greatest excitement of the encounter. Nothing quite like this small inner moon of Uranus had ever been seen before. Almost immediately in the 'instant science' of the encounter, theories were put forward to try to explain the strange ovoid and trapezoidal features that occupied large portions of the moon's surface. These areas generally consist of an approximately 100 km wide outer band of valleys and ridges, some of which have been flooded with material from below. Interior to these bands are a series of ridges and troughs which end abruptly at the outer band. One of the suggested explanations for these terrains was that Miranda had been subjected to some large impact event which broke the moon into many smaller pieces. These pieces then reformed to make a 'new' Miranda with a rocky center and icy mantle. Some of the last pieces to fall back into Miranda in this scenario would be large chunks of rock which would sink down through the mantle toward the core. In the process they would set up a flow in the ice mantle, putting stress on the surface of the moon which in turn would cause the strange semi-circular features we see today. This theory requires several things: 1) that Miranda could have been fragmented at some point in its history, 2) the stresses placed on the surface by the sinker or late rocky impactor sinking down through the mantle would produce the types of features seen, and 3) that indeed such a mechanism involving viscous flow of the ice in the mantle is possible on Miranda.

The first requirement was addressed in the 30 day report of the Voyager 2 imaging team. They found that theory predicts a large number of crater producing cometary and planetesimal impacts with the number increasing the closer the body is to Uranus. However Miranda and Ariel, the next moon out from Uranus, have many times fewer craters than expected, Ariel 5 times fewer and Miranda 14 times fewer, indicating that the surfaces of these moons are much younger than the age of the solar system. With the increasing number of impactors close in to Uranus, the likelihood of large collisions increases. For a small moon like Miranda a large collision would prove catastrophic, fragmenting the moon into many pieces. These pieces would remain in orbit around Uranus and slowly reform or reaccrete. Miranda was estimated to have been subjected to such disrupting collisions about 5 times in its history.

The purpose of the present study, performed by the author in collaboration with Dr. H. J. Melosh, is to examine the second requirement of the sinker hypotheseis: Would such a sinker produce stresses in the surface layer of the planet that resulted in the tectonic expressions we now see? We assume that Miranda had mostly reaccreted and that a late impactor has started to sink down toward the core. We then model Miranda as a spherically symmetric body with a core made of rigid silicate material surrounded by an icy mantle that is warm enough to flow viscously over geologic time scales when subjected to continuous stress, much as glacial ice flows on earth even though frozen 'solid'. The surface of Miranda is then the upper, colder portion of the ice, a thin shell that is so cold that it responds rigidly to stress, that is it cracks, breaks and buckles rather than flows.

The silicate sinker in the mantle weighs more than the volume of ice it has displaced and exerts a downward force on the mantle ice equal to its extra weight times the local gravitational acceleration. This downward force causes the ice around the sinker, and especially above and below it, to flow down toward the core. Where the mantle and core meet, the mantle material spreads out and eventually flows up toward the surface to replace the ice flowing downward behind the sinker. This produces a torus or doughnut shaped area of mantle convection around the sinker (Fig. 1).

FIG. 1



SINKER INDUCED MANTLE FLOW

The first part of the study determined mathematical expressions which allowed the use of a computer to find the shape of the flow field, the speed of the flow and the stresses in various directions resulting from this circulation in the mantle. The results indicate that the shape of the torus is determined by the sizes of the core and mantle, the shape of the sinker and where it is in the mantle. The speed of the flow depends on the force applied by the sinker and the viscosity of the mantle material while the stresses produced depend on all of these factors. This computer model can be used to calculate the stresses placed on the bottom of the outer shell of the body as the mantle flow drags along its base for different sets of conditions.

Once the force acting on the base of the outer planetary crust are known, how these forces are transmitted through the shell can be determined, in particular the resulting stresses at the surface of the planet which are responsible for the surface features there. The computer model calculates the stresses in various directions which can then be interpreted for the kinds of features they would produce (Fig. 2). The stress downward on the surface is taken to be zero so that where stresses along both lines of latitude and longitude (with respect to a 'north pole' over the sinker) are extensional (a), cracks will form which develop into a horst and graben terrain simialr to the basin and range area in the western U.S. These cracks form at right angles to the larger of the two stresses allowing the crust to spread while the area between them drops down to form a valley. Where both longitudinal and latitudinal stresses are compressional (b), thrust faulting develops as one piece of crust rides up and over another piece along a fault and the crust is shortened. These faults also form at right angles to the larger of the two stresses. Also under these compressional stresses, if the crust is thin enough or composed of thin layers, folding of the crust may occur. Where one stress is compressional; and the other extensional (c), stike-slip faulting as along the San Andreas forms which allow the crust to expand in one direction while shortening in the other. A typical set of tectonic features predicted by this model for a sinker in Miranda is shown in Fig. 3. Directly over the sinker a series of thrusts and folds form, extending radially outward. Farther out, there exists a band of strike-slip faults and finally a set a of ridges and valleys caused by extension form a ring around the sinker location. These extensional cracks in the shell would also allow a route for viscous mantle material to erupt in flows onto the surface. For there to be any surface tectonics at all in any of these bands, the stresses placed on the crust must be greater than the strength of the crustal material.

FIG. 2

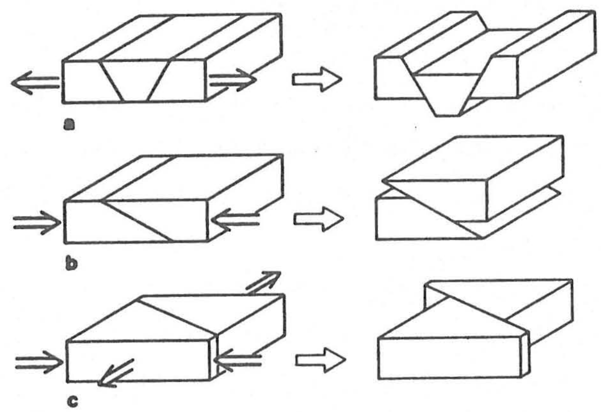
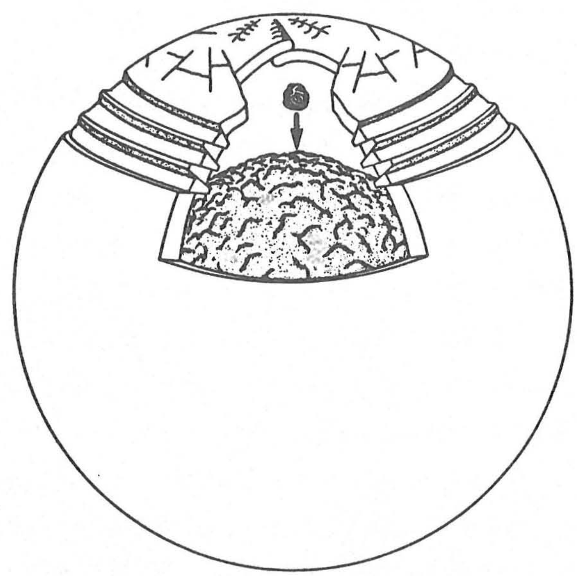


FIG. 3



CUTAWAY VIEW OF SINKER TECTONICS

These predicted tectonic features can then be compared with those actually observed on the surface of Miranda. For a body which has a core whose radius is half that of the planet and which has a thin outer shell, the model predicts that the outer band of extensional faulting will extend from 36^{o} to 55^{o} away from the sinker position. This is in good agreement with the ovoid structures on the leading and trailing hemispheres of the moon, tentatively named Arden Corona and Elsinore Corona respectively. Here the banded or ridge and trough terrains, at least for the portions that are well imaged, appear to form concentrtic rings of extensional valleys and ridges with some extrusional flows. These rings wrap around the center of the features at very nearly the distances predicted by the model.

Unfortunately, the inner portions of these features are not well known since both occur near the limb of the planet as imaged by Voyager 2. They generally consist of a set of intersecting ridges and troughs which termninate against the outer belt. These features may or may not have been caused by the strike-slip and thrust faulting predicted by the model. The trapezoidal area, Inverness Corona, while having a partial outer band similar to those of the ovoids, is much more angular and is not well predicted by this model. The results of this modeling to determine expected features predicted by the theory of sinker induced tectonics, then are at least in good general agreement with those actually seen in the two ovoid coronae.

The third requirement on the theory is that such a mechanism can occur. At its current, very cold temperature, the ice of Miranda's mantle would be too cold to flow viscously. However Robert Marcialis and Richard Greenberg of the Lunar and Planetary Laboratory have shown that if Miranda's orbit were slightly oval rather than round, and if Miranda were not spherically symmetric, then tidal forces would heat the interior of the planet to a high enough temperature for ice to be able to flow until the body settled into a circular orbit. The requirements for this warming could well be met by a reaccreting Miranda since planets generally form in oval, or elliptical, orbits and the extra mass of any sinkers at various points in the body would keep it from being symmetric.

Thus the crucial test of this hypothesis for forming Miranda's surface appears to be the ability of the theory to account for that surface in detail. The present computer model goes some way toward explaining what is seen, but needs continued work to determine how the face of Miranda would change over time as the sinkers go deeper into the planet, how the shape of the sinker affects the expected tectonic pattern and what effect a late impactor composed mostly of ice instead of rock would have.

THE NATURE OF PLANETARY CORES

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Experiments at ultrahigh pressure and temperature provide new insights into the compositions deep inside Earth and Venus. Our measurements strongly support a model in which the metallic cores of these planets consist of iron alloyed with oxygen.

For the first time, we are able to maintain iron alloys at the extreme conditions of the Earth's core: pressures exceeding 1 million atmospheres and temperatures above 3000° C (5400 degrees Fahrenheit). At these conditions we found that iron oxide becomes a liquid metal. In fact, a mixture of liquid iron and iron oxide at high pressures has properties identical with those of the Earth's core. In contrast, iron oxide is not a metal and does not mix with liquid iron at zero pressure. Therefore, the composition of the core is crucially dependent on its high pressures and temperatures.

Our experiments provide direct confirmation of a model for the Earth's core that was proposed by A.E. Ringwood, a geochemist at the Australian National University. Based on its density and other properties, it had long been known that the core is likely to be an iron-rich alloy. In 1977, Ringwood was the first to propose from cosmochemical arguments that the actual composition is of an iron-iron oxide mixture. For such a model to be valid, he had to invode a drastic change in the chemical bonding of iron oxide at high pressures. In the intervening ten years, shock-wave experiments provided some supporting evidence for such a transformation. The shock experiments were done in collaboration with T.J. Ahrens at the California Institute of Technology and with A.C. Mitchell and W.J. Nellis at the Lawrence Livermore National Laboratory.

In our new experiments high pressures are achieved by pinching a speck of sample between the points of two gem-quality diamond. By focusing a high-powered laser through the diamonds, the sample is raised to high temperature. With this technique, we have obtained the first proof that both solid and liquid iron oxide are metallic at the conditions of the Earth's core. This provides definitive support for Ringwood's model.

In addition, we have found that iron oxide melts at a surprisingly high temperature in our experiments. These results suggest that high temperatures, perhaps exceeding 4000° C (7200° F), exist in the liquid outer core of the Earth.

Because we have shown that both very high pressures and temperatures are required to combine oxygen with iron into an alloy, our conclusions pertain only to Earth and Venus. In the cores of the small terrestrial planets, such as Mars, Moon and Mercury, pressures are too low for oxygen to alloy with iron.

RECENT EVIDENCE ON THE NATURE OF THE LATE PLIOCENE IMPACT EVENT

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A major asteroid impact occurred 2.3 million years ago in the southeastern Pacific Ocean. The record of this impact event is contained in cores of deep-sea sediment that were collected two decades ago by the oceanographic vessel, the USNS Eltanin; it consists of a sedimentary horizon containing debris from the impacting extraterrestrial object. This debris was scattered over thousands of square kilometers of the southeastern Pacific. On March 16 at the Lunar and Planetary Science Conference in Houston we are presenting new data indicating that this asteroid was much larger than previously estimated. We now estimate that the minimum mass of the asteroid was 300 million tons, equivalent to a 560 meter diameter. If we assume an impact velocity of 20 kilometers per second (12.5 miles per second) the impact energy was the equivalent of 15,000 megatons of TNT, more than 100 times larger than the largest hydrogen bomb ever exploded. We have also recovered numerous small fragments of unaltered meteoritic material from the asteroid. These represent samples of the largest object ever to impact the Earth and leave recoverable samples; the second largest object was that which generated the Arizona Meteor Crater and left behind iron meteorites.

We first reported the discovery of this impact event six years ago in a paper in Nature by Kyte, Zhou and Wasson (1981). We found anomalously high concentrations of the noble metals iridium (Ir) and gold (Au) in piston core E13-3. This core sampled sediments at 57 S and 90 W in a region called the

Antarctic-Pacific Basin. We also discovered sand-sized particles in this sedimentary layer that were Ir-rich and we proposed that these were debris from the impacting asteroid.

This discovery was only one year after reports of high concentrations of Ir in sediments deposited at the Cretaceous-Tertiary boundary 65 million years ago. The Cretaceous-Tertiary boundary marks one of the greatest mass extinctions in the Earth's history, and these discoveries had sparked a major scientific debate that continues today: did the accretion of a comet or asteroid cause the mass extinctions (including the demise of the dinosaurs) at the end of the Cretaceous?

Our Pliocene anomaly was the first report of an Ir-rich sediment horizon other than at the Cretaceous-Tertiary boundary. The discovery provided important evidence that impacts were capable of producing Ir-rich sediments such as those found world-wide at the Cretaceous-Tertiary boundary. In a subsequent study, Kyte and Brownlee (1985) described the Ir-rich impact debris from this horizon. They found that most of the debris was millimeter-sized impact melt, probably formed when an asteroid impacted the ocean. They also reported that they had found similar particles in E13-4, another piston core, obtained 120 km southwest of the initial discovery, although the latter particles were much smaller and less common than at E13-3. However, the most important finding was that a small fraction of the impact debris consisted of unmelted meteoritic fragments. This proved unequivocably that the Ir-rich horizon had been produced by an asteroid impact.

The data indicate that the asteroid impacted the ocean which is about 5 km deep at this locality. In the analyses of the impact melt debris we have found no evidence of contamination of the asteroidal material with material from the ocean floor. The chemical composition of the impact melt debris is best understood as asteroidal material and products produced by its interaction with sea salt. It does not appear that the asteroid was large enough to excavate a crater on the ocean floor.

We are currently studying additional cores in order to further characterize this event. We have determined a large suite of elements at the second locality, E13-4 and are analyzing four additional piston cores for Ir in order to extend our coverage of the event to a radius of 500 km.

The major thrust of our latest analyses has been to characterize the impact debris and bulk sediment of the Ir-rich horizon in E13-4. We found that Kyte and Brownlee (1985) missed the peak concentration of the debris in this section because they relied on magnetically determined ages that were incorrect. The particles they found were probably scattered, reworked sediment about 0.7 meters above the actual impact horizon. It appears that there is at least 100 times more impact debris at this locality than previously expected.

The extraterrestrial debris deposited at site E13-4 origi nally consisted of a layer of particles about 1 centimeter thick. This compares to the deposit 120 km away at site E13-3 which was probably about 3 millimeters thick. These thicknesses of aste roidal material are much higher than those at Cretaceous-Tertiary boundary sites, but they seemed to be confined to the South Pacific in contrast to the world-wide distribution of the material accreted at the end of the Cretaceous. We estimate that the total amount of impact debris in the area must be at least 300 million tons. This is a conservative estimate; and the mass of the asteroid could be 10 times greater. Even this low estimate leads to a minimum asteroid diameter of 560 meters.

These results have several interesting implications for both meteorite researchers and terrestrial geologists. The meteorite researchers will benefit from description of the unmelted meteoritic debris. Although they are only millimeter-sized particles, the unmelted meteoritic debris is derived from a meteoroid whose linear dimensions are 10 times greater than those of the largest meteoroid of which samples are available for study. The next largest meteoroid was the largely metallic object with a 50-100 m diameter that made the Arizona Meteor Crater. Terrestrial geologists interested in impact phenomena are presented with a unique natural laboratory in which debris from the only known deep-ocean impact is spread over thousands of square kilometers of ocean floor. This event may also be of interest to geologists who seek to understand the relationships between impacts and environmental changes. Although this impact did not generate world-wide mass extinctions as occurred at the end of the Cretaceous, it certainly had a devastating effect on the local ecology, and it is possible that it had a global environmental effect. As of now there is no direct evidence for a direct relationship between this impact and any environmental change, but this is an important area for future research. One exciting possibility is that it triggered the onset of extensive northern hemisphere glaciation. There is evidence that the Earth's climate changed dramatically about 2.2-2.5 million years ago, resulting in what we now refer to as the Ice Ages. (1) Kyte, F.T., Zhou, Z. and Wasson, J.T. (1981) Nature **292**, 417-420. (2) Kyte, F.T. and Brownlee, D.E. (1985) Geochim. Cosmochim. Acta **49**, 1095-1108.

OBSERVATIONS OF INDUSTRIAL SULFUR FLOWS: IMPLICATIONS FOR IO

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During the Voyager 1 flyby of Jupiter in March 1979, one of the most exciting discoveries was the existence of active volcanoes on the innermost of the Galilean satellites, Io. Although much attention has been focused on the spectacular eruptive plumes, equally important to the evolution of Io's surface are the widespread lava flows evident in Voyager's images. Considerable controversy has arisen as to the composition of these flows; while some evidence suggests that they are silicate flows comparable to those seen on the inner planets, other equally convincing lines of evidence suggest that they may consist of sulfur.

While much is known about silicate flows, natural sulfur flows are extremely rare on Earth, having been found in fewer than a half dozen locations (only one has been observed while active). Interpretations of existing data concerning the possibility of Ionian sulfur flows are hampered by poor knowledge of the thermal and flow behavior of sulfur, especially under the conditions present on Io. Recent observations of large-scale industrial sulfur flows on Earth, generated as part of commercial sulfur-mining activities, may provide valuable information concerning natural sulfur flows on both Earth and Io.

Our studies are of sulfur mined by the Frasch process; wells are drilled into sulfur-rich limestone or salt domes and 165°C water is injected, melting the sulfur and allowing it to be pumped to the surface. The molten sulfur is transported to "sulfur terminals", where it is either shipped out as a liquid or poured onto huge cooling vats (about 100 meters on a side) and allowed to solidify. During a typical "vatting", about 500 metric tons (approximately 250,000 liters) of liquid sulfur at 130°C floods the surface of the vat to a depth of 6 to 10 centimeters; individual flows spread as extremely complex, thin (about 1 centimeter), multiple flow units.

Observations of these commercial flows provide insight into the complex nature of sulfur flows in general and have important implications for how such flows may operate on Io, if indeed they exist there. In particular, it is found that flexible crusts develop very rapidly and are rafted along by the flows; as the flows cool, crusts form over much of the surface. The crusts deform easily as molten sulfur continues to flow beneath. Such behavior is in contrast to theoretical predictions: solid sulfur is denser than liquid, so it has been suggested that crusts would tend to break up and sink into the melt, allowing rapid cooling of the liquid and effectively limiting the size of flows. With insulating properties similar to asbestos, solid sulfur would provide a very effective heat-retaining mechanism on crusted flows, potentially allowing the flows to continue for long periods of time before being halted by complete solidification of the underlying molten sulfur. While an explanation for the formation and stability of crusts has not been determined, the rapid formation of crusts on the industrial flows lends support to the idea that sulfur flows on Io could extend over large distances (flows several hundred kilometers long are seen in Voyager images). If these flows are indeed composed of sulfur, such crustal insulation would be essential.

The correlation between the color and temperature of sulfur is another property which has been used in interpreting images of Io. Although typically a yellow solid at room temperature, previous studies have indicated that liquid sulfur should be yellow to orange below about 160°C, whereas a dark reddish-brown to black color is representative of much higher temperatures (greater than about 180°C). During our measurements of active flows, temperatures of about 110°C were recorded for dark reddish-brown liquid sulfur, much cooler than would be expected. Coloration also appeared to vary with the lighting and viewing geometry. These apparent temperature and illumination inconsistencies will require further investigation and could be extremely important when considering Io; color transitions along flows have been cited as one of the lines of evidence for the existence of sulfur flows on that body.

These observations of industrial sulfur flows have provided important insights into the flow properties of molten sulfur. Continued studies will allow a more complete understanding of natural sulfur flows so that the possibility of their existence on Io can be examined from a more informed perspective.

INTERSTELLAR DIAMONDS IN METEORITES

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Interstellar diamonds, more ancient than the solar system, have been found in 3 primitive meteorites. These diamonds contain exotic xenon and nitrogen and hence themselves must be exotic. They are very small and probably formed on cooling of hot gases expelled by a star, much like a process discovered in the lab in 1962. What tales they may tell if once we learn to read them.

Scientists have come to realize in the last 18 years that primitive meteorites contain small amounts of exotic material from outside the solar system. This material can be recognized by its anomalous isotopic composition. One such component is xenon - HL. As xenon is a gas, it must be contained in a solid "carrier" which obviously must itself be exotic. Starting in 1975 Lewis and other scientists have shown this carrier to be some form of carbon and constituting less than 0.03% of the meteorite. This same small fraction also contains anomalous nitrogen, further proof of an exotic origin.

Lewis and his coauthors have now succeeded in separating the actual anomalous xenon carrier from the rest of the meteorite, including most of the carbon, in sufficient purity to allow its identification. It consists of very small, 50Å, diamonds along with some kind of amorphous carbon. The final stage of the separation is quite dramatic, as the black sample suddenly turns white. The diamonds have been identified in several ways: electron microscopy, analytical electron microscopy, electron diffraction, x-ray diffraction, chemical resistance, and visual appearance.

It was a complete surprise that diamonds are the carrier of the anomalous xenon. Diamonds of another kind had previously been found in some rare meteorites. They were made in high speed collisions (either in space or on Earth) when shock pressures briefly reached greater than 100,000 atmospheres, converting some graphite into diamond. The present meteorites were never involved in such violent collisions. Nor do they show evidence for high static pressure, such as is involved in the formation of common terrestrial diamonds deep within the Earth. Some new mode of formation must be involved.

As the isotopic evidence for a presolar origin seems compelling, these diamonds most likely condensed in the gas shell ejected by a star, collecting the nuclei synthesized by that star. On first thought, such an origin for diamonds seems unlikely. The formation conditions, moderately high temperature and low pressure, are far from the high pressure conditions in which diamonds are the stable form of carbon. Recently, however, Japanese and Russian workers, e.g. as reported by Robinson in Science (234, pp.1074-1076, 1986), have demonstrated the metastable growth of diamonds at low pressures in conditions something like those in gas shells expelled by stars. Evidently, what man can accomplish, nature has done before. Nature's products may not be as useful, but they may be more interesting.

These diamonds may be the oldest particles we have, predating the Earth and every other thing formed in the solar system. It is known that old stars (red giants) shed gas shells, which on cooling yield dust grains. The present work suggests that at least in some cases the dust includes diamonds. Later, when the star explodes as a supernova, atoms are ejected at high speed and are buried within the dust grains when they overtake them. There is evidence that a massive supernova exploded near the forming solar system and contributed material to it. Perhaps the diamonds came from the same supernova. Now we can directly analyze such stardust, which must carry as a record of its formation the whole periodic table of the elements. While such analysis may be exceedingly difficult, with many elements too rare to be measured, this may be a unique opportunity to analyze in detail the products of a supernova. If these diamonds have been altered in some recognizeable manner in their subsequent history, then this material may be truly extraordinary, teaching us about both the death of a star and also about the birth of our solar system.

ISOTOPIC ANOMALIES IN METEORITES: NICKEL ISOTOPES IN ALLENDE;

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Until about 1973 astrophysicists and cosmochemists were of the opinion that all chemical elements, that are not affected by radioactive decay or irradiation by high energy particles from cosmic rays, are exactly the same isotopically throughout our solar system. In other words, if any chemical element, such as for example, Calcium, were extracted from a rock collected on Earth, the Moon, Mars or on an Asteroid and analyzed for its isotopic composition, it was expected to show exactly the same relative abundance of its isotopes, regardless of the source of the sample. Isotopes, of course, are atoms of a particular chemical element with slightly different atomic weights. The difference in atomic weight is due to small differences in the number of neutrons within the nucleus of the atom. The nucleus of a Calcium atom, for example, is characterized by containing 20 protons. But there exist 6 stable (i.e. non-radioactive) isotopes of Calcium with atomic weights ranging from 40 to 48. This, therefore, indicates that the lightest of the Calcium isotopes contains 20 neutrons (in addition to the 20 protons) in the atomic nucleus whereas the nucleus of the heaviest isotope consists of 28 neutrons plus its 20 characteristic protons. Returning to our previous subject, this isotopic homogeneity was thought to be the result of thorough mixing of all matter within a hot solar nebula, a short time (several million years) before planetary bodies started to form, some 4.6 billion years ago. All available evidence from accessible solar system bodies, such as the Earth, the Moon and the presumably most unaltered objects since the formation of the solar system, the parent bodies of meteorites, suggested that this mixing process was efficient enough to erase all differences in isotopic compositions which may have existed in the condensing solar nebula in matter produced by various nucleosynthetic processes (generating the chemical elements) in different stars in our galaxy. Without accessible evidence it was difficult to test hypotheses put forward by astrophysicists on the synthesis of the chemical elements and their isotopes in stars.

Some isotopes of various elements are formed in stars called "Red Giants". Other isotopes of an element, particularly those with the highest number of neutrons (such as Calcium-48) are believed to be produced in stars about 10 to 100 times as massive as our sun. Within these stars the temperature (on the order of a billion degrees) changes as one proceeds towards the center of the star. Different nuclear reactions occur in each temperature zone, which can be pictured as concentric shells such as the shells of an onion, producing dramatically varying isotopic signatures of the chemical elements. Towards the end of the lifetime of such a star, when all the nuclear fuel in its interior has been exhausted, the central part of the star collapses and forms a neutron star. The outer parts of the star will rebound and expel the freshly synthesized matter. This is what is called a "Supernova explosion". The expelled material is dispersed into interstellar space. Some of this material will contribute to a freshly condensing cloud of matter which eventually will collapse to form another star such as our sun and its planets.

The first evidence for the existence of some isotopic inhomogeneity,albeit small, was discovered in the early seventies. Initially it was demonstrated that Oxygen extracted from certain inclusions in a meteorite showed excesses in its lightest isotope when compared to, for example, the isotopic composition of Oxygen from sea water. Due to refinements in experimental techniques, inspired by the Lunar Program, this discovery was soon followed by others in elements such as Magnesium and Calcium, both major elements in rock forming minerals. However, these isotopic anomalies were confined primarily to a group of unusual objects (inclusions) found in a meteorite called Pueblito de Allende. This meteorite is a member of the rare group of carbonaceous chondrites, a class of meteorites which had undergone very little change since formation from the cloud of gas and dust which formed the sun and planets. Furthermore, the millimeter to centimeter sized inclusions within this meteorite have very old ages (around 4.55 billion years) and, from their chemical and mineralogical compositions, seem to have formed at high temperatures, and were among the first relatively large solid objects to condense in our solar system.

Since the late seventies isotopic anomalies have been found for many elements in these inclusions. It has been shown that anomalies are quite common in Oxygen, Magnesium, Calcium, Titanium, and Chromium. They are very rare in Strontium, Barium, and the Rare Earth elements Samarium and Neodymium. The most common isotopic anomalies are confined to the heaviest isotope (richest in neutrons) of a particular element. Their relative magnitudes are generally on the order of 0.1% or less when compared to the isotopic pattern of an element extracted from terrestrial material. In other words, the relative proportion of what may be called "exotic" material which still can be recognized with modern measuring techniques is very small. Therefore, the matter which formed these primitive objects in which we find the anomalies must have undergone already sufficient mixing to dilute the individual "stellar signatures" to almost beyond recognition.

Still, the small effects found had a large impact on the astrophysical community - now it was possible to test many important aspects of nucleosynthetic theory, to refine models and attempt to make these consistent with direct experimental evidence. In general, it can be stated that predictions and actual findings were in remarkable agreement. However, there still exist many open questions. One of these unsolved problems was the lack of isotopic anomalies in the element Nickel which were predicted by theory to be present in similar proportions as those found in, say, Calcium or Titanium. In addition, a neutron rich short lived radioactive isotope of Iron with atomic mass 60 (^{60}Fe) would decay to Nickel-60 if it indeed was produced together with the other "exotic" isotopes. If evidence for the existence of ^{60}Fe in the early solar system would be found this could have important implications for the formation of the planets and planetary cores. Because of the short lifetime of this isotope (a few million years) its radioactive decay would free a large amount of energy within a short period of time. If this isotope were present in sufficient amounts and still "alive" after it was incorporated into planetary bodies together with the non-radioactive Iron isotopes it potentially could contribute a large proportion of the heat required for rapid melting of a whole planet and the resulting formation of an Iron core.

Previous efforts to measure Nickel isotopes in the same samples where other anomalies were found all gave negative results, albeit at relatively lower resolution. In a new attempt to solve this problem Birck, Prombo and Lugmair have refined the measuring techniques for Nickel 3 to 5 fold over previous conditions. At this level of precision it now was possible to resolve, at least in some samples, isotopic anomalies in the most neutron rich isotope of Nickel. In addition, on one sample, a small (0.01%) excess on ^{60}Ni, the potential decay product from ^{60}Fe, was found. This small excess, although considered to be real, is not yet sufficient to prove the existence of ^{60}Fe in the early solar system and needs further corroborating evidence from future measurements.

NICKEL ISOTOPES IN ALLENDE

Lugmair, G.W. and Prombo, C.A.

The magnitude of the excess on the neutron rich Nickel isotope, ^{64}Ni, is about three times lower than that observed in elements with slightly lower atomic weight, such as Chromium, Titanium or Calcium. This is the reason why these anomalies escaped detection in previous, lower precision measurements. However, some model calculations of isotope production in supernova stars predict similar enrichments in the heavy isotopes of these elements. If these calculations are correct and these nuclei are produced in similar amounts then one would have to find different, perhaps more mundane explanations for their smaller magnitudes. Chemical or physical processes in the early solar system environment, where the individual stellar components were homogenized, may have affected Nickel differently from the elements listed above. Indeed, the chemical and physical properties of Nickel are very different from those of the comparison elements - Nickel, a so-called siderophile element, is more volatile and shows a much greater affinity for molten Iron than for Oxygen. This different behavior may well have diluted the original relative enrichment to the level we observe today. Still, this somewhat <u>ad hoc</u>, though plausible explanation may not be necessary. A recent calculation, more sophisticated than previous models and extending those, invokes the mixing of different nucleosynthetic zones in supernovae. By this process an excess in Nickel-64 two to three times lower than that in the neutron rich isotopes of Calcium, Titanium and Chromium is predicted, in remarkable agreement with our new results.

TOPOGRAPHY BURIED BENEATH THE PLAINS OF UTOPIA AND ELYSIUM, MARS

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Even a casual glance at either a geologic or a physiographic map of Mars is adequate to demonstrate that the planet is divided into two unequal parts. About two-thirds of Mars makes up what we call the "southern cratered highlands"; it stands relatively high, and its surface is generally heavily cratered. The abundance of craters, and especially of large craters, leads to the inference that the surface of the southern cratered highlands is very old. This inference is based on a comparison with the lunar surface, where generally similar heavily cratered surfaces are about 4 billion years old or older. The remaining third of Mars is the "northern lowland plains", an area averaging 1-2 miles lower in elevation than the southern highlands. The surface of the northern plains is much less heavily cratered than that of the southern highlands, and thus is believed to be much younger. In most places, the boundary between the southern highlands and the northern lowlands is abrupt, and commonly this boundary is a complex scarp. Near the boundary, disrupted and eroded remnants of the older highland crust may be seen protruding through the younger plains materials.

The two-fold division visible on the surface must relate to a fundamental dichotomy in the crustal structure of Mars. This dichotomy is equivalent in importance to the continental crust vs. oceanic crust dichotomy on Earth, where the separation into two types of crust is maintained by plate tectonics. There is no evidence to suggest that similar processes are active on Mars; consequently, determining the origin of the martian crustal dichotomy is one of the major first-order problems of martian history that must be addressed by geologists and geophysicists.

Previous geological studies suggest that the martian crustal dichotomy is very old, at least as old as the end of the early heavy bombardment phase of solar system history, and most likely even older. This places the formative event(s) in the first 500 million years or so of the planet's history; that is, more than 4 billion years ago. Two theories have been proposed to explain the crustal dichotomy: 1) excavation of the northern lowland by a giant impact creating a basin 7,700 km in diameter, or 2) thinning and subsidence of the crust by large-scale convective overturn in the mantle, possibly associated with core formation.

Because of continued heavy bombardment by meteorites, diagnostic smaller-scale landforms that may have been created by the process or processes responsible for the dichotomy have been destroyed. Thus less direct methods must be applied. We are attacking the problem with studies that derive their logical bases from geological experience on Earth -- the history of a region is determined in stages, starting with the most recent events and materials and working backward. In effect, we are attempting to "see through" younger events to the record of older events.

There is abundant evidence that the older highland crust was physically disrupted in and near the northern lowlands of Mars. Highland crust exposed immediately to the south of the highland/lowland boundary is severely faulted and fractured, so much so that many of the crater forms are partially or completely obliterated. Furthermore, the degree of fracturing increases northward towards the boundary, suggesting that the old crust is even more fractured in the area now buried beneath northern plains materials than it is just south of the dichotomy boundary. This observation is consistent with both of the published theories proposed to explain the crustal dichotomy, but only if the observed severe fracturing can be shown to have formed all at once and to be very ancient. But our work suggests that fracturing and associated erosion of highland crust was not a single event, and some of it appears to be relatively young by martian standards. This result does not disprove either a giant impact or mantle convective overturn during the first few hundred million years of martian history, but it does indicate that such violent, one-time events cannot fully account for the observed disruption of the highland crust; that is, the history of the martian dichotomy is almost certainly much more complex than we thought.

The specific objectives of the study summarized by the abstract carrying the above title are to trace the old highland crust northward beneath the younger plains materials, and to describe the topography of the buried highland surface. These are important objectives because they will tell us what the surface of the northern lowland looked like before it was buried, and will provide geological limits or constraints on hypothetical events proposed to explain the northern lowland/southern highland dichotomy. The depth of burial of the old surface may be estimated qualitatively by mapping the distribution of small landforms termed "knobs" and "mesas". These are small hills (up to a few miles across) found throughout much of the northern lowlands.

Near the boundary between southern highlands and northern lowlands it is clear that knobs and mesas represent erosional remnants of the southern highlands. In places, knobs are abundant enough to define the ghosts of highland craters. In other places, the northern edge of the southern highlands is fractured into a labyrinth of troughs with intervening flat-topped remnants of highland surface (fretted terrane); as the troughs become larger and the intervening highland remnants become smaller, this topography grades into northern plains with scattered mesas.

If knobs and mesas represent small erosional remnants of highland crust, then where they are present far to the north the old highland surface must be buried only to a shallow depth; where they are absent, the old highland surface is presumably more deeply buried. The map (Fig. 1) showing where knobs and mesas are present and where they are absent provides an indirect look at the third dimension; if the younger plains deposits that partially fill the northern lowlands could be stripped away, the exposed surface would be high in those areas where knobs and mesas are present, low where they are absent.

Figure 1 is approximately centered on a large, curved area where knobs and mesas are present in the northern lowland. The implied buried topography is a large, curved massif concentric to the adjacent highland/lowland boundary to the south, but separated from it by a curved depression. Most likely, the massif is a segment of one of the raised rings of a very large impact basin (like the Imbrium and Orientale basins on the moon). "Polygonal terranes" (Fig. 1) are deposits characterized by a giant fracture pattern that superficially resembles the pattern formed by mudcracks (but with fractures up to a mile across and "polygons" up to 10-15 miles across!). These deposits occur near the mouths of huge outflow channels, and thus are probably sediments deposited where the flow from the channels reached local low spots. The polygonal terrane on Figure 1 appears to be located near the center of the basin defined by the buried topography, a place that would logically be low because excavation is greatest at the center of a basin.

The results illustrated by Figure 1 support the presence of an eroded and buried giant basin beneath at least part of the northern plains. But is this basin the sole cause for the fundamental dichotomy in the martian crust? Evidently not, for two reasons:

1) A giant impact would cause severe fracturing of the crust peripheral to and below the resulting basin, but this fracturing should be of a single age -- the (ancient) age of the impact itself. There is good evidence for two ages of fracturing and associated erosion, one of which is relatively young, and a strong suggestion of multiple episodes of crustal disruption.

2) Using the beautifully preserved lunar Orientale basin as a model, the center of a basin and the troughs between the raised rings are lower than the original surface that was impacted, but the raised rings are significantly higher than the original impacted surface. The top of the buried massif inferred from the distribution of mesas and knobs (Fig. 1) is much lower than the original highland surface that was impacted <u>unless</u> this surface already was significantly depressed. Alterntively, the entire area of the basin might have subsided 1-2 miles since basin formation. Either way, the subsidence is not due to impact, and thus the basin is not the cause of the dichotomy.

During the early bombardment phase of solar system history, large basins and craters formed over what is now the northern lowlands of Mars, and its surface probably closely resembled that of the southern highlands. Tectonic processes, driven by mantle convection, are apparently responsible for the 1-2 mile depression of the northern third of the surface of Mars and for some of the associated structural disruption of the adjacent southern highlands crust. Much of this lowering probably occurred before the end of early bombardment (before 4 billion years ago), but our results suggest that structural disruption of old crust along the highland/lowland boundary and beneath at least the southern part of the northern plains continued into post-early bombardment times. This implies prolonged tectonic activity in and around the northern plains, and suggests that Mars may have been more active tectonically than we thought.

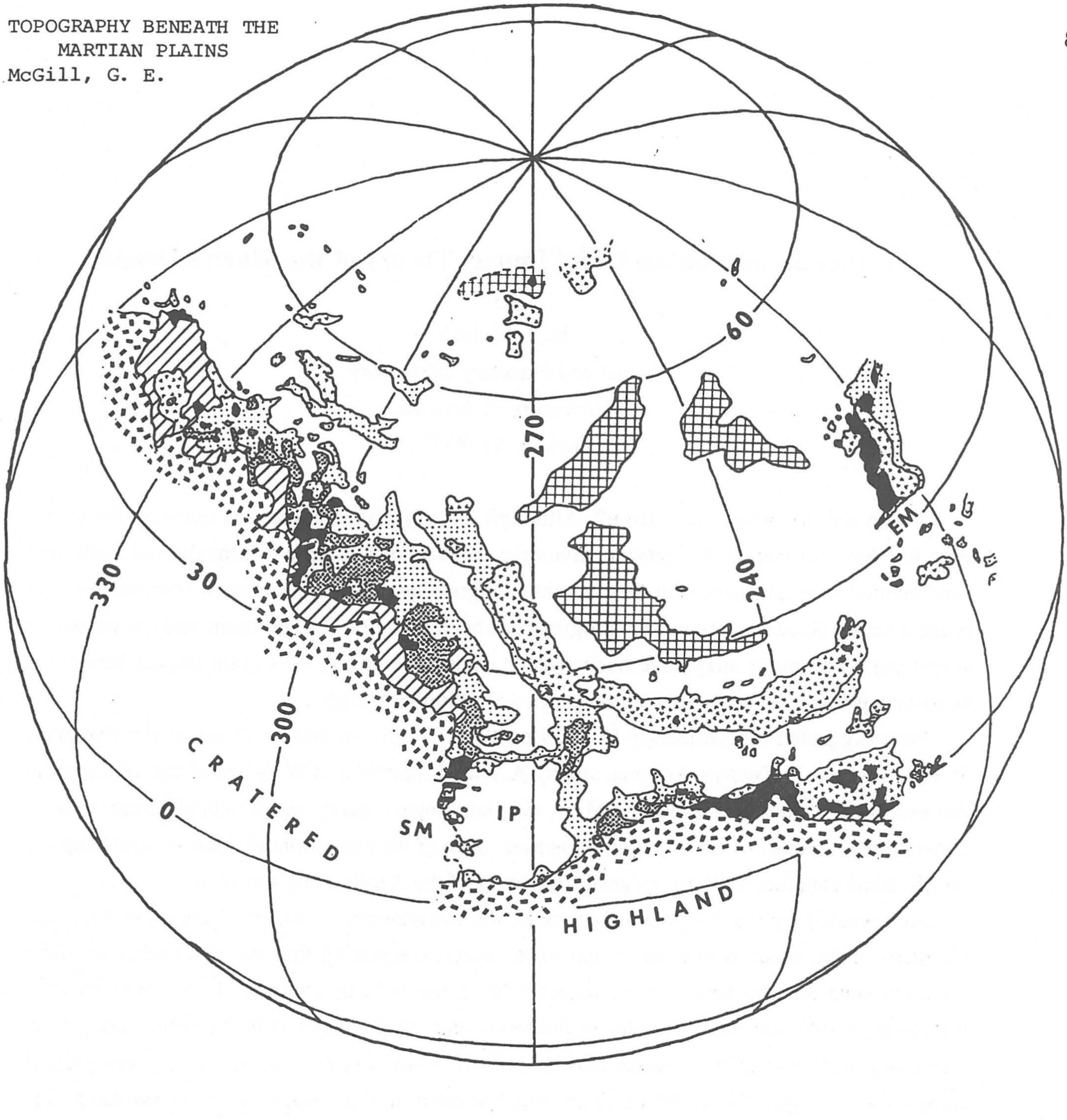

FIG. 1: Distribution of knobs and mesas on the northern plains of Mars between 210 degrees and 360 degrees west longitude. The boundary between southern highlands and northern lowlands is highlighted on the southern side by randomly oriented double dashes. Diagonal striping along the boundary indicates areas of fretted terrain. Patterns within the northern plains are:

black = abundant mesas ($\pm$knobs); v's = scattered mesas ($\pm$knobs);
heavy stippling = abundant knobs; light stippling = scattered knobs;
cross-hatching = polygonal terrane.

Initials locate well known geographic features for reference:

SM = Syrtis Major;
IP = Isidis Planitia;
EM = Elysium Mons.

Further Results on the Giant Impact Theory of the Moon's Origin

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Where did the moon come from? Although scientists have asked this question for years, very few have agreed on the answer. Even the Apollo lunar sample returns did not settle this fundamental question, although they taught us a great deal about the moon's composition and present state. Recently, however, progress has been made on this problem and the answer is surprising: The moon may have been created during the course of a giant impact between a Mars-size protoplanet and the ancestral earth, 4.5 billion years ago.

First suggested independently in 1975 by W.K. Hartmann and D. Davis of the Planetary Science Institute in Tucson, Arizona, and by A.W.G. Cameron and W. Ward of the Smithsonian Astrophysical Center in Cambridge, Mass, the giant impact theory was a radical departure from conventional theories of lunar origin. However, none of the conventional theories could explain the chemical data that had been gleaned from study of the Apollo lunar samples.

As revealed by the returned lunar rocks, the abundances of the most common chemical elements in the moon is similar to that of the earth, suggesting that the two bodies shared a common ancestor. However, the abundances of certain volatile compounds, of which water is the most notable, are much smaller in the moon than in the earth. On the other hand, some refractory, hard-to-vaporize, compounds such as titanium and uranium are highly enriched in lunar rocks. These observations indicate that the material that makes up the moon had a very different history than the earth's material.

The giant impact theory explains these observations by postulating that the ancient earth was struck by a Mars-size protoplanet. Mars is about half the diameter of the earth, but has only about one-tenth of the earth's mass. During the collision part of the earth's outer rocky mantle would be blasted into space at high speed along with some of the impactor's mantle. The collision would be so violent that the material blasted into space is vaporized. Some of this vapor would leave the earth forever. However, more of it would condense within minutes to hours after the impact, forming a cloud of dust circling the earth in highly elliptical orbits. It is out of this dust that the moon is thought to form. Since the material that composes the moon was partly derived from the earth, it is not surprising that the chemistry of the two bodies is grossly similar. However, since the lunar material was once vaporized and then condensed in the vacuum of space, volatile elements such as water would be lost, while refractory elements would be especially abundant.

At first sight, it may seem unlikely that Mars-sized protoplanets could be flying about the inner solar system. Certainly, no such rogue planets are careening about the solar system today. However, 4.5 billion years ago the solar system was new and the planets were in the process of condensing from a great swarm of small planetesimals. Studies by G.W. Wetherill of the Carnegie Institution in Washington, D.C. show that besides a few large planets, many intermediate size planets would form, along with still more numerous sub-planetary objects. The orbits of this large collection of planet-sized objects are not stable, however, and a period of mutual collisions should follow, which only a few were able to survive. These few are the planets as we know them today, and each of them has grown at the expense of the original collection of planet-sized objects. In view of this work, a collision between the ancestral earth and a Mars-size protoplanet seems quite plausible, if not likely. In fact, there may have been more than one such collision, although it is unlikely any of the other impactors was as large as Mars.

Although the giant impact theory thus seems plausible, many details needed to be worked out. Can a giant impact really eject a vapor plume fast enough for much of it to reach orbit? Can a single impact put an entire lunar mass in orbit? Does the material that makes up the moon come mainly from the earth, from the projectile, or is it a 50/50 mixture of both? To answer these and many other detailed questions, I collaborated with M.E. Kipp of Sandia National Laboratories, who is an expert in the computer modeling of impacts. Over the past year we have developed and refined a computer model of the collision between the ancient earth and a Mars-size protoplanet. Our model includes such realistic details as iron cores in both projectile and target, central gravity in the earth, and an accurate representation of the behavior of the rocky mantles and iron cores during a high-velocity collision. We were especially careful to be sure that the computer code treats the vaporization and condensation of rock vapor correctly.

Since the precise details of the impact that created the moon 4.5 billion years ago are not known, we varied parameters like the angle and speed of impact over wide ranges to see how these variables affect the outcome of the collision. We now have six well-studied cases of impacts at both high and low velocity and at very oblique and steep angles of incidence. In every case a high-velocity vapor plume jets from the site of the impact. However, much of this jet escapes the earth entirely in the high velocity impacts . A low impact velocity is more favorable for injecting material into earth orbit. This means that the impactor's orbit must have been rather similar to the earth's, a conclusion that is also supported by other data. The computations also show that more oblique angles of impact inject a higher proportion projectile material to earth material into orbit. The vapor plume in oblique impacts is also somewhat slower than for steeper impact angles.

The results of these computations have been plotted on color film, along with color contours of temperature and density during the first half hour of the impact. Side sequences following the course of the impact will be shown during our presentation at the 18^{th} Lunar and Planetary Science Conference.

This work, however detailed it may be, is still limited to roughly the first half hour after the impact. This limitation is mainly due to the relatively low speed and small memory of the CRAY I computer we are currently using. Although we have plans to use a larger, faster machine, such as a CRAY II XMP, which will allow us to extend the computations to much later times, this work is yet to be performed. However, I have been collaborating with Ann M. Vickery, of the Lunar and Planetary Laboratory in Tucson, Arizona, to circumvent the computer limitations by using an approximate extension of the Sandia CRAY I results. We use the supercomputer results as input for a small hydrocode that treats just the further expansion of the gas cloud and applies orbital dynamics to the dust as it condenses. This second hydrocode runs on the Macintosh Plus computer that sits on my desk.

Although this second model involves a number of approximations and simplifying assumptions, it shows how much of the gas jet computed in the Sandia models either leaves the earth's vicinity forever, remains in orbit, or crashes back onto the earth's surface. The results indicate that a large fraction of the vapor plume remains in orbit, at least a lunar mass in several cases. This work will also be presented in a companion paper at the 18^{th} Lunar and Planetary Science Conference.

This type of work, in conjunction with related efforts by W. Benz and A. G. W. Cameron, is beginning to fill out the details of the giant impact theory of the moon's origin. So far, the theory seems to be the most plausible of all the theories of moon's birth.

Volatile/Mobile Trace Elements in Eucrites - I. Antarctic/Non-Antarctic Comparisons

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Each meteorite that falls on our planet comes from an extraterrestrial object and provides a piece of the puzzle that is our Solar System. We would like to understand the genesis of the Solar System and to do this, we must study material that formed then and was unaltered by later events. The oldest known rocks are meteorites. When studied in the laboratory, they give us unique information on processes that took place when solid Solar System objects formed 4.5-4.6 billion years ago. About 2% of these meteorites are basalts that crystallized from rock melts in the interior of asteroid-sized objects within the first 0.1 billion years of our history. They are therefore the oldest planetary interior samples known and their chemical and physical properties can tell us about the most ancient melting and cooling events in extraterrestrial solid bodies - probably also in the early Earth. Many of these ancient basalts are known as "eucrites" and their light-reflecting properties are similar to those observed by telescopic study of the surface of one of the largest known asteroids, Vesta (550 km in diameter).

Outside of Antarctica, about 2600 different meteorites are known and 55 are eucrites that recently landed on Earth. During the past decade, 7500 meteorite pieces were found in Antarctica by Japanese and U.S. teams and more are being recovered by annual expeditions. These are thought to represent fragments of 1200-3800 different impacts. Nearly all Antarctic meteorites studied so far landed there more than 100,000 years ago. Of 1200 classified meteorites recovered from Antarctica by U.S. teams, 21 are eucrites and, curiously virtually all Antarctic samples have different textures under the microscope than do non-Antarctic eucrites. These textural differences hint at a preterrestrial heating difference between Antarctic and non-Antarctic eucrites - that is, that they come from different parent objects or different melt regions within the same body.

About a year ago, we reported on a comparison of the concentrations of 14 chemical elements in large numbers of the most common sort of meteorite found in Antarctica (called H chondrites) with those observed to fall outside of Antarctica. The elements we studied are generally are very mobile or quite easily lost during preterrestrial heating events. Therefore, their concentrations serve as sensitive markers for meteorite formation and evolutionary events. These elements are all present at trace or ultratrace levels so that we must use a very sensitive technique to measure them. This technique, known as neutron activation analysis, involves placing the sample in a very high intensity nuclear reactor for some days thus making a part of each element radioactive. After this, we chemically separate and count each element.

Our laboratory is the only one in the world that routinely measures most of these elements in rock samples. We found significant differences for about half of the elements that we studied and concluded that these most common sorts of meteorites came from different extraterrestrial sources. That is, the preterrestrial heating histories of H chondrites found in Antarctica and falling today are so different that we must be sampling at least 2 different extraterrestrial parent bodies for these common meteorites. This conclusion was very surprising since existing theories indicated that material from asteroids should not have different orbits over time scales of less than a few tens of millions of years. Because of these chemical results, additional comparisons have been carried out by others and more Antarctic/non-Antarctic differences have been found for common meteorites. Also, ideas about meteorite orbits have been re-examined by others during the past year (prompted by the chemical results) and these support the suggestion that H chondrites found in Antarctica come from a different extraterrestrial source than do those falling today.

Part of the reason that we thought that Antarctic meteorite finds and today's non-Antarctic falls might have different origins were that rare meteorites, like eucrites, found in Antarctica and those falling today look different under the microscope. It would not be surprising therefore to expect chemical differences between these two sorts of eucrites. At this meeting, we are reporting on a study of this. We carried this out by measuring concentrations of 15 mostly mobile elements in a number of samples. Six of the elements have significantly different concentrations, with the Antarctic samples always containing more of each element.

These concentration differences cannot be due to meteorite exposure in Antarctica since we know that weathering there causes trace element loss by leaching. If the differences were terrestrial, the Antarctic samples would have lower concentrations than non-Antarctic ones. The differences must be preterrestrial. The simplest interpretation is that Antarctic eucrites come from a parent region that was on average cooler than the one(s) from which present-day eucrites derive.

These results have at least two major implications. First, the Antarctic/non-Antarctic difference means that each annual recovery of Antarctic meteorites provides extraterrestrial material equivalent to several new space missions. Second, we can now proceed to compare early Solar System genetic processes that led to the formation of at least 2 different sorts of planetary interior samples. Science always advances more rapidly when comparison is possible and we are now a bit farther along in understanding how early differences in planetary evolution might have occurred.

A Micrometeorite "Spectrum" for the Mass Distribution of Well Preserved Greenland Cosmic Dust Grains.

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The nature of the parent bodies of cosmic dust grains, that are currently extracted in large numbers from terrestrial sediments is still not fully understood. This hampers the meaningful use of the grains in planetary sciences. The data reported in this paper contribute in two ways to this important problem: they show that most cosmic dust grains found in the important size range investigated in our work so far (sizes smaller than 0.5 mm), and that happens to contain most of the grains, result from an unexpectedly weak ablation of small micrometeorites in the atmosphere, that partly originated from comets. They also suggest that most micrometeoroids are made of a composite material, that looks different from the constituent material of meteorites.

This study was only made feasible by the discovery of a new collection of cosmic dust grains, extracted from dark sediments collected on the melt zone of the West Greenland Ice Cap. We have already shown that these sediments constitute the richest and best preserved mine of cosmic dust grains yet found on the Earth. The grains were extracted from the sediments by a gentle mechanical disaggregation on a stainless steel sieve and directly hand-picked. Thus any preferential extraction of the grains, associated with magnetic extraction procedures, was minimized .

In this improved collection, we observed the two major families of grains magnetically extracted from deep sea sediments. These correspond to "stony" spherules (abundance of about 50%) with a peculiar chondritic composition and "iron" spherules (abundance of about 2%), composed of an oxidized alloy of iron and nickel and which is made of tiny crystals of magnetite and wustite. We also discovered two major new families of grains, that can hardly be extracted in sufficient amounts from deep sea sediments by magnetic dragging as they are weakly or non-magnetic and easily corroded ("weathered") by sea water. They include glassy spherules (abundance of about 20%) and an unexpectedly high abundance of unmelted grains (25%). During a detailed comparison between the collections of deep sea and Greenland cosmic dust grains, we noted that the abundance of the iron spherules in the Greenland sediments was much smaller (about 2%) than the value of about 50% generally quoted for deep sea sediments. The high abundance of iron grains in deep sea sediments results in fact from the preferential weathering of the stony spherules.

We measured the "differential" size distribution of the four major families of Greenland cosmic dust grains, representing their relative abundance in a given size increment of about 50 micrometers between 50 and 300 micrometers. The major purpose of this analysis was to obtain clues about the origin of the grains. For example, if the grains originate from the ablation of small micrometeoroids in the atmosphere that are made of compact material similar to meteorites, then, a very sharp drop in the abundance of grains larger than about 100 micrometers should be observed. Indeed, reliable computations by Opik for such compact solids, indicate that grains in this size range are completly destroyed upon ablation, as their surface relative to their volume becomes too small to radiate away the frictional heat liberated during their abrupt deceleration in the atmosphere. On the other hand, simulation experiments previously conducted with either a solar furnace or laser pulses indicate that coarser spherules should be generated during the ablation of much larger meteoroids that yield meteorites. We are aware that possible artefacts, related in particular to the preferential destruction of the most friable grains during our disaggregation procedure might have further altered the initial size distributions.

Our first unexpected result was to find much simpler size distributions than initially thought. For example, the stony spherules are extremely hard and cannot be easily crushed, while both the glassy spherules and the unmelted grains are more easily broken. However, the size distributions of the four major families of Greenland cosmic dust are strikingly similar. We also found that this similarity extends to the deep sea iron spherules that are the best preserved grains in deep sea sediments. Consequently, this "universal" size distribution should bear some unique information about the origin of the grains.

We managed to deduce the corresponding mass distribution (mass "spectrum") of the Greenland cosmic dust grains accreted by the Earth over the last 2,000 years or so. This spectrum was extended to grains with sizes smaller than 50 micrometers for the purpose of comparison with the mass spectrum of the micrometeoroid flux in interplanetary space, that shows a typical maximum at about 50 micrometers. This spectrum was compiled by Grün et al, who relied on a variety of data spanning a large time scale: e.g. perforation of metallic foils on satellites and size distribution of micrometeorite impact craters on lunar rocks.

The most amazing result is that our spectrum and that of Grün et al. are unexpectedly similar with regard to the maximum occurring in the 50-100 micrometers size range, and the decreasing abundance of larger grains. They are very different from those measured for varieties of natural grains found, for example, in a volcanic ejecta or in the heavily cratered surface (i.e. "regolith") of small bodies in the solar system such as the lunar regolith or the parent bodies of a variety of meteorites, that are breccias resulting from the shock induced compaction of their parent regolith. Furthermore, the yearly mass accreted by the Earth, as determined from the estimated age of the ice, is very similar to that calculated by Grün.

Simple inferences about the nature of the parent bodies of the Greenland cosmic dust grains can be obtained from this set of new data. First, in the preliminary size range investigated (size smaller than about 500 micrometers), the grains are genuine micrometeorites and not ablation products of much larger meteorites. We can extend to this smaller size fraction, that contains much cosmic dust grains, the recent conclusions of Raisbeck infered for grains with a minimum size of about 500 micrometers in which they measured "cosmogenic" isotopes induced by solar cosmic rays.

Well preserved cosmic dust grains, that are abundantly found in the size fraction smaller than about 500 micrometers are now much more interesting than previously thought. Indeed, their parent micrometeoroids are generally considered as originating from comets, that are the most primitive relics of the solar system history. This direct connection with comets is based on a statistical reconstruction of the cometary type orbits of micrometeoroids that can be derived from their visible and/or radar trails in the atmosphere, down to masses of about 0.1 milligram. These data also represent a series of new "ablation" constraints on the nature of micrometeorites. They show that micrometeorites are only weakly ablated in the atmosphere, and that their survival probability is independent of their initial sizes. This runs contrary to previous predictions valid for chunks of compact solids such as meteorites, indicating that most grains with sizes in excess of 100 micrometers should be destroyed. Thus, micrometeorites constitute a new family of extraterrestrial objects. Furthermore they lose a small fraction of their initial mass (at most 50%), which appears independent of the final ablation residue.

In our view, to be hopefully soon supported by elaborate modeling of the ablation process performed by D. Balageas, these constraints might reveal a "universal" structure of micrometeorites. These micrometeorites would be made of composite material that looks somewhat similar to man made pyrolisable composite materials used as thermal blankets on rockets etc. In this model, a skeleton of volatile grains would be permeated by volatile compounds. At the onset of frictional heating, these compounds would be selectively vaporised, generating a flux of gas that provides a very efficient cooling mechanism, which was not considered in the earlier computations of Opik.

The following conclusion, supported by both the data reported in this paper and from our analysis of the important family of unmelted grains is still tentative. We believe that some of the best preserved cosmic dust grains found in polar ice, are related to the dark primitive sand, that constitutes the surprizing very dark surface of cometary nuclei such as that of comet Halley, observed in March 1986 by instruments on board of the Vega and Giotto spaces probes. After its ablation in the atmosphere, this dark sand loses most of its volatile component. The unmelted grains that are unexpectedly abundant are probably good relics of the nonvolatile component of this sand, which should soon yield interesting information about the early history of the solar system.

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The Venusian Surface: Is It Really Old?
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Theory predicts that the rate of heat loss from a planet is proportional its surface area, whereas heat production is proportional to the volume. Thus, small planets tend to be colder than large planets, and the rates of volcanism, surface disruption (tectonics) and resurfacing on the planets may be directly related to their size. To test this theory, knowledge of the surface age and geologic landscapes for planets of diverse size and mass is required. Venus, the planet closest in size and mass to the Earth, has been of special interest because its internal heat budget is predicted to be similar to that of Earth's.

Because of its total cloud cover, Venus' surface has been accessible only through radar observations from Earth, and several radar-mapping spacecraft such as NASA's Pioneer-Venus orbiter (1978 launch) and the Soviet's Venera 15 and 16 orbiters (1983 launch). From these radar data, the surface of Venus is known to be geologically and topographically complex with abundant volcanoes, extensive lava plains, mountains, highly faulted and disrupted terrains, and a population of probable impact craters. In other ways, Venus is quite unlike Earth; it has a surface temperature of 800° F, a dense atmosphere of carbon dioxide, and no surface water.

The ages of diverse Venusian terrains must be known before the geologic and geophysical development of Earth and Venus can be compared. From afar, the ages of different terrains can be estimated by counting the size and number of impact craters--older surfaces will have accumulated more craters. Relative ages of different terrains on the same planet can be determined directly from the crater counts. Determining "absolute" ages, however, requires knowledge of the cratering rate over time. This knowledge has been developed for the Earth and Moon by isotopic and other methods of age determination of known craters and of the surfaces on which the craters were formed. The cratering rate on Venus can be derived from the estimated cratering rates on Earth from observations of the orbits of the impacting bodies.

One approach to dating Venus' surface taken by Soviet scientists involved assuming that the cratering rate on Venus could be extrapolated from the rate on the Moon by correcting for Venus' different gravity and orbit. They have reported that this method indicates an age of between 500 million and 1.5 billion years for the northern hemisphere of the planet mapped by Venera 15 and 16. The cratering rate on the Moon, however, is averaged over the past 3.3 billion years, a lengthy period of time during which the flux of impacting bodies has probably varied.

E.M. Shoemaker* has noted that the cratering record (for craters larger than 6 miles across) in rocks of the central United States less than 500 million years old is indistinguishable from that predicted from astronomical observations of present Earth-crossing asteroids--a rate at least 2 to 3 times greater than the estimated average cratering rate on the Moon over the past 3.3 billion years. Shoemaker and R. Wolfe* recently recalculated cratering

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rates by asteroid impact on Venus based on astronomical observations and concluded that the current rate is essentially the same as the current asteroid cratering rate on Earth (See abstract-this conference.) Based on these observational constraints, G. G. Schaber*, E. M. Shoemaker and R. C. Kozak* used the Soviet's Venera 15 and 16 inventory of 146 probable Venusian impact craters to estimate an average surface age of about 100 to 200 million years for Venus's northern hemisphere (See abstract-this conference.)

There are many unknowns in absolute crater-dating techniques; perhaps the greatest of these is the relative contribution of comets and asteroids in the crater-forming process. On Venus, the surface dating process is further complicated by the unknown effects of its dense atmosphere in filtering out primarily the cometary component of the impact crater production. There are further difficulties in clearly separating craters of impact origin from volcanic origin given the 3000 to 5000 foot resolution of the Venera 15 and 16 image data. If all but the largest cometary bodies entering the Venusian atmosphere do not form craters on the surface, then, Schaber, Shoemaker and Kozak suggest that the mean age of the northern hemisphere of Venus could be as great as the 450 million year mean age of the Earth's crust.

Thermal evolution models suggest that a planet similar in size and mass to the Earth will not only lose heat at similar rates, but might be expected to have similar resurfacing rates as well. Yet, this heat loss which is the driving force of plate tectonics on Earth apparently expresses itself differently on Venus, as structures characteristic of Earth-like crustal recycling are not readily identifiable on the planet's surface. The upcoming U.S. Magellan radar mapping mission (1990) should resolve some of these questions. Among other things, the Magellan Radar Investigation Group hopes to be able to clearly separate impact from volcanic craters; and thus, better understand at least the relative ages of the planet's diverse terrains. Veneras 15 and 16 mapped only 25% of the surface of the planet; the remaining 75% may tell us a completely different story. The primary objective of NASA's Project Magellan will be to radar-map at least 80% of Venus at a surface resolution between 500 to 600 feet.

MARS-ROCK-METEORITES: A POSSIBLE REASON WHY WE HAVE MORE METEORITES FROM MARS THAN FROM THE MOON, AND A PREDICTION THAT SOME MAY BE FOUND ON MARS' MOONS. Edwin L. Strickland, III, Dept. Earth, Planetary Science; Washington University; St. Louis, Mo. 63130.

Most meteorites are probably broken pieces of the small, stony or rock-and-iron objects called asteroids. Tens of thousands of asteroids circle the sun between the orbits of Mars and Jupiter, while a few hundred stray inside Mars' orbit. Most stony meteorites, called chondrites, contain chondrules, small stony droplets that were melted and then frozen while orbiting in the pre-solar nebula that formed the sun and planets. These chondrites are samples of some of the primordial "cosmic sediment" that the Earth, inner planets, and asteroids formed from 4.5 billion years ago.

The asteroids that the chondrites came from never melted completely after they formed, but at least some asteroids melted inside almost immediately. In these asteroids, molten iron probably separated from the molten rock to form a small core of iron, surrounded by a rocky mantle, and possibly an unmelted crust; forming a miniature planet. After they melted, these asteroids cooled down in a few million years and the rock and iron froze. Some were broken apart by collisions in space, and pieces from them land on Earth as achondrite (without chondrules) stony meteorites and iron meteorites.

Because they formed by the crystalization of molten rock, achondrite meteorites closely resemble igneous rocks formed on Earth. Some are like the fine-grained basalt from Hawaiian volcanoes, some are like coarse-grained igneous rocks that form deep in the Earth as molten rock cools slowly. Unlike igneous Earth-rocks, most achondrites are as old as the solar system. Most have almost no water trapped in their minerals, and they formed where there was no extra oxygen to combine with metallic iron or to "rust" the iron already combined in their minerals. Most contain very small amounts of trapped gases of a distinctive composition. Finally, most have mineral compositions that suggest they are from small planetoids, which were originally made of chondrite material or something very similar, melted once, froze solid, and then had nothing happen to them until they were broken apart in a collision.

A few achondrite meteorites, however, are very different. Three are Moon-rocks, almost certainly blown free of the Moon by the crater-forming explosions that occur when large meteoroids or small asteroids hit the Moon while traveling tens of kilometers per second.

At least eight achondrites are neither typical asteroid-rocks nor Moon-rocks, and have a surprising similarity to igneous rocks from Earth. These meteorites are named Shergottites, Nakhlites, and Chassignite (there's only one) after the places in India, Egypt, and France where the original examples fell. (Scientists studying them often call them SNC meteorites for short.) They are surprisingly young, some may have crystalized from molten rock only 1.3 billion years ago, instead of 4.5 billion. They contain surprising amounts of water: amounts similar to that present in volcanic rocks on Earth. They formed where metallic iron was not present and some iron in their minerals has been further oxidized to form minerals found in Earth-rocks, not Moon-rocks or normal achondrites. Their composition shows that they come from somewhere else in the solar system than the Earth, the Moon, or the small planetoids that most achondrites come from. They appear to come from a larger body which (like the Earth) has strong gravity, held onto its water and atmosphere, and was volcanically active over most of the history of the solar system.

Mars is the only good candidate source for these "SNC" achondrite meteorites, and some more recent discoveries come close to proving that these meteorites are from Mars. R. O. Pepin summarized evidence for this in an article **"Evidence of Martian Origins"** in Nature (Oct. 10, 1985, p. 473). Not only does the composition of Shergottites resemble the composition of martian soil as measured by the Viking Landers on Mars, but the compositions and amounts of gases trapped in glassy parts of one Shergottite is identical within measurement error to that measured at the surface of Mars by the Vikings.

A major problem is how any Mars-rocks could have been thrown free of Mars without destroying them. To escape Mars, an object leaving its surface must be traveling at least 5.04 kilometers/ second (11,300 MPH). Studies have shown that material can be directly accelerated to such speeds by the explosion shock-waves that create a meteoroid or asteroid impact-crater; but not only would rocks be disintegrated, they should be mostly melted and possibly partly vaporized. John D. O'Keefe and Thomas J. Ahrens reported finding one possible solution to this problem. In the article **"Oblique Impact, A Process for Obtaining Meteorite Samples from Other Planets"** (Science, Oct. 17, 1986, p. 346), they presented results of computer models that showed what may happen when small asteroids collide with a planet obliquely, instead of vertically. They found that a jet of vaporized asteroid and planet is "squirted" away from the collision point, parallel to the planet's surface, in the direction the asteroid was moving, and traveling even faster than the asteroid was. They concluded that this high speed plume could literally "blow" boulders from the surface of a planet as big as Mars into orbit around the sun, without the explosion's shock damaging the rock structure more than is seen in the SNC meteorites.

Even if this or other theories explain how rocks could be blown free of Mars, another problem remains. Why do we have more meteorites that may be from Mars than we have from the Moon? George W. Wetherill studied how rocks could get to Earth once blasted free of Mars. In his article **"Orbital Evolution of Impact Ejecta from Mars"** (Meteoritics, Mar. 31, 1984, p. 1), he concluded that we should expect at least several hundred times more rock from the Moon should reach Earth than from Mars.

While puzzling over these problems, I realized that a seemingly unrelated piece of research held a possible answer to

Wetherill's problem. When a meteoroid or small asteroid traveling nearly vertically collides with a planet, the crater that forms is nearly circular and material thrown out is ejected in all directions. When an object impacts at about 10 degrees from horizontal, the crater remains reasonably circular, but most ejecta splashes out to either side and forms a distinctive "butterfly-wing" pattern. At even shallower angles, the grazing impact produces complex, elongated craters with "butterfly-wing" ejecta. Such craters are rare on the Earth, the Moon, and most planets and their moons.

Peter H. Schultz and Anne B. Lutz-Garihan found that oblique-impact craters are far more common on Mars than elsewhere. They presented their results in the article **"Oblique Impacts on Mars: A Record of Lost Satellites"** (<u>Proceedings of the 13th Lunar and Planetary Science Conference</u>, <u>Journal of Geophysical Research Supplement</u>, Nov. 15, 1982, p. A84). They found that up to 8% of the craters in some areas were formed by oblique impacts, instead of the expected 0.7%. Even more surprising, objects forming the youngest, freshest craters were traveling nearly parallel to the equator; objects forming older craters were traveling more north-south. They could find no reasonable explanation for either observation if the objects that formed the craters were the asteroids and comets that formed the craters on the Earth, Moon, and Mercury. Instead, they proposed that the crater-forming objects were the remains of one or more moons of Mars that had broken-up and collided with the planet.

Mars today has two small, irregularly shaped moons, Phobos and Deimos, about 27 and 16 kilometers (17 and 10 miles) long. Both are dark, charcoal-gray and may be captured asteroids made of carbon and (sometimes) water-rich carbonaceous chondrite material. Phobos orbits Mars about 6000 kilometers (3700 miles) above Mars' equator; one orbit takes only 7 hours, 39 minutes (compared with the martian day of 24 hours, 40 minutes). Like our large but distant moon, a small but close moon like Phobos generates a significant tide on its planet. The tide in return slowly changes the orbit of the moon. Our moon is being slowly driven away from Earth, pushed by Earth's more rapid rotation. Phobos instead, is being driven inward as it orbits faster than Mars rotates beneath it. Within a few tens or hundreds of millions of years -- a very small fraction of the age of the solar system -- Phobos will be so close to Mars that it will be pulled apart. The fragments will eventually impact on Mars, travelling nearly horizontally and forming grazing-impact craters! Schultz and Lutz-Garihan concluded that the craters they observed were formed by the breakup of lost satellites, millions to billions of years ago. These could have possibly formed (together with Phobos and Deimos) by the collisional breakup of an original martian moon at least 225 kilometers (140 miles) in diameter.

Here is the possible solution to the SNC meteorite abundance problem: If a moon of Mars broke up and its pieces impacted a few tens to hundreds of millions of years ago, and if oblique impacts can eject Mars rocks into space efficiently without destroying them, large numbers of Mars-rocks could have been ejected into space and now be reaching Earth in far greater numbers then we would otherwise expect. If a series of lost moons broke up and impacted over time, Mars-rocks would have been repeatedly thrown into space, and it would not be some peculiar coincidence that a large number are reaching Earth just now.

While I was figuring out this possibility, a new idea came to mind. Some of the rocks ejected from Mars would almost certainly collide with Phobos and Deimos before either escaping into solar orbit or falling back to Mars. Indeed, if they were ejected by impacts of falling moon fragments, traveling west-to-east, the ejected rocks would also be traveling west-to-east, and would be mostly ejected in the plane of Mars' equator and the plane of Phobos' and Deimos' orbits. This would greatly increase the chances some ejecta would collide with Mars' moons. Also, because ejecta does not need to travel as fast to reach Phobos' orbit as it must to escape Mars (only 80% as fast), slower moving ejecta that can't escape Mars can reach the moons' orbits. Most of the optimally ejected material would impact on the moons' hemispheres that face the direction they move in their orbits, caught-up by the faster moving moon; as they cross themoons' orbit's.

Can Mars-rocks thrown into space survive collision with Phobos and Deimos, or will they be destroyed by the impact? The faster they are traveling, the smaller the chance they will survive. However, if a Mars-rock is ejected from Mars' surface traveling horizontally (as predicted by O'Keefe and Ahrens' model), traveling eastwards, and with just enough speed to reach the moons' orbits, it would collide with Phobos and Deimos at only 0.58 and 0.67 kilometers per second (1300 and 1500 miles-per-hour), respectively. These speeds are low enough that impact will not melt the Mars-rocks, but could pulverise them, especially if they hit a solid rock surface. Observations, however, show that both moons are covered with a deep layer of pulverized rock, called a regolith. Because the slowest-traveling Mars rocks would also land in a thick layer of powder, it is likely that they would be broken into smaller fragments, but not be totally pulverized. Faster traveling rocks will be less likely to survive, but because there will be many more than those arriving at the slowest possible speed, some should survive, even at impact speeds up to 1 kilometer per second or so. Once on the moons, the Mars-rocks should survive till they are buried or destroyed by small meteoroids. Any rocks ejected from the moons' surfaces would be eventually swept up again by the moons.

If lost satellites created the many oblique inpact craters on Mars and ejected Mars-rocks into space to form SNC meteorites, it is possible that the surfaces of Phobos and Deimos are scattered with many fragments of Mars-rocks. Even if lost satellites did not create those craters, if the SNC meteorites are from Mars, then some of them would almost certainly have collided with Phobos and Deimos. Traveling in random directions instead of eastwards, most would have been pulverized by impact on the moons at speeds of a few kilometers per second. We would then not expect to find many intact Mars-rocks on Mars' moons, but pulverized and partly shock-melted Mars-rock should be scattered through the pulverized moon-rock of the moons' surfaces.

The Soviet Union plans to send spacecraft to orbit Mars in 1989, rendesvous with Phobos, "fly" across its surface at only 50 meters (160 feet) altitude, and drop landers on the surface. The second spacecraft may do the same at Deimos if the first is successful at Phobos. These spacecraft may be able to detect if Mars-rocks are present on the Martian moons. Closeup Viking Orbiter pictures of the moons showed that their surfaces have few large blocks thrown out of the large craters that penetrated the moons' thick regoliths. Objects forming smaller craters would not be able to eject coarse debris. Unusual concentrations of blocks and rubble in and around small craters could be the remains of impacting Mars-boulders. The surfaces of Phobos and Deimos are very dark charcoal gray and without detectable color variations (in Viking images). Because Mars-rocks would be expected to be lighter in tone and somewhat brownish in color (because of the relatively oxidized iron in them), color pictures with sensitive cameras should readily detect even small chips of Mars-rock in the moons' regoliths. On Earth's Moon, the low velocity impacts of spent Apollo rocket stages and Lunar Modules splashed out darker lunar soil without pulverizing fresh rock, and made distinctive small dark-halo craters quite different from the small, fresh, bright- halo meteor craters. Small, dark-halo craters have already been observed on Phobos by Viking Orbiters, and it is just possible that they could have formed by the most recent impacts of unusually large martian ejecta.

In addition to passive observations of the moons, the Soviet spacecraft will carry out two active experiments that may both be able to detect isolated Mars-rocks on the moons' surfaces, or Mars-rock debris mixed into the moons' regoliths. A Remote Laser Mass Spectrometer, called LIMA-D, will use a laser to vaporize targets under the spacecraft as it slowly "flies" across the moon's surface. The mass spectrometer will measure the amounts and isotope compositions of elements in the vaporized rock. The DION Remote Mass Analyser of Secondary Ions will fire an ion-beam at the surface, knocking free small amounts of gas atoms for similar analysis. Observations of rocks or craters with Mars-like rock or gas compositions would be direct evidence for Mars-rocks on Phobos. Even if rocks do not survive impact on the moons intact, varying amounts of Mars-rock material mixed into the moons' regoliths could reveal its presence. Only if too few Mars-rocks reach the moons' surfaces and survive, or if they are mixed too uniformly with the moons materials to be detectable, will they be missed. Thus, in three years, we may know whether SNC meteorites are indeed from Mars, and whether Mars-rocks have been abundantly scattered across the surfaces of the Martian moons. In the more distant future, it may be possible to return a diverse collection of Mars-rocks to Earth, included in a sample return mission to the martian moons instead of Mars' surface.

MINERALOGY OF DOMINANT CLASTS IN LUNAR REGOLITH BRECCIA 60019 AND COMPARISON TO YAMATO LUNAR METEORITES. Hiroshi Takeda, H. Mori and T. Tagai, Mineralogical Inst., Faculty of Science, Univ. of Tokyo, Hongo, Tokyo 113, M. Miyamoto, College of Arts and Science, Univ. of Tokyo, Komaba, Tokyo 153, Japan.

The lunar meteorites are rare meteorites derived from the moon and recovered from Antarctica. They are solidified materials of lunar highland surfaces what lunar scientists call regolith breccias. Four lunar meteorites, Yamato(Y) 791197, Allan Hills(ALH) 81005, Y82192 and Y82193 have been identified in the Antarctic meteorite collections (e.g. 1-3). Extensive studies of these samples have been carried out by three international consortium groups (1-8). Because their lunar origin is well established, we now have to answer three questions: (a) are all four samples the same meteorites, (b) are some of them the same as other samples and (c) are there any clues to where they might have originated on the moon? Because these samples contain very small amounts of elements known to be concentrated in a rock type distributed around Mare Imbrium located nearly in the center of the near side, many scientists suggested that they came from the far side or around the margin of the moon (1,7). Since the lunar highland breccias contain wide varieties of mineral signature of lunar crusts and mare basalts distributed around the impact sites, from where the meteorites were ejected, they provide us with a wealth of information of the lunar crust never sampled by the U.S. Apollo or the Soviet Luna missions.

Comparisons of four lunar meteorites and their lunar analogs are thus important, because they inform us local differences of rock types and differentiation trends within the lunar crust, if four were derived from the different locations. The nature of the lunar crust and differentiation trends in different locations will give us important clue to solve the origin of the moon, especially to answer the question how the lunar crusts solidified in space and time from a magma ocean. However, since all lunar meteorites are small in size (27 to 52 g), the difference between the two meteorites might be due to local variation within the same impact site. The heterogeneity within one lunar meteorite is also a problem. The lunar meteorites are complex mixtures of rock and mineral fragments which are called clasts and their comminuted matrix. Thus it is important to study variability of clast types and matrices of lunar highland regolith breccias within a large sample collected by the Apollo mission and in different samples within the one landing site of the lunar highland. Such study is useful to establish genetic processes important in the formation of lunar meteorites, and to deduce the impact site, from where the lunar meteorites were ejected.

Lunar sample 60019 is one of the largest lunar highland regolith breccias analogous to the lunar meteorites, but such samples are not too well characterized mineralogically upto date. Recently McKay et al. (9) characterized many Apollo 16 regolith breccias. They consist of the fine-grained comminuted constituents of the regolith such as rock, mineral and glass fragments, glass spherules with mineral fragments, glassy agglutinates. These are agglomerated to a coherent rock by sintering of hot glass or by shock lithification.

Since two large slabs were sawn from 60019, we have been studying 60019 since 1985 by mineralogical techniques such as electron microprobe (EPMA) and analytical transmission electron microscope (TEM), which is capable of analysing the chemical composition, microstructure of a region as small as 800A. Last year, we found that a fragment of basalt in 60019 is similar to Luna 16 basalt and that highland pyroxene types in 60019 bear a strong resemblance to those in the Yamato lunar meteorites collected in 1982 (10). This year we report on dominant clasts in 60019 and Yamato lunar meteorites and the matrix glass produced by impact events.

Clasts exposed on the cut surfaces of the new slabs of 60019 were mapped and described by C. Galindo (11). Angular fragments of fine-grained white clasts upto 2 cm in diameter are set in a dark glassy matrix. Three polished thin sections (PTS) of dominant clasts were prepared. 60019,205 is a PTS of a subangular, greyish white, fine-grained clast (WF-1) in slab ,135 10 x 15 mm in size. 60019,208 is a PTS of another large fine-grained clast (WF-4) in slab ,127. It is an elongated greyish white clast 8 x 17 mm in size. 60019,207 is a coarse-grained milky white clast(WC-1) 20 x 20 mm in size in slab ,124. Clasts in new PTS's of Y82192, Y82193 and Y791197 from National Inst. of Polar Research (NIPR) have been studied in comparison with 60019. Pyroxenes in the old PTS's of these lunar meteorites have been reported (4,5), but they did not contain large clasts. New PTS's contain more clasts than the old ones.

The matrices of these clasts in 60019 are fine-grained crystalline and show a texture similar to Apollo 16 poikilitic breccias. The lunar poikilitic breccias were believed to have been produced by a large basin-forming impact event. The hot glassy matrix produced by the impact were recrystallized to fine minerals by relatively slow cooling. The difference in grain size of the clasts is mainly attributed to the sizes of the plagioclase fragments in the matrices. The plagioclase is Ca-, Al-containing silicates abundant in the highland rocks. The texture of 60019,208 resembles that of a typical low-K Fra Mauro poikilitic breccia 65015. The matrix is rich in opaque minerals and contains very few fine-grained subround plagioclase fragments. 60019,207 includes large fragments of plagioclase up to 0.63 x 0.80 mm in size and one large olivine fragment 0.92 x 1.11 mm. The matrix shows well developed poikilitic texture and the grain boundaries of the mineral fragments are not sharp indicating thermal annealing. Mafic minerals in a granulitic breccia clast are continuous to those in the matrix, and the coarsest grains in the matrix approached those in the clast. The compositions of olivine and pyroxene minerals are also not much different from those of the matrix.

The texture of 60019,205 is different from the above two and is unique as a breccia. The plagioclase fragments are abundant, fairly uniform in size and very angular. The sizes are between 0.1 and 0.8 mm in the longest dimension. The range of the chemical variation of the plagioclase fragments is smaller than that of other fragments in the entire matrix. A few large blebs of metal are present. The matrix minerals are olivine, pyroxene and plagioclase. The poikilitic texture of the matrix is not as pronounced as that of ,207 but the pyroxene compositions distribute in a manner similar to the Apollo 16 poikilitic breccias (e.g. 65015). These facts indicate that the Apollo 16 regolith breccia contains rock types formed by large basin-forming events according to Spudis (12).

Large, dominant clast types in the new PTS of Y82192 include shocked plagioclase, devitrified glassy clast, impact melt breccias with plagioclase fragments, and granulitic clasts. The old PTS contained a large regolith breccia clast in the breccia (5). Three granulitic clasts (GR1-3) up to 1.02 x 0.79 mm in size include small rounded olivines and pyroxenes in a granoblastic plagioclase matrix. The mineral chemistries of olivines of clasts GR1, GR2 and GR3 and the pyroxenes of GR2 and GR3, and plagioclases lie in the range of the Mg-suite rocks which were differentiated within the magma ocean, but they may be the Mg-rich extension of the ferroan anorthosite trend of the crustal layers as was found in Y791197 (4).

The poikilitic breccias dominant in 60019 are rare in the Yamato lunar meteorites collected in 1982. Ostertag et al. (13) reported some rare examples of micropoikilitic crystalline melt breccias in Y791179. They also reported clast population in Y791197 and ALHA81005. Granulitic breccias and recrystallized cataclastic anorthosites are common in ALHA81005. Granulitic breccias are not uncommon in Y791197, but recrystallized cataclastic anorthosites and feldsparthic crystalline melt breccias are more abundant in Y791197.

The EPMA analyses of the shocked plagioclase show considerable concentration of MgO and FeO, which increases with decreasing (Si+Al). The analytical TEM observation showed that the matrix materials of Y791197, Y82192 and ALHA81005 consist of angular fragments of plagioclase and pyroxene and interstitial glass. All of interstitial glass of ALHA81005 and Y82192 are devitrified to very fine-grained minerals (5). In Y791197, however, interstitial glass in matrix is undevitrified. This observation indicates a different metamorphic annealing history of this meteorite from the other lunar meteorites.

Pyroxene is a silicate mineral, with various amounts of calcium, magnesium and iron. Their compositional variations are plotted in so-called "pyroxene quadrilateral", which is a portion of triangle with these three components Ca, Mg, Fe at the corners. This mineral is probably a mineral which gives us the most valuable information on the components of lunar highland regoliths, because their compositions and inversion and exsolution textures are often unique signatures of certain rock types. Our previous comparison of the distribution of the pyroxene compositions of 60019 and the lunar meteorites demonstrated that ALHA81005 and Y791197 contain Fe-rich pyroxene components from the VLT (Very low Ti) basalts (4) but 60019 and the Y82192 and Y82193 meteorites are poor in these components. VLT basalt flows near the Eimmart crater at the northern margin of Mare Crisium have been proposed for the source of the VLT basalt clast in ALHA81005 (7). Y791197 also contains such basalt. 60019 includes mare pyroxenes of the Luna 16 type, having small amounts of the Fe-rich components. The impact sites of the Y82192 and Y82193 meteorites may be far from a mare basin with a VLT-type lava flow, or the mare basalt in them may carry pyroxenes in other rock types poorer in Fe contents than 60019 such as low-Ti basalts.

In summary, chemical variations of the pyroxene fragments in the matrices indicate that all lunar meteorites show similar distribution trends of the Mg-rich pyroxenes but the Fe-rich trends are poorer in 60019, Y82192 and Y82193 than Y791197 and ALHA81005. These pyroxene fragments are more representative of the rock types distributed around the impact sites than the large lithic clasts, because of their smaller sizes. The clast populations of the PTS's differ from one PTS to another within the one meteorite. The sample size as large as that of 60019 is required to find the most dominant rock types within one sample. Lindstrom et al. (8) showed that compositional variations among breccias from the same crater exceed the variations between two lunar meteorites, Y791197 and ALHA81005.

The poikilitic clasts dominant in the Apollo 16 breccias have been proposed to have been derived from a large basin-forming impact event (12). As explained previously, the absence of such clast in the lunar meteorites suggests that the impact sites may be far from the large circular basin. This conclusion is in agreement with the proposed far-side origin of the lunar meteorites. The predominance of the granulitic breccia clasts in the Y82192 and Y82193 meteorites is in line with the proposal that the crustal composition of the far side may be rich in the granulitic rock type by Lindstrom and Lindstrom (14). Lunar granulitic breccias have metamorphic textures, anorthositic norite compositions, and little or no KREEP component (8). The compositional similarity of the lunar polymict meteorites to monomict granulites suggests that anorthositic norites similar to the plutonic precursors of the granulites are dominant source rocks of the lunar meteorites (8). Plutonic anorthositic norites may be more abundant in the early lunar crust, especially of the far side than is implied by the Apollo collection as suggested by Lindstrom and Lindstrom (14).

The evidence that the dominant rock types of the lunar far side may be different from the near side as revealed by the studies of the lunar meteorites suggests that the exploration of the far side by the geochemical remote sensing sattelite is highly recommended to gain better understanding of the entire moon.

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LUNAR GEOSCIENCE OBSERVER: ANSWERING BASIC QUESTIONS IN PLANETARY SCIENCE. G. Jeffrey Taylor* and Paul D. Spudis+, *Institute of Meteoritics and Dept. of Geology, University of New Mexico, Albuquerque, NM 87131. +Branch of Astrogeology, U.S. Geological Survey, Flagstaff, AZ 86001.

The Lunar Geoscience Observer (LGO) is slated to follow Mars Observer as the next mission in NASA's Observer series, although it has not yet been approved for funding. The mission will use the same type of spacecraft as Mars Observer. It will circle the Moon for a year in a polar orbit and provide global geochemical, mineralogical, and geophysical coverage of the Moon. Previous lunar exploration by Ranger, Lunar Orbiter, Apollo and Luna have returned a great deal of information about the Moon, but have not yielded complete global coverage. LGO is logically the next step in lunar exploration. To help focus attention on the scientific questions LGO will address, the Lunar and Planetary Sample Team, a NASA advisory committee managed by the Lunar and Planetary Institute, has organized a special session at the 18th Lunar and Planetary Science Conference. Although the session will focus on LGO, other future exploration, such as scientific research from a permanently-staffed base on the Moon, will also be discussed.

WHY THE MOON IS IMPORTANT

For thousands of years people have wondered about the nature and origin of the Moon, whose light dominates the night sky. It raises tides on Earth and inspires the human spirit. It might host the first settlement beyond Earth. The Moon also provides a window into solar system history. Though its origin is not known with certainty, it seems likely that it is intimately connected with Earth's origin. Among the rocky planetary bodies such as Mercury, Venus, Earth, and Mars, the Moon is relatively simple and has preserved a more detailed record of its evolution than do the others. In a sense, the Moon is the gateway to understanding the events that shaped the other Earthlike bodies in the solar system. For example, because samples of the lunar crust have been obtained and dated, the Moon serves as the basis for age estimates by crater counts on the surfaces of other bodies. As another example, the concept of the formation of primordial planetary crusts by planetwide melting was developed from lunar sample studies. Because of our understanding of the Moon as a result of the Apollo program, we are in a position to tackle fundamental problems in lunar science by asking detailed questions, the answers to which can be provided by specific measurements. LGO can make many of these measurements and provide the moonwide coverage that is at present lacking.

THE LGO INSTRUMENT PAYLOAD

As soon as the LGO spacecraft is inserted into its near-polar orbit 100 kilometers above the stark lunar surface, it will begin to analyze the Moon with a battery of instruments. The spacecraft will gather data for one year; this much time is essential to properly map the Moon's mineralogical, geochemical, and geophysical properties. The Solar System Exploration Committee recommended to NASA that LGO carry at least the following devices: 1) X-ray and gamma-ray spectrometers, which will produce global maps of surface elemental abundances. 2) Visual-infrared mapping spectrometer, which will provide a global map of surface mineralogy. 3) Radar altimeter, which will yield topographic data for geophysical studies and cartography for selected areas. 4) Radio science, which will map the lunar nearside gravity field by measuring the Doppler shift as the spacecraft changes velocity in response to changing gravitational force along its groundtrack. In addition, other experiments can be added to the core payload, including the following: 5) Magnetometer/Electron reflectometer, which would assemble a global map of magnetic fields and surface anomalies. 6) Imaging, which would produce a global, cartographic control net, support studies of compositional data, and allow photographic study of lunar surface processes. 7) Microwave radiometer, which would produce a map of lunar surface heat-flow. 8) Spacecraft gravity system, which would use a small subsatellite to map the lunar farside gravity field.

FUNDAMENTAL QUESTIONS IN LUNAR SCIENCE

In spite of intense study of lunar samples and geophysical and geochemical data returned by Apollo, the Moon's geologic mysteries are far from solved. We know enough, however, to pose some sophisticated questions.

How did the Moon form?

One of the scientific goals of Apollo was to answer this question. Apollo samples have given us firm data on the Moon's composition, one of the most important bits of information needed to test hypotheses for lunar origin, but the composition of the bulk Moon is still not known with certainty. Thus it is difficult on chemical grounds to test the three traditional models for the Moon's formation--fission from the primitive Earth, capture by Earth, and co-accretion with Earth--or two relatively new ideas--disintegrative capture and the impact-trigger hypothesis. This is an area of active, interdisciplinary research.

Assessing hypotheses of lunar origin requires a better understanding of the bulk composition of the Moon. Two of the most useful parameters are the abundances of uranium and thorium and the ratio of magnesium oxide to iron oxide. These parameters allow us to assess how closely the Moon and Earth are related. LGO will produce an accurate map of the surface distribution of uranium and thorium. The concentrations of these elements have been used by lunar scientists to estimate global abundances of other elements of similar geochemical behavior. The X- and gamma-ray spectrometers will determine the ratio of magnesium to iron over broad areas of the Moon to within plus-or-minus 3%, accurate enough to refine present comparisons with Earth's bulk composition. The magnetometer measurements will determine limits on the radius of a metallic iron core. This will greatly assist us in distinguishing among models for lunar origin.

How did the Moon's crust and mantle form and evolve?

The surprisingly high abundance of plagioclase feldspar (a silicate rich in calcium-aluminum) in the lunar highlands led to the idea that the primitive Moon was enveloped by a layer of magma (molten rock) at least 100 kilometers deep, in which plagioclase, a mineral with a relatively low density, floated to form the original crust. As plagioclase floated, denser minerals such as olivine and pyroxene (iron and magnesium silicates) sank to form at least some of the lunar mantle. This gigantic magma system is commonly called the "lunar magma ocean."

The idea of a magma ocean hinges on the composition of the Moon's crust. Some investigators question whether there really was a magma ocean, suggesting instead that a crust rich in plagioclase could be produced by successive intrusions of magma into a primordial crust (serial magmatism). In each intrusion, plagioclase would still concentrate toward the top, thus becoming the most abundant mineral in the uppermost crust. To distinguish between the magma ocean and serial magmatism hypotheses, we must know how much plagioclase (hence how much calcium and aluminum) resides in the crust and how its abundance varies around the Moon and with depth in it. Furthermore, a firm idea of crustal composition would help to assess how deep the initial melting was, which also helps decide among hypotheses for the Moon's origin, as some models predict total melting of the Moon, whereas others depict less extensive melting.

Available data from rock analyses and remote sensing support the notion of a plagioclase-rich upper crust, but we do not know the global average plagioclase abundance or how deep the plagioclase-rich region is. The combination of X- and gamma-ray spectrometers and visual and infrared spectrometers can unambiguously determine the plagioclase abundance on the surface in the highlands. LGO data will also allow more precise estimates of plagioclase abundance and its variation with depth. The resulting improved estimate of whole crust composition will provide better limits on lunar bulk composition, particularly for aluminum and uranium. Crustal density and density changes with depth in the lunar crust can also help evaluate the composition of the Moon's crust; such information will be obtained from the altimeter, gravity measurements, and the visual and infrared spectrometer.

Details of the mantle's composition and structure are obscure, especially how it varies in composition with depth and laterally around the Moon. We obviously need a global seismic network to make dramatic progress in understanding the nature of the lunar mantle, but progress can be made by obtaining better information about the layers above (the crust) and below (the core); LGO will improve substantially our knowledge of the crust and core.

What is the Moon's magmatic history?

After the magma ocean had solidified (assuming, of course, there was a magma ocean), the Moon's mantle and lower crust began to remelt and a vast array of magmas are thought to have intruded the highland crust during the period from 4.5 to 4.0 billion years ago. Lunar sample studies have identified at least eight types of magmas and more are discovered each year residing inside complex rocks from the lunar highlands. It is not known how these rocks relate to one another, to the magma ocean, or to products that might have come from the magma ocean. Global chemical and mineralogical information will help identify new rock types and discern how at least some of the highland lithologies relate to each other. The limitations on how well this can be done will not be set by limitations in the instruments carried by LGO, but by the jumbled nature of the lunar crust, the areal extent of outcrops, and the distinguishing characteristics of unknown rock types.

The dark, relatively smooth areas on the Moon were formed when lavas erupted and flowed across its barren surface, filling low areas, including most of the giant impact basins on the nearside. Mare basalts, as the dark rocks are called, are important because they formed by partial melting of the lunar mantle. Consequently, basalts are probes of the chemical and mineralogical character of otherwise inaccessible regions of the lunar interior. Because we do not yet know the full range of basalt compositions, we have an incomplete picture of mare basalt origin and, thus, a skimpy knowledge of the lunar interior and of processes operating inside the Moon that could have modified basalt compositions prior to eruption. A global geochemical survey would make the record much more complete. The X- and gamma-ray spectrometers and visual and infrared spectrometer can distinguish different types of mare basalts, even though impacts and mixing have somewhat altered original flow compositions.

Some lunar lavas erupted explosively, producing glassy deposits, such as the orange glass samples by the Apollo 17 crew. These materials are important because they have been affected the least by processes within the Moon, and so contain the most information about the lunar mantle. They also contain deposits of rare, volatile elements on their surfaces. The source of the volatiles is unknown. LGO will be able to map the distribution of glassy deposits (visual and infrared spectrometer) and determine their compositions (X- and gamma-ray spectrometers), including the abundances of some volatile elements such as chlorine and sulfur if they are present in sufficient amounts.

What is the Moon's thermal history?

It is important to figure out how the temperature in the Moon has varied over time and how the heat was transferred in the Moon. It is also important to understand the present temperature distribution inside the Moon as this affects the way we interpret the composition of the interior. Lunar thermal history can be addressed by analysis of surface features, topography, gravity, heat flow, and by estimating how the thickness of the rigid outer Moon has evolved in a given area. Insights obtained from study of lunar volcanism, such as estimates of eruption volumes versus time, will also be useful in unraveling lunar thermal history.

What processes operate during large meteorite impacts?

The scarred lunar highlands attest to the intense meteoroid bombardment the Moon received early in its history. During the first 600 million years of lunar history, the pounding converted at least the outer two kilometers into a rubble pile. Materials were mixed laterally and vertically, obscuring primordial lithologic variations. Nevertheless, Apollo remote sensing data clearly show that areas of the lunar highlands are dominated by one rock type, so not all the record has been lost.

Giant impacts may have confused the record of early lunar magmatism, but it has also revealed the nature of the lower crust and given us the opportunity to study how huge impacts disperse materials across planerary surfaces. This, in turn, will help us understand the mechanics of crater formation and the fate of the massive amounts of material thrown out of the crater. Imaging coverage of better spatial resolution and lighting conditions than currently exists is needed to utilize morphologic clues to the cratering process. The LGO compositional experiments can also reveal crucial information about impact cratering. For example, measurements of the compositions of crater and basin floor deposits can address directly the problem of whether impact melts are homogenized, specifically by looking for compositional variations within the sheet of impact-melted rock resting of crater floors. If ejected melt deposits are found around craters and basins, it is important to establisish their compositional affinities to the main melt sheet. These data will tell us about the process of impact melt homogenization and about probable movements of particles during excavation.

What is the source of the Moon's magnetic field?

The lunar crust is magnetized, although no field is now being generated inside the Moon. The origin of this magnetism is not known. It could be caused by a dynamo that operated in a metallic core or to transient processes such as impact. It is fundamentally important to determine the relative contributions of internal dynamo and impact processes to the production of the lunar magnetic field. Both the electron reflectance instrument and the magnetometer will map the distribution of surface magnetic fields and determine the correlation of magnetic anomalies with surface geology. To distinguish objectively between local and global lunar magnetizing fields, bulk directions of magnetization must be determined for a large number of sources with comparable ages around the Moon. Assuming that any former intrinsic field was dominately dipolar, identification of paleomagnetic pole positions that are significantly clustered for magnetic sources of comparable age would favor existence of an internally generated field. Alternately, if paleofield directions for contemporaneous sources are randomly oriented, then local mechanisms of generating a field would be more likely.

LGO AND FUTURE EXPLORATION

Besides addressing fundamental questions in lunar and planetary science, LGO will lay the groundwork for future exploration of the Moon. The global database this missions produces will allow intelligent selection of landing sites for manned or unmanned sample return missions. It will also allow us to explore for useful materials easily accesible from the surface. For example, there might be ice trapped in permanently-shadowed areas near the lunar poles, which will be readily detectable by the gamma-ray spectrometer. Finally, the information obtained from the LGO mission will help in the selection of the site of a permanently-staffed lunar base.

DEMONSTRATION OF A MASS INDEPENDENT ISOTOPIC FRACTIONATION IN CO REACTION.

by

Mark H. Thiemens and Daniel Meagher

A major goal of cosmochemistry has classically been the delineation of the different processes and components which were involved with the formation history of the early solar system. Of particular interest is the determination of the admixtures of components from different stellar (nucleosynthetic) sources. Specifically, since it is known that <u>all</u> material in the solar system is made by nuclear processes which occur within stars or exploding stars (novae), one wishes to know how many different stars are then required to make up the observed solar system.

More than 10 years ago, it was observed that in specific minerals from the Allende meteorite the oxygen isotopic composition was anomalous. It was concluded that, since no known physical or chemical process could produce such an effect, this exotic distribution must reflect a nuclear process. In particular, the specific details of the abundance distribution appeared to be due to the admixture of a pure oxygen isotopic component from a supernovae. Furthermore, the concussion from this admixture may have been the trigger for the collapse and formation of the solar system.

A few years ago, we reported a new isotope effect which had the unique feature that it altered isotopic ratios on a mass independent basis, the only observation of such a process. Aside from the inherent interest in the new chemical physics, the effect produced oxygen isotopic distributions <u>identical</u> to those observed in Allende and which were thought to represent supernovae debris. Hence, the supernovae scenario based on the inability to chemically produce such an effect was invalidated.

MASS INDEPENDENT ISOTOPIC FRACTIONATION
Thiemens, M. H. and D. Meagher

A limitation with the original work was that it involved ozone. It has coincidentally been demonstrated in the past few weeks that the isotopic effect we produce in the laboratory is observed in stratospheric ozone, and our mechanism is of applicability to the ozone problem. Ozone, however, was certainly never present in the early solar system where the major oxygen bearing species was carbon monoxide (CO). We have studied the isotopic partitioning in CO reactions, and exotic isotopic distributions are observable. It is possible that another new isotope effect is observable, though it is uncertain at present. CO chemistry is particularly important, since all of the inner planets are made largely of oxygen. Therefore, understanding the CO effects is of importance for understanding the very first steps in the planet forming process.

The Viscosity of Miranda

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With the Voyager 2 encounter with the Uranian system in January 1986, the satellites of Uranus have changed from being starlike points of light about which very little was known, to bodies with remarkable geological complexity. This complexity is especially surprising in view of their small sizes (the largest, Titania, has a radius 12% that of the Earth) and their low surface temperatures (around -220°C). Most astonishing, however,is that the satellites Ariel and Miranda, with radii 9% and 4% that of Earth, respectively, show very strong evidence for solid-state resurfacing.

Ariel exhibits some areas of apparently ancient, heavily cratered terrain. The largest crater, however is only 60 km in diameter, and has a clearly bowed-up floor, indicative of viscous relaxation. This process occurs when the near surface material flows, over geological period, like an extremely viscous liquid (perhaps 10^{23} times more viscous than water), to remove topographic relief. Aside from the icy satellites, this phenomenon is also observed on the Moon, Mars, possibly Venus and the Earth, where surface depressions in Scandinavia and Canada left by glaciers 10,000 years ago are slowly becoming shallower.

Other surface processes on Ariel seem elastic in nature: there is much faulting, where the surface has cracked in response to stress (of an as yet unknown origin: possibilities include global expansion due to internal heating or a change in density due to a phase change (a rearrangement of the crystal structure) of part of the interior). The floors of the valleys formed by the faults are convex, characteristic of the flow of a highly viscous liquid such as warm, but not melted, ice (as observed, for example, in glacial flows). In places this flow has continued over surrounding plains, and in one case partially buried a crater.

Miranda, although smaller, appears to have undergone even more geological modification. Overlying an apparently ancient, cratered terrain are assemblages of concentric ridges, scarps and dark banded material. Some of the scarps are 15 km high. Three regions of complex terrain are visible in the Voyager images, which cover virtually an entire hemisphere. These regions are typically 200 km in diameter.

Although Miranda's concentric ridges have some similarity to the grooved terrain on Ganymede (the largest of Jupiter's satellites), they are also associated with what appear to be extensive flow regions that, in some cases, have modified the geometry of the ridges. As in the case of Ariel, the convex topography of the flow indicates that it was extruded to the surface in the solid state. Many of the faults in the older, cratered terrain, lie perpendicular or parallel to complex terrain boundaries. Similar phenomena are observed on Earth, as a result of a process known as *diapirism*. In this process, spheres (or *diapirs*) of salt or mud cause, by stresses associated with their ascent, surface fractures in patterns similar to the spokes and rim of a bicycle wheel. As most circular features on the icy satellites are clearly associated with impact, the ovoid regions of complex terrain on Miranda may be the best candidates yet for terrain formed in this way. Just as spheres of mud or salt rise buoyantly in the Earth, because they are less dense than the surrounding soil, so in this case, the diapirs would be composed of buoyant, heated ice rising through colder, denser ice. It is imporatant, however, for the surrounding material to have a viscosity that is sufficiently low to allow the diapir to rise to the surface before it cools to such an extent that its buoyancy is lost.

We examine the problems that evolutionary thermal and structural models of Miranda must face, to provide an convincing explanation for the observed geologic activity. Since, as temperature increases, viscosity decreases, the evidence for low-viscosity flow indicates higher temperatures in the past, which require mechanism of heating. It would generally be expected that such a small, cold body as Miranda would have an extremely rigid surface. While the observed fault regions are consistent with a rigid surface, there is a major problem: Miranda is so round that its material must have flowed in the past, as described above, to create tis spherical shape. This, in turn, required a substantially lower viscosity (and thus higher temperatures) than exist now. For example, for relaxation of topographic features with diameter 100 km to occur, the surface regions of Miranda must have a viscosity appropriate to a temperature of -116°C, greater than 100°C above the surface temperature.

Two ideas for the formation of Miranda's complex terrain that we consider are that:

(a) It was formed just after a massive impact which blasted Miranda apart, leaving large bodies which, under their mutual gravitational attraction, recombined to form one satellite. This is suggested because Mimas and Tethys (both satellites of Saturn) have craters that resulted from impacts *almost* large enough to disrupt them completely. Some scientists thus believe, in the early solar system, such disruptions actually did occur. In this case, a possible way of heating the satellite to produce the observed flows is by the heat released during the collision of the recombining chunks of Miranda.

(b) The complex terrain represents a disturbed region overlying a diapir, as discussed above.

In the latter case the energy required for resurfacing must have an internal origin, such as radiogenic heating or tidal deformation.

A problem with applying idea (a) to Miranda is that the energy that can be obtained from collisions of recombining material for a body as small as Miranda is unlikely to cause a global rise in temperature greater than 20°C. Of course, local heating arising from point contacts between fragments may much greater temperatures in small regions. One final important problem that this mechanism must face is that, according to various evolutionary models of the icy satellites, radiogenic heating produces a maximum temperature profile for small satellites within the first 100 million years. If the satellite is undergoing a cycle of multiple disruption and accretion, the effect of this heating will be negligible.

Another constraint on the viscosity of Miranda's interior arises from the time required for diapirs to ascend to the surface. Here the low gravity of Miranda (1% that of the Earth's) means that buoyant forces are small, and ascent velocities are slower than would be appropriate for bodies of the same size and density on Ganymede. The viscosity of the ice must be sufficiently low to allow a 100 km diameter diapir to rise to the surface of Miranda before it cools to the temperature of its surroundings (and thus loses its buoyancy). The timescale for this is 300 million years, and the temperature needs to be 100°C higher than that observed, a result in good agreement with that above.

It is possible that an isotope of aluminium, ^{26}Al generated a significant amount of heat in the early history of Miranda. However, its half life is less than a million years, and so any resurfaced terrain that occurred as a result would be substantially older than the observed, very lightly cratered terrain on parts of Miranda.

It appears to be clear that some energy source other than accretional heating is required to provide both the spherical shape of Miranda and the evidence of substantial viscous flow activity. Idea (a) requires enhanced temperatures after the last recombination, placing serious constaints on short term heating processes. In addition, it has a serious problem in accounting for the absence of small-scale impact features on much of Miranda's surface.

Given the difficulties in finding a suitable energy source capable of raising Miranda's global temperature to a sufficient extent to reduce the viscosity of pure ice adequately, it may be possible to imagine that the viscosity of the ice within Miranda was lowered *without* increasing the temperature very much. This could happen if there were impurities such as carbon monoxide, nitrogen, methane or ammonia. In the case of ammonia mixed with ice (which melts at -100°C), the temperatures calculated above may actually have allowed some flow of liquid material.

As far as tidal heating is concerned, the energy required to produce increases in temperature of the extent calculated for the entire satellite, if expended over the period of 300 million years mentioned above is 0.1% of the heating rate associated with the tidal heating of Io (which produces the energy necessary to drive its spectacular volcanism). As yet, however, the orbit of Miranda does not appear to have permitted large amounts of tidal heating.

In conclusion, it should be emphasized that the energy that could be released by recombining fragments of Miranda, following a disruptive impact, could not possibly account for the active geological history of Miranda. Therefore, even if Miranda was disrupted by impact during its early history, some additional endogenic energy source (as yet unknown) was probably also required to produce the geological activity observed.

Simultaneous Measurements of C, Ni, and P in the Toluca and Algarrobo Iron Meteorites

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Carbon is the third most abundant element of the universe after hydrogen and helium. It occurs copiously in stars, in the interstellar medium, and in the outer portions of the solar system, where one finds the giant planets. The element occurs much less abundantly in the terrestrial planets, e.g. the Earth, and in meteorites, probably because carbon easily forms very volatile compounds such as methane, CH_4, or carbon dioxide, CO_2.

Among the meteorites which collide with the Earth, there occur chunks of metal, primarily made up of the elements iron and nickel. All other elements occur in amounts less than 1% by weight. Our scientific predecessors have, long ago, concluded that the formation of these iron meteorites would require the separation of iron and nickel from other elements, the melting of the metal, and very slow cooling and congealing at rates of degrees per million years.

The internal constitution of the metal of the iron meteorites is analogous to that of man-made steels, except that the meteoriticist uses different names for similar phases: kamacite for austenite and taenite for ferrite for example. Iron meteorites contain carbon. Moore, Lewis, and Nava have measured, in 1969, C contents of bulk samples of 100 iron meteorites with the classical technique of burning the C to CO_2. They report contents in the range 0.001-0.06%. Some iron meteorites contain graphite, others a carbide $(Fe, Ni)_3C$, called "cohenite". Owing to the metallurgical industries, we know a great deal about the solubility of C in the various forms of nickel-iron.

The scientific challenge of C in iron meteorites is to determine its distribution on a microscopic scale in order to find whether that distribution is what one expects, or whether it is different in some respects, and why. Ours is the first attempt to achieve these objectives. We have used a nuclear technique in which a fine beam, some tens of micrometers across, of deuterium-nuclei, with energy of 1.2 million volts, is directed onto the sample, which can be moved to expose different spots successively to the beam. Most of the nuclear interactions result in scattering of the deuterons, but occasionally, the reaction $^{12}C(d,p)\,^{13}C$ occurs, that is to say the deuteron is absorbed by a ^{12}C nucleus, a proton emerges, and a ^{13}C nucleus remains behind. We measure these reaction protons. The rate at which they form is proportional to the concentration of ^{12}C nuclei in the surface of the metal where the deuteron beam strikes. The beam also generates X-rays in all elements. We have used these X-rays to measure, simultaneously with carbon, also nickel and phosphorus. All measurements were done at the Cyclotron Facility of the Vrye Universiteit, Amsterdam, The Netherlands.

Our first results show that the Ni-rich portions of the metal are richer in carbon than the Ni-poor portions, which was expected, but we find that the amounts of C in the Ni-rich areas are less than the solubility of C at 600°C. Where did it go? To form graphite grains, which occur both in Toluca and Algarrobo. We find that the Ni-rich portions of the metal contain essentially no phosphorus and that the P-distributions in the Ni-poor areas are very uneven. Both observations were known prior to our work.

From the analytical point of view, we have demonstrated that accurate measurements of C in iron meteorites down to 0.01% are possible with the $^{12}C(d,p)^{13}C$ technique. The measurements are also non-destructive, i.e., the samples remain available for other studies, or even for repeated studies. Currently, this is the only technique available for measuring C non-destructively at the concentration levels of iron meteorites. Improvements on which we are working include: better calibration standards, narrower deuteron beams, and stabler deuteron beams. The technique is of interest to steel-makers also.

Continued studies of C and P in iron meteorites will eventually lead to considerations about metallic cores of large planets such as the Earth. Among the several unanswered questions about such cores is not merely whether they contain carbon, but where did the carbon come from and where did it move during the cooling of these metal bodies?

ARE IDPs AND HALLEY DUST SIMILAR AND, IF SO, SO WHAT?; R. M. Walker, McDonnell Center for the Space Sciences and the Physics Department, Washington University, St. Louis, MO 63130, USA.

This paper discusses the relationship between interplanetary dust particles (IDPs) and the dust from Halley's comet. Several groups have been studying IDPs intensively for several years using a variety of experimental techniques.* The IDPs are collected under clean conditions in the stratosphere using U-2 aircraft. The dust collectors are returned to the Johnson Space Center, where individual particles are removed and given a preliminary examination. Catalogs describing the particles are distributed to the scientific community and individuals submit requests for samples. The curation and allocation process is analogous to that originally developed for lunar samples and Antarctic meteorites. However, the dust particles are extremely small (~ 10^{-3}cm). So small, in fact, that they cannot be seen by the naked eye! All sample picking and handling must be done using microscopes and detailed study of the particles requires highly sophisticated instruments.

Why bother to study such tiny particles? Primarily because of the hope (at least partially realized in practice) that IDPs may be the most primitive, least-altered material left over from the formation of the solar system.

Spurred by this prospect, scientists have developed a range of sensitive techniques for studying IDPs. The abundances of the major elements and the mineral assemblages have been measured using electron beam techniques. Application of mass spectrometry, particularly the relatively new technique of the ion probe, has made it possible to measure the isotopic patterns in different parts of a single particle. This work has shown that many IDPs have small hot spots of carbonaceous material that are greatly enriched in deuterium, the heavy isotope of hydrogen (see abstract by McKeegan et al., this conference). Optical spectroscopic measurements have demonstrated the existence of several classes of particles and show that the spectral properties of IDPs have similarities with those of dust seen in interstellar clouds and comets.

The possible connection of IDPs to comets is an important issue. Part of the incentive for studying interplanetary dust in the first place was the widely-held view that most interplanetary dust originates in comets. Comets, in turn, are believed by many to be the most likely repositories of primitive solar system materials left over from the processes of planet formation.

Last year saw a substantial increase in our knowledge of comets. Four instrumented spacecraft (none of them American) flew close to comet Halley and astronomers in many observatories also studied the comet intensively from the ground. The prospect of finding primitive material that can give new insights into the early history of the solar system also provides the basic motivation for the CRAF Misson (C omet R endezvous A steroid F lyby) currently being planned by NASA and the Comet Sample Return Mission being discussed by the European Space Agency (papers relevant to both of these missions are also being presented at this conference).

There is a complete morning session devoted to cosmic dust studies at this meeting.

ARE IDPs AND HALLEY DUST SIMILAR
Walker, R. M.

Two important consequences follow if it can be shown that interplanetary dust is similar to the dust in Comet Halley. Firstly, the laboratory data available on IDPs could be used to guide the selection of experiments for the comet missions currently being planned. Secondly, we could begin to answer important questions about cometary material prior to obtaining additional data from future missions.

It should be said immediately that we can never prove that IDPs and comet dust are identical. Only future comet missions can finally resolve the issue. It is also true that laboratory studies of IDPs can never answer all the first order questions about comets. For example, any volatile material originally present in IDPs is destroyed as the particles are heated during their entry into the atmosphere. Comet missions and laboratory studies of IDPs can thus be viewed as complementary aspects of the larger problem of understanding the history of the early solar system.

The paper reviews the current situation to see whether an IDP-Halley dust connection is tenable or not. It is the author's view that, at this stage of the game, the answer is yes. Laboratory measurements of the optical properties, elemental abundances, and isotopic structures of IDPs are all consistent with what has been found for Halley dust.

However, it is stressed that the comparisons that can be made at this time are still limited compared to what will be possible in the future. Probably the most relevant data for comparison were obtained by three instruments (PUMA, I, II, and PIA), which were designed by J. Kissel (Max-Planck Institut für Kernphysik, Heidelberg) and flown on the Giotto and Vega Missions. The instruments mass-analyze the ions produced by the impacts of individual dust grains to obtain elemental and isotopic information on a grain by grain basis. The Halley dust particles were tiny (~ 10^{-5}cm), even by IDP standards. The comparison that must be made therefore is between Halley dust and small sub-units of IDPs. The Halley data needs to be further analyzed and more data needs to be obtained on small regions of IDPs similar in size to the grains studied in the Halley mission.

In an interesting paper to be presented at this meeting, Brownlee et al., assert that the dust impact data from Halley are not consistent with small spot analyses of primitive meteorites. In contrast the data apparently are consistent with spot analyses of at least some IDPs. This work supports the view expressed in the present paper.

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