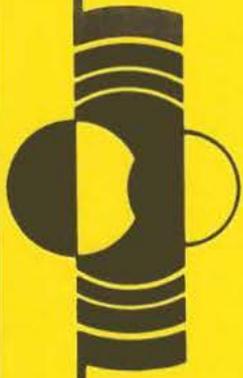


Lunar and Planetary Science XVII



*Seventeenth Lunar and Planetary
Science Conference*

PRESS ABSTRACTS

NASA

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Houston, Texas

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PRESS ABSTRACTS

SEVENTEENTH LUNAR AND PLANETARY SCIENCE CONFERENCE

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PREFACE

The Program Committee for the Seventeenth 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 XVII*.

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.

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Worldwide size distribution of shocked quartz at the Cretaceous-Tertiary boundary: Evidence for a North American impact site. B. F. Bohor and G. A. Izett, U.S. Geological Survey, Box 25046, MS 401, Federal Center, Denver, CO 80225

The discovery of anomalously high amounts of the element iridium in a thin layer of clay exactly at the boundary between rocks of Cretaceous and Tertiary ages in Italy led Luis Alvarez and his coworkers, in 1980, to postulate that a large asteroid struck the earth at the end of the Cretaceous Period some 66 million years ago. They reasoned that this impact raised a dust cloud that encircled the globe, shutting off sunlight for a period of months, thereby causing massive extinctions in life forms, including the dinosaurs, to occur. The thin clay layer containing the excessive amounts of iridium was considered to be the fallout from this dust cloud. This iridium-enriched layer has subsequently been identified at some 75 Cretaceous-Tertiary boundary sites worldwide.

In 1983, shock-metamorphosed quartz grains were discovered in an iridium-enriched Cretaceous-Tertiary boundary clay in Montana. Shocked quartz grains had previously only been identified in rocks associated with known meteorite impact craters (such as Meteor Crater in Arizona) and at sites of nuclear explosions. The unique parallel linear features seen in these quartz grains can form only under conditions of rapid, intense shock loading, such as occur during meteorite impact or nuclear explosive tests. Subsequent identification of shocked quartz grains in many widely separated Cretaceous-Tertiary boundary clay sites around the world that also contain iridium anomalies has confirmed the Alvarez impact theory by direct mineralogic evidence from the rocks themselves. These shocked quartz grains are particles of the target rocks ejected from the crater site by the force of the large impacting meteorite or

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asteroid, and carried in a cloud of debris around the world that subsequently settled out to form the thin boundary clay layer.

Although these discoveries have clearly shown that there was an impact of a large extraterrestrial body with the earth 65 million years ago, the site of the actual impact crater still eludes us. This "smoking gun" would be the final bit of evidence for the impact scenario, and therefore the search for it is being actively pursued on several fronts. On the assumption that the grains of ejecta from the impact would settle out of the dust cloud as a function of distance from the impact site, we have examined the maximum sizes (diameters) of shocked quartz grains in the boundary fallout clay layer at several sites worldwide. Four of these sites are in western North America, five are in Europe (two in Denmark, two in Italy, and one in Spain), one in the North Pacific Ocean, and one in New Zealand. The results of these measurements are given in table 1, and are displayed visually on the map shown in figure 1.

It is immediately apparent that the shocked quartz grains with the largest diameters are found at the North American sites. These grain diameters (in millimeters) are 3-4 times larger in North America than at any of the other sites around the world, indicating that these North American sites were closest to the impact (within the limitation of the number of sites available for sampling). Furthermore, the estimated amounts of shocked quartz relative to unshocked quartz in each sample (table 1) is highest for these North American sites also, again indicating proximity to the impact crater. Therefore, if we make the assumption that the maximum grain size (diameter) and amounts of shocked quartz are directly related to proximity to the impact site, the crater should exist somewhere on the North American continent from our data. A continental target site is much more plausible than an oceanic

Table 1.—Maximum size and relative abundance of shocked quartz grains from the K/T boundary in North America, Europe, the North Pacific Ocean, and New Zealand

Location	Maximum grain size (millimeters)	Ratio of shocked to unshocked quartz grains
Raton Basin, Colo., and N. Mex.	0.58	High
Brownie Butte, Mont.	.50	High
Red Deer Valley, Alberta	.52	High
Morgan Creek, Saskatchewan	.40	High
North Pacific Ocean (GPC-3)	.16	High
Stevns Klint, Denmark	.15	Low
Nye Klov, Denmark	.18	Low
Petriccio, Italy	.19	Low
Pontedazzo, Italy	.12	Low
Caravaca, Spain	.11	Very Low
Woodside Creek, New Zealand	.11	Very Low

Map 5
 60 million years
 Paleocene (Cenozoic)

Mercator
 N = 43 Alpha-95 = 4.7

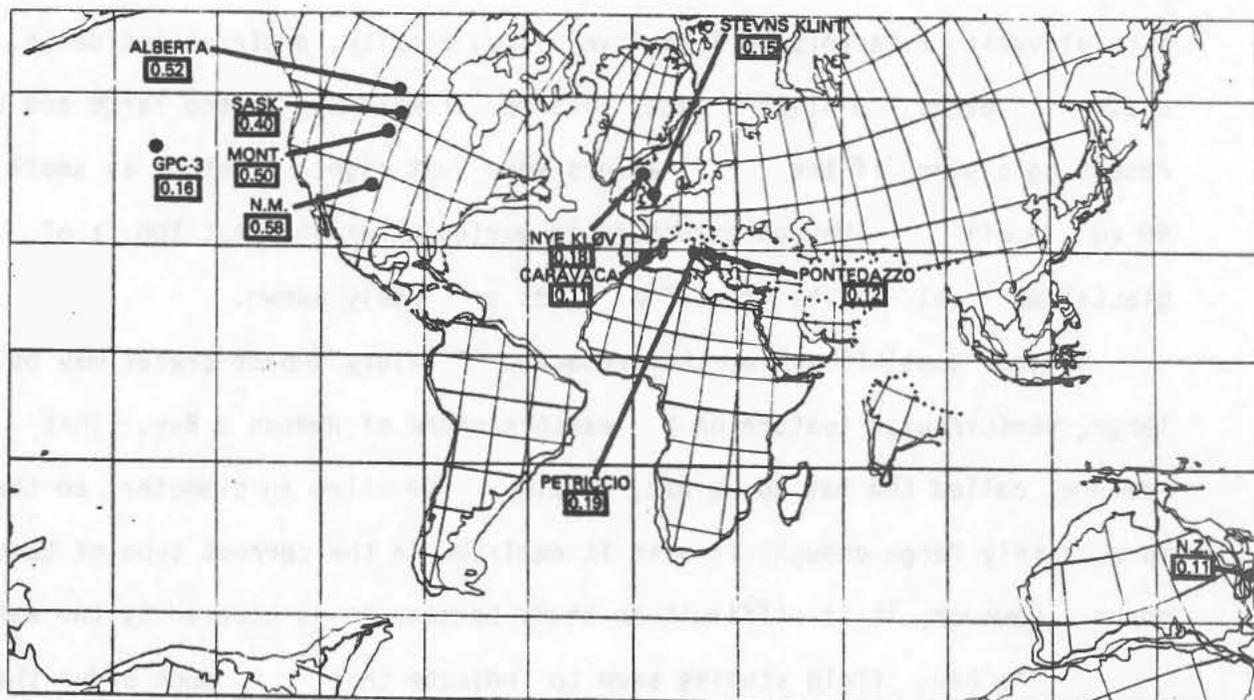


Fig. 1—Paleogeographic world map during Danian time showing the maximum grain diameters (in millimeters) of shocked quartz at K/T boundary sites

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site because of the mineralogy of the shocked grains--quartz is generally not found in oceanic rocks, but is a common component of continental granites, sandstones, etc.

Where might a suitable crater be on the North American continent? One possible candidate is the Manson, Iowa, structure that has been identified as a buried impact crater. It has recently been dated as no older than 70 million years, and is possibly younger. It is in the type of target rocks that would yield the quartz-rich fallout that we find in the Cretaceous-Tertiary boundary clays. The only major drawback is the apparent size of the Manson crater, which is only some 35 km (23 mi) in diameter. The Alvarez scenario postulates an asteroid 10 ± 4 km in diameter striking the earth, which would cause a crater some 100-200 miles in diameter (exact size depending on several variable factors of impact velocity, density, angle of incidence, etc.). However, the Alvarez asteroid size estimate may be too large and the resulting crater (if the other factors were just right) might be as small as 50 km (33 mi). The Manson structure is buried under at least 100 ft of glacial material, so its true size is not accurately known.

Another possibility for the Cretaceous-Tertiary impact crater may be the large, semicircular feature on the eastern shore of Hudson's Bay. This feature, called the Nastapoka Arc, is almost 300 miles in diameter, so that it is certainly large enough; it also is emplaced in the correct type of target rocks. However, it is difficult to study because it is covered by the waters of Hudson's Bay. Field studies seem to indicate that it is much older than 66 million years.

These two craters will be investigated further to see if either one can be shown to be the site of the Cretaceous-Tertiary impact event. Perhaps other candidate craters will be found in North America that fit the criteria of size, location, age, and type of target rocks.

IMPACT EXPERIMENTATION ON THE NASA KC-135 REDUCED-GRAVITY AIRCRAFT: EARLY RESULTS. Mark J. Cintala*, Friedrich Hörz*, and Thomas H. See** (*Solar System Exploration Division, NASA Johnson Space Center; **Solar System Exploration Department, Lockheed EMSCO; both in Houston, TX 77058).

The environment made available by orbital spacecraft -- hard vacuum, unfiltered radiation, and microgravity -- is one that many experimentalists have struggled to simulate or duplicate in the ground-based laboratory. The Space Shuttle has made experimentation in Earth orbit a viable option for many scientific disciplines, and the Space Station will make orbital investigations even more attractive. While the life and materials sciences have been the more active and visible users in these first few years of Shuttle operations, other disciplines will certainly become more involved. Among these future users will be planetary scientists, who have defined a wide variety of experiments that could be flown on the Space Station or Shuttle orbiters. Broadly, these areas include investigations of aeolian dynamics, particle interactions, condensation phenomena, petrological processes, and impact mechanics; descriptions of these and a number of other experiment areas can be found in (1). Improved understanding in these fields will require realistic simulation of Solar System and planetary environments, as they are now and as they were in the past. This would be made possible by the availability of the extreme vacuum and/or the hard-radiation conditions at low Earth-orbit, although the bulk of those experiments dealing with processes active on or in the planets would benefit most from access to low or "zero" gravity. Precursors of some of these proposed laboratories or facilities have already been tested in low-gravity environments; this report will concentrate on the impact investigations.

Rationale: Both theory (2,3) and experiment (4,5) lend strong support to the hypothesis that the results of an impact event are influenced by the strength of the gravitational field in which it occurs. With this in mind, those planetary scientists who study impact craters find it sobering to note that every other solid body in the Solar System possesses a gravitational acceleration which is less than that of the Earth. Therefore, in attempting to interpret the surface history of another planetary body, the results of cratering or collisional experiments in a one-gravity (1-g) field must be extrapolated to the gravitational acceleration under which that surface exists. Difficult in the best of circumstances, this proposition is made even more tortuous by the paucity of data acquired at lower g-levels. Some information exists, thanks to a series of ingenious experiments performed with the NASA Ames Vertical Gun (4), but impediments imposed by the realities of the terrestrial laboratory limit the applicability of the results. In the ideal case, the investigator would be able to vary the g-level, projectile characteristics, and impact velocity for a given experiment, measure the crater after the event is over, preserve the crater and target for later dissection, capture ejecta for subsequent study, and perform other such activities deemed to be important in meeting the objectives of the research program. As a point of comparison, the Ames study utilized a falling platform (supported by springs of different strengths) to simulate various gravity levels. The sand targets were supported by this platform, and the gun was fired as the platform/target assembly fell. Unfortunately, the results of each experiment were lost as the platform impacted the stops at the end of its

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fall, with the only surviving products of the experiments being stereoscopic motion-pictures of the growing craters and widely scattered sand. There was no opportunity to examine the crater after an experiment. Since the ejected material was in flight for too long relative to the fall time of the platform, it could not be deposited under the low-gravity conditions.

In this light, there are obvious advantages for experimentation inherent in a gravity field that could be varied and sustained for extended periods of time (i.e., substantially longer than that required for completion of an experiment). Without belaboring the point, the same types of investigations performed in the 1-g laboratory could also be executed in such an environment. In addition, however, the capability to conduct activities in a virtual "zero-g" state is essential for investigations that cannot be conducted in the terrestrial laboratory: free-floating targets could be impacted, for instance, enabling the direct simulation of asteroid collisions, while the lack of substantial gravitational forces would permit the experimenter to fabricate very weak to strengthless targets, permitting more realistic modeling of small bodies that have been subjected to the ceaseless pounding of high-velocity impacts. Other, more esoteric -- though no less exciting -- experiments have also been suggested. It is with the promise of such a new generation of experiments that a prototype impact facility has been constructed for flight on the NASA KC-135 Reduced-Gravity Aircraft.

The Experimental Environment on the KC-135: The NASA KC-135 Reduced-Gravity Aircraft is essentially a Boeing 707, modified to support parabolic flight. With the familiar internal baggage compartments and most of the seating removed, it presents a large volume available for experiments and the experiment teams. Depending on the requirements, a typical flight lasts on the order of 2.5 hours, during which perhaps 40 individual parabolic maneuvers might be executed. The duration of each maneuver is a function of the desired g-level: "zero-g" can last for about 25 seconds, while martian gravity (0.38g) can be supported for almost 45 seconds. Since even the longest-lived experimental impact-event is over in less than 5 seconds, it is clear that the aircraft meets the principal requirements for a good, variable-gravity platform as mentioned above. (Due to air-mass turbulence and other factors which cause transient accelerations, however, the value of the KC-135 to impact and some other experiments decreases as the desired g-level approaches true "zero-g". The orbital platforms thus become desirable for a number of research areas requiring very low and stable g-levels. Nevertheless, the KC-135 is highly suitable for many experiments in the range of about 0.1 to 2g's.) Unwanted aircraft vibrations are rarely, if ever, present, though low-frequency oscillations around the targeted g-level are not uncommon (Fig.1). While the pressurized cabin supports a shirtsleeve working environment, normally routine activities are often made more difficult by the variable g-levels, which can range from essentially zero to almost 2g's in just a few seconds. With a little imagination, it is easy to understand why motion sickness is an unwelcome but respected aspect of experimentation on the KC-135. This and the desire to accomplish as much as possible in a finite period of time imposes certain requirements on the hardware and the approach to experiment operations.

The Low-Velocity Impact Facility: In order to gain experience in low-gravity operations, a modest impact facility was constructed for flight on the KC-135. In the spirit of learning to walk before running, a simple

approach was adopted in establishing the goals of the activities: learn as much as possible while keeping complexity and costs to a minimum. This philosophy is reflected, to varying degrees, in the facility itself. The projectile accelerator is a standard, air-driven pellet gun, modified to be fired electronically. It is mounted pointing vertically downward into the impact chamber, which is a glass-walled box measuring 52x52x46cm (20x20x18in); it has a hinged top to permit access to the interior, where the atmospheric pressure is the same as that of the aircraft cabin. Between the gun and chamber is a muzzle-blast deflector, on which are mounted two sets of infrared light-emitting diodes and infrared detectors. The launched pellet interrupts the light beam, causing a signal to be sent to logic electronics; since the distance between the two detectors is known, the projectile velocity can be calculated from this distance and the time between interruptions as measured by an integral oscillator. The gun and chamber are supported by an aluminum framework designed to withstand high g-loads in the event of severe aircraft motions. Attached to this platform are a portable microcomputer for event control and data-recording, motion-picture and still cameras for experiment documentation, lighting for the cameras, support electronics, hand- and footholds for control of "body English" during parabolic flight, and other ancillary hardware. The computer serves two very useful functions: it digitally records both cabin pressure and aircraft accelerations while simultaneously acting as a programmable sequencer to initiate and terminate the critical events during an experiment. (Even such a simple facility as this must be utilized in a highly time-constrained and efficient manner as a given maneuver progresses; the critical timing of various aspects of its operation becomes something of a burden for the experiment team -- especially when many of the operations must be performed during the 2-g pullups and pullouts, when one of the team members is suffering from motion sickness ["doing the Technicolor Yawn"], or both. Turning the sequencing over to the computer increases the likelihood that the events will be executed on time.) The team was in agreement that the principal objective of the flight testing was to garner experience in experiment operations and to determine design successes and failures. These goals were to be met by attempting to perform experimentation under these somewhat constrained conditions; if things worked, then the scientific results would be accepted as a bonus.

Some Early Experimental Results: A relatively coarse-grained sand was used as a target during the flight-test program, and identical lead pellets were used throughout the series of experiments. The only variables introduced were the gravitational acceleration and the projectile velocity (and, as a result, projectile energy and momentum). The limited variability of pump-tube pressures in the gun provided a relatively small energy-range of only a factor of 6. Nevertheless, important results emerged and significant lessons were learned.

- o From data on the actual cratering events themselves (see Fig. 2, for example), it was established that the KC-135 is easily capable of supporting experimentation with the precision required for serious planetary investigations.

- o As predicted theoretically and observed in earlier experiments, the cratering process is influenced by the ambient g-level, to the extent that it is immediately apparent even to the casual observer. As the g-level decreases, craters formed at a given impact velocity become larger. Simultaneously, increasingly large fractions of low-velocity ejecta emanate

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from the growing cavity over longer periods of time — an effect easily perceived with the naked eye.

o Each member of the experiment team must understand his/her specific tasks and perform them efficiently. Temporary loss of a team member (e.g., to mechanical problems in his/her area of responsibility, motion sickness, etc.) must be accommodated efficiently by the rest of the team.

o Whenever practical, the computer should perform time-critical tasks. Major decisions, however, must continue to be made by the experimenters.

o The experiment plan should be sufficiently flexible as to allow for various contingencies, such as the inability to fly very low-g maneuvers due to turbulent air; in such a case, a secondary objective at a higher g-level should be examined.

The next step on the road to orbital experimentation is the fabrication and use of a larger facility capable of supporting higher-energy projectiles, greater target volumes, and much lower atmospheric pressures.

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Figure 1. An example of the acceleration history during an impact experiment on the NASA KC-135 Reduced-Gravity Aircraft. The gravity level was recorded 4 times per second; each point represents the average of 10 samples. Note the rapid change in g-level during the transition and the small oscillations around the targeted level of 0.16g. The time of gun firing is indicated at just after 39 seconds.

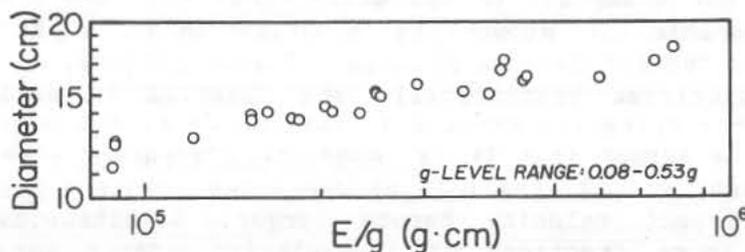
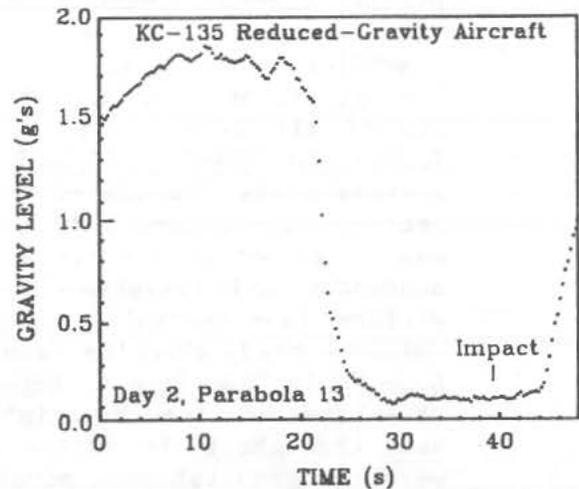


Figure 2. Plot of crater diameter as a function of the ratio of projectile kinetic energy (E) to gravitational acceleration (g), which has the units of "gram-centimeters". The two things to note from this plot are the well-behaved data distribution and the increase in crater diameter as the ratio E/g grows — due to an increase in the impact energy, a decrease in the gravitational acceleration, or both.

OBSERVATIONS OF ACTIVE SULFUR FLOWS ON EARTH:
IMPLICATIONS FOR JUPITER'S VOLCANIC MOON IO

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One of the most exciting discoveries in NASA's program of Solar System exploration is the existence of active volcanoes on the inner-most of the Galilean satellites, Io. Although most of the attention has been focused on the spectacular eruptive plumes, equally important in the evolution of the surface are the widespread lava flows evident in Voyager's images. Considerable controversy has arisen as to the composition of these flows. While some evidence suggests that they may consist of sulfur, other equally convincing lines of evidence suggest that they are silicate flows, comparable to those seen on the inner planets.

Although the controversy regarding the composition of the Ionian flows will probably not be resolved to the satisfaction of everyone until samples can be analyzed, insight can be gained into the nature of the flows by studying possible analogs on Earth. While much is known about silicate flows, natural sulfur flows are extremely rare on Earth, having been discovered in fewer than a half dozen localities. Although far from duplicating the environment of Io, large-scale sulfur "flows" on Earth, generated as part of the commercial mining of sulfur, may shed light on the nature of sulfur flows. The sulfur is mined by drilling wells into sulfur-rich limestone or salt domes; water heated to 165°C (330°F) is injected into the deposit, melting the sulfur and allowing it to be pumped to the surface. The molten sulfur is then poured onto huge cooling vats (about 100 m (330 ft) on a side) and allowed to solidify. A typical 30 minute "pour" totals about 500 metric tons (approximately 66,000 gallons) of liquid sulfur. The flows spread as very fluid complex sheets which cover the surface of the vats.

Observations of these commercial flows provide insight into the complexity of sulfur flows in general and have implications for how such flows may operate on Io, if indeed they exist. In particular, it is found that flexible crusts develop very rapidly and are rafted along the flows. This observation is in contrast to theoretical predictions which suggest that because the density of sulfur increases as it solidifies, crusts should sink upon formation. With insulating properties similar to asbestos or mica, solid sulfur provides a very effective heat-retaining mechanism on crusted flows, potentially allowing the flows to continue for longer periods of time before being halted by complete solidification of the underlying molten sulfur. The observed rapid formation of crusts on the industrial flows lends support to the idea that sulfur flows on Io could extend for great distances (flows several hundred kilometers long are observed on Io). While an explanation for the formation of crusts and their stability for a long period of time has not been determined, the existence of such crusts enhances the possibility that some of the Ionian features are indeed sulfur flows.

The Giant Impact Theory of the Moon's Origin: A Computer Simulation

by
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How did the moon form? This fundamental question has been asked by scientists for centuries, but no definitive answer has yet appeared. Seventeen years ago the first Apollo mission to the moon sought, among other things, to determine the moon's origin. Although a great deal was learned about the moon from the Apollo missions and the rocks they returned, the moon's origin was still very uncertain.

The three classic ideas on the moon's origin are that it either spun out of the earth, was captured from another orbit, or that it accumulated more or less in place from the same building blocks that formed the earth. All of these ideas have severe problems, and none can easily explain the major known facts about the moon.

A recent new idea that has attained great popularity since the 1984 conference in Kona, Hawaii on the Origin of the Moon is that the moon was created in a giant impact of a Mars-size protoplanet with the primordial earth about 4 1/2 billion years ago. This hypothesis can easily explain many of the major facts about the moon discovered by the Apollo missions.

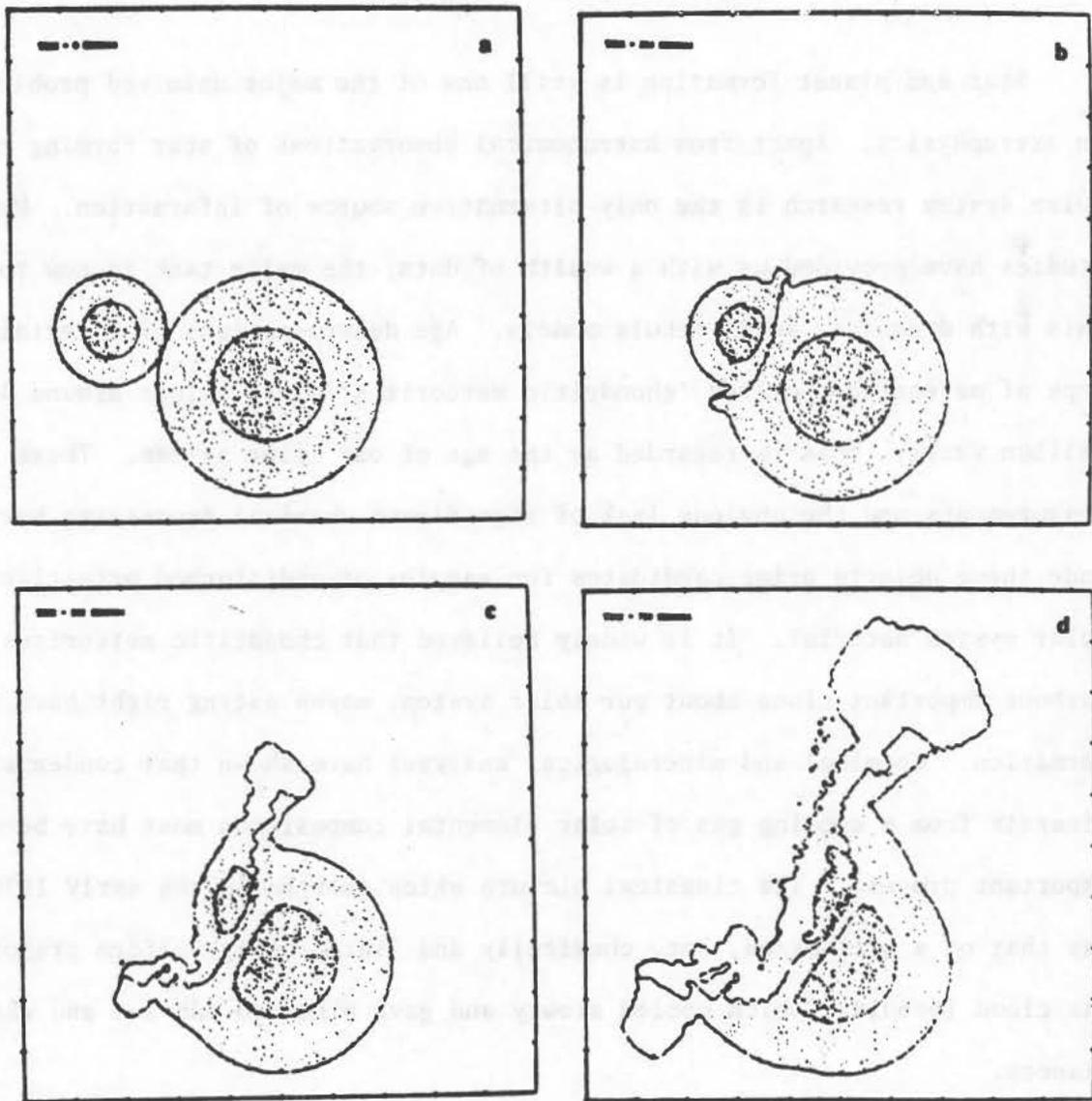
Studies of what happens during the impact reveal that during the early stages of the collision a jet of hot vaporized rock squirts from the contact zone of the earth and the colliding Mars-size protoplanet. This jet does not contain core material (nickel-iron) from either the earth or colliding protoplanet, explaining why the moon is deficient in this material. This hot jet (temperature about 12,000°F) expands and cools after its ejection. Small, pebble-sized rock lumps condense out of the vapor. Many of these pebbles are formed in closed orbits about the earth and eventually coalesce into a natural earth satellite -- the moon.

This scenario explains the moon's extreme dryness and depletion in volatile metals such as Potassium and Cesium because only the more refractory elements can condense from the hot gas cloud as it cools in space. Compounds with low boiling points, such as water, simply do not condense in space and are lost to the growing moon.

Because the rock vapor ejected from the impact contains a large fraction (about 50%) of earth rocks (the rest is from the colliding Mars-size protoplanet), the moon's average composition should be similar to the earth's. This prediction is in fact verified by the study of moon rocks.

To further study this attractive scenario for the moon's origin, we used the supercomputers at Sandia National Laboratory. We employed both two and three dimensional models that simulated a giant impact. The supercomputers confirm the general validity of the scheme described above, while adding much detailed information about pressures, temperatures, densities and velocities of ejected debris. Our presentation at the 17th Lunar and Planetary Science conference will include detailed computer simulations of the events during a giant impact and show how the moon may have originated.

FIGURE 1A-1D. Four stages in the collision of a Mars-size protoplanet with the proto-Earth at 15 km/s. Each frame is separated by about 6 minutes from the previous one. The stipple density is proportional to the material density. The initial velocity of the projectile is horizontal (parallel to the x-axis) from left to right in (a), thus making this an oblique impact with an impact parameter equal to one half of the proto-Earth's radius.



The Formation of The Sun and The Planets: New Information
From Isotope Measurements in Meteorites

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Star and planet formation is still one of the major unsolved problems in astrophysics. Apart from astronomical observations of star forming regions, solar system research is the only alternative source of information. Meteorite studies have provided us with a wealth of data; the major task is now to link this with dynamical solar nebula models. Age determinations of a certain type of meteorites, called 'chondritic meteorites' yield values around 4.5 billion years. This is regarded as the age of our solar system. These age measurements and the obvious lack of significant chemical processing have made these objects prime candidates for samples of undisturbed primitive early solar system material. It is widely believed that chondritic meteorites harbour important clues about our solar system, maybe dating right back to its formation. Chemical and mineralogical analyses have shown that condensation of minerals from a cooling gas of solar elemental composition must have been an important process. The classical picture which emerged in the early 1970's was that of a well-mixed, hot, chemically and isotopically uniform presolar gas cloud (nebula), which cooled slowly and gave birth to our sun and the planets.

In 1973 R. Clayton and co-workers discovered isotopic anomalies in the minerals of small, whitish 'pellets', termed inclusions, embedded within carbonaceous chondrites, a particular subgroup of chondritic meteorites. (Nearly all elements are composed of various isotopes; some are stable, others decay radioactively; isotopes are different forms of the same element). However, other minerals in the same meteorite are isotopically normal. This discovery obviously argued against a perfectly mixed and uniform presolar nebula, where the solids all condensed from an initially hot gas cloud.

At the same time, models of star formation by the gravitational collapse of interstellar clouds were being investigated. Interstellar clouds are very cold (about -260 degree C) aggregates of gas and submicron-sized dust particles. They are seen as dark patches in the Milky Way, where they blot out the light of stars behind them. Their masses are huge, from a few 100 to perhaps a million times the mass of the sun, and astronomical observations have shown convincingly that stars are born inside these clouds. It is believed that our sun and the planets were also born in such a cloud. One of the major problems, it was found, was that of the angular momentum. A contracting cloud rotates faster and faster, until the contraction is stopped by the centrifugal forces. In order to form stars in these interstellar clouds by the gravitational collapse of a subfragment, angular momentum must be lost from the system. Only then will the cloud rotate sufficiently slowly and gravity wins over the centrifugal forces. In the 1940's, C. F. Von Weizsaecker and co-workers investigated the properties of what became known later as 'turbulent accretion discs'. In this scenario the gas and dust from the prestellar cloud form a huge disc-shaped turbulent whirlpool

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(accretion disc) around a growing central object, the protostar. The latter is fed with mass through the disc, whilst at the same time the turbulence transports the angular momentum outwards. The central object eventually becomes a star (in our case the sun), whereas the accretion disc is the birth site for the planets. It is clear that this accretion disc has to be hotter in the central region where the star evolves than in its outer region where it is fed from the cold interstellar cloud fragment, and that turbulence leads to constant intermingling between hot and cooler gas.

The great advance made over the last two years has been to quantitatively couple the cosmochemical research on meteorites with the dynamical models of star formation (or in particular the solar system formation). This theoretically very demanding task involved two major elements: firstly, a theory describing the swirling motion of small dust particles in the turbulent protoplanetary disc gas had to be formulated (a so-called 'transport theory'). Secondly, evaporation of the dust in hot nebula regions, and recondensation of the vapours during chance passages (caused by the turbulence) through cooler regions had to be described mathematically. This problem was solved in 1984 by G. Morfill and H. Völk. New insight into the chemistry and mineralogy of meteorites and the iron/silicate ratios of the terrestrial planets could be obtained.

Now the scope of the theory has been extended even further, by incorporating the possibility to calculate isotope ratios. The first application, reported at the 17th Lunar and Planetary Science Conference, concerns oxygen isotopes. Oxygen has three stable isotopes with masses 16, 17, and 18 atomic mass units. The most abundant oxygen isotope is oxygen-16. During the

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evaporation process, it is easier for the lighter isotopes to be lost, and in cooler portions of the nebula again the lighter isotopes, which are more mobile, are the first to condense. Isotope exchange reactions in the vapour phase also have to be considered. When this is formulated mathematically, finally it is possible to calculate the isotope ratios of solid bodies formed during the early protoplanetary cloud stage. Combining this theory of 'distillation' with the transport theory yields the isotopic distribution in the nebular which in turn 'labels' the meteorites and gives them their specific isotopic signature. Provided the solid bodies then remain undisturbed, e.g. no thermal effects, impact heating during collisions with other bodies etc., they preserve the prevalent conditions of the protosolar nebula during the early stages of planet formation in their chemical and isotopic composition. Comparison with measurements is then meaningful and it is possible to tap the huge reservoir of information, enclosed in the meteorites, to learn something about the physics and chemistry in the primitive solar nebula.

It is early yet to estimate the full impact of the theory. It seems clear, however, that the oxygen isotope data can be understood within the framework of a turbulent accretion disc model, with evaporation and condensation. There is hope that the properties of the protosolar nebula can be defined more accurately using these techniques, and that further insight can be provided into the still elusive problem of star formation and planet formation. It is clearly an important step to link the available observational meteorite data with models of the primitive solar nebula.

AGE OF ANTARCTIC METEORITES AND ICE II

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The polar ice sheet contains the complex environmental records of the past such as ancient atmospheric components, climatic change, global CO₂ cycle, cosmic ray intensity change and so on. The dating of polar ice is important not only for understanding the environmental record in the past but also for understanding ice flow and the history of the polar ice sheet.

There was almost no relationship between meteorite studies and glaciology until the recent finding of over 6000 Antarctic meteorites. Even though the direct measurement of the age of old ice is not yet possible, the terrestrial age (time period between meteorite fall on the earth and the present) of meteorites provides some information on the age of Antarctic ice. In addition, two new dating methods are being studied [1,2]. These are ¹⁰Be-³⁶Cl dating for old ice and in-situ ¹⁰Be-²⁶Al in terrestrial quartz for surface exposure. In the present work, we combine isotope data on the terrestrial age of meteorites and the surrounding ice for understanding the history of the Antarctic ice sheet and the meteorite accumulation mechanism.

We report here measurements of the cosmogenic nuclides ³⁶Cl (half life = 3.0x10⁵ years) and ¹⁰Be (1.6x10⁵ years) in Antarctic meteorites, ice and snow, and ⁵³Mn (3.7x10⁵ years). The ³⁶Cl measurement was carried out by accelerator mass spectrometry (AMS) using the University of Rochester MP tandem van de Graaff accelerator [3]. The ¹⁰Be measurement was carried out also by AMS using the EN tandem van de Graaff accelerator at the ETH, Zürich [4]. The ⁵³Mn results were determined by neutron activation.

ALHA82102(H5) is the only meteorite found inside of the ice in the Victoria Land area (Yamato 74372 is another case in the Yamato mountains area). The meteorite ALHA82102 was found at Far Western Allan Hills ice field, about 70 km west of the Allan Hills themselves and of the Allan Hills Main ice field, where over 2000 meteorites have been found in the last 10 years. It was returned to U.S.A. inside the original ice block (field No. 2995) by the 1982-1983 U.S. expedition team. The surrounding ice was examined by A. J. Gow at the Snow and Ice Branch, Cold Regions and Engineering Lab, New Hampshire. The ice was determined to be original and not refrozen.

The ³⁶Cl in ALHA82102 was found to be 20.4±0.9 dpm/kg metal and corresponds to a terrestrial age <1.2x10⁵ years. The ¹⁰Be in the meteorite was found to be (5.60±0.15) dpm/kg metal and (14.47±0.38) dpm/kg bulk sample. Assuming that the meteorite fell on the snow or on firn in a snow accumulation area, and was transported to the Far Western ice field where ice is continuously ablated, the age of the ice, like the terrestrial age of the meteorite, should be less than 1.2x10⁵ years.

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The ^{10}Be and ^{36}Cl found in the ice were produced by cosmic ray interactions with atmospheric nitrogen and oxygen (^{10}Be) and argon (^{36}Cl), according to presently accepted ideas. Both nuclides after production are attached to aerosols and removed by precipitation. The ratio of ^{10}Be to ^{36}Cl expected to be a function of the age of ice. We expected that the $^{10}\text{Be}/^{36}\text{Cl}$ ratio gives an age, Δt of ice [A] compared to ice [B] according to the following equation [1].

$$\Delta T = \frac{1}{\lambda_{36} - \lambda_{10}} \ln \frac{[^{10}\text{Be}/^{36}\text{Cl}]_A}{[^{10}\text{Be}/^{36}\text{Cl}]_B} \quad [1]$$

where λ_{36} and λ_{10} are the decay constants of ^{36}Cl and ^{10}Be , respectively. The fresh snow sample used for comparison was collected at the Allan Hills Middle Western ice field the day after it fell (Jan. 5, 1984) by one of the authors. The snow contains $(1.53 \pm 0.10) \times 10^4$ atom $^{10}\text{Be}/\text{g}$ and $(4.32 \pm 0.35) \times 10^3$ atom $^{36}\text{Cl}/\text{g}$. The $^{10}\text{Be}/^{36}\text{Cl}$ ratio, 3.54 ± 0.37 is somewhat lower than the contemporary value 5 [5]. The snow may contain small amount of bomb-produced ^{36}Cl . However, the ^{36}Cl contents in the ice #2995 were (5130 ± 360) atom/g (0 - 10 cm depth) and (4970 ± 460) atom/g (10 - 17 cm). The ^{10}Be contents in same ice #2995 were $(9.88 \pm 0.43) \times 10^4$ atom/g (0 - 10 cm) and $(14.40 \pm 0.50) \times 10^4$ atom/g (10 - 17 cm). The $^{10}\text{Be}/^{36}\text{Cl}$ ratio were (19.3 ± 1.6) and (29.0 ± 2.9) respectively. If we adopt the above equation, the ages of the ice samples are calculated to be 0.7 My (0 - 10 cm) and 0.9 My (10 - 17 cm). The large discrepancy between the age of meteorite ALHA82102, < 0.12 My and the age of the ice block #2995, and the two different ages found within the same ice block (0 - 10 cm and 10 - 17 cm) indicate that the ^{10}Be - ^{36}Cl dating method may not work for Antarctic ice. The variation of the $^{10}\text{Be}/^{36}\text{Cl}$ ratio may be caused by climatic effects, for example changes in air circulation between stratosphere and troposphere in the polar region. This must be studied further.

During the survey of the terrestrial age of Antarctic meteorites, we found two stony and two iron meteorites which have the lowest terrestrial ages so far observed for stone meteorites. The preliminary results on ^{36}Cl in ALHA78045 (L6), 4.01 ± 0.18 dpm/kg metal, and ALHA 78153 (LL6), 2.54 ± 0.28 dpm/kg metal, indicated that the terrestrial ages were $(7.5 \pm 0.8) \times 10^5$ year and $(9.5 \pm 1.0) \times 10^5$ year, respectively. Both meteorites and ALHA77002 (7×10^5 year) [6] were found near the east edge of exposed blue ice at Allan Hills Main ice field but at different locations (2-4 km apart). Although we don't know that the Allan Hills Main ice field is directly connected to the Far Western ice field, it is clear that older meteorites were collected only near the east edge of the blue ice area (downstream of the ice flow). So far only young meteorites were found in the western area (upstream) of blue ice. This is the same trend as young blue ice at Far Western ice field and old blue ice of Main ice field. This picture strongly supports present ideas of meteorite accumulation mechanism and the theory of ice flow dynamics [e.g. 7, 8].

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The current scenario of the meteorite accumulation mechanism is that, (1) meteorites fall into the snow accumulation zone and become buried in the snow, which under growing pressure becomes firn and ice; (2) they are transported to the edge of the Antarctic continent by ice flow; (3) where ice movement is blocked by obstacles such as the Yamato mountains and the Allan Hills, the flow stagnates; and (4) in such places ice is continuously ablated by wind and meteorites are exposed on the surface.

On the other hand, Frontier Mountains meteorite (which was found by German expedition team), FRO 8403 which was expected to have a long terrestrial age based on a low ^{26}Al content (29.2 ± 1.2 dpm/kg) [9], showed 17.6 ± 1.6 dpm ^{36}Cl /kg. The calculated terrestrial age is $(1.1 \pm 0.9) \times 10^5$ years. So far old stony meteorites were found only on the Allan Hills Main blue ice field. Two Antarctic iron meteorites, Derrick Peak 78001-9 and Lazarev have longer terrestrial ages, $(1.25 \pm 0.23) \times 10^6$ and $(2.73 \pm 0.25) \times 10^6$ years based on the ^{53}Mn - ^{36}Cl ratio [10]. Both meteorites were found on rock, on the slope of mountain and moraine. From the field information, Derrick Peak meteorite probably fell at the collecting location. If this is the case, the ice sheet did not cover the Derrick Peak in the last 1.3 million years. The evidence of these two old meteorites and exposure age of the peak of Allan Hills (over 1 million years based on in-situ produced ^{10}Be and ^{26}Al in quartzite which was collected at the peak of Allan Hills [2]) may provide key information for study of Antarctic ice sheet for last few million years. Actually, Drewry predicted that old terrestrial age meteorites would be found at the mountain from glaciological point of view and observation of the uplift movement of the Transantarctic mountains [11]. We will extend this study to other locations for understanding the histories of Antarctic ice and meteorites.

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HISTORY OF GROWTH OF THE CONTINENTAL CRUST OF THE EARTH

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[see abstract in conference volume "Continental crust genesis on Earth: need for systematic Nd isotopic study of terrains 3.8 Ga to present"]

Approximately 40% of the Earth's surface consists of the continents on which man's various civilizations exist. Unlike the volcanic crust of the ocean basins, none of which is more than 200 million years old, the Earth's continental crust contains the "fossilized" products of geological events back to 3.8 billion years ago, representing three-quarters of the age of the Earth. The history of production of this continental crust is one of the major goals of geological and planetary sciences.

Conceptually, it is convenient to think of the history of the continental crust in five time segments, as follows:

1. From 4.5 (creation of Earth) to 3.8 billion years ago. No rocks have been found from this time.
2. From 3.8 to 3.1 billion years ago. Real continental rocks were made by geologic processes, but only very tiny amounts survive today.
3. From 3.1 to 2.6 billion years ago. Vast amounts of continental crust were produced in this time interval. At least 50%, maybe even 90%, of today's continents were really separated from the interior of the Earth during 3.1 to 2.6 billion years ago.
4. From 2.6 to 0.6 billion years ago. In this time interval, there is definite evidence for movement of continental plates around the surface of the globe, similar to present-day plate tectonics. New continental

crust was produced, but the amounts compared to the 3.1 to 2.6 billion-year interval are not known.

5. From 0.6 billion years ago to present. Definitely plate tectonics operated, and geologic activity such as mountain-building repeatedly occurred when plates pushed against each other. Some new continental crust was made, but many scientists think that the amounts were very small indeed.

The central problem is to determine how much of the continents grew during 3.1-2.6 billion years ago, and how much afterwards. If 90%, or even 100%, of the continents were produced by 2.6 billion years ago, then all the activity of the Earth's surface since that time has been variations on a basically steady state situation. On the other hand, if less of the continental crust is greater than 2.6 Ga old, say 50% or 70%, then the geologic events and plate-tectonic processes taking place afterwards do involve further chemical evolution of the Earth, and this might therefore be continuing today. The implications for the underlying nature of recent geologic processes is quite different in these two scenarios.

We, and other workers in North America and Europe, are applying neodymium isotopic geochemistry in a systematic way to the study of crustal genesis processes and history. Neodymium (Nd) is one of the elements whose isotopic composition is changed by long-lived radioactivity, in this case of the isotope ^{147}Sm (samarium). As a result of ancient chemical fractionations between samarium and neodymium, such as occur during continental crust genesis, different geologic materials have different Nd isotopic characteristics today. By measuring the samples, we can therefore deduce many things about their past history. For continental crust, we can determine the time that it was separated from the interior of the Earth. Thus we can study

continental crust stabilized during the 2.6-0.6 billion-year and 0.6 billion-year to present intervals, and determine if they contain a lot of newly-produced crust, or if they consist largely of recycled older crust from the 3.1-2.6 billion-year time. In this way we would determine if there really was major crustal growth after 2.6 billion years ago, and so get an idea of whether the Earth is evolving or is in a steady state.

We have studied continental crust of 1.9-1.7 billion-year age over large regions of Europe, Greenland and North America. Some of the data, particularly in the U.S., comes from other groups. We find that we do identify substantial new crust production, in a wide zone extending from Arizona through the U.S. midcontinent, south Greenland, Sweden, Finland to the northwestern USSR. We think this represents a huge belt of new continental crust produced by processes like present-day plate tectonics. There is also substantial recycling from 3.1-2.6 billion-year crust, and actually about half the regions studied (see map in conference abstract) consist of older continent that has been "reworked" into 1.9-1.7 billion-year terrane. Thus we do think that there was substantial addition to the continental crust after 2.6 billion years ago, but the scale of what remains to be done is shown by the fact that, vast as it is, our study area is only about 10% of the Earth's continental crust. Only a systematic terrane-by-terrane approach using, like our studies, neodymium isotopes and geological knowledge will solve the problem of the history of the continental crust.

There is another related area where isotopic studies are poised to make an exciting contribution. Geologists know that young mountain belts are often assembled by sticking together a jumble of small crustal masses, often known as "exotic" or "suspect" terranes. Often, these microplates are hypothesized to come originally from thousands of miles away from their present location.

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Because different blocks of crust usually have different neodymium isotopic signatures, we can study the processes by which mountain belts form by "tagging" blocks of crust using Nd isotopes, and then maybe identifying from where they came. So far, this obvious application of isotopic studies has not been pursued. The North American Cordillera, stretching from Alaska to southern Mexico, is ideal for such studies because much of the most recent understanding of mountain building and microplate tectonics originates there, and because tectonic processes for this young mountain belt are anyway much better understood than, for example, 1.9-1.7 billion year-old terranes.

We think that isotopic studies of geologic processes, particularly using neodymium, are poised to make a truly major advance in study of the history and processes of evolution of the continents.

NEW LIGHT ON THE ORIGIN OF THE MOON

Ted Ringwood

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There is something very strange about the Moon, in relation to the "terrestrial planets" Earth, Mars, Venus and Mercury. All of these planets have dense, metallic cores, amounting to 20-60 percent of the planets mass and their cores are surrounded by mantles comprised of relatively light magnesium silicates. However, geophysical measurements show that the Moon has only a very small core, less than two percent of its mass.

Scientists now know that Earth, Mars and Venus contain very similar relative abundances of major elements such as iron, magnesium and silicon. Even though the Moon was born in the primordial solar system from material derived somewhere between the orbits of Mars, Earth and Venus, it turns out to be drastically depleted in iron as compared to these planets. Indeed, the mean density of the Moon is almost exactly equal to the mean density of the Earth's mantle. This remarkable coincidence suggests that the Moon is very special and could have been formed by quite different processes than those responsible for the creation of the terrestrial planets.

The Earth-Moon Connection

Ted Ringwood, Professor of Geochemistry at the Australian National University and Heinrich Wänke, Director of the Max Planck Institute in Mainz, West Germany, have shown that this interpretation indeed is correct. Moreover, they have demonstrated beyond reasonable doubt that the Moon was derived ultimately from the Earth's mantle. The key supporting evidence comes from the geochemical behaviour of siderophile elements in the Moon and Earth.

Siderophiles are a class of elements which have a chemical affinity for metallic iron and accordingly, are preferentially concentrated in the metallic cores of planets. The siderophile element abundances which remain in the silicate mantles of planets after core formation are decided by several complex factors connected with the core-forming process. These factors vary considerably between different planets. The siderophile element abundances in the mantles of planets therefore constitute a unique fingerprint reflecting the nature of the core-forming process in that particular body. For example, the "siderophile signature" of the Earth's mantle is quite different from those of the mantles of Mars and differentiated meteorites.

The Moon's tiny metallic core formed under relatively low pressures and temperatures. On the other hand, the Earth's core is large (32 percent of its mass) and formed under extremely high pressures and temperatures. Moreover, the composition of the Earth's core (iron-rich) and lunar core (nickel-rich) are quite different. Accordingly, drastic differences would be expected between the siderophile signatures of the terrestrial and lunar mantles.

This comparison is made in Figure 1, where abundance ratios of

siderophiles in the Moon and Earth's mantles are plotted against their metal/silicate partition coefficients. (These coefficients provide a measure of the strength of the siderophile character of a particular element.) The abundances of moderately siderophile elements (Mn, V, Cr, Fe, W, Co, P, S, Se, Ni) are similar in both bodies. Elements more siderophile than nickel (Cu, Mo, Ag, Re, Au) are depleted in the Moon to degrees which correlate well with their metal/silicate partition coefficients. These depletions can be explained quantitatively if the Moon possesses a "terrestrial mantle" bulk composition, and had experienced internal segregation of a very small metallic core (~1% of the lunar mass).

The overall similarity in siderophile element abundances in the Earth's mantle and the bulk Moon illustrated by Figure 1 has important implications for the origin of the Moon. In view of the grossly different conditions of core formation in both bodies, it strongly implies that the material from which the Moon was formed was somehow derived from the Earth's mantle after the Earth's core had separated, and was thus endowed with the siderophile signature of the terrestrial mantle. After accreting from this material, the Moon itself differentiated to form a tiny core which further depleted the most highly siderophile elements, but did not substantially affect the abundances of moderately siderophile elements.

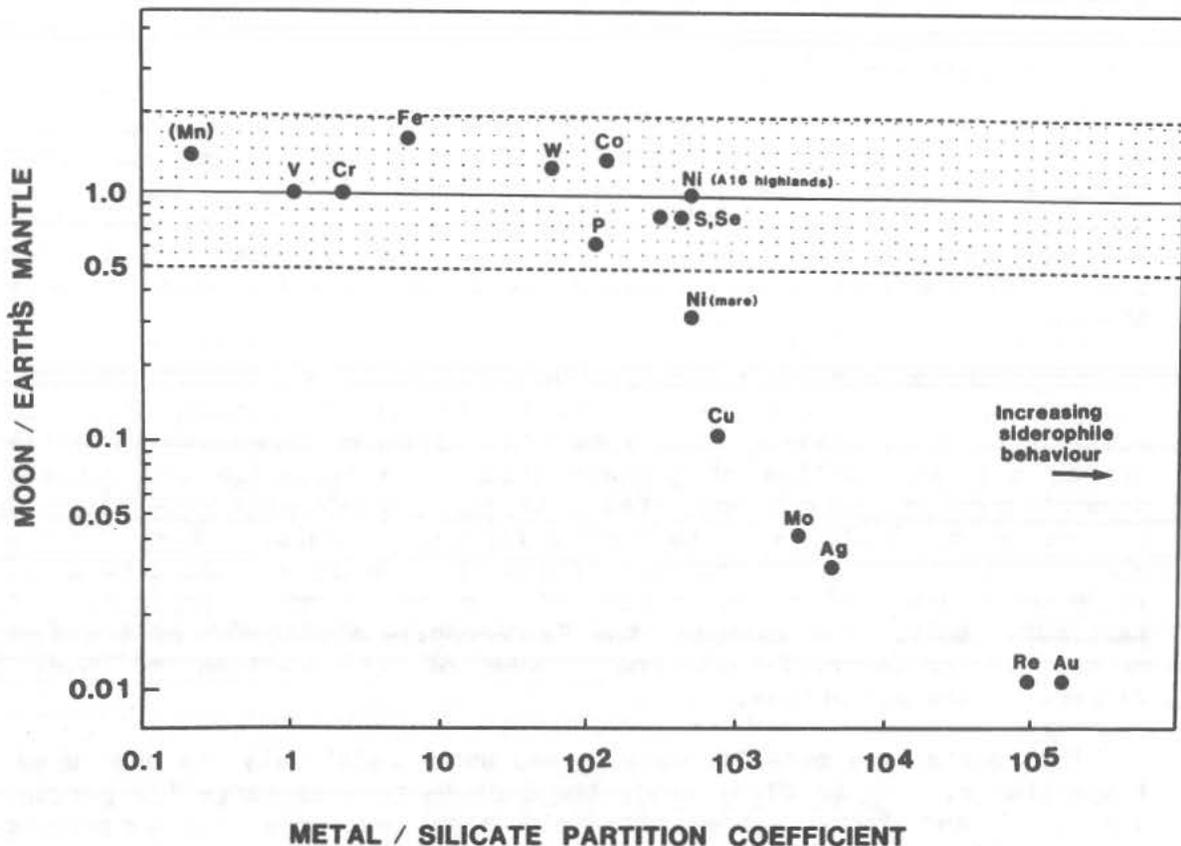


Figure 1 Abundance ratios of siderophile elements in the Moon and Earth's mantle plotted against their metal/silicate partition coefficients (which provide a measure of the strength of the siderophile nature of the particular element).

The Making of the Moon

What was the mechanism which removed about 1 percent of the Earth's mass and placed it in orbit around the Earth? Everyone is familiar with the effort needed to put tiny artificial satellites in orbit. Obviously a colossal energy source was required to eject the Moon from the Earth.

Sir George Darwin first suggested in 1879 that the Moon could have been torn from the Earth's mantle. However, the proposed mechanism was later found to be physically impossible and so the idea was abandoned. About 25 years ago, Ringwood became attracted to this hypothesis because of new geochemical evidence, and proposed a different physical mechanism. This recognised that the Earth had formed by the coagulation (accretion) of a swarm of small solid bodies (planetesimals) and dust which were initially in orbit around the sun. As the Earth grew, so its gravitational field grew, and planetesimals and dust therefore collided with the Earth's surface at increasingly high velocities, generating large amounts of heat. In the later stages of accretion, the energies liberated by colliding planetesimals and dust were very high indeed, amounting to about 60 kilojoules per gram. At these energies, a planetesimal and several times its mass of target material would be completely vapourized. Ringwood proposed that, ultimately, the energy needed to remove proto-lunar material from the Earth had been provided by the very large source of power represented by the gravitational energy evolved during accretion of the Earth.

Accretion of the Earth was also accompanied by the generation of a large primitive atmosphere, mainly hydrogen, produced partly by degassing of planetesimals when they impacted the Earth (and were thereby vaporized), and partly captured from the surrounding solar nebula. The primitive terrestrial atmosphere co-rotated with the Earth which was then spinning very fast with a period of 5 hours. In consequence, the primitive terrestrial atmosphere was spun out into a disc, as shown in Figure 2. During the later stages of accretion of the Earth, high temperatures were produced as planetesimals fell on the Earth. At these high temperatures, silicate material from the Earth's mantle was evaporated into the primitive terrestrial atmosphere and spun out into the disc. As the primitive terrestrial atmosphere cooled and dissipated, the silicates recondensed to form a ring of Earth-orbiting planetesimals, something like the rings of Saturn, only much more massive. A ring of this size would have been dynamically unstable and promptly coagulated to form the Moon.

It is worth recalling that Ringwood's model, formulated long before the Apollo landings, successfully predicted some important properties of the Moon, including its depletion in volatile elements and its thermal history. Nevertheless, his scenario encountered one serious problem which precluded widespread acceptance. In order to generate the sustained high temperatures necessary to evaporate part of its mantle, the Earth must accrete quite quickly, probably over a timescale of about one million years. According to conventional wisdom, accretion of the Earth was estimated to have taken place over a period of 10 to 100 million years.

The problem was neatly solved by a variation of the Ringwood model proposed by Hartmann and Cameron and their colleagues in the mid 1970's. This new "giant-impact" scenario has recently become very fashionable. Rather than achieve high mantle-evaporation temperatures via a continuum of

relatively small planetesimal impacts over a short period (< 1 million years) as in Ringwood's model, giant-impact models achieve these conditions by one (or a few) collisions from huge planetesimals which might be as large, or larger than Mars. These giant collisions generate enormous energies and transient high temperatures which evaporate silicates from the mantles of both the Earth and the impacting body and spin them into a disc, very much as Ringwood had earlier suggested. The advantage of these "giant-impact" models is that they permit a longer timescale for accretion of the Earth, up to 100 million years.

Ringwood has expressed some reservations about giant-impact models because of certain geochemical problems and he currently prefers a scenario intermediate between his earlier rapid-accretion models and the current giant-impact models. This is shown in Figure 2.

At a late stage of accretion, the Earth would have received a great number of impacts from quite large planetesimals possessing radii between 100 and 1000 km. (Note that these are very much smaller in mass, by factors of 50 to 50,000, than the Martian-sized planetesimals required for the giant-impact scenario). Nevertheless, the impact of large numbers of these relatively small planetesimals arriving at high velocities (in the

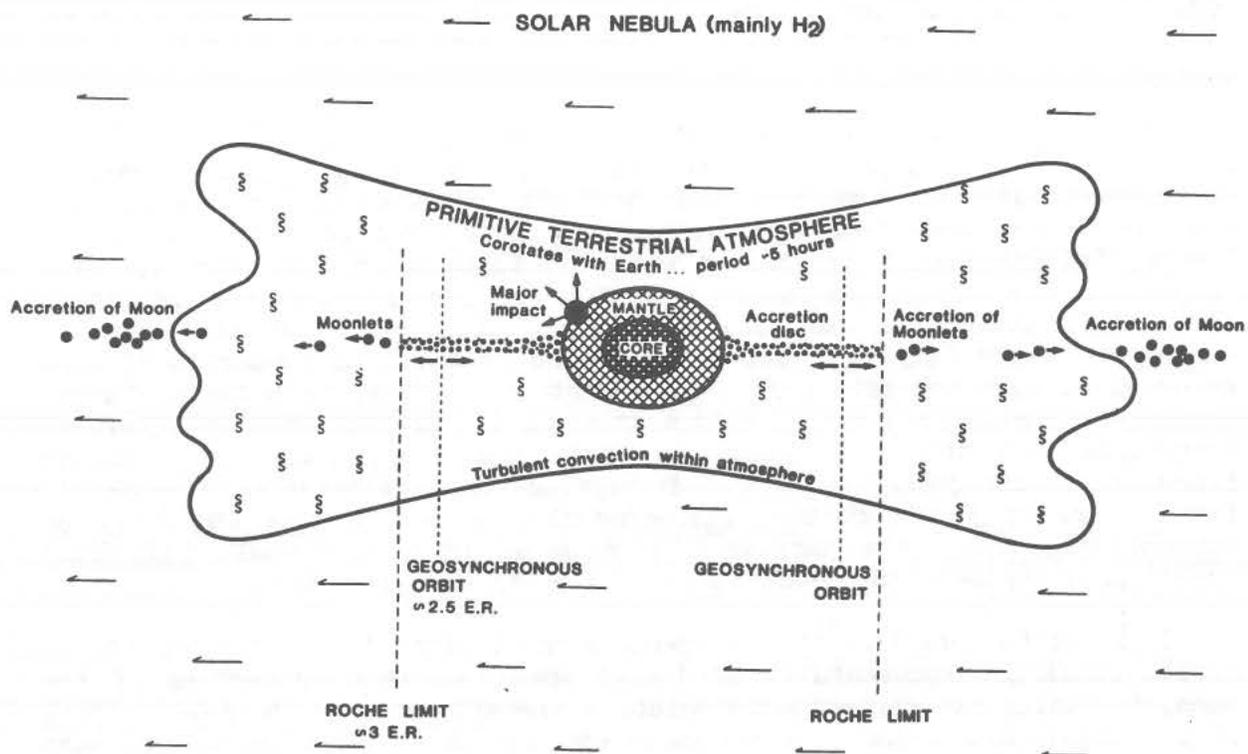


Figure 2 Ringwood's model showing formation of the Moon via the evaporation and ejection of material from the Earth's mantle by impacts from late-accreting planetesimals in the presence of a co-rotating primitive terrestrial atmosphere.

vicinity of 12 km/sec) would have had some dramatic effects, causing extensive shock-melting and evaporation of material from the Earth's mantle. After impact, the expanding "impact clouds" accelerate gases and liquid droplets to high velocities. Impact ejecta and condensates would have been trapped within the co-rotating primitive atmosphere and forced, via friction with the atmosphere, into circular co-planar orbits. In this way, a disc of Earth-orbiting planetesimals was generated, as shown in Fig. 2.

The majority of planetesimals probably accreted inside the geosynchronous orbit at about 2.5 Earth-radii for a rotation period of 5 hours (i.e. about 10,000 km out from the Earth's surface). Within this limit, the laws of physics show us that the planetesimals rotated faster than the gases. Hence they felt a "headwind" and thereby lost energy, spiralling back to join the Earth. However, a significant proportion of the material ejected from Earth by the impacts would have formed planetesimals beyond the geosynchronous limit. Here the conditions were reversed because the co-rotating gases of the atmosphere span faster than the orbiting planetesimals. In consequence, this population of planetesimals received energy from the atmosphere and was accelerated outwards, away from Earth. They soon reached the boundary between the co-rotating terrestrial atmosphere and the surrounding gases of the primordial solar nebula.

In this manner a ring of Earth-orbiting planetesimals, or moonlets, was formed. The moonlets consisted mainly of material evaporated from the Earth's mantle. However, the orbiting ring was dynamically unstable and coagulated on a short timescale, thereby forming the Moon. The energy of accretion caused melting of the outer part of the Moon, permitting a small amount (~1 percent) of metal to segregate to form a lunar core. This had little effect on the relative abundances of the moderately siderophile elements, but depleted the highly siderophile elements to the degrees which are observed (Fig. 1).

A TEST OF THE HYPOTHESIS THAT IMPACT-INDUCED FRACTURES ARE
PREFERRED SITES FOR LATER TECTONIC ACTIVITY

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Because impact cratering has been such an important process on the solid objects of the solar system and because the cratering event is generally accompanied by faulting in adjacent terrain, impact-induced faults are nearly ubiquitous over large areas on the terrestrial planets. The suggestion has frequently been made in the planetary geology literature that these fault systems, particularly those associated with the largest impact features, are preferred sites for later deformation in response to lithospheric stresses generated by other processes. Much of the evidence in support of this view is circumstantial, however, such as a perceived clustering of orientations of tectonic features either radial or concentric to the crater or basin in question.

An opportunity exists to test this suggestion more directly on Earth. The terrestrial continents contain more than 100 known or probable impact craters, with associated geological structures mapped to varying levels of detail. Prima facie evidence for reactivation of crater-induced faults would be the occurrence of earthquakes on these faults in response to the intraplate stress field. Either an alignment of epicenters with mapped fault traces or fault plane solutions indicating slip on a plane approximately coincident with that inferred for a crater-induced fault would be sufficient to demonstrate such an association. As a first step toward testing this hypothesis on Earth,

A TEST OF IMPACT-INDUCED FRACTURES

Solomon, Sean C. and Duxbury, Elizabeth D.

we have examined the known record of earthquakes for evidence of seismic activity near terrestrial impact craters. We found no support for a generally enhanced level of activity along crater-induced fault systems.

We began with the 25 probable impact craters with diameter D greater than or equal to 20 km. We then searched standard seismicity catalogs for earthquakes having epicenters in the vicinity of each crater, taking care to compare the rate of activity around each crater with the background seismicity in the region. The earthquake catalogs have magnitude thresholds that vary spatially and with time; these have been taken into account in the interpretation of the results. The findings from local or microearthquake studies performed with temporary seismic stations near a few craters are also incorporated.

The 25 craters with $D > 20$ km are all located in the stable interiors of continents, distant from plate boundaries. The lithosphere in the vicinity of these craters is nonetheless subject to the intraplate stresses generated by plate tectonic forces, topographic and density variations, and the effects of vertical loading and unloading. These stresses are known to give rise to intraplate earthquakes.

For 8 craters with $D = 25$ to 40 km (Araguainha Dome, Clearwater Lake West and East, Slate Is., Mistastin, Kamensk, Steen River, and St. Martin), the standard earthquake catalogs list no earthquakes within 2° in latitude or longitude of the crater. For an additional 10 craters with $D = 20$ to 100 km (Popigai, Puchezh-Katunki, Kara, Carswell, Manson, Teague, Boltysh, Strangways, Gosses Bluff, and Haughton), fewer than 5 earthquakes have occurred within 2° - 3° in latitude or longitude in the last two decades, rates of seismicity that are comparable to or below background levels.

Five craters with $D = 23$ to 140 km (Sudbury, Manicouagan, Siljan, Ries, and Rochechouart) have seen one to several earthquakes occur within two crater

radii of the crater center during the last 20 years. These earthquakes are relatively small (body wave magnitude $m_b < 5$), however, and the level of seismic activity in the vicinity of the crater is not noticeably higher than the regional background level.

Two large terrestrial craters are associated with high levels of recent seismic activity. During the last 20 years, several thousand small to moderate earthquakes occurred within one to two crater radii from the center of the Vredefort structure ($D = 140$ km) in South Africa. All or nearly all of these earthquakes, however, are rock bursts resulting from deep level gold mining operations in the Witwatersrand.

Finally, the Charlevoix impact structure ($D \approx 50$ km) is centrally located in La Malbaie seismic zone in Quebec, one of the most seismically active areas of North America east of the Rocky Mountains. Modern seismicity is concentrated near the conjunction of the St. Lawrence rift system and the 360-m.y.-old crater. Earthquake epicenters and focal mechanisms obtained from first motion and surface wave studies, however, indicate that it is the NE-striking, moderately to steeply dipping, rift-related faults that are slipping rather than those created by the impact.

Modern intraplate seismicity thus does not show any general correlation with fault structures associated with the largest terrestrial impact craters. For the two craters with higher than normal levels of nearby seismic activity, other factors appear to control earthquake occurrence. We conclude that terrestrial analogs offer little support for the hypothesis that impact-induced fractures remain preferred sites for the release of lithospheric stress long after the impact event.

Meteorite Isotopic Anomalies Can be Produced by Ultraviolet Light

by
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Two years ago we reported the existence of a new and unique isotope effect in oxygen. There are several major and important features of the new effect aside from the purely academic interest in the mechanism, particularly as it pertains to the evolution and formation of the solar system. Some 12 years ago, it was demonstrated by another group that the oxygen isotopic distribution observed in meteorites was anomalous. The special isotopic distribution which was observed suggested that these pristine meteoritic inclusions must possess oxygen derived from a nuclear event, since there was no known chemical or physical process which could produce this peculiar and unique isotopic fractionation. In particular, the meteoritic oxygen isotopic component was interpreted as representing the addition, prior to the formation of the solar system, of pure ^{16}O (one of the three stable oxygen isotopes). Furthermore, it was suggested that the site for production of the mono-isotopic oxygen was a supernova or exploding star. Since oxygen is the major element in the meteorites and many planets, the amount of material injected would have been substantial, as much as 4%, in these objects. It was also suggested that the concussion from this exploding star may have triggered the collapse and ultimate formation of the solar system.

The oxygen isotopic pattern we were able to produce by our laboratory experiments is identical to that observed in meteorites. This immediately invalidated the long held assumption that a simple and internal (no supernova) chemical effect may not be responsible for the meteoritic oxygen isotopic observations and which required injections of alien, pure ^{16}O nuggets. The entire theory for the supernova was based

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on the premise that there are no non-nuclear means which would produce this unique isotopic signature and which we have shown to be false.

In order to determine whether the effect we observe is responsible for the meteoritic observations, it is crucial to know (1) the mechanism for the effect and (2) the type of environment which would produce the effect. In this year's abstracts, we have shown that a wide range of excitation sources will produce the effect, extending from the ultra-violet through the microwave. In addition, this recent work and proposed mechanism shows that it really is a rather general effect and does not require highly constrained circumstances to produce it. It appears all the more likely that the new isotope effect we first demonstrated may be the agent responsible for producing the meteoritic components and, hence, was a significant process in the formation of the solar system.

Martian Origin of SNC Meteorites: The Giant-Crater Hypothesis

by

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Almost all meteorites are approximately 4.5 billion years old and are believed to come from either the asteroid belt or from the cores of extinct comets (that is, comets whose icy parts have been completely vaporized, leaving only the small, rocky portion still orbiting the sun). The SNC meteorites, however, are only 1.3 billion years old or less. They differ from all other meteorites not only in age but also in chemical composition and evidence of having undergone repeated episodes of melting and recrystallization. One of them contains noble gases whose elemental and isotopic composition resembles that of the Martian atmosphere. These unusual characteristics have led several scientists to conclude that the SNC meteorites are fragments of the planet Mars.

The major drawback to the Mars origin hypothesis is the difficulty of accelerating large pieces of rock to velocities large enough to allow them to escape from Mars's gravitational field, 5 km/s or more than 11,000 mi/hr. One of the SNC meteorites, Nakhla, consists of fragments whose total weight is more than 80 lbs. This weight corresponds to a single stone a foot or two in diameter. By contrast, the only meteorites from the moon that have been found so far are about the size of a golf ball.

Furthermore, there is evidence that at least some of the SNC meteorites must have been much larger: When a rock is in space, it is exposed to cosmic rays which interact with atoms in the rock to produce unusual kinds of atoms. The longer a rock is exposed to cosmic rays, the greater the concentration of these unusual atoms. By studying these cosmic ray exposure products, scientists can estimate the duration of cosmic ray exposure.

The SNC meteorites have three sets of cosmic ray exposure ages, 10 million, 2.5 million, and 0.5 million years. One obvious interpretation is that they were ejected from their parent body (Mars?) as small (less than a foot or two in diameter) rocks in three separate cratering events at times corresponding to their cosmic ray exposure ages. This requires an unreasonably high cratering rate on Mars. Furthermore, only 10-15% of Mars' surface is young enough to

correspond to the ages of the SNC meteorites. It is difficult to explain why there should be three meteorite-producing events on the young part of Mars and none on the much more extensive older parts of Mars.

An alternate interpretation of the differing cosmic ray exposure times is that all of the SNC meteorites were ejected from Mars at the same time. If very large rocks were ejected, only their outermost portions would have evidence of cosmic ray exposure for the entire time. In this scheme, the large rocks that were originally ejected from the parent body were broken up in space at times corresponding to the observed cosmic ray exposure times. The outer portions that recorded long cosmic ray exposure times were lost and only the inner portions have been recovered on Earth. The latest time for a common ejection is the oldest cosmic ray exposure age, 10 million years. In this case, the meteorite with the youngest cosmic ray exposure age must have originally been 3 m to 5 m (10-15 ft) across for the inner portion to have been shielded from cosmic rays for 9.5 million years. The radioactive isotopes in the four shergottites (the "s" of "SNC") show that they experienced a strong shock event 180 million years ago, making this the most likely common ejection time. In this case, the meteorites with 0.5 - 2.5 million year exposure ages must originally have been at least 15 m, or 50 feet, in diameter.

There are two advantages to the common ejection time scheme, and one major disadvantage. First, having one cratering event on the young part of Mars and none on the older part is much more likely than having three events on the young part and none on the old part. The second has to do with the relative abundance of SNC and lunar meteorites. Since the Moon is much smaller than Mars and is much closer to Earth, you would expect many more lunar meteorites than Martian meteorites if both lunar and Martian meteorites are delivered to Earth at constant rates. George Wetherill of the Department of Terrestrial Magnetism in Washington, D.C., has calculated that most of the rocks lofted off Mars should reach Earth within 1- million years. If craters large enough to eject rocks from Mars occur at intervals of 10 million years or less, there should be an approximately constant rate of delivery of Martian rocks to Earth. The fact that there are more SNC meteorites than lunar meteorites implies that Martian rocks are not being lofted off the planet at intervals comparable to, or less than, every 10 million years, and is thus most consistent with a common ejection time much more than 10 million years ago.

The disadvantage of this scheme is that it requires the ejection of very large rocks, at least the size of a large van and more likely, the size of a house. For most processes associated with cratering, the pressure necessary to accelerate large rocks to Mars' escape velocity exceeds the crushing strength of rock, so that only small rocks, certainly less than 1 m, and probably less than 10 cm, achieve the requisite velocity. The exception to this may be according to Jay Melosh's spall model, a thin surface layer of rocks that are accelerated by a high pressure gradient (change in pressure with depth) while not exposed to high absolute pressure. Even this process, however, cannot accelerate rocks larger than a meter or so from a 30 km diameter crater, which is usually taken to be the size of the largest crater on the young portion of Mars.

In this study, we temporarily lay aside the issue of what is the largest crater on the young part of Mars, and ask the question, "How large a crater is required to explain the Martian origin of SNC meteorites?" We approach the problem in two ways: First, from George Wetherill's study of Mars-to-Earth transit times and delivery rates of SNC meteorites compared to all stony meteorites, we find that it would be necessary to eject 10^{14} kg (440 billion tons) of 15 m rocks from Mars 180 million years ago in order to produce enough rocks reaching Earth at the right times and with cosmic ray exposure histories. Using Jay Melosh's spall model, R. Schmidt's and K. Holsapple's scaling rules for the variation in crater size with impactor size and velocity, and the constraint that none of the SNC meteorites were subjected to more than 50 GPa of pressure (50,000 times atmospheric pressure at sea level on Earth), we were able to calculate the total mass of crater spall ejecta that is accelerated to 5 km/s or more as a function of crater size and impact velocity. An impact velocity of 12 km/s (the average impact velocity of asteroids on Mars) requires a crater more than 100 km in diameter to produce 10^{14} kg of 5 km/s ejecta; higher impact velocities require even larger craters, and impact velocities less than 10 km/s produce no solid 5 km/s ejecta.

The second approach was to use another aspect of the Melosh spall model in conjunction with the Schmidt-Holsapple scaling rules to predict the size of the largest rock that could be accelerated to 5 km/s as a function of crater size and impact velocity. A 200 km diameter crater is required to produce 5 km/s ejecta at least 15 m in diameter at an impact velocity of 10 km/s; as before, higher impact velocities require larger craters, and no solid, 5 km/s ejecta is produced for lower impact velocities.

In summary, the dynamical constraints on the Martian origin of SNC meteorites are most consistent with their being ejected from a single, very large crater. A large crater is necessary to explain both the large total mass ejected and the large rock size that are required by model of a common ejection time. A common ejection time model is preferable to a multiple ejection time model because it requires neither an unreasonably high cratering rate nor an explanation for preferential sampling of a small portion (the young part) of Mars' surface area. Since very large craters are much rarer than smaller ones, a giant crater would produce a "spike" in the rate of delivery of Martian rocks to the Earth, consistent with there being more (putative) Martian meteorites than lunar ones. A 100 to 200 km (or larger) crater would throw out a vast volume of ejecta from widely separated areas and various depths and explain the variation in rock types among the SNC meteorites.

The only remaining problem is to identify a suitable parent crater for the SNC meteorites. A 180 million year old crater that is more than 100 or 200 km across should be easy to spot on Mars. Because Mars is relatively geologically inactive compared to Earth, such a crater should not have been eroded away, filled with sediments, smashed to unrecognizability in a rising mountain range, or subducted down an oceanic trench into the mantle; there are no oceans on Mars to hide it in, and the Martian polar ice caps are probably thin enough for such a vast crater to be seen beneath them. (Although most scientists now believe that the extinction of the dinosaurs was caused by a giant impact 65 million years ago, a suitably large crater has not yet been identified, presumably because it has been destroyed or has somehow been hidden.) There are a few craters on Mars that are large enough, and some of them have fresh-enough looking ejecta blankets to be young enough. All but one, however, are on parts of Mars that have been hitherto classified as much older than the SNC meteorites. The exception is a 130 km diameter crater in the extended Tharsis region. Although this crater is just barely large enough by our calculations, the only apparent alternatives are to suggest that some of the terrain classified as much older by crater counting techniques is really much younger or to postulate the very unlikely event that a large crater sampled only a small island of recent igneous activity in the midst of the old terrain. The search for likely craters continues, and the results will be presented at the 17th Lunar and Planetary Science Conference.

LABORATORY SHOCK EMPLACEMENT OF NITROGEN AND NOBLE GASES INTO BASALT;

A Martian Meteorite Analogue Experiment

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An interesting new discovery in the study of meteorites concerns their possible origins. Conventional wisdom told us that meteorites come from small bodies--the asteroids and perhaps comets--which have relatively weak gravitational fields. However we now have at least three unambiguous samples of lunar meteorites collected in Antarctica, aided in their recognition by comparison with lunar samples from the Apollo program. We also think we have one meteorite, and maybe seven more, from an even larger body, Mars.

Identification of these meteorites as samples of Mars is difficult without having other known martian rocks for comparison. These eight stones, dubbed the SNCs from the names of their subgroups (shergottite, nakhlite, and chassignite), have similar and unique characteristics. Their unusually young formation ages, about 1.3 billion years or less, and petrologic features more similar to terrestrial basalts than to other meteorites led Wasson and Weatherill in 1979, and later others, to speculate that they originated on one of the planets, and suggested Mars as the least unlikely. Then in 1982 Bogard and Johnson discovered that a glassy phase of the shergottite EETA 79001 contained noble gases with elemental and isotopic ratios matching those measured in the martian atmosphere by the Viking spacecraft. Additional evidence for the presence of martian

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atmospheric gases came from nitrogen, which in the martian atmosphere is strongly enriched in the heavy isotope. Our group at Minnesota found nitrogen in EETA 79001 less enriched than the Viking measurement, but consistent with a mixture of heavy martian atmospheric nitrogen and isotopically lighter nitrogen from the martian interior.

The trapped gases in EETA 79001 glass provide the main link in the martian origin hypothesis for the SNC meteorites. The question is, how did these gases come to be trapped in the glass? The glass was apparently produced from molten rock during a physical shock event, probably a meteorite or asteroid impact. Other SNC meteorites have petrologic evidence of varying degrees of shock, but no significant amount of glass, which appears only in highly shocked samples. It is thought that the gases in EETA 79001 were trapped in the glass at the time of the shock, but very little is known about how gases are actually implanted by such an event.

From comparisons between the trapped gases in EETA 79001 and the martian atmosphere we can deduce some characteristics of the gas entrapment. Figure 1 shows the partial pressures of the noble gases, nitrogen, and carbon dioxide plotted for trapped gases in EETA 79001 along the horizontal axis, and in the present day martian atmosphere at ground level, from which we assume the gases in EETA 79001 were trapped, along the vertical axis. The gases appear to have been trapped without mass fractionation; i.e., light gases were not preferred over heavy gases. Also active gases were not implanted preferentially to inert gases, with the possible exception of CO₂. But probably the most striking feature is that the partial pressures

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of gases in the glass are roughly as high as in the contemporary martian atmosphere. That is, their implantation efficiencies (defined as partial pressure of gas in sample / partial pressure of ambient gas) appears to be nearly 100%.

In order to learn more about the possible mechanisms for trapping gas we, along with D. Bogard, P. Johnson, and F. Hörz at the NASA Johnson Space Center, began conducting experiments that attempted to mimic the conditions under which the gases were trapped in EETA 79001. In the laboratory we impacted basalt samples of similar texture in bulk and powdered form in the presence of three atmospheres of ambient gas with a high-speed projectile at velocities yielding shock pressures roughly comparable to that experienced by EETA 79001. In Figure 2 we see that gases were implanted without fractionation (preference of heavy or light gases) except for a possible deficiency of neon. Nitrogen in the bulk (disk) sample is high relative to the noble gases, probably because nitrogen in organic contamination covering the sample surface was driven into the interior along with the ambient N_2 gas. However, the most interesting result is that implantation efficiencies are significantly lower than for EETA 79001 glass (the data for which lie along the solid line in Figure 2). The disk sample shown attained only 1.8% efficiency. In subsequent measurements of the same and similar powder and disk samples we have found variations of up to a factor of three in efficiency, but have not achieved greater than 28% efficiency in any experiment. In addition, preliminary results by Bogard et al. indicate that when the ambient gas pressure is lowered to .01 atmospheres--roughly equal to pressures at the surface of Mars--the implantation efficiency may be

even lower by up to an order of magnitude.

These results imply that our experiments have not duplicated the conditions under which the martian atmospheric gases were implanted. One possibility is that there may have been an atmospheric overpressure related to the event causing the shock, so that the implied 100% implantation efficiency for EETA 79001 is not real. It is unlikely, however, that an overpressure could suffuse rapidly enough and to sufficient depth into the pore spaces of the EETA 79001 material. Another possibility, suggested by strontium isotopic studies, is that molten rock material from the exterior could have been injected into void spaces, trapping the gas already in the spaces. A third, related possibility is that pores and void spaces per se may play an unexpectedly important role in trapping gases more efficiently. We believe that the higher implantation efficiencies in the powder samples compared to disk samples were due largely to their higher effective porosity. We are currently conducting a series of tests to determine the effects of larger (up to 1 mm) void spaces on gas implantation efficiency.

Were it not for the gases efficiently trapped in EETA 79001 glass, a martian origin, and the possibility of deriving meteorites from planetary-sized bodies, would only be inferred. As it is, we can now use the trapped gases to further our understanding of the martian atmosphere and its origins. Unfortunately, we still do not understand how the gases were trapped with an apparent 100% efficiency, and it may be difficult to duplicate in the laboratory the natural conditions under which this happened on Mars.

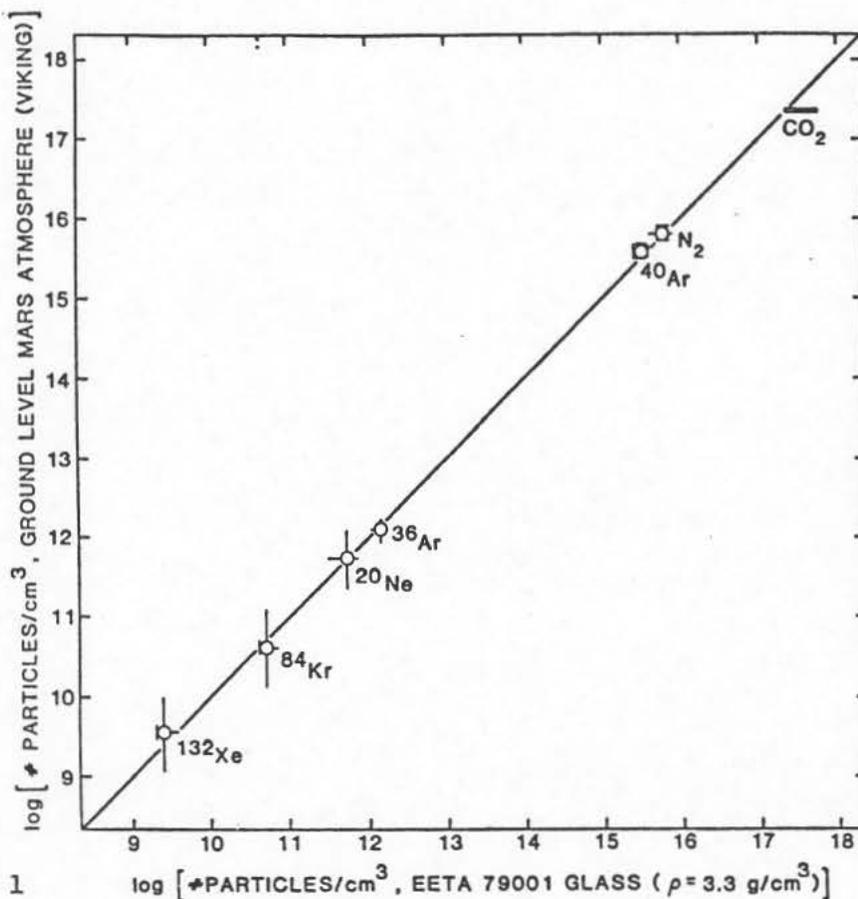


Figure 1

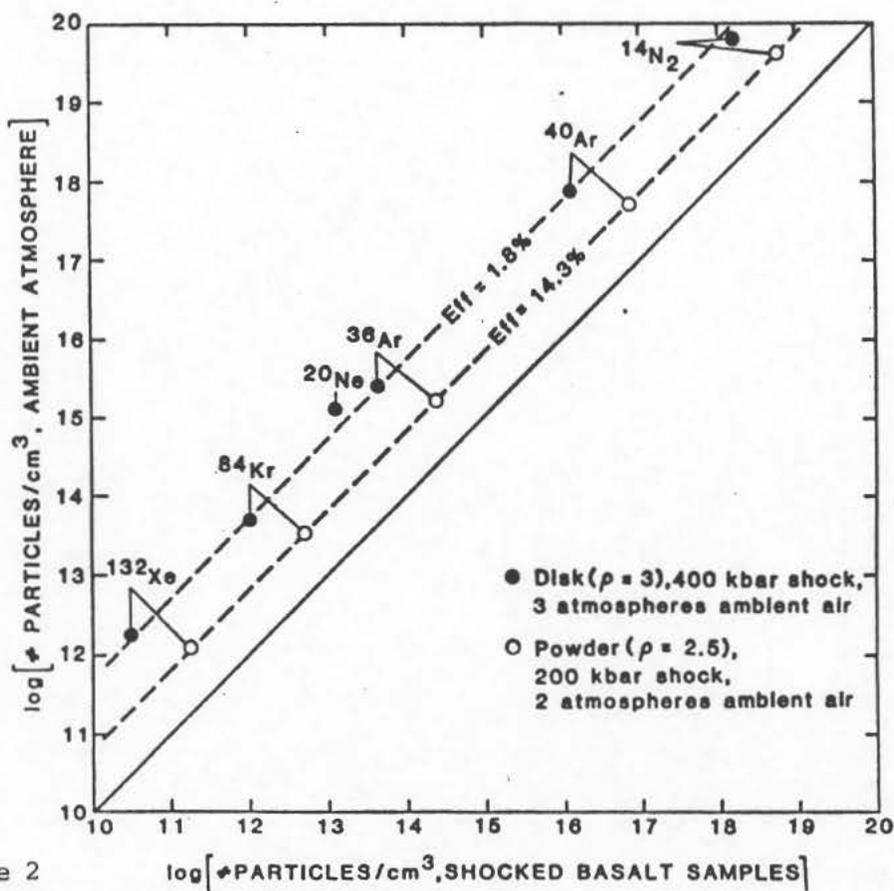


Figure 2