Lunar and Planetary Science XIII

Press Abstracts
Thirteenth Lunar and Planetary Science Conference
March 15-19, 1982

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PRESS ABSTRACTS

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PREFACE

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

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

The following abstract was also thought to diserve widespread attention, but could not be rewritten in time to appear in this volume (page number denotes location in *Lunar and Planetary Science XIII*):

Volcanic processes on Venus
J. W. Head and L. Wilson, page 312

IMPACT OF AN ASTEROID OR COMET IN THE OCEAN AND EXTINCTION OF TERRESTRIAL LIFE, by T.J. Ahrens and J.D. O'Keefe, Seismological Laboratory, California Institute of Technology, Pasadena, CA 91125.

Computer calculations reported by Drs. Thomas J. Ahrens and John D. O'Keefe of the California Institute of Technology on March 15, 1982 at the 13th Lunar and Planetary Science Conference in Houston, Texas describe the huge 3-mile-high-water-wave which is likely to have resulted from the impact of an asteroid or comet with the Earth some 63 million years ago. This is exactly the time that some 90% of the animals which had evolved on the Earth suddenly disappeared. These animals included the tiny plankton living near the sea surface, many corals, elaborately chambered swimming marine animals called ammonites and on land some 26 species of dinosaurs living in what is now the Montana-Wyoming region of the United States, Western Europe and Mongolia. The evidence that such a hugh impact in the ocean may have occurred now resides in a thin 1 to 5 inch thick boundary layer of fine dust or clay composed of what appears to be almost 20% meteorite material, which has now been recognized in sedimentary rocks exactly 63 million years ago and appears to be worldwide. Occurrence of this layer which is identified as being meteoritic in origin because it contains some 5 to 1000 times the ordinary earthly abundance of metals such as iridium, osmium, gold, platinum and palladium has now been discovered in 63 million year-old rocks formed in marine environments in Western Europe, North Africa, New Zealand, Haiti and very recently in Texas. Moreover, this meteorite, or platinum metal-rich layer has also been recovered from numerous sediment cores of exactly 63 million year age by the Deep Sea Drilling Project in both the Atlantic and Pacific Oceans. Evidence which most scientists now agree proves that a giant meteorite or comet hit the Earth 63 million years ago also has been recovered and a dust layer has been found in freshwater deposited coals, in New Mexico and Montana. Recently results from the Berkeley, California Laboratory of the father and son team Luis and Walter Alvarez and from paleontologist, Professor William Clemens, demonstrate that in the Hells Creek, Montana locality the dust layer lies some 10 feet above the fossilized leg-bone of the awesome dinosaur, Tyrannosaurus. This was in fact one of the largest of the giant flesh-eating dinosaurs, weighing 7 tons, and standing some 16 feet tall on powerful hind legs. This creature had an estimated total length of 45 feet. The Alvarezs' proposed in fact that the meteorite dust layer which was caused by the impact process was spread worldwide and obscured the Sun for an extended period and this caused the demise of the dinosaurs. Current estimates of the time of complete darkness are now 3 months. This dramatic hypothesis in which the production of plant life by photosynthesis might have been disrupted and affected both the marine and land food chain has been one of the most controversial issues in the study of evolution of ancient life since Charles Darwin first proposed his basically gradualistic hypothesis of survival of the fittest species in 1859. It is the Alvarezs' hypothesis which led Ahrens and O'Keefe of Caltech to describe a somewhat different disaster scenario in which they have studied the effect of a meteorite impacting in the deep ocean. The reasons for studying an ocean impact is that the Earth's surface is composed of 70% ocean and since a crater of the expected diameter, about 100 miles, on land of the correct age has not found, an oceanic target is the most likely. Moreover, they note that some 51% of the ocean floor that existed at 63 million years ago has now been recirculated into the deep Earth's interior, and hence the Earth has a way of hiding impact scars on the ocean floor. The size object

IMPACT OF AN ASTEROID OR COMET

T.J. Ahrens

they assume for their calculation, 7 miles in diameter, is obtained using the observed concentration of platinum group elements in the boundary layer and the total mass of material found in the boundary layer. The Caltech scientists calculate that the 4 seconds after impact of an asteroid hitting a 4-mile deep ocean on the Earth at 25 miles/second, a cavity some 25 miles wide and 20 miles deep would be produced at the impact point and contain super heated water and vaporized rock. A 30-mile diameter steam bubble extending some 25 miles into the atmosphere would cover over this transient crater. The water ejecta from such an event would contain some 12 to 14% of the 1 billion megatons or so of equivalent TNT energy of this impactor. Aside from launching from 10 to 100 times the projectile mass of rocks and water into the upper atmosphere Ahrens and O'Keefe claim that this is the origin of the worldwide dust layer. Finally, the transient cavity in the ocean would produce a giant tidal wave. They calculate that such a wave would envelop the entire Earth at 27 hours. Ahrens and O'Keefe further suggest that even in the deep oceans tidal wave will be 500 feet high halfway around the Earth. They conjecture, since at the time of the extinction of the dinosaurs 63 million years ago the Earth had little or no ice in the polar caps about 25% of what is now land area was submerged by shallow inland seas connected to the ocean. Ahrens and O'Keefe speculate that the impact-induced tidal wave would cause a major catastrophe in dinosaur country. Paleontologists have described the dinosaur habitat as land that is marshy and can supply the large amount of plants that these huge reptiles, or the reptiles that fed on the reptiles, required to sustain them. Thus they propose that an impact in the ocean produces a tidal wave that upon running onto land will cause extensive stripping and silting over all vegetation. They suggest that this would cause destruction of the food chain for all large land animals. Although their calculation assumes an ocean impact Ahrens and O'Keefe believe a tidal wave might well have been produced, even if an impact occurred on land, since the energies of the 63 million year-old impactor involved correspond to those calculated to be equivalent to a Richter magnitude 12 earthquake. The very energetic impact on land would probably produce a seismic sea wave as well as trigger landslides both on land and mud flows on the marine continental shelves. They in fact are troubled by the lack of evidence for such a disturbance of the sediments that have been studied to date. They suggest that evidence for impact breccias, such as are found around large impact craters on land and submarine landslide deposits need to be sought in the many localities that the 63 million year-old boundary layer has now been found.

VOLCANIC RESURFACING OF THE LUNAR NEARSIDE HIGHLANDS. C. G. Andre and P. L. Strain, National Air and Space Museum, Washington, D.C. 20560; and W. J. Dove, University of Maryland, College Park, MD 20742.

There are striking physical and chemical differences between the nearside and farside terra provinces of the Moon that must be accounted for in any evolutionary model of the lunar crust. The term "terra" includes both the nearside and farside "highlands", that is, the material surrounding the iron and magnesium-rich basalts that fill the large basins.

Although samples have never been collected from the farside surface, remote sensing data indicate that the far side has a) higher elevations; b) a thicker crust; c) higher reflectivity; d) higher concentrations of aluminum; e) lower concentrations of magnesium, iron, thorium and titanium, and f) a lower density. This low density material (anorthosite) is believed to be the earliest solid crust to form by rising to the top of the molten outer portion of the Moon. It is rare on the surface of the near side. Places on the near side where it does occur are thought to be representative of the subsurface, e.g., crustal material uplifted during basin formation or excavated from large craters during meteorite impacts. This suggests that much of the near-side highlands has been "resurfaced", creating a chemistry differing from the underlying rocks and those on the far side.

One possible cause of the chemical disparity between the lunar hemispheres is nearside terra volcanism that covered pre-existing surfaces. The form and texture of many nearside terra units suggest a volcanic origin, although the long history of meteorite impacts has subdued the sharpness of the volcanic features and destroyed the smallest ones.

Therefore, volcanism was commonly proposed prior to the Apollo 16 landing in the Descartes Highlands to explain many terra units on the lunar near side. The belief that the light-colored plains were volcanic, based on photogeologic criteria, was one of the main scientific reasons for selecting the landing site. However, the results from the samples collected at the Apollo 16 high-land site were totally unexpected; there was no textural evidence that the plains there were volcanic. Instead, the samples were, for the most part, breccias (cemented broken rock fragments).

Since this finding, impact-related interpretations of geologic units, rather than volcanic ones, have predominated. Another conflict was created, however, between the "hard" evidence, from the landing site samples, against volcanic activity, and remote sensing data from the orbiting spacecraft. That is, chemical variations detected by the remote X-ray spectrometer showed higher concentrations of magnesium and lower concentrations of aluminum for many plains units compared to the surrounding terra. This observation strongly implies that these units are not local material reworked by impact activity, nor are they part of a widespread ejecta deposit from some distant source. Rather, it is more likely that they are iron and magnesium-rich volcanic materials extruded into low-lying areas within the nearside terra.

There is clear evidence in the orbital X-ray data that other nearside terra units are also volcanic in origin. We have studied the terra west of the Fecunditatis basin. Diverse rock types can be distinguished there based on variations in the magnesium to aluminum (Mg/Al) ratios (Figure 1). For instance, the unit of hummocky material exhibits the highest Mg/Al values (solid circles) for six orbits over the area; whereas the undivided terra to the west registers the lowest values (open circles). The profile below the map shows the continuous variations along the groundtracks of the northernmost orbits within the coverage indicated. The highest Mg/Al values from the southernmost orbits do not show a significant increase over the central terra values. However, in the data for the hummocky unit, the ratio of magnesium to aluminum increases 75% compared to the terra to the west. This ratio is only 21% less than the iron and magnesium-rich basalts that filled the Fecunditatis basin at a later date. The calculated MgO weight percent is as high as 9.27 and the Al_2O_3 weight percent is as low as 19.4. FeO and TiO_2 weight percent values from gamma-ray data are 10.5 and 3.5 respectively, well above the farside terra.

The hummocky unit is characterized by multiple subparallel graben (linear extensional fractures) trending northwest/southeast in the direction of the lunar grid and radial to the Imbrium basin. The graben extend hundreds of miles across both basin fill and highlands. Non-circular rimless depressions are associated with the graben. Smooth, relatively dark patches can be seen, and many large craters with modified floors and irregularly-shaped central peaks are common in and around the unit. The high Mg/Al values for the unit with respect to surrounding terrain, its relationship to deep-seated crustal fractures (laval sources?), volcanic crater forms and modified crater features all suggest that volcanism has resurfaced some of the primitive terra material in this region. Other areas of the nearside terra currently under study also indicate that early volcanism in the terra is, indeed, a major contributor to the chemical differences between the nearside and farside terra provinces.

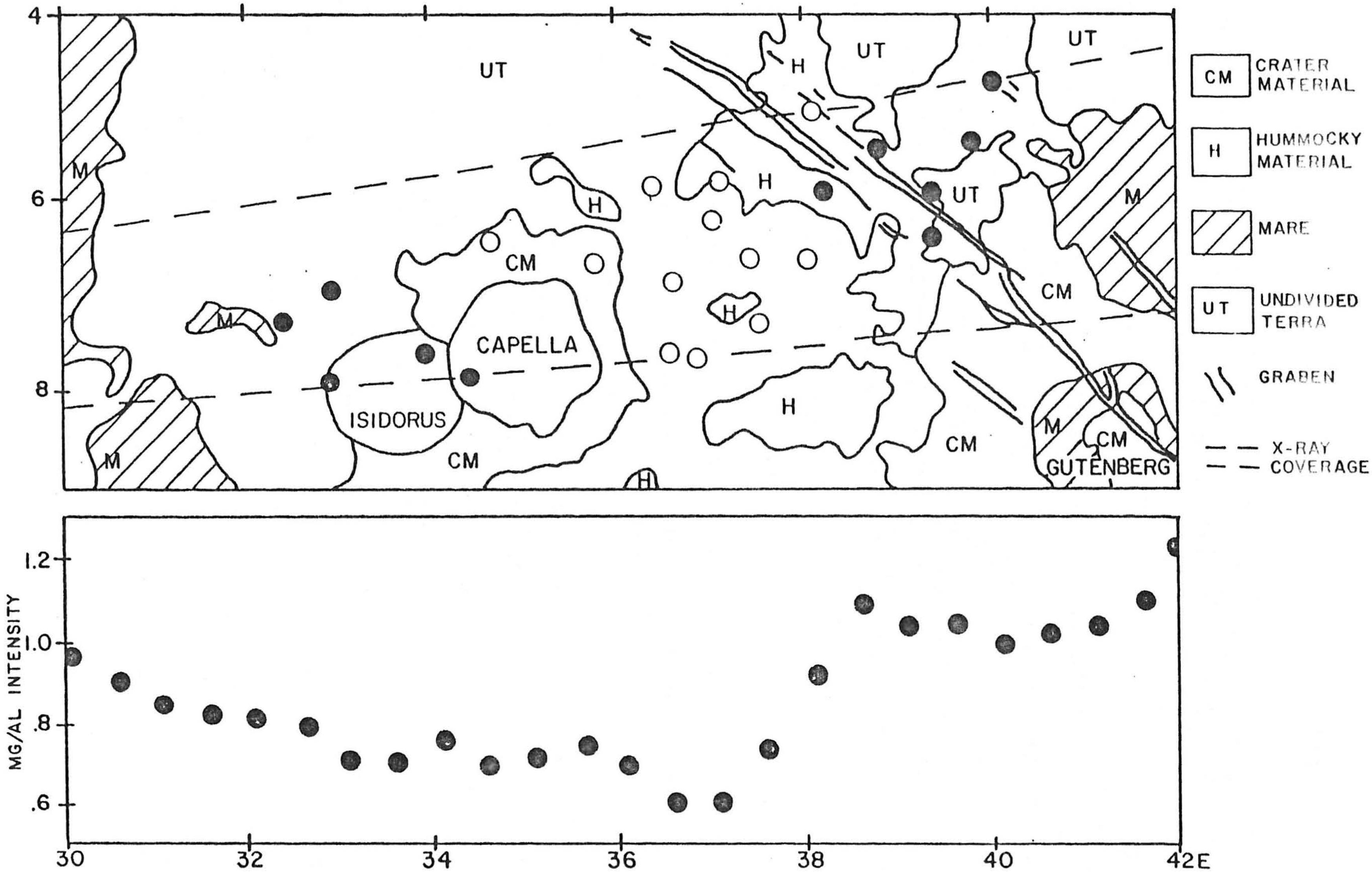

Fig. 1. Top, sketch map of study area showing different geologic units. Solid circles mark highest magnesium to aluminum ratios. Note how they cluster in hummocky unit indicating it has a composition distinct from that of surrounding terrain. Bottom, profile of magnesium to aluminum ratios across region pictured in sketch map. Note rise in value across hummocky unit.

METEORITES FROM MARS? THE DEBATE CONTINUES

Lewis D. Ashwal[1], Jeffrey L. Warner[2], and Charles A. Wood[2]
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Of the thousands of meteorite samples in museums throughout the world, there are nine unusual ones, about which scientists have recently become extremely excited. The reason: the peculiar properties of these rocks suggest that they may be samples from the surface of Mars. Samples from Mars would be extremely important in helping scientists understand the Red Planet. The nine "SNC" meteorites (shergottites, nakhlites and chassignites) are different than other meteorites because they formed relatively late in solar system history, about 1.3 billion years ago. Nearly all other meteorites are much older (about 4.5 billion years), and are thought to represent fragments of asteroids that were formed during the construction of the solar system. The young SNC meteorites are igneous rocks with a "cumulate" texture, meaning that they formed from molten silicate rock, perhaps a lava flow, which cooled slowly enough so that minerals crystallizing from it could sink, or "accumulate" due to gravity. Since asteroids are thought to be too small to maintain sufficient heat to produce magmatic or volcanic activity as recently as 1.3 billion years ago, a larger planetary body must be considered as an alternative source. On these grounds it has been argued by Charles A. Wood of NASA's Johnson Space Center and Lewis D. Ashwal of the Lunar and Planetary Institute, both in Houston, that Mars is the best candidate. The case for Mars is strengthened by other features of the SNC meteorites, including their chemical composition, which is similar to that of Martian soil analysed by the Viking lander in 1976.

METEORITES FROM MARS?

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The main difficulty with the meteorites-from-Mars theory is the enormous energy required to lift rocks into space, away from the influence of martian gravity. Escape velocity for Mars is about 5 kilometers per second (11,000 mph) as compared to 2 1/2 kps (5400 mph) for the Moon, and about 11 kps (25,000 mph) for the Earth. Large meteorites impacting the surface of Mars could provide the needed energy, but the ejected fragments of Mars' surface sould be highly shocked, if not vaporized by the blast. Some SNC meteorites have been shocked, but not enough, some scientists feel, to have been derived by impacts on the Martian surface.

Because of these difficulties, scientists Ann Singer and Jay Melosh of the State University of New York at Stony Brook suggested at the 13th Lunar and Planetary Science Conference in Houston that instead of being derived from Mars, the SNC meteorites represent pockets of melted rock caused by impacts on large asteroids. They think that objects 3 to 6 miles across hit the asteroids and left thick sheets of molten rock in the bottoms of the craters. These melt sheets are proposed to have cooled slowly enough to produce the cumulate textures of the SNC meteorites. Later collisions then blasted the SNC meteorites to Earth.

In a presentation given at the same meeting, Lewis Ashwal and colleagues Charles Wood and Jeffrey Warner disagreed with the theory of Singer and Melosh. They pointed out that melt sheets produced by meteorite impacts would not have the characteristics of the SNC meteorites. Studies of thousands of samples of impact melts from the Moon and from meteorite craters on Earth show that the melt cooled very quickly by violent mixing with cold rock fragments from the target area; too quickly to produce the cumulate textures of the SNC meteorites. No cumulate textures, therefore, have ever been observed in impact melts, even from the largest meteorite craters on Earth. Additionally, details of the chemistry of the SNC meteorites are inconsistent with the

Singer and Melosh hypothesis. Hence, Ashwal and his colleagues continue to endorse the Martian origin for the SNC meteorites.

How then did these unusual meteorites get transported from Mars to Earth? In another presentation at the conference, Lawrence Nyquist of Johnson Space Center discussed a possible mechanism. He said that if incoming projectiles struck the surface of Mars at a shallow enough angle, Mars rocks might riccochet into space rapidly enough to escape Mars' gravity field. His calculations also show that the ejected rocks might not have been shocked too intensely, and the cumulate textures of original Mars lavas could thus be largely preserved in the SNC meteorites. Cratering studies show that such shallow angle impacts leave characteristic "butterfly" ejecta patterns. These are plentiful on Mars and a few are even found on the flanks of large Martian volcanoes. These enormous volcanoes, then, may be the ultimate source of the SNC meteorites.

The debate about the SNC meteorites will probably continue because whatever their origin, it is likely to be exciting, and may provoke scientists to rethink their ideas about where other meteorites came from.

The Dark Side of Iapetus Jeffrey F. Bell[1,2], Dale P. Cruikshank[2], Michael J. Gaffey[1], Robert Hamilton Brown[1,2], Robert Howell[2], Charles Beerman[2], and Mark Rognstad[1]. [1]Planetary Geosciences, Hawaii Institute of Geophysics, University of Hawaii [2]Institute For Astronomy, University of Hawaii.

The Saturn satellite Iapetus has been one of the solar system's mysteries ever since its discovery in 1671 by G. D. Cassini of the Paris Observatory. Cassini noted that the satellite was about six times brighter when on the western side of Saturn than when on the eastern side, and that its brightness varied smoothly between these extremes. He concluded from this that one hemisphere of Iapetus was much brighter than the other, and that the satllite's rotation was synchronous with its rotation about the planet like that of the Earth's moon. Exactly three centuries later in 1971, infrared observations demonstrated that Cassini's explanation was correct. From telescopic data it was possible to establish that Iapetus possessed two totally different surface units: dark material (as dark as the darkest asteroids) on the "leading"hemisphere which faces forward in the direction of orbital motion, and bright material reflecting about 50% of the incident sunlight on the trailing hemisphere (with a projection onto the leading side at at least one pole). The Voyager images have recently provided dramatic confirmation of these ground-based observations. While infrared spectroscopy in 1976 showed that the bright material is mostly water ice, the composition of the dark material and the reason for its peculiar distribution have remained obscure.

Over the past several years the authors have made new observations with the 2.2-meter telescope of the University of Hawaii and the 3.8-meter United Kingdom Infrared Telescope (both on Mauna Kea, Hawaii) which provide the basis for an interpretation of the dark material's composition. The reflection spectrum of a planetary surface (the fraction of sunlight reflected at different colors) is diagnostic of the surface's minearlogical composition. Analysis of such spectra has led to the discovery of H_2O, SO_2, and CH_4 ices on other outer solar system satellites, and a variety of silicate minerals on asteroids and terrestrial planets. The spectrum of Iapetus taken when the dark side is turned toward Earth (Fig. 1) resembles that of the complex mixture of organic compounds found in the carbonaceous chondrite meteorites. (Shallow water ice absorbsion bands are also visible in the infrared due to the "polar caps" which extend onto the dark hemisphere.)

No other common meteoritic materials exhibit the combination of a steep red spectrum in the visible with a constant reflectivity in the infrared (1-2.5 microns). Carbonaceous chondritic meteorites contain only up to about 3% organics and have considerably different spectra.

Since the Iapetus material appears to be spectrally dominated by the organic component, it must be much richer in carbon compounds than any known meteorite. Such "ultra-primitive" meteoritic assemblages are likely to have formed in cool regions of the original protoplanetary nebula. (A class of asteroids--the "D-type"--have spectra very similar to that of Iapetus and

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may be made of the same material. These objects are rare in the main asteroid belt but are common in the Trojan asteroids which live in the orbit of Jupiter, suggesting that the hypothetical organic-rich material is common in the outer solar system.)

The distribution of the dark material is precisely centered on the direction of orbital motion, which has suggested to many that some assymetry in the external environment is responsible. Some years ago it was shown that debris knocked off the outermost Saturn satellite, Phoebe, will spiral toward Saturn due to light-pressure effects. Since Phoebe orbits in the opposite direction to Iapetus, the Phoebe-dust will collide with the leading side at high velocity. The hypothesis that the dark material is Phoebe-dust coating the original ice surface is not confirmed by spectrophotometry of Phoebe, whose spectrum shows no similarity to that of the Iapetus material. We propose a modified version of this idea, in which the dark material was originally a minor constituent of the icy surface. The impacting dust from Phoebe preferentially vaporizes the ice, leaving the dark material behind as a thin surface coating.

An alternate theory holds that the dark material is the product of eruptive volcanism in the distant past. This concept does not explain (a) the correlation with orbital motion, (b) the lack of recent craters penetrating the dark material, (c) an apparent systematic increase in brightness of the dark material toward the boundary. Study of the structure along the boundary in the Voyager II images may resolve this question. The modified Phoebe-dust model predicts a specific correlation of brightness with terrain as shown in Fig. 2, while an internal origin would imply dark material confined to low regions in the transition zone.

The Dark Side of Iapetus

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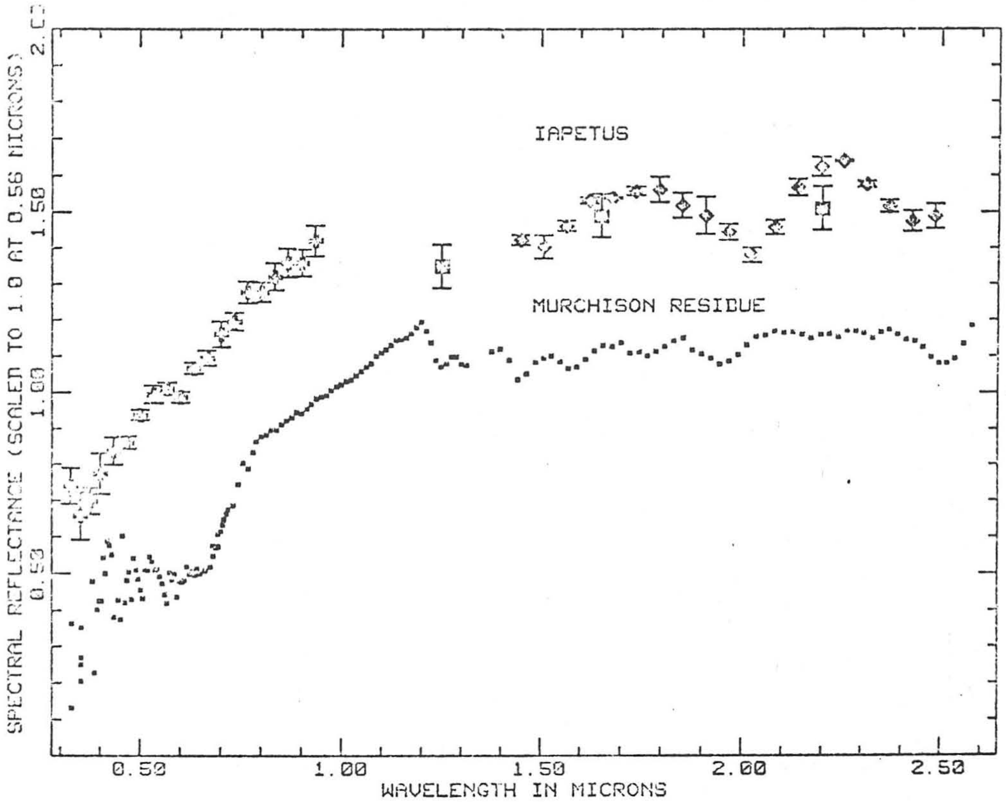

Figure 1: The observed spectral reflectance curve of the dark face of Iapetus (top) compared to the laboratory curve of the organic residue from the Murchison carbonaceous chondrite.

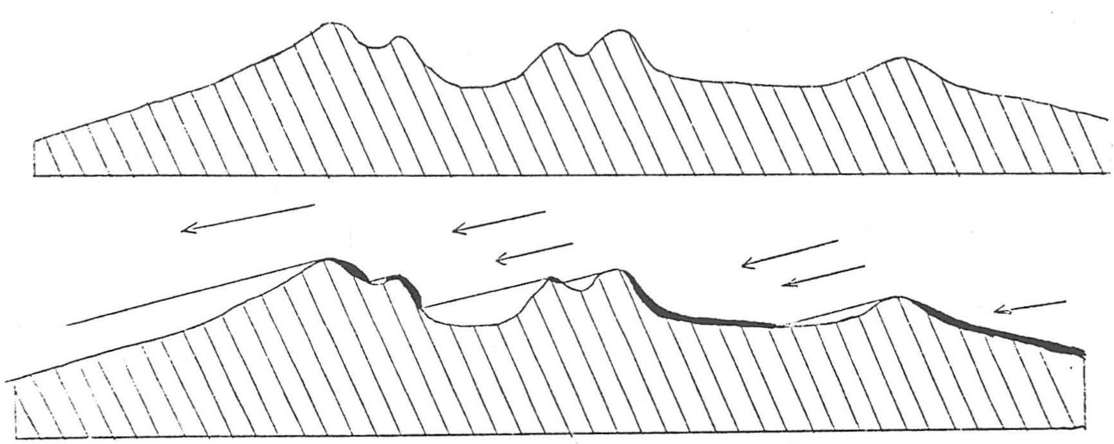

Figure 2: Schematic representation of the effect of surface topography on the selective volatilization of ice by impacting Phoebe dust near the boundary between the leading and trailing hemispheres. The organic residue left by the removal of the water ice would be concentrated on those surface areas exposed to the incoming dust flux and be absent on surfaces shielded from the flux.

I-Xe AGES OF INDIVIDUAL BJURBÖLE CHONDRULES, Caffee M.W., Hohenberg C.M., Hudson B. and Swindle T.D., McDonnell Center for the Space Sciences and Department of Physics, Washington University, St. Louis, MO 63130 USA.

Meteorites, extraterrestrial stones which occasionally fall on the earth, are believed to be the remnants of asteroid-sized objects that were among the first solid objects formed in the solar system.

Now for the first time, relative formation ages of individual chondrules, BB-sized balls found in most meteorites, have been determined. These ages, obtained using iodine-xenon (I-Xe) dating, seem to indicate that the chondrules formed at times about a million years different from the time of formation of the meteorite as a whole.

When dated using a variety of radioactivity-based methods, most meteorites appear to be about 4.5 billion years old, much older than any rocks from the earth. The study of meteorites can thus give information about what happened as the solar system formed.

One big puzzle about meteorites is chondrules. These tiny spheres are embedded in material similar to that of the chondrules, but their roundness indicates they formed as liquid drops. How, when and where the chondrules formed is uncertain, as is how and when they were put together with the surrounding material.

In an attempt to find out more about the when of these questions, several chondrules from the meteorite Bjurböle were analyzed using the I-Xe dating method.

Other dating techniques can give absolute ages, usually with a precision of tens to hundreds of millions of years. I-Xe dating can't tell how old an object is, but it can tell the age of one compared to another with a precision of tens to hundreds of thousands of years.

Like most dating schemes, the I-Xe method uses as its clock a radioactive isotope that decays in a very regular fashion. In I-Xe dating, the isotope is iodine-129 (^{129}I), which has a halflife of 17 million years.

Originally, the element iodine came in two isotopes, stable ^{127}I (which we observe today) and ^{129}I. But since ^{129}I is radioactive, the ratio of ^{129}I to ^{127}I halved every 17 million years.

Today, none of the ^{129}I is left. However, its decay product, stable ^{129}Xe, is left as a record of its one-time existence.

Solids that formed early in the history of the solar system, back when ^{129}I was still present, contained within their mineral structures various quantities of iodine, with the ratio of ^{129}I to ^{127}I depending on the time when the mineral formed.

Today, we still observe ^{129}Xe in these ancient mineral sites. It is the ratio of the ^{129}Xe (from ^{129}I decay) to stable ^{127}I that provides the way to read the I-Xe clock.

To date a sample, it is first taken to a nuclear reactor and bombarded with neutrons, which convert a fraction of the ^{127}I into another isotope of xenon, ^{128}Xe.

Using a noble gas mass spectrometer, which separates atoms of different isotopes by giving them an electrical charge and sending them through a magnetic field, the amount of each isotope of xenon present can be found. When the data is analyzed, the initial iodine composition and thus the formation time can be determined.

The primary difficulty in finding I-Xe ages for objects as small as chondrules is the amount of xenon present. The chondrules aren't very big to start with, and less than a billionth of the chondrule is xenon. The experiment thus requires both a mass spectrometer sensitive enough to detect such small amounts and a very clean system for extracting the gas from the chondrule.

Since only relative ages are determined, they must be given in reference to some standard. That standard is usually the meteorite Bjurböle, since experiments with different chunks of Bjurböle have all given the same age.

However, when chondrules from Bjurböle were analyzed, they gave ages distinct from the rock as a whole. Of the first two analyzed, for example, one was about 900 thousand years younger than the whole rock, and the other was about 900 thousand years older. Other chondrules gave results that weren't as clear-cut, but they were all consistent with formation at various times in this interval.

The chondrules clearly formed before the whole meteorite was put together. The fact that some chondrules give ages younger than those measured for the rock as a whole indicates that these "whole rock" ages are probably dating the time the matrix (the material surrounding the chondrules) formed, not the time when the matrix and chondrules clumped together to form the meteorite.

The total spread in ages among the parts of Bjurböle is, however, less than the spread in I-Xe ages among different meteorites. This seems to indicate that, on a cosmic scale, the different parts of Bjurböle all formed at about the same time and place. Once they formed, they probably no longer mixed with the material that eventually went into other meteorites.

ANOMALOUS $^{107}Ag/^{109}Ag$ IN THE CAPE YORK METEORITE

J. H. Chen, T. Kaiser, and G. J. Wasserburg, The Lunatic Asylum, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125

We have been searching for silver with an anomalous isotopic composition in iron meteorites. Previous investigations have shown the presence of silver with large excesses of the isotope ^{107}Ag in a rare class of iron meteorites. In order to establish whether the presence of this anomaly is commonplace and if it is directly due to the decay of the extinct isotope ^{107}Pd (palladium 107), we investigated the Cape York meteorite, which was originally discovered by Admiral Perry in his Arctic explorations. A new fragment of this meteorite was most recently found by Vagn Buchwald of Copenhagen in his searches in west Greenland. This meteorite contains both nickel iron metal and iron sulfide and represents one of the most common types of iron meteorites. Because of the relatively high silver content the measurements were especially difficult. In our study it was possible to establish that it contained excess ^{107}Ag and that the excesses of this isotope correlate with the presence of the element palladium. These observations provide strong evidence for the presence of ^{107}Pd in the solar system at the time that small planets were first formed. The half life of the ^{107}Pd is 6.5 million years and thus must have been produced by intense bombardment of high energy particles in the early solar system or result from the injection of freshly synthesized nuclear material from a supernova in the general region from which the solar system was formed. These results, in conjunction with the observations of excesses of ^{26}Mg from short-lived ^{26}Al (half life 700,000 y) indicate that short-lived nuclei were widespread throughout the materials which went to make up the terrestrial planets and asteroids.

THE COMET CONNECTION: NASA's COSMIC DUST PROGRAM; U.S. Clanton[1], J.L. Gooding[1], D.S. McKay[1], A.M. Isaacs[2], I.D.R. MacKinnon[3], G.A. Nace[2], E.M. Gabel[4], J.W. Warren[4], and C.B. Dardano[4]. 1 NASA Johnson Space Center, Houston TX 77058. 2 Lockheed Corp., 1830 NASA Rd 1, Houston TX 77058. 3 MacKinnon Consulting Services, 15911 Parksley, Houston TX 77059. 4 Northrop Services, Inc., P. O. Box 34416, Houston TX 77034.

Comets - perhaps the most spectacular and popularized of all astronomical phenomena - are of enigmatic origin. Astronomers have theorized that comets may be compared to "dirty snowballs" - bodies of ice, dust and perhaps rock that are frozen remnants of material left over from the earliest period of formation of the solar system.

With the approach of a comet toward the sun, volatile materials and small dust grains are swept antisunward to produce the comet's tail - a feature extending for millions of miles outward from the dense nucleus. With repeated passes near the sun the volatile material will be largely lost and only the heavier dust and debris will remain in the orbit about the sun. In time the orbit of the dust grains may cross that of Earth and material from the parent comet will then be swept up in our atmosphere. Using knowledge and techniques which directly derived from the Apollo voyages to the Moon, NASA's Johnson Space Center (JSC) in Houston, Texas, is currently collecting and studying tiny particles found in Earth's stratosphere. Many of these particles are believed to have come from comets. The collection probably already includes particles from Comet Halley, the most famous of the hundred or so known "periodic" comets. Comet Halley will again pass through Earth's region of the solar system in 1986.

"Cosmic dust" which populates interplanetary space has several postulated origins including disaggregated comets, asteroid collisions, meteorite-planetary impacts, residual material left over from the formation of the solar system, and interstellar dust which pre-dates our solar system formation. Whatever its origin it is estimated that about ten thousand tons of cosmic dust enter Earth's atmosphere each year, mostly as small particles a few microns (a human hair is about 75 microns in diameter) to a few millimeters in diameter. These "micrometeroids" enter the atmosphere at high speed (commonly about 9 miles per second but at speeds ranging from 7 to 45 miles per second; 15 km/sec with a range of 11 to 72 km/sec) and are slowed by aerodynamic drag which results in frictional heating. The larger particles may melt or vaporize completely, producing the "shooting stars" one observes in the night sky. Although many of the particles smaller than 50 microns also become hot (probably 500 to 1000°C for a few seconds), a significant fraction survive the heating and deceleration unaltered and eventually reach the surface of the Earth only to become lost among comparatively enormous volumes of soil and ocean sediments. Fortunately, those particles which survive atmospheric entry require at least one to two days to settle from the upper atmosphere to the surface, thereby making atmospheric collection attempts possible. Given the continuous infall and relatively slow settling of such particles, it is estimated that, at 12 mi. (20 km) altitude, one extraterrestrial particle in the range of sizes of 5-50 micron should be found in each 1000 cubic meters of air, a volume which is easily sampled by high-altitude aircraft. The collected particles are then taken into the laboratory and studied in detail, using instruments and techniques which were driven to their current states of refinement by the scientific demands of the Apollo lunar sample program.

THE COMET CONNECTION: NASA'S COSMIC DUST PROGRAM

Clanton, U.S. et. al.

Beginning in 1974, a limited effort to collect extraterrestrial dust samples from the stratosphere using impactors mounted on NASA U-2 aircraft was initiated at NASA Ames Research Center, Moffett Field, California, by Dr. Donald E. Brownlee (University of Washington, Seattle). Research on these collected grains has provided scientists with new clues to our understanding of the origin of the universe and has identified a third class of extraterrestrial material - material not represented in lunar and meteorite samples.

In order to provide a greater availability of these samples to the scientific community, JSC began, in May of 1981, a program dedicated to the systematic collection and curation of cosmic dust for scientific investigation. Collections were made at 60,000 to 65,000 feet (18 to 20 km) altitude by means of collectors mounted under the wings of a WB57F. When the aircraft reaches operating altitude, the collector plates (impactors) are extended into the ambient airstream with the collection surface normal to the airflow. To prevent particles from bouncing off the surface, the impactors are coated with a film of high viscosity silicone oil. The impactors are sealed in canisters to minimize contamination when not collecting.

NASA-JSC has now flown three sets of eight collectors with collection intervals of 65, 45 and 35 hours. The total volume swept by these 24 impactors is in excess of two million cubic meters. Calculations indicate that the collection should contain about 2,000 cosmic dust particles larger than 8 microns in diameter and perhaps 18 to 20 particles almost 50 microns in diameter. The larger particles, especially, provide a rare opportunity for several laboratories to co-operate in a research program.

An ultra-clean Class 100 (less than 100 particles larger than 0.4 microns in diameter per cubic foot of air) facility at JSC is used for pre- and post-flight handling of the collectors and the curation of collected particles. (This facility is over a hundred times "cleaner" than are our best lunar labs.) Individual particles in the size range of 4 to 35 microns are removed from the silicone oil on the impactors using a micromanipulator and placed on a polycarbonate substrate that was previously bonded to a graphite mount. Complete mounts of 16 particles each are washed with hexane to remove the silicone oil. The particles are not stuck to the substrate and can be removed from the mount for further analysis at any later date.

Preliminary examination of the particles has indicated that they represent not only extraterrestrial material but also some fraction of terrestrial contamination from both natural and man-made sources. This examination involves a combination of optical microscopy, scanning electron microscopy (SEM) and qualitative bulk elemental analysis using an energy dispersive x-ray spec-trometer (EDS) to characterize each particle. Operating conditions were carefully chosen to minimize particle damage by heating, radiation, or contamination, and to minimize the production of artifacts.

The preliminary information has been compiled into a loose-leaf catalog with all of the data for one particle on a single page. Each page has a SEM micrograph "mug shot" that shows the over-all grain morphology. In addition, optical observations (500X) and EDS spectra are included. The EDS spectrum represents a qualitative bulk elemental analysis of the entire particle. The catalogs are intended only to inform potential investigators as to the types of particles available for research and should not be considered as anything more than preliminary data which are subject to change.

A preliminary classification of particles was made to assist catalog users in choosing appropriate particles for detailed study. We emphasize that the classification is very tentative and somewhat subjective and is based only on gross morphology and EDS spectra. Of the 105 particles in the first catalog, 14% are judged to be natural terrestrial contaminants including quartz, clay particles, carbonates, and possibly volcanic ash; 42% are judged to be man-made contaminants including rocket exhaust particles and debris from aircraft or spacecraft. The largest group of particles, 43%, are judged to be cosmic dust or meteorite ablation products. This group contains a varied assortment of particle morphologies including aggregates, ablation spheres and massive types. Approximately 1% could not be easily assigned to any of these general categories. Catalogs of the preliminary SEM/EDS data are available to the scientific community so that interested scientists may request particles for detailed study.

The aircraft collecton periods coincide with the peak periods of several meteor showers. Orbital characteristics of many well studied meteor showers have been previously correlated with those of certain comets, giving rise to the belief that the JSC collections should contain some particles of cometary origin. Collector set #1 may contain material from the Daytime Beta Taurid shower (correlated with Comet Encke). Collector #2 may contain particles from both the Omicron Draconid (Comet 1919 V Metcalf) and Perseid (Comet 1862 III Swift-Tuttle) showers. Collector set #3 may contain particles derived from the October Draconid (Comet 146 V Giacobini-Zinner), Orionid (Comet Halley), and Southern and Northern Taurid (Comet Encke) showers.

In the absence of a comet sample-return mission, the Cosmic Dust Program probably provides the best opportunity to study materials from comets. Although some scientists, notably D. E. Brownlee and collaborators, have previously pointed out the possible cometary components among cosmic dust samples, such studies have been unavoidably limited to relatively few particles. The new JSC program will provide a much larger inventory of well-documented particles which should facilitate numerous scientific studies not previously possible because of the lack of adequate samples. By studying a large number of particles, the relative importance of the postulated sources may be determined, thereby strengthening our understanding of the space environment and the evolution of the sun and planets. Furthermore, participation is being encouraged among all interested members of the international scientific community. Among students of extraterrestrial materials, the year 1982 may later be recorded as the beginning of revitalized interest and new opportunities for the study of cosmic dust and its possible cometary connection.

Rb-Sr, Sm-Nd AND K-Ca STUDIES OF CRETACEOUS-TERTIARY BOUNDARY SEDIMENTS: POSSIBLE EVIDENCE FOR AN OCEANIC IMPACT

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Background

One of the intriguing mysteries of geologic history is the abrupt disappearance of a large number of life forms about 65 million years ago, at the end of what is called the Cretaceous period. In a geologically very short period of time, marine and flying reptiles, and all of the dinosaurs apparently disappeared. Sweeping extinctions also occurred for plankton--microscopic floating animals and plants that live in the near-surface waters of the oceans. However, land plants, many land animals (including mammals), and deep ocean organisms were hardly affected. Overall, about half of the genera living on the Earth at the time perished during what can be termed a true catastrophe.

What has puzzled geologists for many decades is the apparent suddenness of the extinctions. From studies of one locality in Spain where the rocks preserve a continuous record of fossil plankton forms, it is estimated that most of the plankton disappeared within a span of perhaps as little as 50 years. Such a short time span, which is only a maximum limit on the actual time involved, is instantaneous in geological terms. Typically, thousands or millions of years are required for large changes to occur. Generally, species are thought to become extinct because of gradual changes in environmental conditions and competition from other species that adapt better to the new conditions. So-called sudden extinctions are not unknown in other parts of the geologic record but the evidence for how sudden or gradual they were is fuzzy for those that occurred hundreds of millions of years ago. The documented suddenness of the catastrophe that happened 65 million years ago is, therefore, difficult to explain in terms of familiar slowly changing geologic processes. Also troublesome is why the catastrophy was so selective. Some types of animals were completely eradicated while others were unaffected.

A giant step toward a solution to this problem was made by Luis and Walter Alvarez of the University of California, Berkeley, and Frank Asaro and Helen Michel of Lawrence Berkeley Laboratory. They analyzed clay from precisely the stratigraphic level that should correspond to the time of the extinction. What they found was a peculiarly high concentration of Iridium, an element with metallic properties, that is normally absent in rocks found near the Earth's surface. They were able to show that the only likely source of this Iridium was extraterrestrial rock material--a meteorite. This led them to the hypothesis that the mass extinctions could have been caused by the impact of a large meteorite, about 6 miles in diameter. Studies of asteroids that have Earth-crossing orbits around the sun show that a large asteroid is likely to hit the Earth about once every 100 million years--approximately the right frequency. The shock of the impact may have had little direct effect on life, but the explosion would have excavated a huge crater--some 100 miles in diameter--and blown a tremendous amount of pulverized rock into and through the atmosphere. Much of this dust would then have remained suspended in the stratossphere, thereby blocking out sunlight, and causing the entire Earth to be plunged into complete darkness for a period of about three months. Darkness would prevent photosynthesis, which is the starting point of food chains, so many animals would be starved out of existence. The Iridium-rich dust eventually would have settled out of the atmosphere and accumulated as a thin layer of clay on the ocean floor, indelibly marking the time of the extinctions in the geologic record. Other effects of the explosion could have included warming of the atmosphere and oceans, and changes in ocean water chemistry. A complete understanding of all of the effects of a meteorite impact has not been reached.

The findings of Alvarez, Alvarez, Asaro and Michel have since been confirmed and extended by their own further investigations and those of others. The hypothesis of a single large asteroid impacting the Earth has now been broadened to include as alternatives, a comet or a disaggregated asteroid, colliding with the Earth. An asteroid approaching the Earth might be disaggregated by the Earth's gravitational field (tidal disruption). One of the problems with the single impact hypothesis is that there is no evidence for a large crater of the right age, although if the body fell into the ocean the crater might be difficult to identify. It has also been suggested that the Iridium-rich clay actually has too much iridium in it, considering that terrestrial rock should have made up 98% of the dust.

New work: Purpose, results and implications

To attempt to answer some of the outstanding questions about the asteroidal impact hypothesis for the massive Cretaceous extinctions, we have measured the isotopes of three elements--strontium, neodymium and calcium--in some of the clay layers that mark the time of the extinctions. This represents the first reported isotopic data of this type on any of the materials that contain excess iridium. This study differs from previous work in that we are not primarily concerned with documenting the presence of extraterrestrial material, but rather we are studying the terrestrial part of the boundary clay (which is presumably the dust generated by the impact) to learn more about the explosion itself. One thing the isotopes can tell us is where the dust came from; for instance, whether the impact was in an ocean or on a continent. We also want to determine if the iridium-rich clay material marking the Cretaceous-Tertiary boundary is isotopically uniform all over the Earth. If it is, and if it is different from the clay in the sedimentary layers above and below it in the stratigraphic sequence, this would be strong corroborative evidence for an impact, and could help choose between a single asteroid impact and the tidal disruption hypothesis.

Our isotopic data provide preliminary evidence that the "boundary clay" may be uniform across the globe, based on the observation that the isotopic composition of clay from Caravaca, Spain and from a deep-sea drill core in the mid-Pacific, are nearly identical. Also, the Caravaca boundary clay is clearly much different from clay in the sediments stratigraphically above, and below, it. These results, if confirmed by further measurements, would offer substantial support for the asteroidal impact hypothesis. Furthermore, they argue against the tidal disruption hypothesis, because in its simplest form, this model implies that the boundary clay should be similar to the local sediment, simply diluted with extraterrestrial dust. Our results show that this is not the case; the boundary clay is mostly terrestrial material, but not of local origin. A modified impact hypothesis, with some tidal disruption, is still a possibility.

Our results also argue strongly that the meteorite impact would have to have occurred in an ocean rather than on a continent. This is based on a comparison of the isotopic ratios of strontium-87 to strontium-86 and neodymium-143 to neodymium-144 in the boundary clay and in typical oceanic and continental rocks. These ratios depend mostly on the age of the rocks, so they are different in ocean-floor rocks relative to continents because the ocean floor is much younger. An oceanic impact would clear up some troublesome aspects of the asteroidal impact models, but might also cause some problems. For instance, it would explain why there is no obvious geological evidence for the huge crater that should have formed. Although knowledge of continental geologic features is fairly complete, the geology of the ocean floor is poorly known by comparison. It is not even certain what the impact feature should look like in terms of oceanic topography, especially since the impact could have triggered large outpourings of lava that might have filled in a crater. The possibility also exists that the impact scar has been subducted back into the mantle, as a result of plate motions in the last 65 million years.

An oceanic impact would help resolve the discrepancy between the small fraction of extraterrestrial material expected in the impact ejecta, and the relatively large apparent fraction found in some of the boundary clay samples based on the iridium contents. Jay Melosh from SUNY Stony Brook has recently pointed out that much of the "ejecta" from an oceanic impact would be water, which would eventually just rain out into the oceans, but would not act to "dilute" the extraterrestrial dust in the boundary clay.

This same aspect of the oceanic impact may necessitate some rethinking about the environmental effects that caused the extinctions. Most attention has been focused on the darkness resulting from atmospheric dust as the chief biological stress causing widespread mortality. However, if most of the ejecta from the impact explosion was water, the climatic effects may have been quite different. This possibility is in fact supported by our isotopic data. The amount of "dust" thrown into the atmosphere might therefore be substantially reduced in comparison to current estimates, while the water vapor might have caused a substantial atmospheric temperature increase. It is not obvious in this case if the temperature or the dust would have had the more important biological consequences.

One of the samples studied in this work was composed of tiny balls, or spherules, of the mineral sanidine, which are found in the boundary clay at Caravaca, Spain. The origin of these spherules is enigmatic. It has been suggested that they are actual pieces (originally liquid droplets) of the asteroid or comet. However, our isotopic data show that they are not. They were derived instead from terrestrial rock. An interesting sidelight is that these peculiar objects may provide a rare opportunity for determining the absolute age of the extinction event, which has never been done on marine rocks, where it is most sharply defined. To attempt this, we are using a newly-refined dating technique developed in our laboratory at U.C.L.A. that involves the elements potassium and calcium.

Analytical techniques and measurements

The results described here are based on measurements of isotopic ratios of the elements strontium (Sr) and neodymium (Nd) which were made in the laboratory of D.J. DePaolo at the University of California, Los Angeles. These elements are each composed of several isotopes which differ in atomic mass. One isotope of each element is formed from another element by radioactive decay. Strontium-87 forms by decay of rubidium-87 and neodymium-143 by decay of samarium-147. The rate of radioactive decay is imperceptibly small, but is significant over the long times involved in geologic history. Strontium-87 and neodymium-143 accumulate in different rock types at different rates, depending on how much rubidium and samarium the rocks contain. Analysis of rocks from all over the Earth have shown that the variation of strontium-87 and neodymium-143 contents of rocks is systematic; it depends on their age and how they originally formed. Consequently, these isotopes can be used as tracers. In sedimentary rocks (this study is an example), they can be used to determine where the sediment came from, just as they could theoretically be used to determine the source of the clay in a piece of pottery. These isotopes are present in small amounts in everything, including for instance, human bone. With sensitive techniques, involving the use of mass spectrometers, their amounts can be measured to high precision. The clay in the Cretaceous-Tertiary boundary layer was determined to be different from the sediments above and below it because the amount of neodymium-143 it contains was higher by 3 parts in ten thousand and the amount of strontium-87 was lower by about one-half percent.

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RECENT RESULTS OF APOLLO 16 STUDIES: O.B. James, U.S. Geological Survey, Reston, VA 22092

At present, there is a very active research effort on the geology and rocks of the Apollo 16 landing site. Although it has been nearly a decade since the Apollo 16 mission, the geology of the site and the processes that formed the returned samples are still not fully understood. Before the mission, the plain on which the site is located and the bordering hummocky mountains were thought to be of volcanic origin. The nature of the returned samples, however, proved that the plain and adjacent mountains are deposits of debris produced by meteorite impact. Supplied with this "ground truth," the photographs of the area taken from orbit were restudied and it was found that the formation of the plain was somehow related to the formation of the giant Imbrium basin, a meteorite impact scar 1500 kilometers across centered 1600 kilometers NW of the landing site.

Many questions about the origin of the debris deposits that form the plain and mountains should be answered by current studies. Are the mountains bordering the plain just a hummocky variant of the plain, or are they a deposit of different debris related to a different impact basin, the 850-kilometer Nectaris basin centered 600 kilometers to the SE of the site? Were the rocks of the plain actually thrown all the way to the landing site from the Imbrium basin, 1000 kilometers away? Or were the rocks mostly excavated from bedrock close to the landing site by bombardment of debris from the Imbrium basin? Was a great thickness of material deposited by the giant impacts, or, like gigantic winds, did they simply redistribute the materials already at the lunar surface? What kinds of rocks are present in the plain and mountains deposits? When were the deposits laid down? The answers are important in helping scientists predict the geology of plain and mountain areas on cratered planets -- necessary if we ever attempt to colonize the moon or send exploratory landers or orbiters to the moon or to other cratered planets.

The current studies of the Apollo 16 rocks have shown that most of the returned samples are of two types. One type, the "anorthosites," formed by solidification of a melt produced by internal heating processes within the moon. The other type, the "melt rocks," are rocks that were completely remelted by meteorite impact and subsequently resolidified. Individual samples of anorthosites are not very different from each other. Many different sorts of melt rocks have been found, however, with formation ages ranging from 4.05 to 3.6 billion years and a wide range of compositions.

Studies of the samples have further shown that similar types of anorthosites and melt rocks are present in both the plain and mountains. (The mountains appear to be richer in anorthosites than the plain, and the plain appears to be richer in melt rocks, however.) This information suggests that the origin of the mountains was somehow closely related to the origin of the plain, although the nature of the relationship is not yet fully understood. Age determinations on the returned samples indicate that the mountains and plain were laid down some time between 3.95 and 3.85 billion years ago -- much more work is required to define the times more precisely and determine if the time of deposition was the same or different for the two units. Geochemical data obtained from lunar orbit indicate that most of the material in the plain and mountains probably formed relatively close to the landing site and that very little of it can have come all the way from the Imbrium basin.

Many scientists are concentrating on another aspect of Apollo 16 studies -- the question of what the anorthosites can tell us about the origin and very earliest history of the moon. Very soon after the Apollo 11 mission, scientists discovered that the moon had experienced extensive melting immediately after it formed 4.5-4.6 billion years ago. It was suggested that this melting produced a global ocean of molten rock, which then solidified. Anorthosites are generally thought to have formed as a floated "scum" on this ocean. The magma-ocean hypothesis has been revised somewhat since Apollo 11 days, but all newer hypotheses still call for large amounts of early melting and formation of anorthosites very near the beginning of lunar history.

Unfortunately, up to the present, it has not been possible to confirm this view of early lunar history by measuring the age of the anorthosites. In the last five years, though, a new technique of age determination has been perfected (called the "samarium-neodymium" technique) that is capable of measuring the age of the anorthosites. An anorthosite sample is now being dated by this technique; the results will be available late this spring.

Other current studies of the anorthosites have revealed several interesting points. Detailed chemical studies show strong similarities to terrestrial anorthosites -- intriguing because so far the moon rocks have been distinguished primarily by their <u>dissimilarity</u> to earth rocks. Studies of the minerals of the anorthosites have shown that, if anorthosites did indeed form in a global magma ocean whose composition was the same as the composition of the bulk moon, then the bulk moon must be lower in calcium, aluminum and sodium than previously thought.

These studies and similar research on other samples of ancient lunar rocks are particularly exciting and important, because they are yielding insights into the origin and earliest history of not only the moon, but the earth and other rocky bodies in the solar system as well. Many of the processes that operated on the primordial moon also operated on the primordial earth, but on the earth continued evolution of the crust has erased all evidence of its history before about 3.8 billion years ago. The discovery that the moon was very hot soon after it formed has revolutionized thinking about the early history of the earth. Prior to the Apollo missions, it was generally thought that the earth and moon were cold when they formed and that they subsequently heated up due to radioactive decay. Now, theories of the evolution of the early earth are being revised to take into account the extensive melting and outpouring of lavas that must have occurred. An additional major advance has come from recent studies of trace-element and oxygen-isotope contents of lunar and terrestrial rocks and meteorites. These studies have established that the earth, the moon and the parent body of the eucritic meteorites had a common or related origin. Up until a few years ago, it was generally thought that the moon and the earth must have formed in different parts of the solar system, because of the very large differences in major-element contents of their rocks. The nature of the relationship between the earth and the moon and the process that formed the moon are still unsolved mysteries, however.

PRIMARY EJECTA IN CRATER RAYS: AN EXAMPLE FROM COPERNICUS

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Introduction and Background. For fresh large impact craters a discontinuous field of secondary craters and bright rays usually surround the crater, often extending hundreds of kilometers. Two different popular points of view that concern the nature of extensive rays from large craters can be summarized as follows: 1) The ray material is a depositional unit of foreign material excavated by the crater. The ray is brighter than the substrate because it is of a different composition and/or is fresher (less altered by soil maturation). 2) The ray material is fresh local material that has been brought to the surface by a relatively small amount of high velocity foreign material ejected by the primary crater. A few laboratory experiments as well as analyses of material from large terrestrial craters suggest that locally derived material dominates crater deposits beyond a few crater radii (1, 2). We present evidence that surface deposition of foreign material may be an important process in the emplacement of at least the uppermost part of the ray unit.

Copernicus is a fresh, bright rayed impact crater 95 km in diameter on the lunar nearside (9.5°N, 20°W). The stratigraphy of this area before the impact was thin basaltic mare material overlying Imbrium basin deposits and the pre-Imbrium lunar highlands crust. Bright rays extend in all directions from the crater, many exceeding distances of 600 km from the crater center. The rays to the north are observed on a variety of Imbrium mare material, both low titanium intermediate age basalts and younger high titanium basalts (3,4).

Techniques. Recent advances in remote sensing technology allow new data to be obtained which address unsolved problems in planetary science, in this case the nature of crater rays. The principal technique used in this study is near-infrared spectral reflectance (or analysis of the color of reflected light beyond the red portion of visible light). Other types of remote sensing data are also being examined and will be reported elsewhere. Near-infrared reflectance spectra obtained in the laboratory for returned lunar samples as well as terrestrial materials have shown that rocks and minerals have characteristic absorption features that can be used in compositional identification (5, 6). Remotely obtained spectra can thus be examined for such characteristic mineral absorption features and, if found, components of the mineralogy of an unsampled surface are identified (7, 8).

Sunlight reflected from a planetary surface such as the moon is collected using an earth-based high altitude telescope and is analyzed with a spectrometer sensitive to near-infrared wavelengths. The spectrometer separates the incoming light from a small area into 120 channels from 0.70 to 2.50 μm (or from 7,000Å to 25,000Å where 6,500Å is visible "red" light). These 120 channels comprise the infrared reflectance spectrum for the particular lunar area, which can be as small as 5 km in diameter.

A number of high quality near-infrared spectra of lunar areas were obtained at Mauna Kea Observatory, Hawaii, which at 13,800 ft. elevation is above a significant portion of earth's atmosphere. This high altitude, along with very low atmospheric turbulence, allows most terrestrial atmospheric absorptions to be calibrated and removed from the data.

The Measurements. The location of 5 small areas for which spectra were obtained on 7/5/81 are shown in Figure 1. The targets were areas near the crater within the continuous ejecta of Copernicus and outward along a major ray. A neighboring region in undisturbed mare was also observed (M-1). Good repeat spectra for a few of these areas were also obtained on three other nights. The spectra (shown in Figure 2) are typical for lunar soils, both those obtained in the laboratory and those obtained remotely using a telescope. Lunar soils become brighter with increasing wavelength, and superimposed on this general sloped continuum are several weaker absorption features near 1.0 and 2.0 μm. For each spectrum a straight line continuum is estimated (usually tangent at .73 and 1.60 μm) in order to examine the nature of the weak absorption features near 1 μm. [Note that in Figure 2 for the top four spectra associated with Copernicus ejecta and ray a different continuum should be estimated for the feature near 2 μm]. The spectrum is divided by the estimated continuum and the residual absorption (spectrum/continuum) around the 1 μm feature is shown in Figure 3.

It has been well documented since the earliest studies of returned lunar samples and remote measurements of the lunar surface (9, 10) that fresh lunar surfaces have strong mineral absorption features and mature soils have much weaker features. After at least 2.5 billion years exposure to the solar wind and micro-impacts by solar system dust, most lunar soils become somewhat altered in form. Fresh surfaces exist on the moon by the excavation of subsurface material during an impact event. As a fresh soil matures it becomes darker and its absorption features become weaker. For a crater ray to be fresh or disturbed local material, it must not only be brighter, but it _must exhibit stronger absorption_ features than the local soil.

Experience has also demonstrated that the spectrally dominant mafic mineral for most lunar material is pyroxene. The feldspathic highland materials exhibit orthopyroxene absorption features (absorption centered near .93 μm) and the basaltic mare exhibit more calcium-rich clinopyroxene features (centered beyond .95 μm) (11, 5). By analyzing the nature of an absorption band in a remotely obtained spectrum the average type of pyroxene can thus be estimated and with it the compositional distinction between the two primary types of lunar material: the feldspathic highlands crust and the basaltic mare.

Data Analysis. It can be clearly seen from Figure 3 that all the spectra associated with the Copernicus ray exhibit absorption features that are _weaker_ than the local mature mare area (M-1). This observation is completely inconsistent with the interpretation of ray material as immature local material. Furthermore the band centers near 1 μm of the ray and ejecta material are at slightly _shorter_ wavelengths than that for the mature mare suggesting a difference in the average type of pyroxene.

Interpretation. These data suggest that the uppermost surface materials of the observed crater ray are dominated by materials of highland composition rather than either mature or immature soils derived from subjacent mare deposits. We interpret these data as evidence that the high albedo surface material of this Copernicus ray (the upper few millimeters which interact with solar radiation) may be largely a depositional unit rahter than immature local mare excavated by secondary craters. Mixing models are being investigated to estimate the possible amount of local material that could be present.

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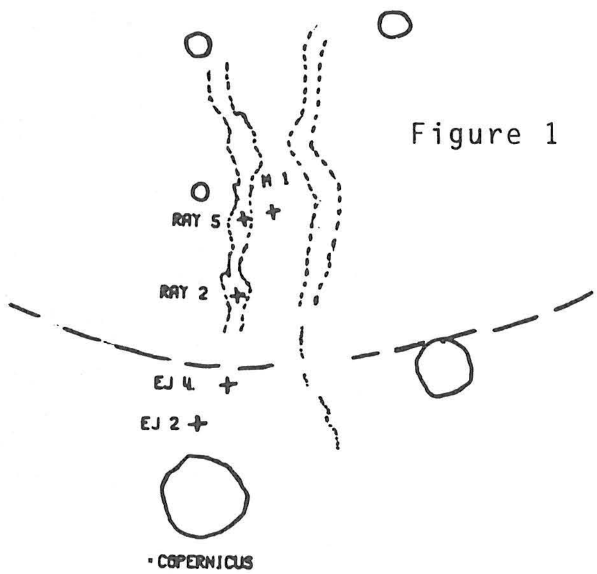

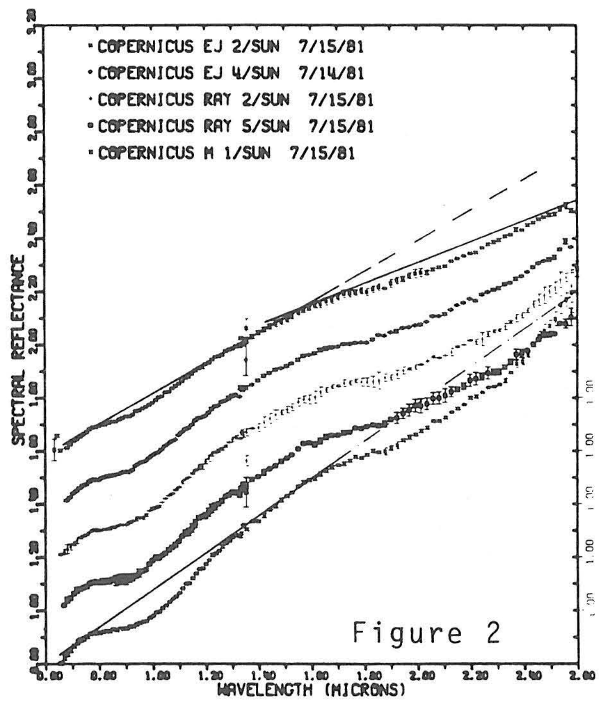

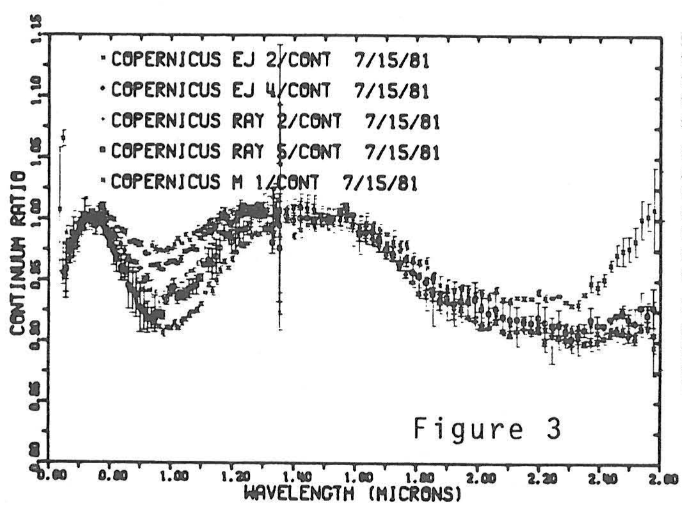

Figure 1. Schematic representation of the southern portion of Mare Imbrium and Copernicus. Two major crater rays are outlined with dotted lines. The +'s indicate the locations of five areas for which near infrared spectra were obtained.

Figure 2. Reflectance spectra (scaled to unity at 1.02 μm and individually offset) for the five lunar areas shown in Figure 1. The upper spectrum is closest to Copernicus; the following spectra progress outward along the ray; the lower spectrum is a mature mare region located nearby the outermost ray spectrum. Straight line continuua are fit around the 1 μm feature.

Figure 3. Residual absorption (superimposed) for the spectra in Fig. 2 (spectra/continuum). The weakest absorption is for the area closest to Copernicus. The absorption increases for areas outward along the ray. The strongest absorption is for the mature mare region.

THE COMPOSITION OF THE MOON, AND WHY LUNAR SAMPLE ANALYSIS IS NOT FINISHED, EVEN IF SOME PHILISTINES SAY IT'S OVER

Being a Press summary for
"Ferroan anorthosite 60025, adcumulate growth, and the bulk composition of the Moon"

by
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If we knew the composition of the Moon as a whole, we would be in a better position to divine its origin, for then we could better compare it with other objects. Many different approaches to the determination of the Moon's composition have been tried. The ways most likely to be accurate are those which somehow use lunar rocks themselves, and actually we know some of the chemical characteristics of the Moon, such as its lack of water and its very low abundances of other volatiles, from a fairly simple examination of lunar samples. Unfortunately it can be shown that most lunar rocks have been processed through two or more igneous events--in other words, starting with a bulk Moon, any given rock is the product of melting, crystallizing, remelting, crystallizing, etc. A severe problem is that when rocks melt, complicated things happen. Unlike partly melting ice, in which case the result is ice and a liquid of the same composition (water), partly melting a rock yields a liquid which is different in composition from the solid; to make matters worse, the liquid changes in composition as more solid is melted. A similar thing happens when a liquid crystallizes: the crystals are not the same composition as the liquid. Separation of the crystals from the liquid during melting makes things even more complicated. Extrapolating back from a multi-processed rock to the bulk composition of the Moon is more complicated than solving Rubik's cube, and in fact there is no unique solution. Unrelated mechanisms, such as mixing and melting by impacts add problems to the interpretation of lunar samples.

Some rocks, the anorthosites, do appear to have formed in a one-stage process from the melting and crystallization of the Moon. Anorthosites consist mainly of plagioclase feldspar (a calcium-and aluminum-rich mineral) and seem to have floated to the top of a molten Moon. We believe this because of their wide-spread occurrence, and because of subtle chemical and isotopic arguments which suggest that they are almost as old as the Moon itself--so for one thing they did not have much time to go through more than one melting event. Figuring out the composition of the liquid from which a rock crystallized is not easy, because the rock might have trapped some unknown quantity of the liquid from which it crystallized, changing its bulk composition by some unknown amount. Most attempts to understand anorthosites have assumed that they contain some trapped liquid (which of course has crystallized by now). Even knowing the anorthosites' "parent" liquid, to get the composition of the original liquid which had evolved to produce it requires figuring out what crystals had already solidified before anorthosites started to form, and in what order.

Kurt Marti and Gunter Lugmair (University of California at San Diego) want to determine a precise age on an anorthosite, something which has not yet been accomplished, using a technique that was not even developed when the first lunar samples were brought to earth. They requested that Lunar Curatorial personnel search out a piece of anorthosite which contained some mafic minerals (magnesium-and iron-rich), as well as feldspar, a requirement for the sophisticated isotopic analyses to be made. My search showed that at least one rock, 60025, which is as big as a fist, had a few chunks of mafic minerals at one end. These had been bypassed in the original study of the rock, which had concentrated on one small part of the rock. Some of this material has been allocated for the age determination (at the time of writing the analyses are still underway). To support Marti and Lugmair's study I have made a new mineralogical study of the rock, including the mafic mineral chunks, making detailed analyses of many mineral grains. I have found that it is a mixed-up rock (from impacts) but that all the bits are related, at one time being part of a much larger igneous sequence of rocks successively crystallized from an evolving liquid. From the mineralogical characteristics I concluded that 60025 contains none of the trapped liquid discussed above, a conclusion supported by chemical data. Most other anorthosites fit the pattern shown by 60025, and it appears that none have trapped liquid. This tells us a lot about the physical conditions under which anorthosites crystallized, but perhaps more importantly, it makes it much easier to work out the compositions of the liquids from which the anorthosites crystallized. The results also suggest that we have samples from among the very first anorthosites to crystallize on the Moon, and trace element chemical data allow us to deduce the order of crystallization of minerals from the liquid which had evolved to produce them.

COMPOSITION OF THE MOON

G. RYDER

While there is still a lot to learn and several "ifs" and "buts" with which we contend, I believe we can now constrain the bulk composition of the Moon reasonably well, or at least better than before. This is so as long as we are safe in our assumption that anorthosites formed in a single-stage igneous process from a bulk Moon composition. (If they didn't, they are very strange indeed.) If it is a safe assumption, then the Moon is not just of volatile-depleted chondritic meteoritic composition (roughly, bulk solar system composition) as is now commonly assumed. It is instead enriched in aluminum and has a lower calcium/aluminum ratio. It is even more depleted in volatiles than presently thought: sodium is perhaps three times less abundant than the previous lowest estimate. The significance of this for lunar origin remains to be debated, but certainly producing a calcium/aluminum ratio lower than that of the chondritic meteorites is conceptually easier with liquid-vapor than with solid-liquid reactions, and I suggest that the Moon was held at temperatures well above those necessary merely to melt it, during or just after its formation. This would certainly explain its very low abundance of volatiles, too.

This study, as well as several others, shows that significant problems are still being tackled, and progress still being made, 10 years after the last samples were brought to earth (this appears to suprise many). Why? One reason is that many samples are brecciated, i.e. mixed up by impacts, and unravelling them both physically and mentally takes time. A second reason is that it is not easy to look at an entire sample in detail, and indeed, most allocations have been from a small piece of a rock, partly for convenience, and partly to preserve the rocks (which are after all a national treasure, not just the purview of scientists). In many cases, as proven by the study of 60025, this is inadequate for scientific investigation, and sometimes even misleading. Such convenience took over because the processing of lunar samples is time consuming, requiring much photography, weighing, and paperwork. Not surprisingly, frustration sometimes results, because it takes a long time--a year or more in some cases--to figure out what data is needed from what sample, request the sample, have the sample request approved, processed, and allocated, and finally, to receive it. The allocated samples are also necessarily very small, much smaller than one would use for most terrestrial rock studies. While this has certainly led to the development of refined techniques, the problem remains that a small sample is not necessarily representative of a large rock. In many cases, a ¼-inch chip must be allocated to do the job that a 1-inch chip (which is 64 times more massive) would do for a terrestrial rock. These small pieces then need to be studied intensively to produce results, which are sometimes difficult to interpret because of the small sample size.

On top of all this is the plain fact that we are still learning how to deal with single samples--they are fine for survey studies, but do not lend themselves readily for problem-solving. One would hardly take hand-samples from a few boulders and cobbles of a random glacial deposit in Wisconsin, analyze some small chips from some of them, and expect to obtain a good understanding of the evolution of the earth, or even a significant part of it. Some idea, yes; deep understanding, no. This does not mean that we have an impossible task with lunar samples, because the Moon is undoubtedly simpler than the earth, and we are learning how to do it, albeit slowly. It is interesting that because of these lunar sample investigations, we are re-examining how we study terrestrial samples, that is, questioning what information we can get from single samples or a few samples, and what we can't get.

Undoubtedly interest in lunar samples among scientists has waned--certainly the Apollo-period excitement, which attracted the good, the bad, and the ugly, has gone. Some of the decline probably results from the frustration over sample allocation, and some from the lack of Apollo-period excitement. But more importantly, I think, it results from two far more serious issues. First, we are now in a problem-solving stage, by which I mean one of very serious thinking, not the "let's see-what's-basically-there" stage; problem solving is much, much more difficult, and more time-consuming. Among scientists, perhaps any chaff has already gone, wheat remains. Second, there is some feeling that all the significant problems which can be solved with lunar samples have been solved. To the contrary, I believe that recent results of carefully thought out work suggest very strongly that the accepted understanding of the Moon and its evolution are substantially wrong, and that thinking better about lunar sample analysis can get us on the right track, thus causing some important principles to emerge. The inference of Rene´ Descartes (1596-1650) that "the ground of our opinions is far more custom and example than any certain knowledge" (even if the customs and example are of recent development) is, I think, appropriate. Certainly the lunar evolution models currently in vogue are in sharp contrast with the basic characteristics of many of the rocks. This in large part results because a wide audience listened to the conclusions made from the survey work of several years ago, but a much smaller audience has paid attention to the continued thorough, painstaking work.

Lunar sample studies are by no means finished, but the problems and ways to their solutions have to be thought out clearly. Unfortunately, the trend to reduced budgets is bound to bring lunar sample studies to a virtual standstill, making samples more inaccessible, reducing their curation (especially cutting back on the badly-needed processing work required in problem-solving) and their analysis. It will be unfortunate if intellectual Philistines who have never actually thought about it, but who consider that all must have been learned after 13 years, create a closed, small story for Lunar Samples Studies: "Founded 1969, Funded 1969-1982, Foundered 1983".

FORGOTTEN SATELLITES OF MARS: A POSSIBLE RECORD FROM OBLIQUE-ANGLE IMPACTS

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Most impact craters on the Moon, Mars, and Mercury are relatively circular even though we know that they were formed by asteroids and comets impacting at angles away from the vertical. However, a few craters display a unique pattern of ejecta and appearance that can best be explained by planetary bodies striking the surface at very oblique angles ($<5°$ from the surface). Mars has more than ten times as many examples of such grazing (oblique-angle) impacts than does Mercury or the Moon (after correcting for surface area and selection effects). There are several possible explanations, but one of the more plausible (and intriguing) possibilities is that these grazing impacts resulted from a family of near-equatorial martian satellites, of which Phobos and Deimos are the largest remnants. If this interpretation is correct, there are several interesting implications for the origin and evolution of Phobos and Deimos and for shifts of the martian crust through time.

Craters formed by grazing impacts are identified on the basis of distinctive features revealed in laboratory experiments. The most characteristic features are an oblong shape in the direction of impact and a butterfly pattern of ejecta with the "wings" spread in a direction perpendicular to the impact direction. The crater Messier (14 km x 6 km) on the Moon nicely illustrates these patterns; additionally it has a saddle-shaped rim and a ridge down the middle of the crater floor. These characteristics were used to identify grazing impacts on Mars. Over 175 such craters larger than 3 km across were found, but these represent only the best examples; double craters, irregular oblong craters, and circular craters with asymmetric ejecta patterns were not tabulated. For comparison, less than a dozen examples are found on the Moon or Mercury. Thus, there seems to be an unusually large number of grazing impacts on Mars.

The large number of Mars grazers is only part of the story. After classifying these craters according to age (on the basis of the preserved detail in the ejecta deposits), we found that the most recent examples struck the surface in an east-west direction, whereas older impacts struck in progressively more northerly directions. The east-west grazers might be understood in two ways. First, they could represent asteroids with orbits only slightly inclined to the ecliptic (the plane closely matching the orbit of Mars). Second, they could represent satellites with orbits slightly inclined to the martian equator.

The first possibility reflects the proximity of Mars to the asteroid belt and the greater likelihood of its intercepting asteroids if they travel in the same orbital plane. Grazing impacts near the martian equator will selectively record east-west directions, whereas grazers near the pole will have randomized orientations due to the rotation of Mars. We can show that the percentage of grazers (relative to the total number of impacts) near the poles should be greater than the percentage of grazers near the equator. Yet, most oblique-angle impact craters are found near the equator (within 35°). We also would expect that the relative number of all grazers to the total crater population should be the same on Mars as on the Moon and Mercury if they are from low-inclination asteroids orbiting the sun. Yet there is clearly an excess of grazing impacts on Mars. The second possibility (martian satellites with slightly tilted orbits) seems more reasonable, particularly since Phobos and Deimos have orbits tilted only 1° and 2°.8, respectively, from the martian equator.

FORGOTTEN SATELLITES OF MARS

PETER H. SCHULTZ & ANNE LUTZ-GARIHAN

Older grazing impacts appear to have occurred with different orientations. We can interpret this change as: (1) a different family of Mars-orbiting impactors with more inclined orbits; or (2) a change in the orientation of the martian crust. If the first interpretation is correct, then there should be random northerly orientations of impact directions due to the tilt of the martian spin axis. If the second interpretation is correct, then there should be concentrations of impact directions that correspond to previous orientations of Mars.

To test these alternatives, we determined the orbital plane of each satellite impact from the direction and location of the crater on Mars. We plotted the points on Mars where the axis of the orbit would pierce the surface; such points can be viewed as the poles of the original satellite orbit (or orbit-pole points). The most recent Mars-grazers have orbit-pole points that cluster near the present Martian poles. The older Mars-grazers (older than Tharsis plains, but younger than Lunae Planum) have orbit-pole points that cluster along a small circle from near the present pole to near the equator (15°N) at 180°W (Amazonis Planitia) to near 45°N at 295°W (Utopia Planitia). The oldest grazers (older than Lunae Planum) have orbit-pole points that cluster along the same small circle with the addition of a concentration near Tempe.

Thus, there appears to be a non-random distribution of Mars-grazer orbits, thereby adding weight to the idea of satellite orbits fixed in space while the crust of Mars shifted below. The orientation of Mars in space can shift due to both changes in obliquity (the tilt of the spin axis) and polar wandering (shift of the crust with respect to the spin axis). Past research in orbital dynamics has predicted natural oscillations in the tilt of the spin axis from 10° to 45° (the present value is 23°). The orbital decay of low-inclination satellites during oscillatory variations in the obliquity should result in NW- and NE-trending impact directions symmetric about the average spin-axis orientation owing to the rotation of the planet. We find, however, preferred impact directions that are asymmetric about the present poles of Mars but cluster in certain non-polar locations at times past. Therefore, we favor the interpretation that the crust of Mars has shifted due to changes in the distribution of mass on Mars, e.g., the formation of the Tharsis bulge. Significantly, the locations of the orbit poles indicated by the Mars grazers closely coincide with the location of the ancient polar deposits reported by Schultz and Lutz-Garihan at the last Lunar and Planetary Science Conference.

In summary, we propose that Mars once possessed a family of satellites, of which Phobos and Deimos are the largest surviving remnants. As these satellites gradually spiraled in and collided with Mars, they recorded the ancient orientations of the martian crust much as the remanent magnetism in rocks on the Earth has recorded the shifting continents.

A PARTIALLY MOLTEN MAGMA OCEAN MODEL. David N. Shirley
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Chemical trends in minerals from the lunar crust are consistent with the outer portion of the Moon never having been fully molten. This interpretation suggests an alternative to a fully molten moonwide 'magma ocean' shortly after its formation.

In order to produce a fully molten magma ocean, a tremendous amount of heat must be supplied. The most probable source is heat released by infalling meteoritic debris during formation of the Moon. Radioactive decay of short lived nuclides has also been suggested but, there are serious grounds for doubting this source. Consideration of the magnitude of these heat sources suggests that there was not enough heat to generate a fully molten magma ocean. It is this discrepency that inspired the present search for an alternative to traditional magma ocean models. Our efforts show that the chemical and petrological data can also be understood even though the outer few hundred kilometers were only partially melted.

As the outer portion of the Moon was heated, melt formed in cracks between mineral grains. The initial fraction of melt near the Moon's surface is believed to be about 20%, the maximum possible consistent with the solid matrix retaining enough strength to maintain its rigidity. At higher amounts of melt the solid collapses and separates from the liquid due to their differing densities. Consideration of the thermodynamic properties of the minerals believed to be present show that the fraction of melt must have decreased steadily to a value of zero at a depth of 300-400 kilometers.

PARTIAL MELT MODEL

Shirley, D.N.

The existence of a moonwide magma ocean on the early Moon has been postulated by many lunar researchers since early Apollo missions returned the first samples of the lunar crust. Primary evidence for the existence of a magma ocean is the extreme abundance of the mineral plagioclase in the lunar curst and the large amount of the mysterious component KREEP which show the same incompatible element pattern at all sampled lunar locations.

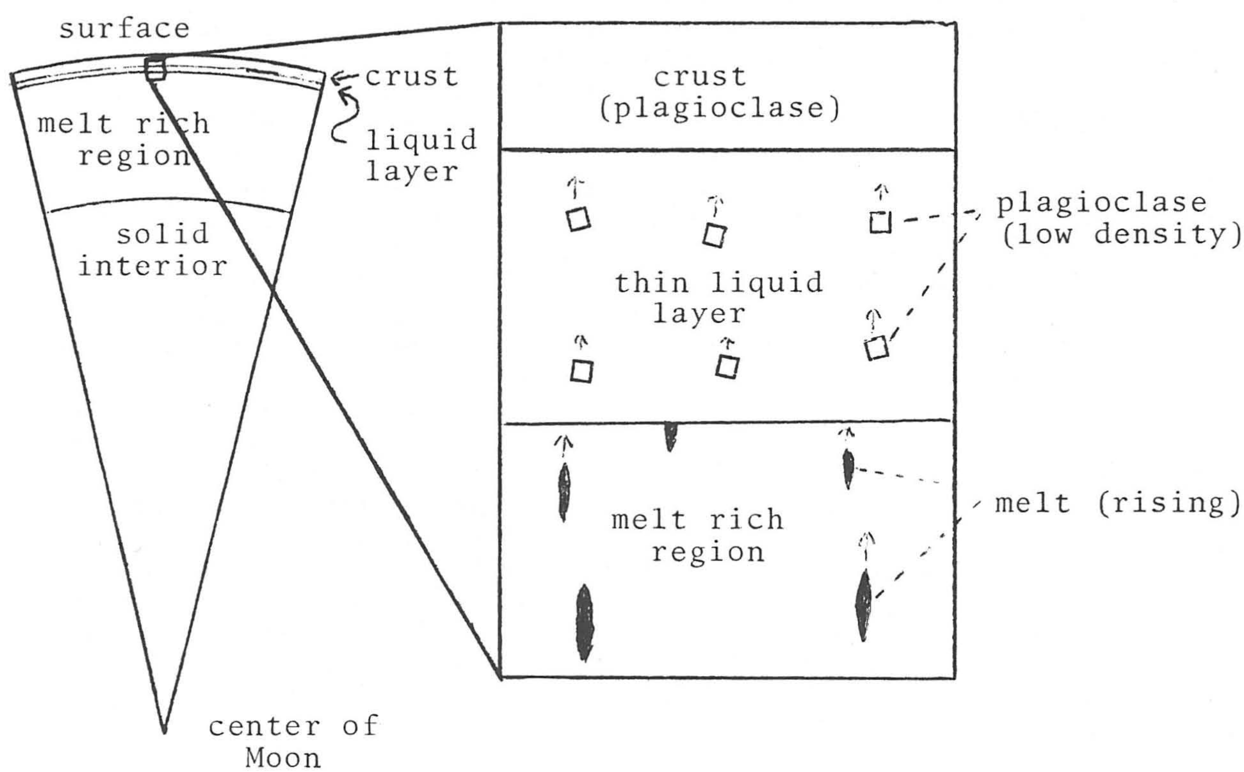
The appearance of plagioclase in rocks collected also suggest that they had formed by floatation over a body of magma. The results of this study suggest that the layer of magma which the lunar crust floated over may have been far thinner than that envisioned for a magma ocean. As this thin layer crystallized, additional magma was constantly added to it from the thick partially molten zone described previously (see Figure 1 for further explanation).

Chemical trends in the elements Mg, Fe, Na and Ca in minerals from the lunar crust are consistent with this model if the thin layer of magma remained nearly constant in thickness during the formation of the crust. Some trends predicted by this model such as nearly constant Ca/Na ratio in ferroan anorthosites which make up much of the lunar crust, have provided difficulties for other magma ocean models. The high enrichment of incompatible elements in KREEP is also readily understood by the model. It appears that a partially molten magma ocean model offers a more realistic framework in which lunar history can be viewed.

PARTIAL MELT MODEL

Shirley, D.N.

Figure 1. Cross section of a thin slice of the early Moon. On the right a representative part of the region near the liquid layer. Plagioclase is crystallizing from the liquid and floating up and adding to the thickness of the crust. Melt is rising up through the thick melt rich region and is added to the liquid layer. The rate at which crystals are removed from the liquid layer is about the same as the rate at which melt is added to it. This allows the liquid layer to maintain an approximately constant thickness while the crust thickens. Note: The melt rich region is initially about 10% molten and the fraction decreases as the crust thickens.



Possible Asteroidal Origin of SNC Meteorites

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Shergottites, Nakhlites, and Chassignites, often referred to collectively as SNC meteorites, are a small group of highly unusual meteorites. Scientists believe that meteorites originally come either from the asteroid belt or from the cloud of com ets surrounding the solar system. The unusual characteristics of the SNC meteorites have led several scientists, however, to suggest they may have originated on another planet, perhaps Mars. Our work challanges this view. Instead, we favor an asteroidal origin under the unusual circumstance of a meteorite impact. Any model of the origin of SNC meteorites must be able to explain their unusual characteristics, which are discussed briefly below.

The most unusual aspect of the SNC meteorites is that they are very young: studies of their radioisotopes show that they solidified from melted rocks only about 1.3 billion years ago. Similar work on other meteorites give ages of 4.5 - 4.6 billion years. Therefore, SNC meteorites must have formed where there was enough heat to melt rocks about 1.3 billion years ago. The most likely sources of heat are either radioactive heating within a major, rocky planet (Venus, Earth or Mars) or heat generated by a meteoroid impact on a parent body or bodies.

Secondly, the SNC meteorite's mineral grains have "cumulate" textures, which indicates that the melt from which they formed cooled slowly. As a melt cools, mineral crystals begin to grow within it. When the crystals have grown large enough and heavy enough, they sink to the bottom of the melt pool and accumulate there, hence the name "cumulate" (which means "heaped" in Latin). Different minerals start to crystallize at different temperatures. Those that begin to form at higher temperatures begin to accumulate first. As the melt cools, lower temperature minerals begin to accumulate. Thus, slow cooling tends to separate minerals that crystallize at different temperatures. In contrast, when a melt cools quickly, there is not enough time for crystals to grow very large or for different minerals to separate from each other. The difference in texture between slowly and quickly cooled rocks is quite distinctive. Since the SNC meteorites are clearly cumulate rocks, a model for their origin must include not only a heat source at 1.3 billion years ago, but also an environment in which the melted rock could cool slowly.

Thirdly, the details of the chemical composition are quite complex. The variation among the most abundant (major) elements is not much of a problem: the major element variation among the shergottites, for example, can be explained by their being from different portions of a single cumulate rock group. However, the lack of a simple pattern in the variation of trace elements tends to suggest that parent rocks of SNC meteorites had a complex history involving a number of episodes of partial melting. When a rock is partially melted, only those minerals with low melting points melt. Since the melt is less dense than the solid rock, it tends to rise and separate itself from the solid residue. The atoms of certain trace elements preferentially enter a melt rather than remain incorporated within mineral crystals. These elements therefore migrate from the solid residue into the melt as it is separated. Thus partial melting changes both the major and trace element chemistry of the derived rocks. The complexity of the trace element patterns of the SNC meteorites seems to indicate that their parent rocks must have undergone a number of episodes of partial melting and solidification of the melt. Therefore a model for their origin must include either an environment in which melting could have occurred a number of times previous to 1.3 billion years ago, or some other explanation of variation in trace elements.

The fourth requirement for a good model is a physical mechanism capable of removing the meteorites from their parent body and putting them on a collision course with the earth. The most obvious candidate is a meteorite impact on the parent body(ies), throwing the rocks fast enough to escape from the gravitational attraction of the parent. The larger the parent body, the greater its gravitational attraction and the faster the ejecta must travel to escape. In 1979 L. E. Nyquist and coworkers calculated that Shergotty, one of the shergottites, must have been at least 100m in diameter when it was removed from its parent body. For a large asteroid, with an escape velocity of only 1 km/s (2,200 mi/hr) removal of such a large intact chunk would not be too difficult. Mars' escape velocity is 5 km/s: an impact large enough to accelerate ejecta to such high speeds would almost certainly vaporize, melt, and crush to fine dust most of the ejecta.

John Wasson and George Wetherill hypothesized in 1979 that meteorites come from Mars. Martian surface rocks contain large amounts of frozen water and carbon dioxide, which would vaporize upon impact and possibly give enough of an extra boost to the ejecta for rock fragments to achieve escape velocity. Although this was only a brief suggestion, with no calculations to support it, the idea was seized upon by a number of petrologists, notably Edward Stolper, who realized that a number of anomalous features of SNC meteorites could be readily explained if they originated on Mars. The bulk chemistry of the SNC meteorites is consistent with what little is known of the composition of Martian soil. The great shield volcanoes of the Tharsis region, such as Olympus Mons (which rises approximately 23 km above the surrounding terrane), and their associated lava fields demonstrate melting occurred within Mars fairly late in the planet's history. If the melt collected in a pocket beneath the surface, it would cool slowly and produce the observed cumulate rock texture. Furthermore, it is quite feasible that Martian rocks have evolved through time via episodes of partial melting, etc., which would explain their complex trace element chemistries. The main difficulty of a Mars origin is the mechanism of ejection.

We have done calculations of the effect of an expanding gas cloud (the vaporized water and carbon dioxide) on ejecta velocities. Although the calculations are far from complete, the preliminary results indicate that even with this extra boost, it would be impossible to remove large chunks of rock from the surface of Mars by this mechanism.

We therefore have investigated the possibility that SNC meteorites orginated as impact melts on large asteroids, whose escape velocities are low enough that later removal of large chunks of rock is not a major problem. Studies on some terrestrial impact and explosion craters indicate that at least in some craters, a pool of melt forms which is covered by a thick layer of rock rubble (breccia) from the impact. This breccia would serve to insulate the melt pool so it could cool slowly. In many terrestrial craters, some of the cold breccia mixes with the melt, causing it to cool rapidly. This mixing may be facilitated by the presence of water in the rocks at the impact site; since asteroids have little or no water, there may be much less mixing of the breccia with the melt, permitting slower cooling of asteroidal impact melts than of terrestrial impact melts. Too little is known about the details of formation of impact craters to say for sure.

Some studies show that impact melts tend to be chemically homogenous, that is, target rocks at the impact site of different compositions mix

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together thoroughly in the melt. This would imply that each of the SNC meteorites originated in a separate impact event, requiring at least 9 such events, one for each of the known SNC meteorites, at approximately 1.3 billion years ago and no other such events at other times. Such a coincidence in time seems unlikely. However, the work of Marchand and Crocket on the Mistastin Lake crater in Labrador shows that although the major elements are relatively well homogenized, the trace elements are not. For example, the ratio of two isotopes of strontium $^{87}Sr/^{86}Sr$, in the Mistastin Lake impact melts at the time of their origin varies as much as does the same ratio for all of the shergottites. Asteroids may very well have at least as much variation of their chemical components as do the target rocks at the site of Mistastin Lake crater, and therefore impact melts on asteroids could be expected to show at least as much variation in trace elements as the ones at Mistastin Lake. The complex patterns of trace elements in SNC meteorites may thus be due to incomplete mixing during impact; this does away with the requirement that parent rocks of the meteorites formed via a long series of partial melting events, etc., which could only happen within a major planet such as Mars. Each group, shergottites, nakhlites and chassignites may thus have been formed by a single impact event, requiring a total of only three asteroidal impacts.

In conclusion, the question of where and how SNC meteorites originated remains unsolved. Mars may be more attractive from a petrologic viewpoint, but there is as yet no known physical mechanism by which the meteorites could be extracted from the planet. Removing them from asteroid-size parent bodies by means of a second impact is not a difficult physical problem. The explanation of their petrological pecularities in the asteroidal model is somewhat unorthodox and depends on assumptions concerning the formation and distribution of melt in impact craters. Detailed mechanisms of crater formation are not well understood, but observations at terrestrial craters suggest our proposed mode of melt emplacement is feasible. Our model therefore incorporates plausible mechanisms for the formation of SNC meteorites on their parent bodies and for removing them from their parents at a later time, whereas the Mars origin model contains no physically reasonable model for the removal of large intact masses of rock from the planet.

HEAT TRANSPORT IN H_2O-ICE COMETARY NUCLEI. R. Smoluchowski, Univ. of Texas, Austin, TX 78712

For centuries the appearance of comets has been associated with all kinds of catastrophic events such as wars, plagues, floods etc. Only within the last few decades it became clear that there are millions of huge — a mile or two in diameter — chunks made of ice, snow and dust that circle our Sun at distances much greater than any known planet. They are very cold and invisible. Once in a while because of various perturbations motions of some of these chunks of ice are changed so that they may approach the Sun. The nearer such a cometary nucleus comes to the Sun the warmer it gets, water begins to evaporate and finally in proximity of the Sun the water vapor and other gases escape from it so rapidly that they carry away small bits of ice and dust. These gases and particles are illuminated and heated by the Sun and form the familiar cometary tails. After the comet passes by the Sun it begins to cool off, the tail diminishes and finally the cold nucleus again becomes invisible. Then after many many years the comet may return to the proximity of the Sun and repeat its showy performance or it may escape again into the outer regions of the solar system never to be seen again.

If we want to understand the formation and the size of the cometary tail we have to know what happens to the heat produced by the solar radiation, how much of it is simply reflected as light, how much goes into the heating of the inside of the nucleus and how much is used for heating the surface of the nucleus and producing the visible cloud, the so-called coma, and the tail of the comet.

It turns out that so much heat penetrates into the cometary nucleus that after passing the Sun the nucleus cools off slower than it was heated up on its initial approach to the Sun. It is shown that this slow cooling causes the tail to be more prominent after the passage of the Sun than before and that the tail will reach its maximum sometime up to 100 days after the encounter. This is in agreement with observations. Also it is shown that since very likely the ice in the cometary nucleus is not solid but porous much of the heat entering it goes not only through the ice itself but also through the pores filled with water vapor. It turns out that at low temperatures, that is for comets which do not come closer to the Sun than say the planets Mars or Jupiter, this additional heat flux through the pores is of no importance. If however the comet on its nearest approach to the Sun comes as near to it as for instance the Earth then the heat flux through the pores is much higher than through the solid ice and this affects greatly the formation of the tail.

It is believed that some cometary nuclei also contain other ices besides the normal water-ice which we know from ice cubes in tall drinks or as snow flakes. These other ices may be either what we often call "dry ice," that is frozen carbon dioxide, or frozen ammonia etc. These other ices evaporate at lower temperatures than water-ice and their effect on the heat flux in the cometary nucleus and on its thermal history can be easily determined using the same mathematical methods that have been used here.

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STRUCTURE AND FRAGMENTATION OF ASTEROIDS. G. J. Taylor, E. R. D. Scott, A. E. Rubin, P. Maggiore, and K. Keil, Inst. of Meteoritics and Dept. of Geology, Univ. of New Mexico, Albuquerque, NM 87131.

Asteroids are small planets that orbit the sun between Mars and Jupiter; the largest has a radius of only 510 kilometers compared to 1738 kilometers for the moon. Many asteroids probably never heated up to their melting points when they formed 4½ billion years ago. Consequently, they preserve a record of the processes operating and the nature of the materials existing before and during planet formation. Much has been discovered from telescopic observations of asteroids, but detailed information can come only from direct study of rock samples. Fortunately, collisions in the asteroid belt and gravitational forces have delivered small chunks of asteroids to Earth free of charge. These chunks are called meteorites.

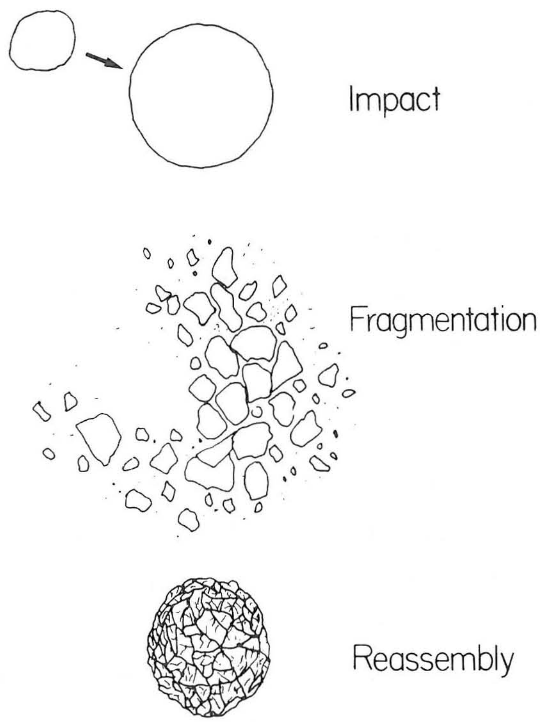
The most common types of meteorites are the ordinary chondrites. Although composed mostly of silicate minerals, ordinary chondrites also contain metallic nickel-iron. Compositions of the metallic minerals can be used to determine the rate at which a given meteorite cooled (at about 500^{o}C, well below the melting point) while residing in its parent asteroid. (These cooling rate measurements are not affected by heating as a meteorite blazes through Earth's atmosphere; though intense, this heating affects only the outer millimeter of a meteorite.) We and others have determined the cooling rates of ordinary chondrites. Most chondrites cooled at rates between 1 and 100 degrees (C) per million years. The data can be used to shed light of the original structures and on the fragmentation histories of the parent asteroids of the ordinary chondrites.

Asteroid structures: Some meteoriticists believe that the parent asteroids of the ordinary chondrites formed with onion-shell structures. In this view, the most metamorphosed (heated and recrystallized, but not melted) chondrites, called type 6 by meteoriticists, formed in the cores of asteroids and were surrounded by successive layers of less metamorphosed types 5 through 3 chondrites. The onion-shell model calls for the metamorphism to have taken place inside the parent asteroids and, therefore, requires that there be a correlation between the chondrites' metamorphic types and cooling rates (i.e., the most metamorphosed type 6 chondrites ought to have cooling rates slower than type 5, etc.). However, it is also plausible that the maximum metamorphic temperatures were reached in smaller planetesimals, perhaps only a few kilometers in radius. Subsequent accretion of the hot planetesimals into parent bodies would ensure that cooling rates at 500°C were controlled by burial depths in the parent asteroids, but there would be no correlation of cooling rate with metamorphic type. Our results demonstrate clearly that no such correlation exists. Therefore, metamorphism must have taken place in small bodies before they accreted into parent asteroids. If the energy released by the decay of a radioactive isotope of aluminum (aluminum-26 or ^{26}Al) was the heat source (as seems likely), then accretion of 100 kilometer-sized chondritic asteroids must have taken place after most of this short-lived isotope had decayed. This means accretion probably took longer than about 10 million years.

Fragmentation history of asteroids: Some ordinary chondrites were formed by compaction of the battered, fragmental materials on the cratered surfaces of asteroids. These meteorites, called regolith breccias, are mixtures of chondrites of different metamorphic types. Metallic nickel-iron grains in individual meteoritic regolith breccias indicate cooling rates of between 1 and 1000 degrees (C) per million years. This wide range in cooling rates implies that the meteoritic materials that were mixed to form breccias on the surfaces of chondritic asteroids came from a wide range of depths inside the asteroids. Calculations indicate that these depths ranged from a few kilometers to about 100 kilometers in asteroids 200 kilometers in radius. Because impacts among asteroids (or between comets and asteroids) cannot excavate to such great depths without destroying an object 200 kilometers in radius, we conclude that the parent asteroids of ordinary chondrites must have been disrupted after cooling, but then reassembled (see figure).

The idea that asteroids could experience such a fragmentation history was originally proposed by D. R. Davis and C. R. Chapman (Planetary Science Institute, Tucson), who showed from theoretical calculations that break up and reassembly is possible for a large range in impact energies. (Similar disruption-reassembly histories have recently been suggested for many of Saturn's moons.) After gravitational attraction has put a disrupted asteroid back together again, the asteroid is a large rubble pile that contains near its surface materials derived from virtually all depths throughout the original body. Compaction (presumably by small impacts) of the surface rubble produces the coherent rocks that are ultimately delivered to us as meteorite regolith breccias.

In summary, we see that asteroids are complex, chaotic bodies. They formed from thousands of metamorphosed planetesimals. At least some asteroids broke up into millions of pieces and reassembled as rubbly piles of debris.



EXTRATERRESTRIAL WATER

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Water is the key substance that is responsible for the Earth environment. Venus, a twin to Earth in size and density, is very different partly due to its lack of water. Mars clearly had abundant water in the past and its surface shows the effects of that water. The lack of water on the Moon and asteroids contributes to the distinctive nature of rock samples from those objects.

But it has always been a bit puzzling that meteorites are completely free of water because (i) carbonaceous chondrite meteorites appear to have been "soaked" in water at some time in their complex history, and (ii) water is one of the more abundant molecules in the solar system.

Many scientists have searched for traces of liquid water in meteorites with no success. Now a group of scientists centered at the Johnson Space Center in Houston Texas have discovered tiny pockets of liquid water in a dozen meteorites, and their discovery has been confirmed by researchers from the U.S. Geological Survey in Reston, Va.

The tiny pockets of liquid water occur as inclusions in pyroxene and olivine crystals in the meteorites. Called fluid inclusions, they range in size up to 50 micrometers across (one micrometer = 1/25,000 inch). Fluid inclusions are distinguished from the more common glass and mineral inclusions because they consist of a liquid with an enclosed vapor bubble (see photos). The vapor bubble moves about the fluid inclusion spontaneously at room temperature proving that there is a liquid in the inclusion. Another way to prove that the fluid inclusion contains an equilibrium mixture of liquid plus vapor is to homogenize the mixture. This is accomplished in a microthermometry apparatus which is a heating-freezing stage mounted on an optical microscope. The suspected fluid inclusion is mounted in the apparatus and the temperature is raised while monitoring the inclusion through the microscope. (Actually the microscope image is monitored by a TV camera and the scientists watch a TV screen). If the inclusion is a true water fluid inclusion, the liquid and vapor bubble will homogenize by the time the temperature is raised to 374^{o}C, the critical point of water.

The discovery of aqueous fluid inclusions in meteorites is interesting, but what is really important is to determine the chemical composition and density of the included fluid. With that information, much can be deduced about the conditions in which the meteorites formed, and in turn about the origin of the Earth. But it is not a simple matter to analyze the fluid contained in a fluid inclusion, and many techniques are being developed to accomplish that goal. Results thus far indicate that the mixture contained in fluid inclusions in meteorites has peculiar chemical and physical properties.

The density of the fluid is calculated from the homogenization temperature once the chemical composition of the fluid is known. But the meteorite water does not cooperate with even this simple measurement. In Earth rocks all the fluid inclusions in a given sample display nearly the same homogenization temperature. But each fluid inclusion in a given meteorite displays a different homogenization temperature.

The chemical composition of the included fluid of terrestrial fluid inclusions is usually calculated by measuring the freezing point depression. But the water in meteorite fluid inclusions does not generally freeze, even though the temperature is lowered to the temperature of liquid nitrogen (-180^{o}C). Because of the lack of freezing, the Johnson Space Center scientists took the meteorites with the fluid inclusions to a laboratory in Nancy, France where they were analyzed using a new laser Raman spectograph. The experiment was to test for the presence of water and other molecules in the fluid inclusions. This research demonstrated that water was present, and no trace of molecules containing carbon, nitrogen, or sulfur.

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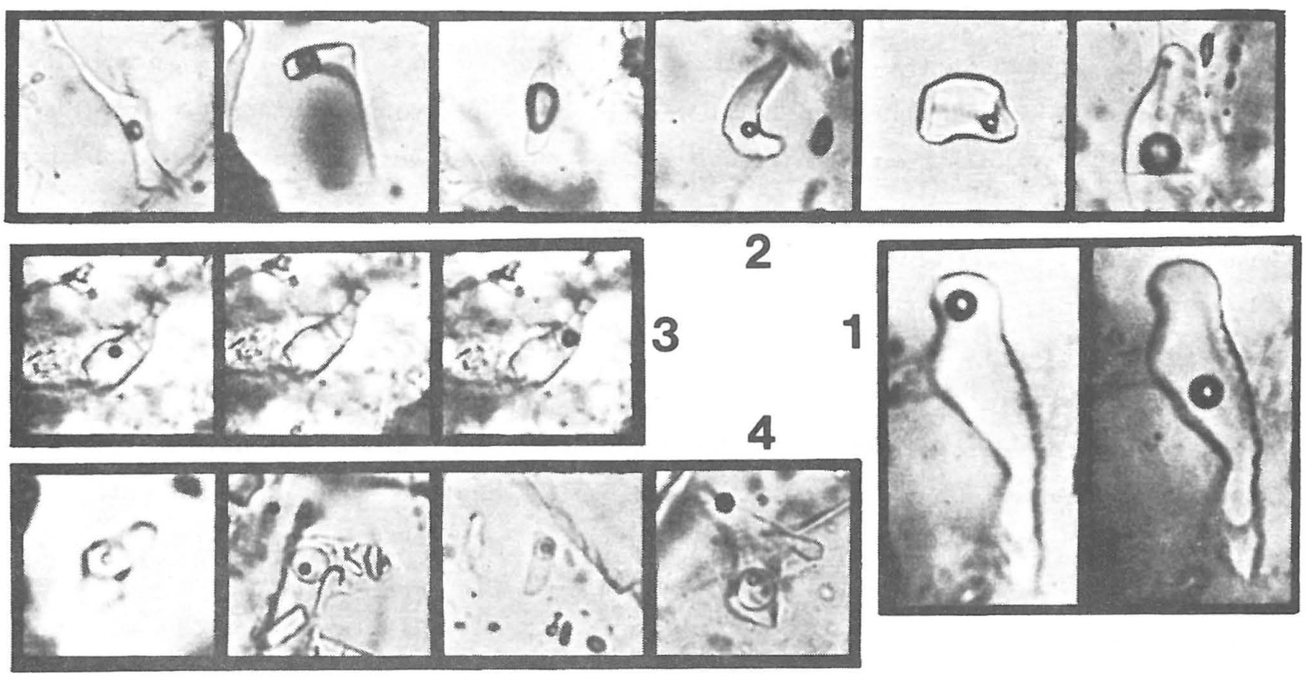
So what could be dissolved in the water to stop it froom freezing? The scientists suspect that the water has a very high concentration of salt, such a high salt content that the liquid is syrupy and freezing is made difficult. Similar solutions occur in the lakes in the dry valleys of Antartica.

But the problem is not yet solved. The scientists must determine the detailed chemical composition of the the included fluid. To do that they are developing a new laser micr oprobe at the Johnson Space Center. This laser microprobe will be used to "drill" open one fluid inclusion at a time. The evolved fluid will then be routed to a mass spectrometer and a gas chromatograph for analysis of the salt.



GRANITE FROM THE MOON

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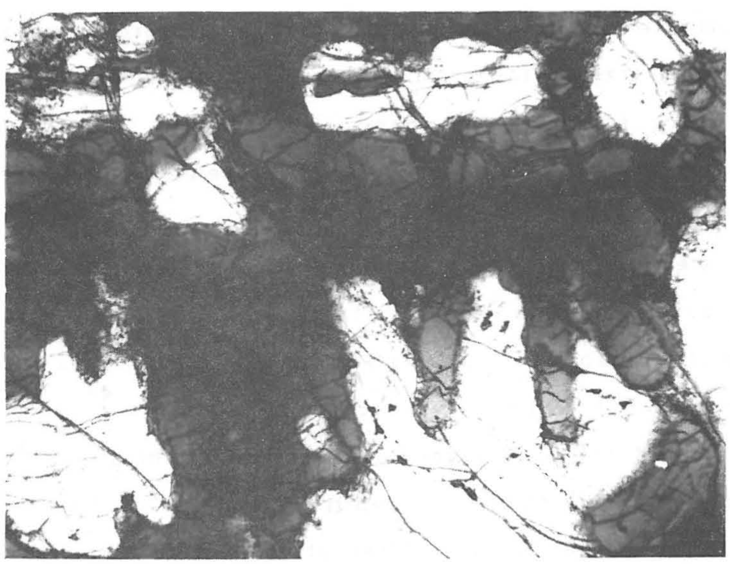
Granite, which is an igneous type of rock (that is, a rock formed by solidification of molten magma), is one of the most important rock types in Earth's crust. Earth's continents are believed to be underlain mostly by granite and similar rock types. Most of the oldest Earth rocks are granites or related metamorphic rocks (gneisses). Before the late sixties, there were many who believed that granitic rocks were predominant in the lunar crust. However, the only lunar "granites" found until now have all been so small that that they may well actually be unrepresentative pieces of rocks only remotely related to true granite (for example, diorite). One large granite-like lunar rock, sample 12013, was found in 1969. Unfortunately, 12013 is a mixed breccia. A mixed breccia is a rock which consists of a mechanical mixture of unrelated older rocks. Breccias are produced when giant meteorites impact the crust of a planet, crushing, heating, and mixing up the rocks near the surface; most rocks exposed on the Moon's surface are mixed breccias. The original properties of the granite-like component in 12013 were obscured (we can be reasonably confident that it was a granite, however), when it became mixed up with other rocks at the time the mixed breccia was formed. Some geologists have even resorted to discussing tiny, unrepresentative portions of lunar rocks of a type (called basalt) completely unrelated to granite, under the heading of "lunar granites." Valuable information has been derived from such samples, but until now there have been no large, unadulterated lunar granite samples available for study. In the course of a survey of clasts (a clast is a small rock-fragment within a mixed breccia; most, but not all, clasts are themselves mixed) among rocks returned by the Apollo 14 mission, we recently discovered two unadulterated granites, one of which is "large" by lunar sample standards. At present, a chemical analysis is available only for the larger granite clast, so in our abstract we focus most of our attention on it.

The "large" granite, known officially as Apollo sample number 14321.1027, is only 16 millimeters (about 0.6 inches) across in its longest dimension. It is estimated to be 0.6 cubic centimeters in volume, and to weigh 1.9 grams (about 0.07 ounces). That does not sound like much, but NASA-funded scientists have perfected techniques for analysis of lunar rocks that require only tiny amounts of material. For example, last year an accurate age was measured for a 3.8-billion-year-old lunar rock using only 6 millionths of a gram (less than one millionth of an ounce) of material (Papanastassiou and Wasserburg, in their paper presented at last year's Lunar and Planetary Science Conference). The granite is only one of hundreds of diverse clasts, most of them completely unstudied, which occur in a 9-kilogram (20-pound) mixed breccia, sample number 14321, nicknamed "Big Bertha" (note: the rock as a whole is mixed, but this particular clast within the rock is NOT mixed). The other granite, an unmixed clast known officially as sample number 14303.204, is reasonably large in two dimensions (11 x 6 mm), but not at all thick: its mass is estimated to be only 0.17 grams (0.006 ounces). Its "parent" rock, sample number 14303, is 0.9-kilogram (2.0-pound) mixed breccia, which also contains hundreds of as yet unstudied clasts.

Both clasts are granites in the strictest sense of the word, being made up primarily of the minerals potassium-feldspar and quartz. Both granites have suffered some crushing due to meteorite impacts (almost all of the older types of Moon rocks have been crushed at least a little). However, in both clasts there are still many large areas where the original (igneous) texture (the fabric of sizes and shapes of adjoining crystals, visible when ultra-thin slices of the rocks are viewed through a special microscope) is completely unmodified. This is most fortunate, because the textures are extraordinary. In both cases, the potassium-feldspar and the quartz are generally found in large intergrown crystals (see photograph below). This is a common texture among Earth granites, called graphic granite texture, because the intergrown crystals sometimes resemble cuneiform writing. (Several tiny granite-like clasts from the Apollo 15 and Apollo 17 collections were previously known to have



Photograph of ultra-thin (0.025 millimeters, or 0.001 inches) slice from granite 14321.1027, viewed through a light-polarizing microscope (the light is being transmitted through the slice, from below). The area shown is 1.5 x 1.15 millimeters. The white areas are potassium-feldspar (two crystals), the grey areas are quartz (a single crystal). Note the odd shapes of the crystals.

roughly similar textures, except that the sizes of their intergrowths are much smaller than normal for terrestrial graphic granite. The intergrowths in 14303.204 and 14321.1207 are 5-10 times larger than the largest ones known from any other lunar sample, and well within the range of normal terrestrial graphic granite intergrowths.)

A controversy has long raged over whether the parent liquids of lunar granites formed via fractional crystallization (separation of crystals of one composition from magma of another composition) or via liquid immiscibility (separation of magma into two immiscible liquids). One way to resolve the issue for any given granite is to check certain element-to-element ratios. We have analyzed 14321.1027 (an analysis of 14303.204 will be performed later this year), for many of the pertinent elements. In most of the cases where experimental data exist bearing on the ratios expected to result from liquid immiscibility, the data are consistent with liquid immiscibility. However, in several cases the data are not consistent with a certain theory concerning the distribution of elements between the two immiscible liquids. We conclude that either the theory is not quite accurate, or 14321.1027 is not a product of liquid immiscibility, despite the empirical evidence.

Most terrestrial graphic granites are found in pegmatites, which generally contain abundant evidence of crystallization from volatile-rich magmas. Many of the various hypotheses for the origin of the texture emphasize the importance of solid-liquid-vapor interactions. Yet neither of these first two reasonably large lunar granites, which both feature classic graphic granite texture, appears to bear the slightest evidence of crystallization from a volatile-rich magma (e.g., none of the minerals are hydrous; no fluorine-rich phases are present). This suggests that there is no cause-and-effect relationship between the presence of volatiles and the formation of the graphic texture.

In the future, we hope to arrange to have other geochemists analyze the isotopic composition of at least the larger granite, to determine its age (the time since it crystallized from molten magma). That should help to answer a very important question: If the age(s) turn out to be very near to 4.5 billion years, that will suggest that the granites formed out of the very last molten bit of the magma ocean that is believed to have covered the Moon to a depth of several hundred kilometers shortly after it formed, 4.5 billion years ago. Alternatively, if the age(s) turn out to be less than about 4.35 billion years, that will tend to suggest that they formed from the last molten portions of smaller magma bodies, produced by partial melting of the Moon's interior. In any case, the lunar granites almost certainly did not form in the same way that most Earth granites do. Earth granites generally form in great

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masses (called batholiths), via crystallization of magmas that are granite-like in composition as soon as they become molten (such magmas are probably produced via melting of the lower parts of Earth's crust). The lunar granites probably formed only in small masses, via crystallization of great masses of magmas that were originally not at all granite-like in composition: If a magma that is initially not granite-like solidifies via fractional crystallization, or if liquid immiscibility takes place, the magma's composition will evolve and become more granite-like. However, this mechanism is only capable of yielding relatively small amounts of granite, which is probably why lunar granites are so scarce.

It has been more than nine years since the last U.S. lunar mission (Apollo 17, in December, 1972) returned to Earth with its precious cargo of 111 kilograms (244 pounds) of lunar rocks and soil. An unmanned Russian probe, "Luna 24" brought back 170 grams (6 ounces) of lunar soil in 1976, but since then no new lunar samples have come to Earth. However, about one-half of the Apollo rock samples are complex mixed breccias, made up of fragments (clasts) of diverse pre-existing lunar rocks. In such cases each clast is, geologically speaking, practically as valuable as if it were an entirely separate rock. Many such mixed breccias contain hundreds of discrete clasts, so the number of potentially unique rocky materials returned by our astronauts is tremendously larger than than the number of discrete rocks they returned. Consequently, even after nine years, geologists working on the Moon samples are still far from finished with the task of examining even in the most preliminary way all of the lunar materials at hand. In a very real sense, exploration of the Moon continues at a rapid pace. Each time a geologist slices open one of the mixed breccias, there is a good chance that he will be unlocking one of our sister planet's greatest secrets. The late discovery of these two important fragments points up how much information remains to be gleaned from the Apollo lunar sample collection. These clasts were picked out almost at random from among the thousands of similar fragments that have yet to be studied even in the most cursory fashion. Unfortunately, funding for lunar sample research is dwindling at a much faster rate than the supply of unstudied, yet extremely interesting, samples.

THE MOUNTAINS OF IO. J.L.Whitford-Stark, Department of Geology, University of Missouri, Columbia, Missouri, 65211.

During their passage through the Jupiter system, the two Voyager spacecraft transmitted startling images of the inner Galilean satellite, Io. The images showed the surface to be mottled with red, yellow, white, orange, and black patches. Domal features rising above the limb of the satellite were soon identified (1) as volcanic eruption plumes. The largest of these plumes had a diameter equivalent to the width of Texas and a height 30 times greater than Mt. Everest. Subsequent mapping(2) using the medium resolution images, which cover about 35% of Io's surface, revealed approximately 170 volcanic vents in excess of 14 km diameter; making Io the most volcanically active body in the Solar System. If the Earth were to have a similar volcano density, there would have to be over 12 times more volcanoes than are actually present.

A major problem since the discovery of volcanism on Io has been that of defining the composition of the surface materials. A predilection for materials commonly produced during terrestrial volcanic eruptions, has led to proposals that the Ionian volcanics are sulphur, silicates, or a mixture of both. The study which was undertaken was an attempt to constrain the possible compositions of the volcanics on the basis of the mechanical properties of the volcano-forming materials and to determine the relative ages of the different volcanoes on the basis of photogeologic relationships.

Although the Io volcanoes have a large variety of shapes, there is a dramatic difference between the so-called "mountains" and the remaining volcanoes. The mountains form about 2% of the mapped area of Io, they are steep-sided, have heights of about 30,000 feet, and have extremely rugged surfaces. The remaining volcanoes are generally low, have very gentle slopes, and fairly smooth surfaces.These markedly contrasting features suggest that the mountains are composed of a material which is different to that which forms the remaining volcanoes.

Studies of terrestrial volcanoes are revealing that their shapes are determined by numerous factors. Among the more important factors are the pre-eruption gas content of the molten magma and the flow characteristics of the erupted lavas. The pre-eruption gas content can be envisaged as determining the explosivity of an eruption; the higher the gas content, the more explosive the eruption. As the explosivity increases, the material which is ejected is broken into progressively smaller pieces and thrown to greater distances. The volume of material ejected and the distance it travels can be employed as a measure of an eruption explosivity (3). For example, on a scale of 1 to 8, the main Mt. St. Helens eruption would rate a magnitude of 5, the eruption which produced Crater Lake a magnitude of 6 (4), and the big Io eruption as probably a 7 or 8. It is readily apparent that the further the material is thrown, the flatter will be the shape of the volcano. Conversely, if a lot of the material is ejected only to a short distance,it will pile up around the vent and produce a steep-sided cone.

In the least explosive eruptions, magma is emitted as molten lava. The flow characteristics of the lava appear to be largely controlled by the rate at which the material is emitted from the vent and the lava viscosity. The viscosity is a measure of the inability to flow. For example, treacle flows less readily than water so is described as being more viscous. Typically, silicate lava has a viscosity over 100,000 times greater than water. Longer lava flows are therefore produced at higher eruption rates and are composed of lower viscosity material. If the lavas are produced at low eruption rates and are of high viscosity, the resultant volcano will again be steep-sided. Most terrestrial volcanoes are a mixture of both lava and explosively ejected material. Analyses of rock samples collected from terrestrial volcanoes indicate that most steep-sided structures are composed of material that is more silicic than that which forms the less steep structures.This is not, however, a universal truth.

We do not have, and are unlikely ever to obtain, samples of the surface materials of Io. However, the colors of the surface materials and the results of various remote-sensing experiments indicate that sulphur is an important component of the Io volcanic eruptions (5). It is also a component of terrestrial eruptions, as anyone who has suffered the unpleasant experience of attempting to breath downwind of an active volcano will attest. The main problem with Io is that the remote-sensing experiments can only determine the compositions of large surface areas and only record information about the upper few millimeters or less. Therefore a thin,widespread layer will mask information about the composition of any areally small anomalous region and the underlying material.Can we, therefore, determine anything about the composition of the surface materials of Io from the shapes of the volcanic constructs ?

It is possible to use the mechanical properties of different substances to place some constraints on the nature of the mountain material. When subjected to a continuous force, every substance will deform over a given time period. Gravity is a continuous force acting at the surface of every planetary body, therefore all of the materials on and within a body are being deformed. The time required for the deformation to take place differs for different materials. This time can be estimated from data which relates the inability of a material to flow (viscosity) to its ability to resist the force that is trying to deform it (rigidity). For example, if gypsum were subjected to a continuous force it would deform in about 650 years. Silicates subjected to the same force would take over a million years to flow. The images returned by Voyager 1 show that flowage and fracturing has taken place on some of the mountains. Unfortunately we cannot use these observations to determine the composition of the mountains because we do not know their ages. If the mountains are young (geologically-speaking), the observation that their surfaces may have deformed by flow would argue against them being composed of pure silicates.

Another property of materials is their strengths; that is, a measure of the amount of force that it is necessary to apply to produce failure. The stability of a structure is dependent upon its strength, and the gravitational force acting upon it. At a certain critical height, which varies for the same material on different planets because of the different magnitudes of the gravitational force, a mound built above the surface will become unstable and will deform. A volcano can grow above this critical height (e.g. , Mars) but the weight of the volcanic pile will cause the rocks to flow outward over a period of time. This rock flow will ultimately reduce the volcano to the critical height. If the mountains on Io are at a stable

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height, they cannot be composed of sulphur since the strength of the material needed to sustain a 9 km high feature is far in excess of the sulphur value. At the other extreme, the material need not be a silicate since the 9 km height can be maintained by material with a lesser strength than silicates. It is therefore concluded that the mountains are unlikely to be purely sulphur or purely silicate in composition and may be neither or a mixture of both. They may even be composed of materials which are relatively uncommon on Earth. Possible candidates might include the arsenic sulphides realgar and orpiment, both of which occur in shades of red and yellow.

If, as seems probable, at least two compositionally distinct materials have been erupted on Io, it is critical to our interpretation of the chemical evolution of the body to determine the relative ages of the two volcano groups. We know by direct observation that the non-mountain volcanoes are being formed at the present time but how old are the mountains ? Preliminary geologic maps (2) indicated that the mountains are the oldest unit exposed at the surface of Io. Detailed geologic mapping currently in progress indicates that this interpretation may need revision and, although perhaps not the youngest unit on Io, the mountains may also not be the oldest.

It is possible to derive relative ages of different surfaces on a body by comparing the relative densities of impact craters; the most densely cratered areas being older. No impact craters have been observed anywhere on Io (including the mountains). The entire surface is geologically young and the crater-counting technique is ineffective. Craters on the steep mountain slopes could, however, have been obliterated by downslope movement.

A second observation employed to characterize the mountains as being old is that their rugged surfaces are more deformed than adjacent materials. It was then argued that since the adjacent units do not exhibit such deformation, they must have formed after the mountains. It was shown above, however, that the mountains could flow and fracture because they are higher than their surroundings. Since the surroundings are lower, there is no reason that they should exhibit the same deformation features as the mountains.

The third line of argument is stratigraphic, based on the principle that the uppermost unit is the youngest. The mountains are surrounded by layered plains. There are two mutually exclusive interpretations of the age relationships between the mountains and the layered plains. The currently accepted model(2) is that the mountains were already formed when the layered plains were deposited (Fig.1a). The progressively younger layered plains units overlapped more and more mountain material as the mountains were increasingly buried. The new model is that the mountains are younger than, and superimposed upon the layered plains (Fig 1b). In the absence of reliable age data for each unit, it is extremely difficult to distinguish between overlap and superposition on the basis of photogeologic criteria. The overlap model is questioned because the layered plains do not appear to become thinner (as determined by scarp heights) - which they should do - where they intersect mountains material. Secondly, the scalloped edges and isolated remnants of some mountains suggest that they are being subjected to the same erosional mechanism that causes scarp retreat of the layered plains. With the overlap model, the layered plains should be separated from the mountains by a zone of eroded mountains material (Fig. 1c) - such a zone

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is not seen.

To summarize, this alternative interpretation of age relationships indicates that the mountains may not be the oldest volcanic features on Io. Furthermore, they are composed of a material with an unknown chemistry but which has a substantial strength and which can also flow over an undetermined time period under the environmental conditions prevailing at the surface of Io. The mountains need not be composed of silicate; some terrestrial volcanoes emit strange products, such as washing soda and iron oxide lavas, as well as sulphur. The sharp contrast between the morphologies of the mountains and the remaining volcanoes suggests they are formed of two compositionally distinct materials. This differs from the terrestrial situation where volcanic rocks typically exhibit a continuous compositional spectrum and highlights the different evolutionary paths of the two bodies. The magma which produced the mountains was viscous and volatile-depleted whereas that forming the remaining volcanoes has a low viscosity and is enriched in volatiles. Since the materials surrounding the mountains are relatively undeformed, the crust of Io must have a significant strength at shallow depths to prevent the mountains sinking into the substrate under their own weight. Therefore, on the basis of this interpretation, it is unlikely that Io has a thick sulphur crust. This conclusion would preclude some current proposals as to the nature of the interior and evolution of Io.

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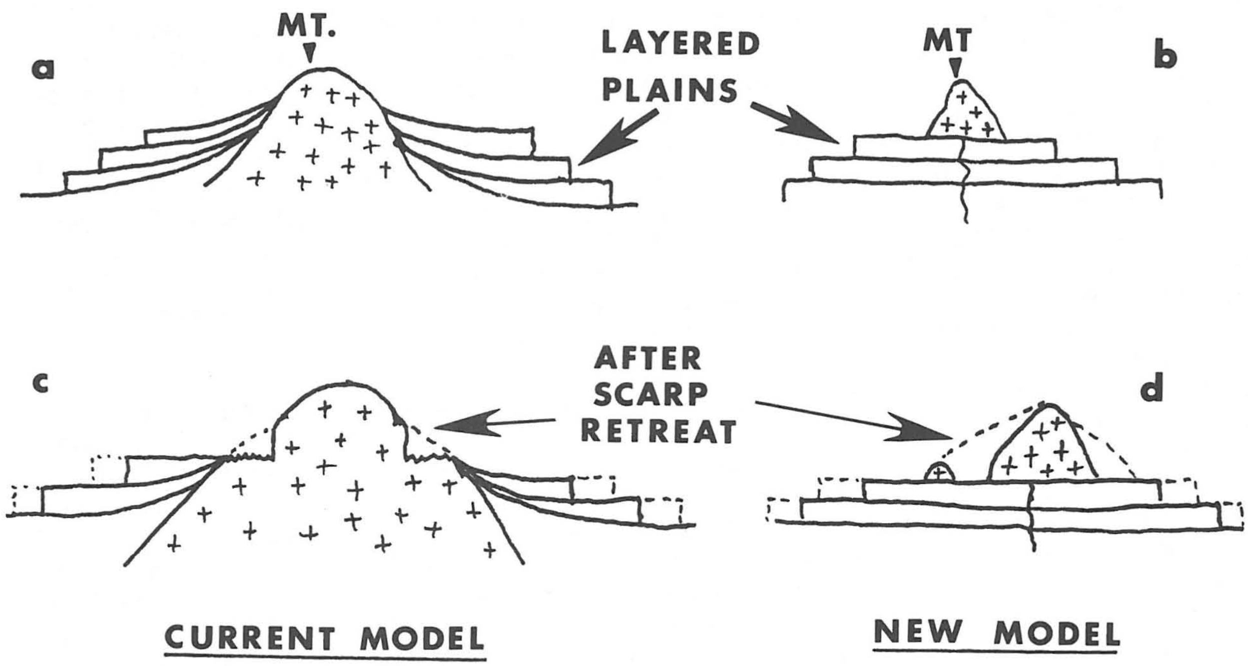

WHERE DO METEORITES COME FROM?

being a press release summary of
"Comets, Asteroids, Meteorites and Meteors:
A New Paradigm of Interrelations"
by

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For nearly two centuries most scientists have believed that the main source of meteorites was the asteroid belt between Mars and Jupiter. Today, at the 13th Lunar and Planetary Science Conference, two NASA scientists challenged that traditional view and proposed instead, that although some meteorites probably are asteroidal fragments, the most common ones may be pieces of the rocky cores of extinct comets.

Charles Wood and Wendell Mendell of Houston's Johnson Space Center pointed out that scientists who study the orbits of asteroids, meteorites and comets have argued convincingly that only a small fraction of meteorites are likely to be derived from objects in the main asteroid belt; most meteorites are probably fragments of cometary cores whose mantles of ice and dust have evaporated during repeated passages near the Sun. These dynamical arguments have not been accepted by meteoriticists, whose studies of the mineralogy and chemistry demand that the meteorites were formed close to the Sun, as rocky bodies, rather than far from the Sun as icy snowballs - as postulated by a widely accepted model of comet origins.

During the last 10 years important new evidence of meteorite origins has come from comparison of telescopic observations of asteroid colors and brightness with similar laboratory measurements on meteorites. Clark Chapman of the Planetary Science Institute in Tucson and other workers have discovered that most asteroids have features similar to two relatively uncommon types of meteorites - carbonaceous chondrites (primitive stony meteorites rich in carbon, sulphur and water) and stony-irons (meteorites with about equal amounts of metallic iron and stony material). Smaller numbers of asteroids look similar to other rare meteorite types, such as irons and various types of igneous meteorites. The remarkable fact about the asteroid belt is that searches have failed to turn up a single unambiguous parent body for ordinary chondrites, which constitute about 80% of all terrestrial meteorite falls! Although various investigators try to minimize this embarrassment, and others offer convoluted explanations for the undetectability of ordinary chondrite parent bodies, Wood and Mendell accept the observational result at face value. Thus, they declare that ordinary chondrites are not samples of the asteroids, a result totally consistent with the orbital analyses.

Recently Wood has made a discovery that links one subset of ordinary chondrites to comets. He found that some meteorites travel through space in clusters (meteorite streams analogous to the well known meteor streams) with an orbital period of about 30 years, which is unlike any asteroid but is similar to some comets. Additional circumstantial support for the meteorite-comet connection was dramatically provided on Nov. 16, 1981, when a shower of ordinary chondrite meteorites fell on a village in Thailand. This event occurred during the annual Leonid meteor shower, and the meteorites came from the same place in the sky as the meteors. The remarkable importance of this observation is that the Leonids, like nearly all meteor showers, are known to be debris from a comet!

In order to tie together the orbital evidence that many meteorites come from comets and the mineralogical data that meteorites are geologically complex and could not have originated inside a comet, Wood and Mendell propose a new scenario for the ultimate origin of at least some comets: ordinary chondrite parent bodies formed in the inner solar system as planetesimals - small bodies which eventually coalesced to form the present planets. Some planetesimals escaped incorporation into growing planets and were hurled into the outer reaches of the solar system by gravitational interaction with Jupiter. There they may have accreted an icy covering. These objects, and many others from other parts of the solar system, are safely stored in the outer solar system until some disturbance throws them back toward the Sun as comets. After repeated passes near the Sun any ices present disappear, and there reamins a small rocky core, the proposed source of the common meteorites. This theory, while still speculative, fits the known data, and suggests that meteorites (brought to Earth at no cost to NASA) sample more areas of the solar system that previously believed. It also implies that current theories of the origin and nature of comets may be only partially correct. Extensive reevaluation of all of the characteristics of small bodies (comets, asteroids, meteorites and meteors) in the solar system and new spacecraft observations of comets (as the Europeans, Japanese and Russians plan for Comet Halley) may be necessary to choose between the new and old theories.

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