Lunar and Planetary Science XI

Press Abstracts
Eleventh Lunar and Planetary Science Conference
March 17-21, 1980

NASA
National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
Houston, Texas

LPI/USRA
Lunar and Planetary Institute
Universities Space Research Association

PRESS ABSTRACTS

ELEVENTH LUNAR AND PLANETARY SCIENCE CONFERENCE

MARCH 17-21, 1980

Compiled by the
Lunar and Planetary Institute
3303 NASA Road One
Houston, Texas 77058

LPI CONTRIBUTION 398

PREFACE

The Program Committee for the Eleventh 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 XI*.

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 *iv*. Feel free to call for more information.

The following abstracts were also thought to deserve widespread public attention, but could not be re-written in time to appear in this volume (page numbers denote location in *Lunar and Planetary Science XI*):

Atmospheric Origin and Evolution: The Evidence from Venus
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VIKING: A CONTINUING U.S. PRESENCE ON MARS, A. L. Albee, N. Evans, R. S. Saunders, C. W. Snyder, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91103

We are approaching in July the Fourth Anniversary of the arrival and landing of Viking at Mars. Not only is Viking one of NASA's most ambitious undertakings but also its most long-lived success. Plans began in 1969 to launch two spacecraft, each with a satellite orbiter and an automated landing laboratory intelligent enough to land itself on the planet's surface and search for evidences of life. The successful arrivals and landings occurred in July and September of 1976. The mission was to have ended six months after these landings, but the equipment has refused to become non-functional; even now, one orbiter and both landers still operate as Earth's most distant stationary outposts in space. Together with the now quiet Orbiter 2, they have returned more than a million-million bits (binary pieces) of information, making Mars the most-observed of our planetary neighbors. Much of this information is in the form of spectacular color pictures of the planet's surface, taken from both landed and orbital perspectives. Best-guess estimates place the failure of the remaining orbiter in mid 1980; but one of the landers is programmed to continue data return to Earth through 1990.

The most recent phase of the mission has been a broad areal survey between July 1979 and October 1979. The survey acquired images at moderately high resolution with optimum illumination of regions considered to be candidates for future landings. A pair of orbit trims was designed that moved the longitude of periapsis about 160 degrees east so that a region of old cratered terrain north of the equator could be photographed. The maneuvers were executed on May 19 and July 19, and following the latter the Survey Mission commenced.

The Viking Survey Mission has provided the first contiguous high resolution images of an extensive region of Mars. These images have provided new insight into processes that have modified the ancient cratered terrains. The 2400 frames cover the region between Chryse Planitia and Isidis Planitia with resolution between 15 m/pixel and 60 m/pixel (Fig. 1). The purpose of the Survey Mission was to image a strip of northern hemisphere cratered terrain under optimum illumination conditions in order to have an image data base for planning a future Mars sample return mission.

Several distinct terrain types are observed in the images. These include intercrater ridged plains with normal impact crater populations, basin-related smooth plains, and a large region of complex small-scale irregularities, with no fresh craters. This latter terrain type has a geomorphic style that is best described as one of inversion of topography. Parts of valley systems and crater floors that were initially negative relief features now appear in positive relief. This suggests differential erosion in the area where the features occur.

On Earth topographic inversion of valleys occurs along the west flank of the Sierra Madre range in California where basaltic lava flows have occupied river valleys. Erosion has removed the unconsolidated gravels adjacent to the flows producing sinuous lava ridges where the river channels once were. Parts of several Martian channels in the region imaged by the Survey Mission exhibit a similar inversion of topography. This suggests that the valley floors were more resistant to erosion either because they were armored by material such as lava or have been indurated by some Martian rock-forming process. The irregular pattern of the erosion suggests an eolian erosion mechanism. The entire region is topographically somewhat higher than adjacent unmodified terrains.

The Survey Mission images have demonstrated the importance to geologic analysis of 1) wide area coverage, 2) contiguous coverage, and 3) better than 100 m/pixel resolution. A summary of recent Viking activity is given in Table 1.

Table 1. Summary of Recent Viking Activity

Viking Survey Mission	July 20 - Nov. 5, 1989
Viking Completion Mission	Nov. 6 - May 30, 1980

4 weeks very high resolution mapping 500 - 800 km
11 weeks high resolution contiguous mapping 1000 - 25000 km
35 weeks medium range "gore-filling" mapping 3000 - 10,000 km
50 weeks meteorological monitoring utilizing IRTM, MAWD, and VIS instruments
7 Lander-2 relays
18 Lander-1 direct-link, high-rate telemetry passes
30 Lander-1 ranging passes with near simultaneous Orbiter-1 ranging
30 Radio occultation passes

Plus the following special events:

Search for a third Martian satellite
4 full-disk mosaics near Mars opposition simultaneously with observations from Hawaii and Australia
The largest color panorama ever acquired from the Landers

The current phase of orbiter operations, the Viking Orbiter Completion Mission (VOCM) began on November 6 with an orbit trim that returned to a 24.0-hour orbit period and placed periapsis in the middle of the pass over the DSN station in Spain. The principal mission objective is to fill in as many as possible of the gaps in moderate resolution mapping that were left when Orbiter 2 was unable to complete its planned mapping mission. Enough attitude control gas remains in the orbiter to continue operations through at least the month of May 1980.

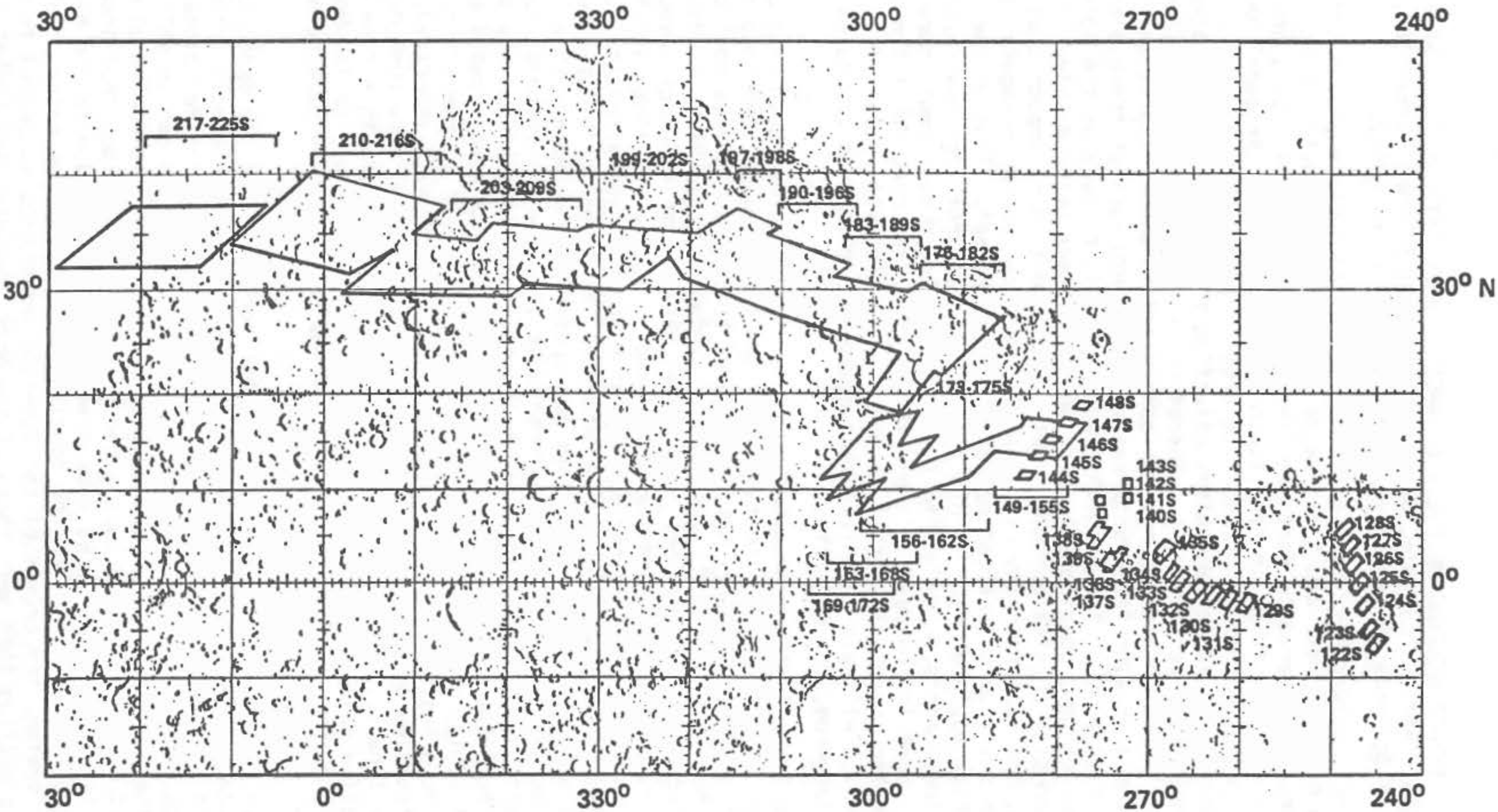

Figure 1. Survey Mission Coverage: Plot of high resolution strips and high resolution contiguous mapping coverage.

IMPACT HEATING OF H_2O ICE TARGETS: APPLICATIONS TO OUTER PLANET SATELLITES. Mark J. Cintala, James W. Head, and E. Marc Parmentier, Dept. of Geological Sciences, Brown University, Providence, RI 02912.

Impact craters have been seen on every solid surface planet and satellite observed by spacecraft and Earth-based instruments. Studies of meteorites, lunar samples returned to Earth by the Apollo and Luna missions, and rocks collected at terrestrial craters (such as Meteor Crater, Arizona) have shown that the collisions which produce the craters are, and have been, one of the most important geologic mechanisms affecting the surfaces of the planets, their moons, and the asteroids. Therefore -- with certain exceptions -- the effects of impact cratering must be considered in almost any scientific investigation involving the crusts and even the interiors of these planetary bodies, especially in those which treat the early history of the solar system. For these reasons, considerable time and effort are being devoted to unraveling the complex physics associated with the formation of impact craters. Until recently, the vast majority of studies have concentrated on impact crater formation in solid or pulverized rock targets. Many satellites of the outer planets have surfaces rich in H_2O ice; since spacecraft are now capable of observing these moons, impacts into ice are receiving considerably more attention than they have in the past. In addition to learning more about the physics of the cratering process itself, important information will result from these studies which will aid in solving the geological mysteries of bodies such as Europa, Ganymede, and Callisto.

This investigation concentrates on the thermal effects which accompany the impact of meteoroids into targets of ice (thus giving some idea about the formation of craters on icy satellites) and basalt (an igneous rock characteristic of most planets in the inner solar system, such as Mercury, Mars, Earth, and the Moon). In particular, it examines the effects of shock waves -- waves which travel faster than the speed of sound -- similar to those which make "sonic booms" in the air after passage of high speed jet aircraft. Such waves are created during the impact of a meteorite into a solid target, and are the principal agents which actually form the crater. Associated with a shock wave, in most cases, is a rise in temperature. While the temperature rise of the air after a supersonic aircraft flies by is usually not felt by those who feel and hear the sonic boom, the intensity of a shock wave created by the impact of a high velocity meteorite (usually at tens of kilometers per second) is often so great that solid rock is melted and often even vaporized. Indeed, a large fraction of the rocks returned from the Moon had once been melted by meteorite impacts, solidified "lakes" of "impact melt" (as this type of molten rock is often called) are visible on photographs of craters on the Moon and Mercury, and large impact melt "ponds" -- now solid rock -- have been studied in craters by geologists here on Earth.

Since ice melts much more readily than rock, it might be expected that larger quantities of impact melt would be created during impacts into ice than into solid rock, with the same conclusion also applying to the volumes of vapor produced by these events. The calculations carried out in this study confirm the initial impression and demonstrate that, while the total mass of ice melted and/or vaporized by a given impact is larger than that produced in the rock target, the volume is even greater -- a result due to the higher density of the rock. Thus it can be concluded that, over the entire history of the solar system, the crusts of the ice-rich moons were subjected to more widespread melting than were those of the Moon, Mercury, and probably the other silicate-rich (i.e., rocky) planets.

IMPACT HEATING OF H_2O ICE TARGETS

Cintala, M.J. et al.

The crusts of Ganymede and Callisto, as pointed out earlier, are comprised predominantly of H_2O ice and rock-like material. It is generally thought that the rocky debris is suspended in the ice. If the ice were suddenly melted, as would occur during a large impact event, the rocky material would sink rapidly in the lower density water. The impact melt would then freeze at the floor of the crater with only a small fraction of the dark, rocky fragments remaining near the surface. The result, when observed from the vantage point of a spacecraft above the planet, would be a circular patch brighter than the surrounding terrain. Such features -- some as large as 600 km across -- have been observed in Voyager photography of Ganymede and Callisto. During the early histories of bodies such as these two jovian moons, the high rate of impact cratering might have melted large fractions of their icy crusts, allowing planetwide separation of dense silicate material from the melted ice. If the deeper layers of these planets were liquid water (as might have been the case, due to radioactive heating of their interiors) and the craters were large enough, the rocky material could have sunk all the way to the cores of the satellites.

The hotter a gas, the faster its individual molecules travel. If the temperature were sufficiently high, the speed of H_2O molecules could exceed the escape velocity of a body the size of Europa, Ganymede, or Callisto. The vapor produced during a high velocity impact event is usually very hot -- tens to hundreds of thousands of degrees Centigrade. Temperatures such as these will impart very high velocities to water molecules, past those necessary to escape from the target planet's gravity field. Computer models of impact cratering events devised by T. J. Ahrens and J. D. O'Keefe of Cal Tech, however, indicate that most material heated to these levels would be ejected from the growing crater at extremely high velocities by processes not related to the thermal mechanism. This effectively rules out "thermal escape" as an efficient process by which such bodies would lose H_2O. The lower gravities of smaller bodies, however, would allow more H_2O vapor to escape by this mechanism -- making the less massive moons of Saturn likely candidates.

On the Moon, Mercury, and Mars, fragments of target material thrown out of a growing crater reimpact the surface at distances dependent on the ejection velocity and angle, creating "secondary craters" -- small craters which surround the original ("primary") crater. In most cases, the projectiles which created observed secondary craters were probably solid, and no visible quantities of melt were formed by their impact. Impacts into icy targets, on the other hand, could ejecta a much larger fraction of molten target material from the crater, thus allowing the liquid "drops" (many meters across, in some cases) to create their own craters. In addition, if the liquid projectiles were thrown far and fast enough, they could melt more ice upon their impact. After many cratering events, the net effect of this process on the icy planet's surface might be (1) the formation of a solid crust over the fragmental debris caused by other impacts, or (2) welding of the fragmental surface material into a more coherent deposit. The degree to which this process might affect the surface layers of the target body is uncertain at present, and must be evaluated by statistical studies.

Finally, the likelihood that more impact melt would be formed by impacts into ice means that more melt will remain within the final crater when compared to the lunar and mercurian cases. The larger volumes of melt within these craters implies that the thicknesses of these deposits would exceed those observed in craters on the Moon, for instance. Larger structures would be "drowned" or buried by these deposits, making the floors of craters on icy bodies smoother than their lunar counterparts. This effect might impede efforts to make interplanetary comparisons of the appearances of crater interiors. Thus, while more information about cratering mechanics and the geological histories of ice-rich satellites might be gained through the analysis of craters formed in ice, such inauspicious results will no doubt make the path a slippery one.

IO - THE ENIGMA. Dr. Fraser P. Fanale, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91103.

Jupiter's four largest moons are called the Galilean satellites after Galileo, their 17th century discoverer. Two of these satellites (Ganymede and Callisto) are as large as the planet Mercury. But the moon-sized Io, closest to Jupiter, reigns supreme as an object of continuing scientific wonderment. Io has long been regarded by many scientists as the most bizarre and fascinating object in the solar system. Even before the Voyager mission, when Io was only a point of light to telescopes, we knew it had a very strange surface. We knew this because spectroscopic analysis of the sunlight reflected by Io suggested that the components on its surface were not those that dominated the surfaces of any of the other spectrally studied objects in the solar system, including all the planets, all the other satellites and hundreds of asteroids and meteorites. Moreover, peculiar transient brightening of Io has been observed from earth following Jupiter eclipse -- but not after <u>every</u> Jupiter eclipse! Long before Voyager Io was also found to be surrounded by a huge cloud of neutral sodium atoms which captured and re-emitted energy from the sun in a certain wavelength. Somewhat later it was discovered that clouds of S^+, S^{++} and K also surrounded Io. In one paper, one scientist studying the problem stated that the observations "suggest Io's surface is unlike that of any other body in the solar system." A journal editor referred to Io as "the enigma of the solar system."

Scientists studying earth-based spectra of Io suggested in 1974 that the surface of Io was probably covered with a mixture of elemental sulfur and salts. Such a mixture, they reasoned, would best explain the peculiar spectral reflectance of Io. They went on to speculate that the sodium in the cloud was "sputtered" off Io by bombardment of the object with trapped magnetospheric radiation (Jupiter is known to have a magnetosphere and charged particle belts like the earth's "Van Allen radiation belts" -- only far larger and more powerful).

These scientists deduced that Io must have gotten hot enough to degas this S and any salt-forming components from its interior. The problem with this hypothesis is that the only continuing heat source they could suggest to drive the volcanism was decay of radioactive elements like uranium. Given the very low trace concentrations of these elements in meteorites and their inferred abundances in Io, it seemed that Io was too small to be hot enough to drive the volcanism and degassing required by this model. Therefore it was suggested that lower temperature volcanism involving H_2O and other volatiles as carriers of the S and other constituents was involved. However, this also had a serious problem: based on the absence of "water bands" in its reflectance spectrum, the surface of Io is thought to be absolutely bone dry. If low temperature volcanism with water was involved, then where was the water? It was speculated that water might have been more easily sputtered away leaving a surface rich in S and salts.

IO - THE ENIGMA

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Shortly before the Voyager encounter the pieces began to fall into place. A detailed theoretical study of the tides produced in the body of Io by Jupiter's gravitational field as Io revolved around Jupiter led to the prediction that such "tidal friction" heating of Io was three times as important as the heating by radioactive decay as referred to above. Now there was plenty of heat to drive any volcanism desired. It was still not obvious what might have happened to the degassed water, however.

When Voyager I encountered Io it found an object even more bizarre than had been suggested on the basis of earth-based observations: the surface was garishly mottled with areas which were tar black, snow white, orange and yellow and six gigantic volcanic plumes were found hurdling dust and gas over 100 miles into space! Indeed, the surface coloration appears to be entirely consistent with a surface composition dominated by orange, black and white forms of sulfur. Also, an infrared spectrometer aboard the Voyager spacecraft was able to identify a "wisp" of SO_2 gas (still less than 1/10,000,000 of an earth atmosphere of pressure) just over one of the active vents. Also, astronomers at the observatory atop Mauna Kea in Hawaii and at the Ames Research Center (observing from a high altitude aircraft) observed a deep "absorption band" in a part of Io's spectrum not scanned by the spacecraft. Laboratory workers at the University of Hawaii and Caltech's Jet Propulsion Laboratory were able to identify the band as belonging to frozen sulfur dioxide.

Thus, thanks to the combined discoveries from spacecraft obervations, theoretical insights, earth-based telescope observations and laboratory studies, we now have this picture of Io: Io is covered with garish orange, white, black and yellow regions which represent various forms of sulfur made at different temperatures. Another important compound is sulfur dioxide which is present as frozen SO_2 frost or snow in the plumes and as atmospheric gas. These materials are supplied to the surface from volcanic vents that are not atop huge volcanic structures like on earth, but nonetheless can shoot material 100 miles high. Some of the SO_2 and S may simply ooze from the foundering crust or come up in tiny fumaroles. These can appear and disappear, and regions can change colaration on a timescale of days! There are giant pools of black sulfur tens of miles across. All this activity is driven mainly by tidal friction as Io goes around Jupiter, but other energy sources may play a role as well. We still haven't seen any evidence of water, yet most of the observations that relate tangentially to the water question continue to force us to postulate that Io started out with a great deal of water and lost it.

What don't we know about Io? 1.) Where did the H_2O go? 2.) What was Io like early in its history? (This is a really fascinating question because not only do we seem to have to postulate that Io once degassed huge amounts of H_2O, but most workers believe that Jupiter was like a small sun for a very short time in its history and once supplied as much energy to Io as the sun now supplies to the earth!) 3.) Io's atmosphere is very interesting. Is it "buffered" by SO_2 snow and ice? (That is, is SO_2 snowing out here and there to lower the pressure when the pressure is "too high" and evaporating to raise the pressure when it is "too low"?) In this very, very thin atmosphere, are there nonetheless complex "weather" patterns we can study? 4.) How does the material get into Io's huge secondary clouds of Na and S? Obviously Io is the source, but is it sputtered off the surface by atomic particles, shot out

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directly by volcanoes, or swept off the top of the atmosphere by Jupiter's magnetic field? 5.) What do the different forms of S mean? Why is one found in one place and another elsewhere? How hot is Io inside and how can the volcanoes shoot the material so exceedingly high?

Hopefully continued ground-based and laboratory work will continue to unravel Io's mysteries. However, we place most of our hope in Galileo — a mission to be flown to this Jupiter system in the late 80's. It will send a probe into Jupiter's atmosphere and send an orbiter into such an orbit that it will have ample opportunity to study Jupiter's moons far more closely and with a far more sophisticated arsenal of instruments than has yet been utilized.

In the meantime, puzzles listed above continue, despite our many recent breakthroughs in our understanding, to maintain Io's long held position as "the enigma of the solar system".

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OCCULTATION OBSERVATIONS OF 3 JUNO: A DIRECT MEASURE OF ASTEROID SIZE AND SHAPE. A. W. Harris, Jet Propulsion Laboratory, Pasadena, CA 91103.

One of the most fundamental pieces of information which can be known about an object is its size and shape. Asteroids are so small and so distant that this basic information is beyond our grasp by simply looking at asteroids in very powerful telescopes. Instead, one must resort to more subtle techniques. Perhaps the most direct method that can be accomplished from the earth is to observe an asteroid as it passes in front of a star, an event called an "occultation". The moments when the star winks out and reappears can be timed accurately. By combining many such observations made from different locations, one can construct a silhouette of the asteroid as it would have appeared if we could see such a tiny image directly. I describe here the partial results of just such an occultation.

The asteroid involved was number 3 Juno, which passed in front of a star slightly fainter than itself shortly after midnight on December 11, 1979. The path of the occultation was predicted well in advance to pass across the U.S. from Minnesota to Southern California. Plans were made to observe the event from portable telescopes as well as from several permanent observatories in the Southwest. In addition to JPL, expeditions to observe from portable telescopes were planned by Lowell Observatory, MIT, and University of Arizona. Observing plans were revised less than a week before the event based on measurements of the asteroid's path as it approached the star, and then plans were revised again only hours before to seek clear skies as weather systems moved across Utah and parts of California and Nevada. Ultimately nearly all observers were directed to clear skies in appropriate locations to yield an exceptionally complete silhouette of the asteroid. (At the southernmost site, the sky cleared only an hour before the event!). At least 17 observations of the event have been reported, from Wisconsin to Hawaii. A complete analysis of all of the observations is in progress at the Lowell Observatory. The results given here are based on the JPL data only (5 observing sites).

The observations made from the five sites are summarized in Table I. Only Table Mountain is a professionally operated observatory - the other observations were made by amateur or student volunteers. The "N. Little Lake" observation was made visually with a portable telescope; all other observations were recorded with photoelectric instruments.

The apparent paths of the star behind the asteroid as seen from the various sites are plotted in Figure 1. The interval during which the starlight disappeared is indicated, thus producing a silhouette of the asteroid. I have "connected the dots" with an ellipse 291 km across by 238 km, to indicate a likely figure of the asteroid. The actual figure undoubtedly departs from this due to mountains, craters, and other such irregularities. Such features will be apparent in the more complete picture which is in preparation at Lowell Observatory.

It is known from basic laws of physics that an object spinning freely in space must rotate about its shortest axis (that is, it must be bigger through the equator than through the pole). Juno's axis of rotation (its North and South Poles) must therefore lie approximately along the line of

FIGURE OF JUNO

A. W. Harris

the short dimension, indicated in the figure. As Juno spins about this axis, it appears to get slightly brighter and fainter, indicating that it is a <u>triaxial ellipsoid</u>, a little longer through the equator in one direction than in the other. (A triaxial ellipsoid differs from a sphere in the same way that the shape of a shoebox differs from a cube). The brightness of Juno

FIGURE 1.

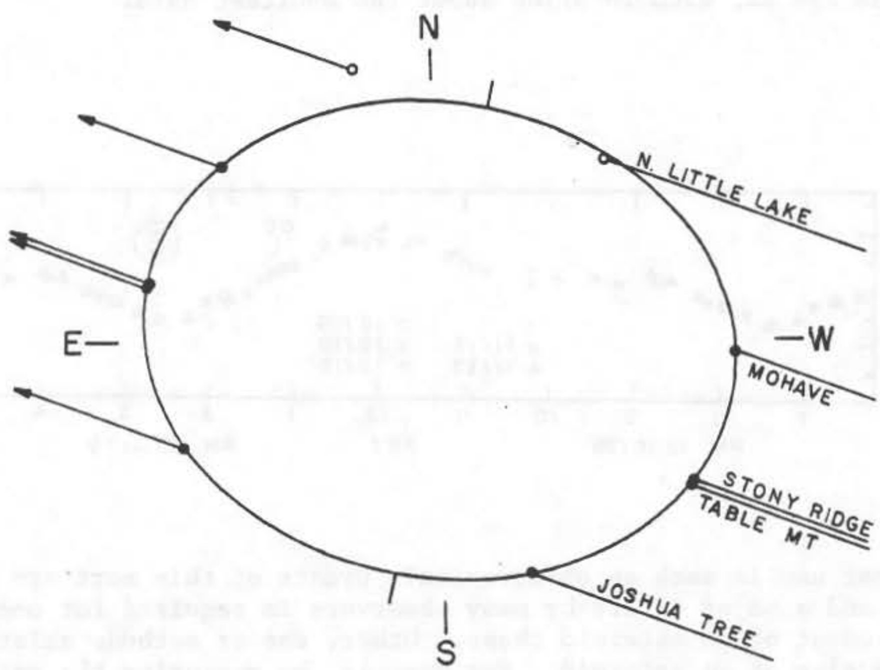

TABLE 1. SUMMARY OF JPL OBSERVATIONS

LOCATION	OBSERVER(S)	DISAPPEARANCE	DURATION OF EVENT
Joshua Tree	R. Stanton	1:09:53.8 AM,PST	43.02 seconds
Table Mt.	A. Harris, W. Sandman, W. Spiesman, C. Abbot	1:10:04.2	67.53 seconds
Stoney Ridge	J. Faulkner	1:10:11.3	67.3 seconds
Mohave	R. Tucker	1:10:03.2	63.8 seconds
N. Little Lake	J. Young	1:10:12	31 seconds?

was monitored on several nights near the time of the occultation. These observations are shown in Figure 2, superimposed on one another as if all measurements had been made during a single rotation cycle of 7.2 hours. It can

FIGURE OF JUNO

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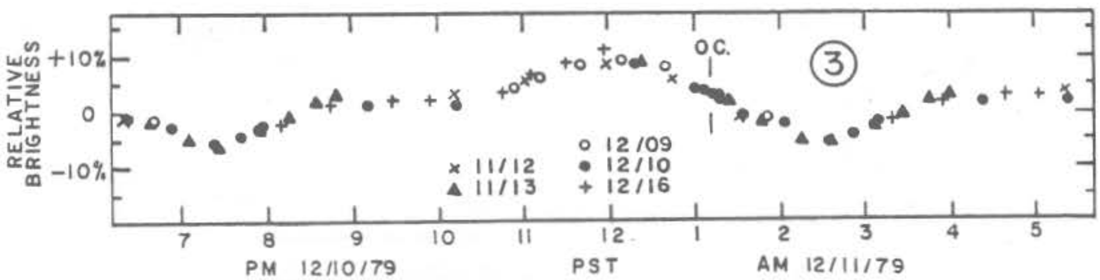
be seen that Juno varies by approximately 10-15% in brightness as it turns on its axis. If this is due entirely to the apparent size of the object as it rotates, rather than to darker or lighter patches on the surface, we can estimate that Juno must be 10-15% longer than it is wide in the two equatorial dimensions. At the instant of the occultation, it was almost exactly half way between the maximum and minimum brightness. Therefore, we estimate the two equatorial dimensions as equally larger and smaller than the equatorial dimension measured at the moment of occultation. The three dimensions of the ellipsoid (analogous to length, width and height) are thus 308 km, 274 km, and 238 km, with rotation about the shortest axis.

FIGURE 2.



Of what use is such an observation? Events of this sort are rather uncommon, and a major effort by many observers is required for one successful measurement of an asteroid shape. Other, easier methods exist for estimating the size of an asteroid. For example, by measuring the reflected sunlight from an asteroid and comparing that to the infrared (heat) energy radiated by the asteroid, one can determine how dark the asteroid surface is. Knowing how much reflected light is being seen, and what fraction of the incident sunlight that is, we can estimate how large a surface must be reflecting the light. Unfortunately, the result we get from this method depends to some degree on how light is reflected in different directions, and how the asteroid heats up and cools down as it turns on its axis. In order to determine the validity of indirect measurements of asteroid size, such as the radiometric method which I have just described, we want to measure a few asteroids directly, by a method that cannot be wrong. The occultation method is just such a technique. To date, only two asteroids have been measured by occultation to sufficient accuracy to make meaningful comparisons with indirect size determination: 2 Pallas and 3 Juno. In the former case, the indirectly determined diameter proved to be about 5% too large, in the latter case, about 5% too small. It thus appears that the indirect diameter measurements are probably quite accurate and don't differ from true diameters in a systematic way (i.e. always too small or always too large).

About 200 asteroids have diameter determinations made by indirect methods. It is hoped that we can check about 10 or more of those diameters by direct occultation measurements over the next few years. A more complete discussion of occultation techniques and results is given by Millis and Elliot (ref. 1).

FIGURE OF JUNO

A. W. Harris

A second reason for observing occultations has recently come to light: If some asteroids have satellites like those of the major planets, one might be detected as a secondary occultation. Indeed, a number of such secondary occultations have been reported in the past by observers who were clearly out of the path of the primary occultation, or who reported more than one disappearance of the star. Most of these observations are dubious for one reason or another. In fact I have estimated (ref. 2) that only a few at most of these observations could be valid, even if every asteroid has as many satellites as possible without colliding with one another! None-theless, a few observations are suggestive of real secondary events, and observers of the Juno occultation made a special effort to detect such events. In addition to the 17 observers within the primary occultation track, the light of the asteroid plus star was monitored from several other sites outside the track (McDonald Observatory, University of Arizona, and Lowell Observatory). To my knowledge, no secondary events were reported within 10-20 minutes of the primary event time by any of the observers. One negative result does not discount all previous reports, of course. We must repeat this type of thorough coverage of many occultation events before the question of asteroidal satellites can be resolved.

ACKNOWLEDGEMENTS

An experiment of this sort depends on the cooperation of many for its success: I particularly thank the observers listed in Table I for their dedication and excellent work. George Fischbeck of KABC Eyewitness News, Los Angeles, provided invaluable aid in avoiding cloudy skies. L. Wasserman and R. Millis of Lowell Observatory provided computational assistance. This work is supported at JPL by the Lunar and Planetary Program of NASA under contract NAS7-100.

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THE EVOLUTION OF AN IMPACT GENERATED ATMOSPHERE; M.A. Lange, Inst. f. Mineralogie, University of Munster, W. Germany and T.J. Ahrens, Seismological Laboratory, California Institute of Technology, Pasadena, CA 91125

1. INTRODUCTION

The question regarding the origin and evolution of the Earth's atmosphere and hydrosphere is of general importance for the understanding of the geologic and biologic history of our planet. A number of different models attempt to consider this question. One class of models explains the formation of an atmosphere by the gradual, secondary degassing of the Earth during the course of geologic time.

The purpose of this study is to quantify some of the processes related to another group of evolutionary models for the formation of atmosphere and hydrosphere. Arrhenius et.al. (1974) first proposed the idea that the early terrestrial atmosphere might be of primary, rather than of secondary origin. They claimed that the bodies forming the Earth (i.e. the so-called aggregates) included a minor amount of volatiles (noble gases, hydroxyl ions, etc.) which were released, when these bodies hit the surface of the growing Earth. Thereby, atmospheric gases accumulated gradually, parts of which eventually condensed to form an early hydrosphere.

This model was recently challenged by Jakosky and Ahrens (1979). They demonstrated that, although a sufficient amount of water to explain the present terrestrial hydrosphere might be produced by a process as envisioned by Arrhenius et.al. (1974), the hydration of surface minerals (i.e. the formation of water bearing substances) would quickly remove all the water previously released from the aggregates. Thus, the available water would constantly be buried within the crustal layers of the accreting Earth and could only be removed by secondary degassing, later in the Earth's history.

Due to the lack of data, the precise conditions which lead to the release of water during an impact of a water bearing body were not determined in any of the above cited models. These models also did not take into account the secondary release of previously recombined water in hydrous surface minerals. This is the task of the present paper. Since water is a major constituent in the Earth's volatile budget, calculations are presented which specify:

a) the impact conditions for the release of water from serpentine, a water bearing mineral which is a common component in certain meteorites (which are thought to resemble the aggregates of the solar nebula forming the Earth) and the Earth's crust;
b) the conditions which lead to the formation of a primary atmosphere/hydrosphere during accretion.

2. SPECIFICATION OF IMPACT CONDITIONS FOR THE RELEASE OF WATER FROM SERPENTINE

Water is released from a hydrous mineral, when its internal energy exceeds the binding energy between the non-hydrous constituents and the OH^--groups of the crystal. Dehydration of serpentine has been studied experimentally by Brindley and Hayami (1964). The dehydration temperatures, valid on a much smaller time scale as characteristic for processes taking place during an impact, can be determined from this study. Finally, critical entropies are calculated from these temperatures (entropy = theoretical measure of energy which cannot be transformed into mechanical energy in a thermodynamic system).

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Based on shock wave data (Compendium of shock wave data, 1977), entropies as a function of impact velocity and impact pressure can be calculated for serpentine. Comparison of these results with the critical entropies yield critical impact velocities v_{min} and critical impact pressures p_{min} for the release of water from serpentine crystals.

During accretion, the surface layer of the Earth (here, the target) had a porous rather than a solid character. Hence, impacts into porous material have to be considered for the purpose of the present paper. A measure of porosity is the distension m, which specifies the ratio between the densities of non-porous to porous material. Distensions between 1.0 and 1.8 are used in the present study.

In Figures 1 and 2, critical impact velocities v_{min} and critical impact pressures p_{min} are given for serpentine as a function of the target distension m. The values for v_{min} additionally depend on the material of the impacting body (i.e. the projectile), while p_{min} does not. As can be seen, four different materials are considered (iron=Fe, enstatite=En, forsterite=Fo, and aluminum=Al). These materials represent roughly the major constituents of the Earth's body (Al is taken as an analogue for anorthite, a common crustal mineral) and should be characteristic for the composition of the Earth-forming aggregates.

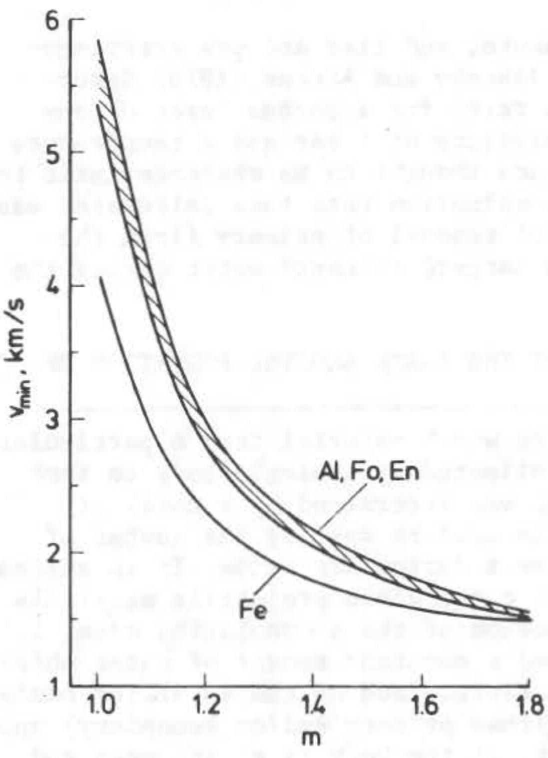

Figure 1: Minimum impact velocities v_{min} as function of target distension m for the dehydration of serpentine. The projectile materials considered are denoted on the curves. Further details, see text.

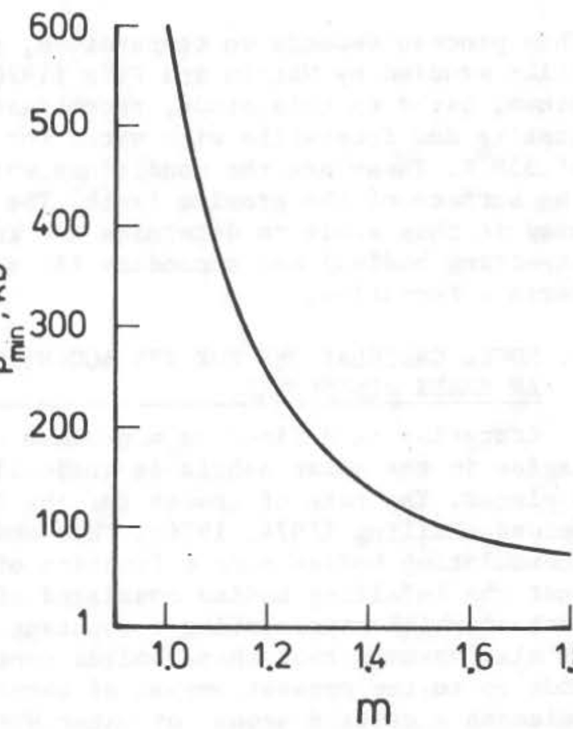

Figure 2: Minimum impact pressures p_{min} as function of target distension m for the dehydration of serpentine.

As can be seen, p_{min} and v_{min} strongly depend on the distension m for $1.0 \leq m \leq 1.4$ and less so for $m > 1.4$. The values for v_{min} are similar for Al, En, and Fo and uniformly higher than for an iron projectile.

In order to understand the impact induced dehydration of a water bearing target, an additional parameter has to be specified. Since we are not dealing with single crystals, but with a complex mixture of hydrous and non-hydrous minerals, not all of the water initially released upon impact will actually leave the target. The ratio between water leaving the target and initially released water at each crystal site, here called diffusion rate Dr, varies between zero (i.e. all released water is retained within the target) and one (i.e. all released water leaves the target). The influence of Dr on the model results is discussed below.

3. RECOMBINATION OF WATER WITH NON-HYDROUS MINERALS

When non-hydrous minerals like forsterite and enstatite are brought together with water, serpentine will be formed, as follows:

$$\underset{\text{Forsterite}}{Mg_2SiO_4} + \underset{\text{Enstatite}}{MgSiO_3} + \underset{\text{Water}}{2\,H_2O} \rightleftharpoons \underset{\text{Serpentine}}{Mg_3Si_2O_5(OH)_4}$$

This process depends on temperature, pressure, and time and was experimentally studied by Martin and Fyfe (1970). Jakosky and Ahrens (1979) determined, based on this study, recombination rates for a porous layer of enstatite and forsterite with water for a pressure of 1 bar and a temperature of $350^{o}K$. These are the conditions which are thought to be characteristic for the surface of the growing Earth. The recombination rate thus calculated was used in this study to determine the rate of removal of primary (from the impacting bodies) and secondary (from the target) released water during the Earth's formation.

4. MODEL CALCULATIONS FOR THE ACCRETION OF THE EARTH AND THE FORMATION OF AN EARLY ATMOSPHERE

Accretion is defined as a process during which material from a particular region in the solar nebula is gradually collected by a single body to form a planet. The rate of growth for the Earth was determined by a model of Weidenschilling (1974, 1976). This model is used to specify the number of accumulating bodies n as a function of time t during accretion. It is assumed that the infalling bodies consisted of the above given projectile materials each of which representing a constant fraction of the accumulating mass. It is also assumed that these bodies contained a constant amount of water which adds up to the present amount of water on Earth. Each of the infalling bodies releases a certain amount of water WVA (either primary and/or secondary) upon impact, which depends on the kinetic energy of the body (i.e. its mass and velocity, the latter variing with time).

The accretion process is in the present model study divided into a number of time steps of length Δt. During each time step, a certain fraction of the total mass of the Earth (according to the model of Weidenschilling, 1974, 1976) Δm is accumulated by n bodies. Hence, for each step the amount of primary and secondary released water can be determined as the product MVA $\cdot$ n. This amount is numerically balanced by the removal of free water due to hydration of surface minerals during Δt. The system atmosphere/hydrosphere is thereby gradually established following the scheme given in Figure 3.

The model calculations demonstrate that the major parameter govering the fate of an early atmosphere/hydrosphere is the above defined diffusionrate Dr. This is illustrated in Figure 4 which gives the amount of water WGRG, which is constantly bound within the Earth due to hydration of forsterite and enstatite, as a function of time during accretion. For the illustrated models, a constant recombination rate as given by Jakosky and Ahrens (1979) was used.

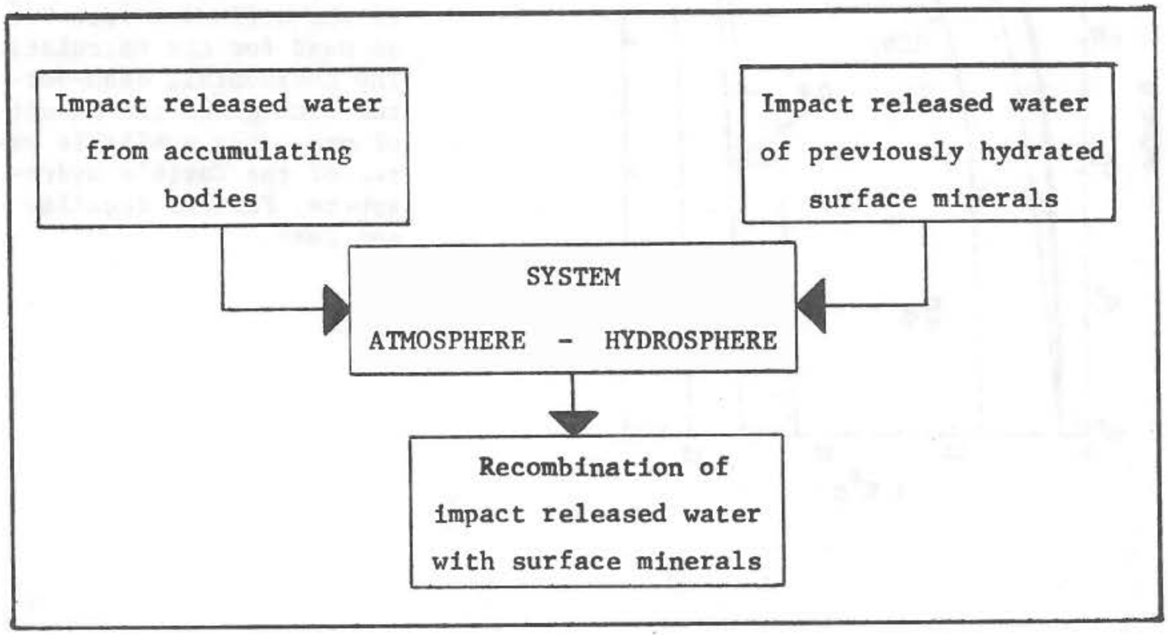

Figure 3: Schematic representation of the major sources and sinks of water for the system atmosphere/hydrosphere, as considered in the present model calculations.

As can be seen, with increasing values of Dr, more and more water will be remobilized by the impacts (i.e. WGRG decreases) regardless of the removal of water due to hydration of forsterite and enstatite. For $Dr > 0.35$, $\sim 90\%$ of the presently available water will reside on the surface of the Earth and thus establish an early terrestrial atmosphere/hydrosphere. Thus, under these conditions (i.e. $Dr > 0.35$) impact vaporization more efficiently releases water than can be bound by hydration of forsterite and enstatite during each time step.

5. DISCUSSION

The present model calculations demonstrate that the formation of an early terrestrial atmosphere/hydrosphere as proposed by Arrhenius et.al. (1974) is indeed possible. It is shown that the fate of an impact generated atmosphere is governed by the diffusion rate Dr and not by the recombination of water with forsterite and enstatite, as proposed by Jakosky and Ahrens (1979).

Experimental data on the size of Dr are not yet available. On the other hand, results of the present study indicate that most of the target which undergoes dehydration belongs to the highly comminuted ejecta material. It is thus plausible to assume that values of $Dr > 0.35$ are likely to be found in natural impacts of the kind envisioned in this study.

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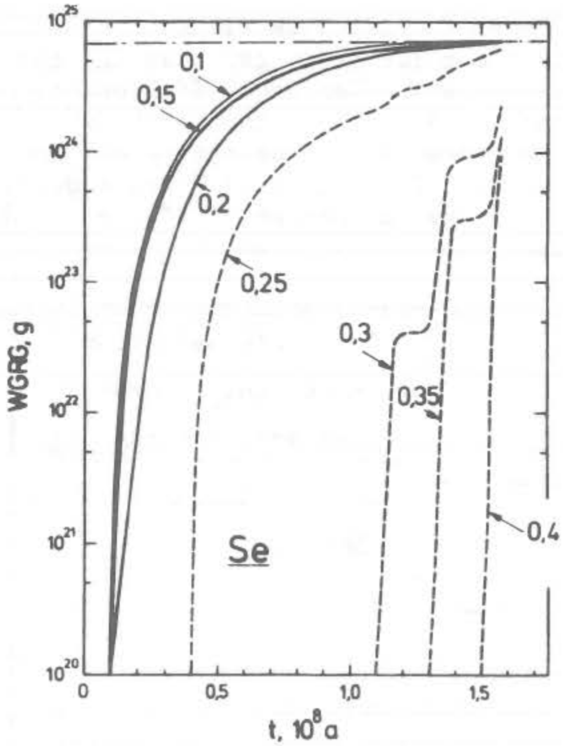

Figure 4: The amount of permanently retained water WGRG within the Earth as function of time t during the Earth's accretion. The number on each curve denotes the value of the diffusion rate Dr, as used for the calculation. The horizontal, dash-dotted line gives the amount of presently available water of the Earth's hydrosphere. Further details, see text.

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GEOLOGY OF THE ICY SATELLITES OF JUPITER, Harold Masursky, U. S. Geological Survey, Flagstaff, Ariz. 86001.

This description of Jupiter's icy satellites, Europa, Ganymede and Callisto, is based on information included in two articles published in Science magazine by the Voyager imaging team (Smith et al., 1979a, b) and analysis of new mosaics of the satellites made from specially enhanced images acquired by Voyagers 1 and 2.

The essentially icy nature of the three outer Galilean satellites, first suspected from pre-Voyager determinations of satellite diameters and densities has been confirmed by the more precise measurements obtained by Voyager:

NAME	DIAMETER (KM)	DENSITY
Europa	3130 ± 30	3.03
Ganymede	5280 ± 30	1.93
Callisto	4840 ± 30	1.79

Yet the geomorphic and geologic features seen on their surfaces vary dramatically. A large variation in albedo has also been noted, with more than a factor of three difference between Europa and Callisto having been measured. Dark linear features and a near absence, at the resolution obtained by Voyager, of craters characterize Europa's surface. Dark, polygonally shaped, heavily cratered areas, and brighter regions with grooved terrain are seen on Ganymede. Dark Callisto is heavily cratered, and is characterized chiefly by very large, circular ghostlike ringed features. All three satellites have very smooth limbs, verifying that local and regional relief is very small. This factor distinguishes them from the terrestrial planets Earth, Venus, Mars, Mercury and Moon as well as the Jovian satellite Io; all of these exhibit considerable local relief (5 to 25 km).

The many dark linear features seen on Europa extend for thousands of kilometers and are as much as 50 km wide; they look like fracture systems. They show little local relief and appear to be filled by bright material, dark material or both. Other linear features with a cuspate pattern have a ridge form. They may be as much as 200 m high. Appropriate regional slopes away from these linears have not been observed. Only three circular features that are thought to be impact craters have been observed in the low resolution images of Europa. However many other features in the darker, rough areas may also be craters that are at or below the present resolution limit. The paucity of impact craters on Europa may be due to flooding of the surface when water oozed upward through fracture systems in the crust.

In contrast, Callisto surface is very heavily cratered; a multitude of small impact craters with bright ray material extending outward dot the surface. Many larger craters, called "Palimpsests", are ghost-like. The icy crust evidently flowed and filled the cavities of these craters. Also seen are three large impact basins with bright areas in their centers; these crater forms also appear to have been filled by crustal flow. They are surrounded by a multitude of concentric rings that resemble the rings around large impact basins on the Moon and Mars. However as many as twelve rings surround the Callisto features, whereas only three or four rings are seen on the Moon or Mars. The Callisto rings consist of flat-topped ridges that may have been formed when water leaked upward along fractures in the crust.

Ganymede is the most complex of the satellites. Two fundamental terrain types are seen there; dark polygonal areas that are heavily cratered and therefore thought to be ancient, and bright regions whose grooved terrain exhibit varying crater concentrations and therefore varying relative ages. Covering these terrains are thin, blue-white deposits that probably are water-ice.

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The ancient dark terrain has even better examples of craters Palimpsests; they are probably ancient impact craters that have been filled by crustal flowage. Many impact craters in this terrain have radial ejecta blankets and lines of secondary craters with both bright and dark ejecta. Also visible are ancient ringed impact basins like those on Callisto except that, on Ganymede, the ring ridges have central grooves. These areas preserve the record of ancient heavy bombardment of the crust. The surface here is probably comparable in age to the ancient crusts of the Moon, Mars and Mercury.

The grooved terrain is brighter. In places the cratering is intense; these areas are probably as old as the dark crusts. In other areas there are few craters; they may be as young or younger than the lunar maria. In some places the grooves offset craters, showing that the grooves are faults that distort the crust. In other areas the grooves do not disrupt the older terrain; these grooves appear to be breaks in the crust along which water may have risen. In still other areas there are different numbers of grooves on opposite sides of cross faults. One impact basin with a coarse, rough ejecta blanket and a flat floor, has a diameter of 150 to 200 km. Secondary craters radiate outward from it. The older craters may have been made in a mobile crust; however this crater looks more like craters on the Moon and Mars, suggesting that the crust was ridged when it was formed. Tectonic (faulting) activity appears to have occurred throughout much of the satellites history.

When the Galileo project orbits Jupiter, probably in 1986,we will receive higher resolution image data as well as data on the chemistry of the surface materials.

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PIONEER VENUS RADAR RESULTS: GEOMORPHOLOGY FROM IMAGING AND ALTIMETRY, Harold Masursky and Eric Eliason, U.S. Geological Survey, Flagstaff, Ariz., P.G. Ford, Massachusetts Institute of Technology, Cambridge, Mass., G.E. McGill, University of Massachusetts, Amherst, Mass., G.H. Pettengill, Massachusetts Institute of Technology, Cambridge, Mass., G.G. Schaber, U.S. Geological Survey, Flagstaff, Ariz., and Gerald Schubert, University of California, Los Angeles, Ca.

Spacecraft and ground based radar altimetry and images have permitted a first look at the global distribution of terrain units and allowed a preliminary interpretation of the geologic history of Venus. Pioneer Venus radar observations 74° N to 63° S have shown that about 20 percent of the planet mapped consists of "lowland" plains characterized by radar dark areas with few rocks, 1° to 2° slopes and elevations between 0 km and -2.9 km (from the mean radius of 6051.4 km). These low areas may be covered by basaltic lava flows, like the basins of the Earth and Moon. Seventy percent of the surface mapped is rolling "uplands" with slightly higher rms slopes 1.5° to 3°, and elevations between 0 km and 3 km. The USSR Venera 8 landed in such terrain and indicated granitic composition. The "uplands" are characterized by many dark-floored, very shallow "craters", many smaller ringlet "craters", and whispy linear features that are radar bright and rough but with little relief that may be fault zones. Alpha Regio (25° S 5° E) is a low plateau (+1.5 km) in the rolling "cratered" uplands. It is cut by complex linear features, probably faults, that resemble terrestrial Basin-Range structure. It is surrounded by "cratered" plains and may represent exposed ancient crust. Crater densities of the upland region from the ground based Areciblo radar images lie along the curves for cratered uplands of Mars and the Moon. Tectonic trend rosettes closely resemble some terrestrial and martian rosettes and strongly differ from the "lunar grid" patterns that characterize the Moon and Mercury. The remaining 10% of the planet is "highlands" characterized by radar brightness due to rocky surfaces and greater slopes (3° and 10°), and elevations as high as 11.2 km (the top of Maxwell Montes: 65° N at 0° longitude). The highlands observed thus far consist of two continent-sized masses-Ishtar Terra and Aphrodite Terra - and a group of "islands" (e.g. Beta Regio) that are isolated higlands. A fourth elevated feature about 3 km high, not yet observed by Pioneer Venus, has been described as lying on the equator (long. 190° to 200°) from Earth-based observations (Campbell, et al., 1972).

The Northern highland (Ishtar Terra) is as large as Australia and consists of a high plateau, Lakshmi Planum, with mountain ranges (Akna Montes and Freyja Montes) lying on the west and north, respectively. The plateau is radar dark about 5 km above the planet's mean level rms slopes vary from 1° to 4.5°. There is a suspected boundary fault scarp about 2 km high along the southern margin. A parallel scarp about one km high steps down into the adjacent lowland to the south. If the plateau were basaltic lavas it would produce a large gravity anomaly, but none has been observed (Phillips et al., 1979). Therefore, it may consist of thin lavas on uplifted ancient crust, as in the Tharsis plateau on Mars.

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Maxwell Montes, which sits atop the 5 km high plateau, Ishtar Terra, appears from Earth-based high resolution images to be a tectonically disrupted volcanic construct of relatively old age. A 100 km diameter rimless crater, possibly a caldera, is offset to the east of the center of the highest level of Maxwell Montes. Again the lack of a gravity anomaly indicates that the mountain may not be basaltic, but rather intermediate to silicic in composition. Farther to the east of Maxwell Montes an extended area of complex ridges and troughs and high 4.5^{o} to 10^{o} slopes may represent additional evidence for tectonically disrupted crust. The extreme brightness of the Maxwell Montes feature on Ishtar Terra indicates that the steep slopes of this Mt. Everest of Venus are covered with rocks larger than 10 cm. The remainder of the upland plateau east of Maxwell Montes has fewer rocks but similarly high slopes at the meter scale. Earth-based depolarization studies predicted the blocky and topographically rough slopes of Maxwell Montes (Jurgens, 1970).

Aphrodite Terra, half the size of Africa, lying on the Venus equator, may be older and more degraded than Ishtar Terra as it does not appear to contain uplifted plateaus or volcanic constructional mountains. The "continental" feature rises to 6 km above the planet's mean level and is radar bright. East of Aphrodite, a broad (60^{o} x 60^{o} of latitude and longitude), uplifted plateau rises an average of 2 km above the mean level and contains a complex of curved ridges and trenches. The trenches (Pettengill et al., 1979) have distinct raised rims, and the general region is characterized by high slopes that on Mars are indicative of rugged canyon walls and chaotic terrain. A 1500 km diameter, semi-circular feature with two ridges and an intervening trough is an intriguing structure of possible volcano-tectonic or impact origin located on the low plateau at latitude 35^{o} S, longitude 140^{o}.

Beta Regio is the third recognized highland feature and consists of two large features. The features, (Theia Mons and Rhea Mons), are shield-shaped and stand 5.4 km high above mean level. A large ridge of 2 km relief extending south of Theia Mons turns to the east and continues south to terminate at approximately 20^{o}. The southernmost part of this ridge contains a large canyon-like structure first described from high resolution Earth-based Goldstone radar images by Malin and Saunders (1977) and Goldstein et al., (1976). A second linear structure 4500 km long extends S 50^{o} W from Rhea Mons and is characterized, as is the south-trending structure, by high (4.5^{o} to 10^{o}) slopes; it is radar bright. Farther to the south, two additional highland areas lie along the north-south tectonic trend. The Theia Mons feature is seen on high-resolution Earth-based images to have bright streaks radiating away from its central region in a ray-like pattern. The shield shape of these features, in addition to a summit depression on Theia Mons, has led some to suggest that these "islands" of highland terrain are young basaltic volcanic constructs. The USSR Veneras (9 and10 landed just east of these shields and determined from gamma ray spectrometry that the rocks were "basaltic".

The distinctly unimodal distribution of relief on Venus and a low center of mass-center of figure offset of < 400 m. (Pettengill et al., 1980) could indicate that the 70 percent of the planet described above as "rolling uplands" may represent ancient continental crustal material. If such a universal level

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of continental crust does exist, it could imply that the crust deforms easily and that the continents were widely distributed over much of the planet's surface at an early stage. On the other hand, if Ishtar Terra and Aphrodite Terra are geologically old, their height above mean radius indicates that the continental crustal rocks must be relatively creep resistant and that water is scarce or absent in the crust (Weertman, 1979). Further analysis of the Pioneer Venus data may provide some important clues as to the age of these geologically important terrains.

The broken crustal areas lie in three regions: around Beta, and east of Aphrodite and east of Ishtar. From the present ground based and spacecraft data we do not seem to have the planet-wide girdle of mid-ocean ridges and troughs adjacent to the continents that, on the Earth, are related to plate tectonics.

Geologic history: there was a widespread differentiated cratered ancient crust that forms the present "uplands". In the "highlands" two areas of continental size were formed, possibly over mantle plumes, although clear-cut evidence of uplift and volcanic constructs are seen only in the northern one. East of the two continents lie tectonically disrupted zones of ridges and trenches that descend into lowlands that may be floored by mare-type basalt flows that are uncratered, therefore probably young. The overlap relations show that tectonism occurred at several times. Continued widespread tectonism with local volcanism occurred in the Beta Region with construction of basaltic shield volcanoes.

Venus seems to share some geologic and geophysical features that are much like the Earth while other appear to resemble Mars. It now appears that Venus may be different and unique. Perhaps the future high resolution data that may be taken by the Venus Orbiting Imaging Radar mission in 1986 will allow us to explain the dramatic differences between Venus and Earth despite their similar sizes and masses.

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MULTI-RINGED BASINS IN THE SOLAR SYSTEM: A "NEW" UNDERSTANDING OF THEIR ORIGIN. William B. McKinnon, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125 and H.J. Melosh, Department of Earth and Space Sciences, SUNY Stony Brook, Stony Brook, NY 11794.

Multi-ringed basins are the single most important geologic structures in the solar system. These structures, some of which are over 1000 miles across, have been found in the last 20 years by NASA spacecraft on the Moon, Mars, and Mercury. Their origin is controversial, but now Voyagers 1 and 2 have discovered basin-ring systems on Ganymede and Callisto, two of Jupiter's satellites. These discoveries make multi-ringed basins much more understandable.

A multi-ringed basin has a broad circular central depression surrounded by one or more concentric mountain rings or cliffs. All planetary scientists agree that they are formed by the impact of a massive meteorite or asteroid. However, the details of how this happens have been hotly debated. We believe that there are three mechanisms responsible for ring formation. They all take as their starting point an enormous impact. The three types of rings produced are called (1) collapse rings, (2) wave rings, and (3) nested rings.

Collapse rings, which we have analyzed in detail, form because the massive crater produced by the asteroid impact cannot stand up under its own weight. This is illustrated in figure 1a. The deeper layers of a planet are warmer and deform more easily under pressure. They will flow towards the center of the crater, causing the upper layer around the crater to break along a concentric cliff or series of cliffs and collapse inward. This kind of collapse scarp or ring is seen in the Orientale Basin on the Moon.

The spacing between these collapse rings depends on how hot a planet is at a given depth below the surface. The higher the temperature, the closer the spacing (see figure 1b). The old basins discovered on Ganymede and

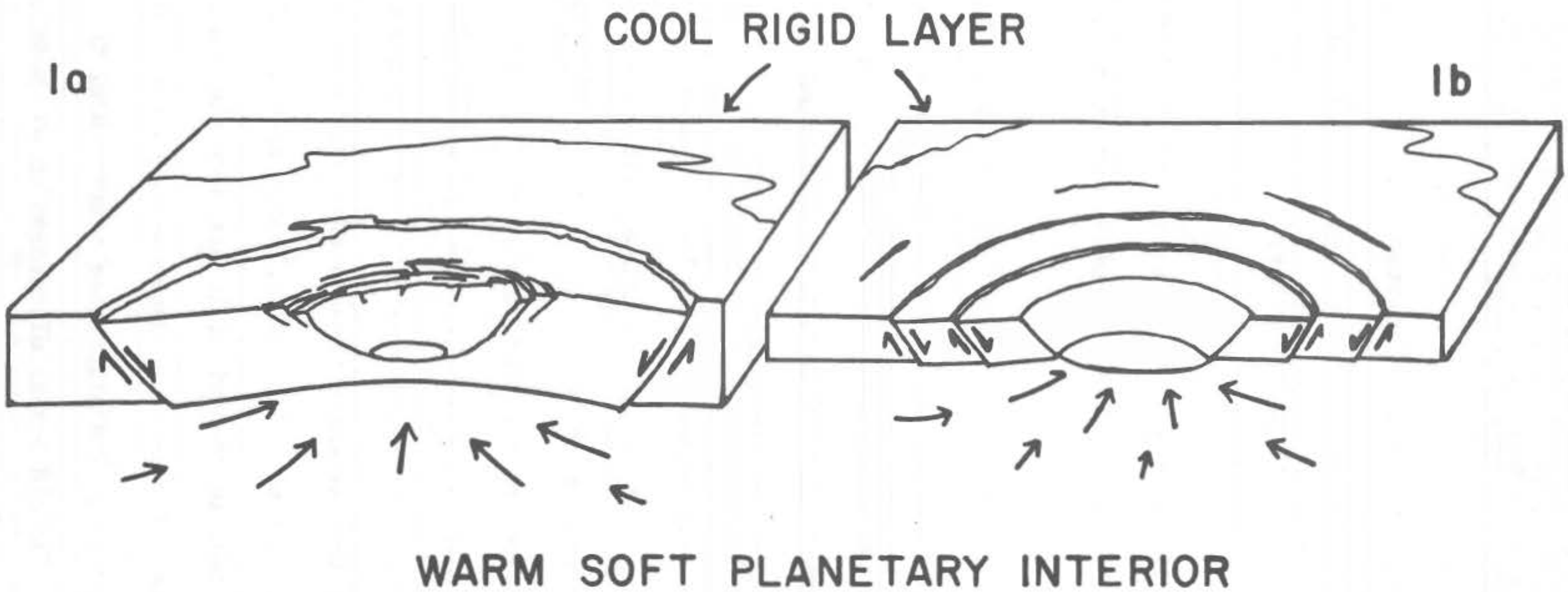


Figure 1. A schematic view of the interior flow and collapse ring formation that follows a large impact. (a) Warm interior and thick rigid outer layer. (b) Warmer interior and thinner outer layer leading to closer ring spacing. This comparison may be applied to basins of different sizes formed at the same time on a planet, or to basins of the same size formed at different times when the planetary thermal structure has changed.

Callisto have much closer ring spacing than the young basin on Ganymede (30-60 versus 150 miles). This is to be expected as the upper layers of a planet cool and become more rigid over geologic time. Other studies of the deformation of small craters on Ganymede show that its crust was much softer in the past, confirming this view.

Wave rings are formed in impact basins of a generally smaller size. The fractured and broken rock surrounding the crater immediately after formation can flow as a very thick fluid. A great wave oscillation can occur, somewhat like a raindrop hitting a small puddle. However, the cratered rubble acts more like hot lava than water. The mechanism by which debris flows in this manner is not understood at present, but there is mounting geological evidence for it. The energy which keeps the material fluid dissipates even as the wave ring is forming. This causes it to freeze in a certain position, unlike water waves which flatten out completely if you wait long enough. These kind of rings are seen on our Moon and the planets Mercury and Mars.

Nested rings are formed by an impact into a weak layer overlying a strong layer. The strong layer may be hard rock and the weak one could be rubble, or sediments, or even ice. An example would be small craters (less than 600 feet across) formed in the lunar maria. In this case there is about 60 ft. of basalt rubble above solid basalt (a kind of volcanic rock). Whether nested rings form at the scale of the great solar system basins is uncertain.

In summary, examination of ringed basins across the solar system, especially on the Galilean satellites recently visited by NASA's Voyager spacecraft, show that not all ringed basins can be formed by a single mechanism. By physical and mathematical analysis three mechanisms are found to be valid. They are not necessarily exclusive. The largest basins can form collapse rings and the spacing of these rings can be used to help unravel a planet's thermal history.

GLOBAL FAULT PATTERNS ON OTHER PLANETS. H.J. Melosh, Department of Earth and Space Sciences, SUNY Stony Brook, Stony Brook, New York 11794.

Global fault systems appear on the surfaces of planets when they are either despun, reoriented, or distored by the action of powerful tides. Mercury, the planet closest to the sun, has probably been despun by solar tides from an initial period of perhaps 20 hours to its present 59 day rotation rate. This despinning produced a characteristic pattern of faults on its surface which has been recognized by careful photogeologic mapping using photos returned by the Mariner 10 spacecraft.

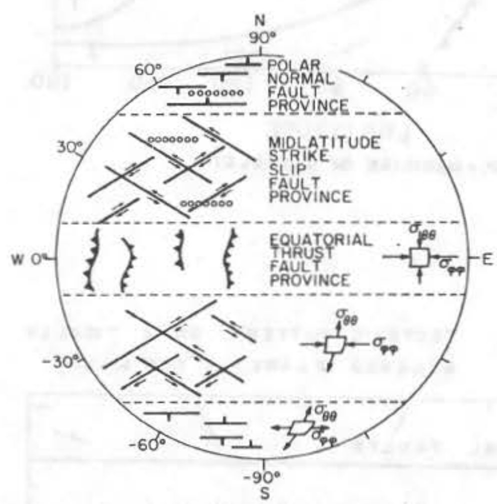
The position of the rotational pole of the planet Mars may have moved several thousand kilometers as the large volcanic dome of the Tharsis area developed. The extra mass of these huge volcanoes resting on the planet's surface would have tipped Mars so as to bring the volcanoes close to the equator, where they presently lie. As Mars tipped over, its rocky crust was subjected to large stresses and fractured in a characteristic pattern which may yet be recognizable, even though the pole probably moved more than a billion years ago.

Our Moon was once much closer to the earth than it now is. Energy dissipated by the tides it raises on the earth causes the diameter of the Moon's orbit to slowly increase and the earth's rotation to slow down. When the Moon was closer to the earth it was strongly distorted by tides, being elongated like a football along a line connecting the earth and the moon. Although the amount of this elongation was small--only a few kilometers--as the Moon moved away from the earth and tidal forces lessened, the bulge collapsed and could have created faults in the Moon's crust. It is not known whether any of the faults now seen on the moon are due to this process. Calculations show that the best place to look for them is in the moon's polar regions, which are not yet well mapped geologically.

GLOBAL PATTERNS ON OTHER PLANETS

MELOSH, H.J.

Calculations of the kind we have done show that characteristic global fault systems form when a planet is either despun, reoriented, or distorted by tides. If such a fault system is recognized on a planet it provides evidence that the associated event occurred. Mercury shows reasonably clear evidence that it was despun. Mars may have been reoriented and the Moon tidally distorted, but the evidence of these events has not yet been fully examined. Computation of the expected patterns, however, helps planetary mappers to know what features to look for and where the critical places on a planet's surface are.



Tectonic pattern on a despun planet - Mercury.

FIG. 1. Schematic representation of the stresses and associated faulting in the three tectonic provinces which can occur on a despun planet. These stresses are a consequence of the relaxation of the planet's equatorial bulge. The rows of small circles in the strike-slip and normal faulting provinces indicate alignments of volcanic craters and represent the fact that dike injection proceeds perpendicular to the least principal axis. Vertical dikes controlled by the global stress pattern should thus strike east and west.

from: H. J. Melosh, 1977, Global tectonics of a despun planet. Icarus 31, 221-243.

GLOBAL PATTERNS ON OTHER PLANETS

MELOSH, H. J.

FIG 2. TECTONIC PATTERNS ON A REORIENTED PLANET — MARS?

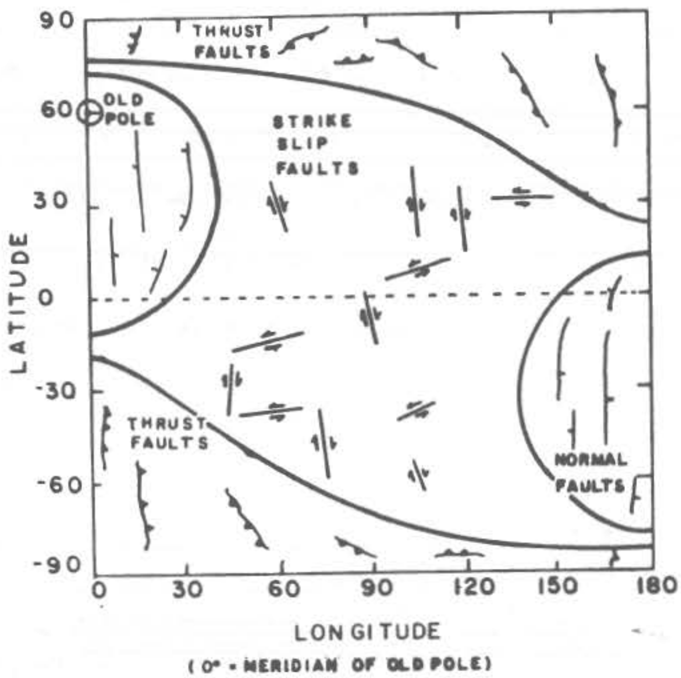
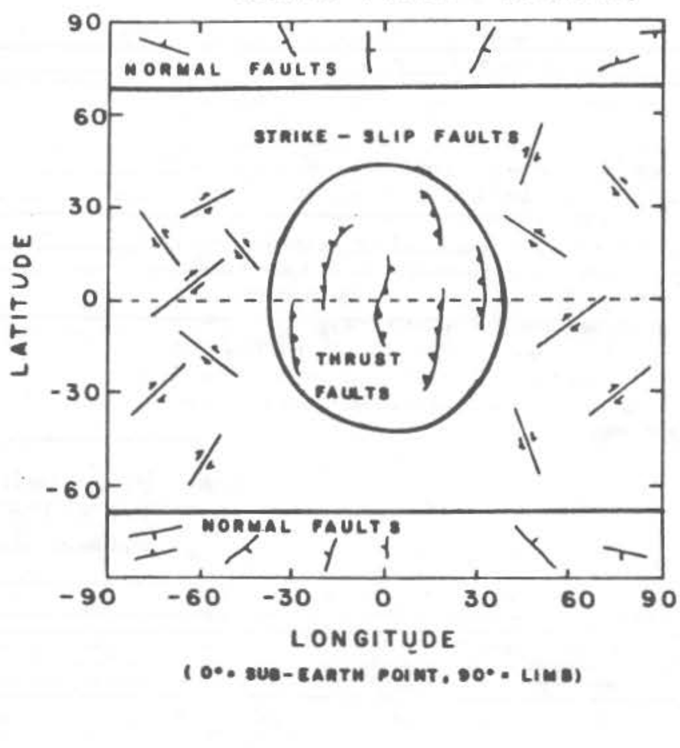


FIG 3. TECTONIC PATTERN ON A TIDALLY RELAXED PLANET — THE MOON?



SHALLOW MOONQUAKES: ARE THEY COMPARABLE TO EARTHQUAKES?

Yosio Nakamura, The University of Texas, Marine Science Institute, Galveston Geophysics Laboratory, Galveston, Texas 77550

We people living on the earth occasionally experience a trembling of ground called an earthquake. Some earthquakes are so energetic and damaging that they cause great concern, especially to people who live in areas where they occur often. The existence of earthquakes also shows us that the earth is an active planet undergoing profound changes.

If the earth has earthquakes, do the planets have planetquakes, and the moon, moonquakes? If so, are these quakes like earthquakes? By comparing quakes on various planets, we could then widen our understanding of the evolution of our solar system. At the same time, we might gain valuable insight into the cause of earthquakes.

The moon, indeed, has moonquakes. In fact, three different types of moonquakes have been discovered (Fig. 1).

The most numerous - about 2000 per year - are deep moonquakes. They are very small, and occur at depths nearly halfway to the center of the moon. They are caused primarily by tidal force - the force exerted on the moon by the changing gravitational pull of the earth.

The next most abundant - about 300 per year - are moonquakes caused by impacts of meteoroids - countless small solid bodies in the solar system which would become meteors if they entered the earth's atmosphere. All meteoroids that are in a collision course with the moon hit its surface without being slowed down or being burnt up because there is no atmosphere on the moon. Their impacts produce moonquakes.

The third type of moonquakes are the shallow moonquakes. They are the rarest - 4 to 5 per year - but the most energetic of the three types. They occur at depths generally shallower than about 100 km, and appear to be the only moonquakes that may be related to earthquakes in their origin.

On the earth, the overwhelming majority of earthquakes occur in such places as Japan, Alaska and the west coast of the United States, which lie along boundaries of so-called "plates". Only a small number of plates cover the entire surface of the earth. The plates move relative to each other, though very slowly at rates only a few centimeters each year. According to a theory called "plate tectonics", these slow movements are directly responsible for causing most earthquakes. In contrast, on the moon, there is no indication of present-day plate motion which might account for shallow moonquakes.

However, there are a few earthquakes that occur away from plate boundaries on the earth. Examples are earthquakes in the eastern seaboard and the central region of the United States. Some of these earthquakes can be quite large. These earthquakes are called intraplate earthquakes because they occur within lithospheric plates.

Strangely enough, the shallow moonquakes appear to be quite similar in several ways to these latter earthquakes:

(1) The occurrence of neither shallow moonquakes nor intraplate earthquakes is controlled by tides:

Unlike the deep moonquakes, the shallow moonquakes occur randomly in time. No clear correlation with the tidal cycle is observed. This is also true with earthquakes, including intraplate earthquakes. Scientists who have searched for evidence that tides trigger earthquakes have found little correlation between the occurrence of earthquakes and the tidal cycle.

(2) Both shallow moonquakes and intraplate earthquakes appear to occur

in locations where there are signs of structural weaknesses:

Intraplate earthquakes are found to be concentrated in certain zones where there are indications of weakness in lithospheric plates. The shallow moonquakes, as located by the Apollo seismometer network, appear to be correlated with ancient impact basins (Fig. 2). These basins are apparently zones of weakness due to scars of the impact processes.

Earthquakes also occur in old impact structures on the earth. For instance, a group of Canadian scientists found a series of St. Lawrence Valley earthquakes associated with an impact structure which was caused by a giant meteorite that fell some 300 to 400 million years ago. Most impact structures on the moon are older than three billion years.

Ancient impact structures on the moon are also the sites of anomalous electrical conductivity - differing resistance to conduction of electricity through the ground. Such anomalies are caused by differences in physical properties and possibly in temperatures between impact basins and surrounding areas. Association of intraplate earthquakes with anomalous distribution of electrical conductivity is also observed on the earth, for example in the middle of Australian continent.

(3) The relative abundances of small and large quakes are similar for shallow moonquakes and for intraplate earthquakes, suggesting that similar causes produce these quakes:

One way to describe a group of earthquakes is to compare the relative abundance of large and small earthquakes. The relationship is normally plotted as a graph showing the number (frequency) of observed earthquakes for given ranges of size (magnitude). Figure 3 shows this relationship for the shallow moonquakes. The relative abundance is usually expressed by the slope of such a curve, called its "b-value". The b-value is large if small earthquakes are relatively abundant, while it is small if large earthquakes are relatively abundant.

The b-value of the shallow moonquakes is about 0.5. In comparison, deep moonquakes give b-values generally larger than 1.5, while most earthquakes give b-values close to 1.0. The low b-value for the shallow moonquakes means that large moonquakes are proportionately more abundant than in normal earthquakes. Interestingly, low b-values of about 0.5 are also found for earthquakes occurring in continental interiors.

(4) The estimated levels of activity are nearly the same for shallow moonquakes and for intraplate earthquakes:

The level of shallow moonquake activity is not easy to estimate. When large quakes are proportionately abundant, most of the energy released by the entire group of quakes is attributable to the largest ones. The estimated Richter magnitude of the largest shallow moonquake we observed during the eight years of observation is 4.8. If this were the largest ever expected, the average energy release would be about 2×10^{17} ergs per year for the entire moon - nearly the same amount of energy released by exploding one thousand tons of TNT at 0.1% efficiency.

However, there is no reason to believe that we have actually observed the largest expected shallow moonquake in such a short time. Large moonquakes are expected to occur much less frequently than once every eight years.

Unfortunately, the presently available data are not sufficient to predict the magnitude of the largest expected shallow moonquakes. However, as an example, if we extrapolate the observed magnitude-frequency relation of Fig. 3 to Richter magnitude of 6.0, we will obtain an estimated average energy release of 5×10^{20} ergs per year for the whole moon. A shallow moonquake of such magnitude is expected to occur only once in 150 years.

This is still a very small fraction of the average annual energy release by all the earthquakes, which is estimated to be 10^{24} to 10^{25} ergs. Of this latter amount, intraplate earthquakes account for about 0.2%, or about 10^{22} ergs/year. If we take into account that the volume of the earth is about 50 times larger than that of the moon, and that the surface area of the earth is more than 13 times that of the moon, 5×10^{20} ergs/year for the whole moon is quite close to the energy release rate for intraplate earthquakes.

The largest expected shallow moonquakes may have magnitude even larger than 6.0 used in this example. Because of the thicker lithosphere in the moon than in the earth, much larger amounts of energy may be stored in the lunar lithosphere for infrequent release by rare, large moonquakes.

These comparisons all indicate that shallow moonquakes are quite similar to intraplate earthquakes. It is possible that they may be of similar origin.

There are some important implications of this observation.

First, for the moon: Even though shallow moonquakes appear to be associated with ancient impact basins, the estimated amount of energy released by them is far greater than expected from simple settling of original weight imbalance produced by impacts. The energy of shallow moonquakes, therefore, must be supplied by the heat released by cooling of the lunar interior.

Second, for the earth: Recently, there has been increased interest in interpreting intraplate seismicity in terms of plate tectonics. To the contrary, the moonquakes have shown us that it is possible for a significant number of quakes to occur without apparent plate movement. The lunar data thus suggest that the plate tectonic interpretation of intraplate seismicity may not be a valid one.

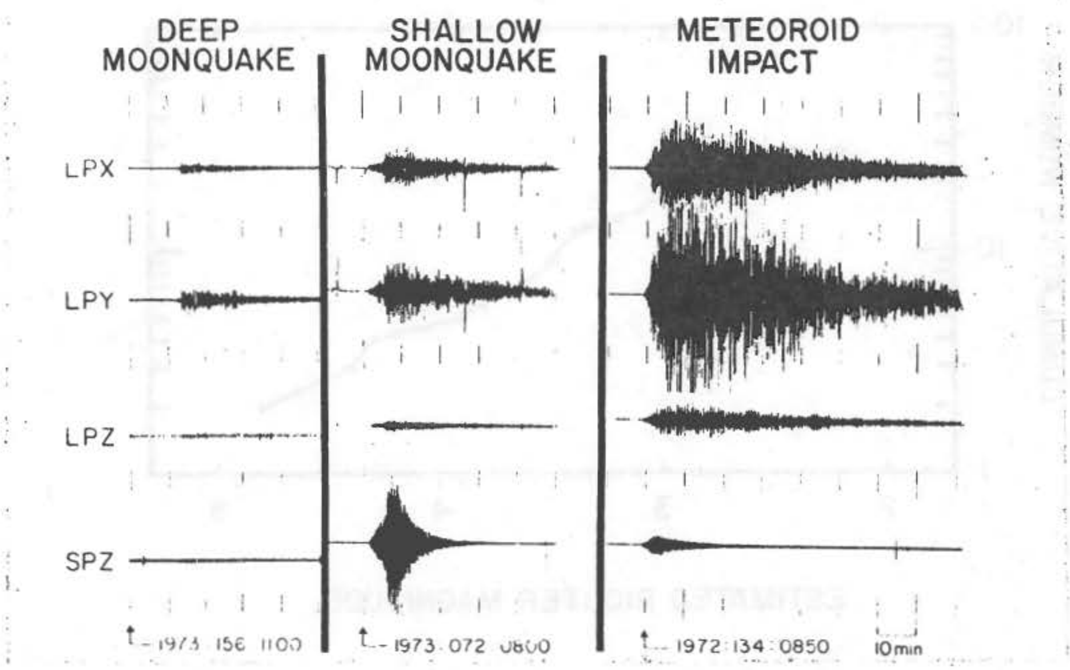


Fig. 1. Seismograms of a deep moonquake, a shallow moonquake and a meteoroid impact.

SHALLOW MOONQUAKES

Nakamura, Y.

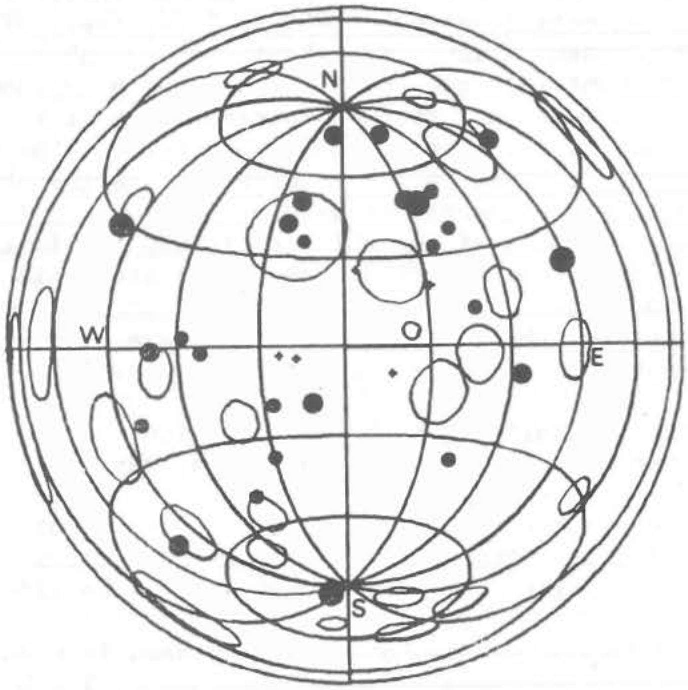


Fig. 2. Shallow moonquake epicenters and impact basins. The base map is the entire surface of the moon in an equal area projection.

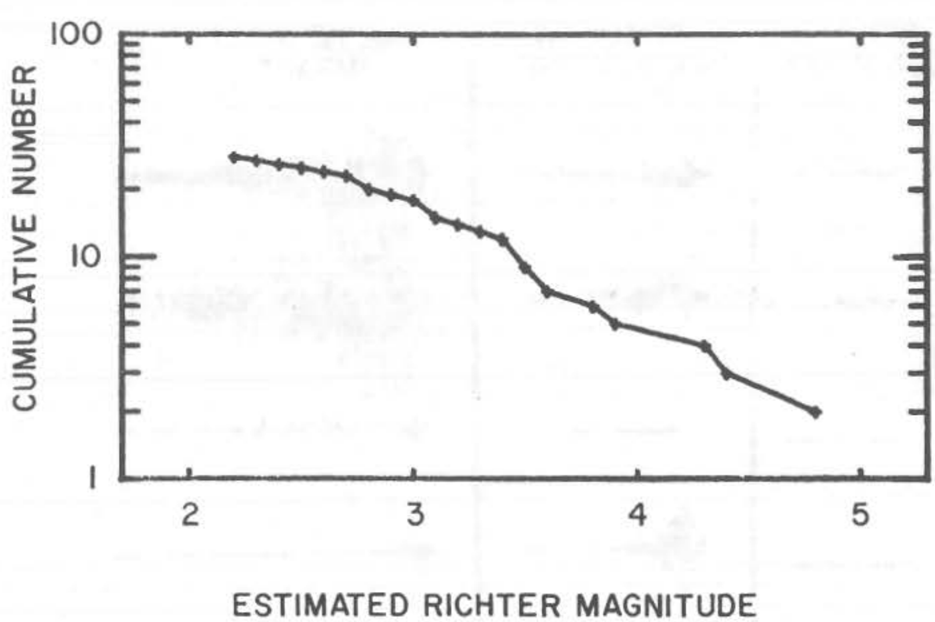


Fig. 3. Magnitude-frequency distribution of observed shallow moonquakes.

PERIODICITY IN IO'S ATMOSPHERIC MASS: EVIDENCE FROM POST-ECLIPSE BRIGHTNESS.

D. B. Nash and D. L. Matson, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91103.

Voyager 1 and 2 may have flown past the Jovian satellite Io during a period when its active volcanism was at a low period, according to scientists at the Jet Propulsion Laboratory.

Geologist Douglas B. Nash says ground-based observations lead him and his colleague Dennis Matson to believe there is a major change in the amount of atmosphere on this satellite of Jupiter, and the best way to explain it is that the overall volcanic activity on Io turns on and off in some regular way.

Astronomers over the past 18 years have noted a "post-eclipse brightening" on Io: When the satellite comes out from behind Jupiter — after having been in the planet's shadow — it occasionally seems to be brighter than it is a short time later.

But other observers looking at Io at other times cannot see or measure the changes in brightness. This led to considerable controversy and suggestions that the so-called brightenings may have been only erroneous observations.

"We found that the observed post-eclipse brightenings appear to occur at regular intervals of about two years," Nash says. "Then they seem to go away.

"If the observations and our assumptions about them are correct, it would appear that both the Voyager 1 and 2 spacecraft passed Jupiter and Io when volcanic activity was at a low point," Nash says.

Nash and his colleagues performed laboratory analysis of sulfur dioxide, the material found by Voyager experiments to be coming from the volcanoes of Io. They found that sulfur dioxide frost can explain the post-eclipse brightenings quite adequately. It has the correct optical properties (color contrast with Io's surface) and physical properties (it condenses and evaporates at the temperatures and pressures known to exist on Io's surface).

They then examined the idea that variations in post-eclipse brightening implies variations in abundance of sulfur dioxide in Io's atmosphere.

That means Io's surface environment is not in a steady-state equilibrium, but is highly variable.

Voyager 1 flew past Jupiter (and Io) on March 5, 1979. Shortly afterward, scientists at Jet Propulsion Laboratory, where the Voyager project is managed and controlled, discovered at least eight currently erupting volcanoes on the satellite.

Voyager 2 flew through the Jovian system on July 9, 1979, and found that the largest of Io's eight volcanoes had stopped erupting.

PERIODICITY IN IO'S ATMOSPHERIC MASS:

D. B. Nash and D. L. Matson

Nash is not certain yet just what causes the changes in Io's volcanic activity, but he and his colleagues believe there could be several possible answers.

"It could be due to undiscovered resonances in the gravitational interaction between Io and other satellites of Jupiter," he says; "tidal stresses in the crust of Io could periodically cause global fracturing and release of stored up gas."

Nash and Matson predict that the spring and summer of 1980 will be a gassy period on Io and a good time for earthbound astronomers to search for post-eclipse brightening of the satellite.

Nash presented the results of the research at the 11th Annual Lunar and Planetary Science Conference in Houston, Texas.

CRYSTALLIZATION SEQUENCE OF THE LUNAR MAGMA OCEAN: CLUES FROM TRACE ELEMENTS. Marc D. Norman, Northrop Services Inc., Lunar Curatorial Labs, P.O. Box 34416, Houston Tx 77571.

A few thousand years after the solar system formed from the dust and gas of the cosmic nebula, temperatures on the Moon became hot enough to melt rock. Great pools and seas of lava began to form, eventually covering the entire surface of the Moon with an ocean of magma (molten rock). Later, as the Moon cooled, minerals crystallized from this "magma ocean" much as rock candy crystallizes from a hot sugar solution. The heavier minerals-those containing mostly the elements iron and magnesium combined with silicon-sank forming the lunar "mantle" (FIGURE 1). The lighter minerals-those containing more aluminum and calcium combined with silicon-floated forming the rocks of the lunar "crust" (Figure 1).

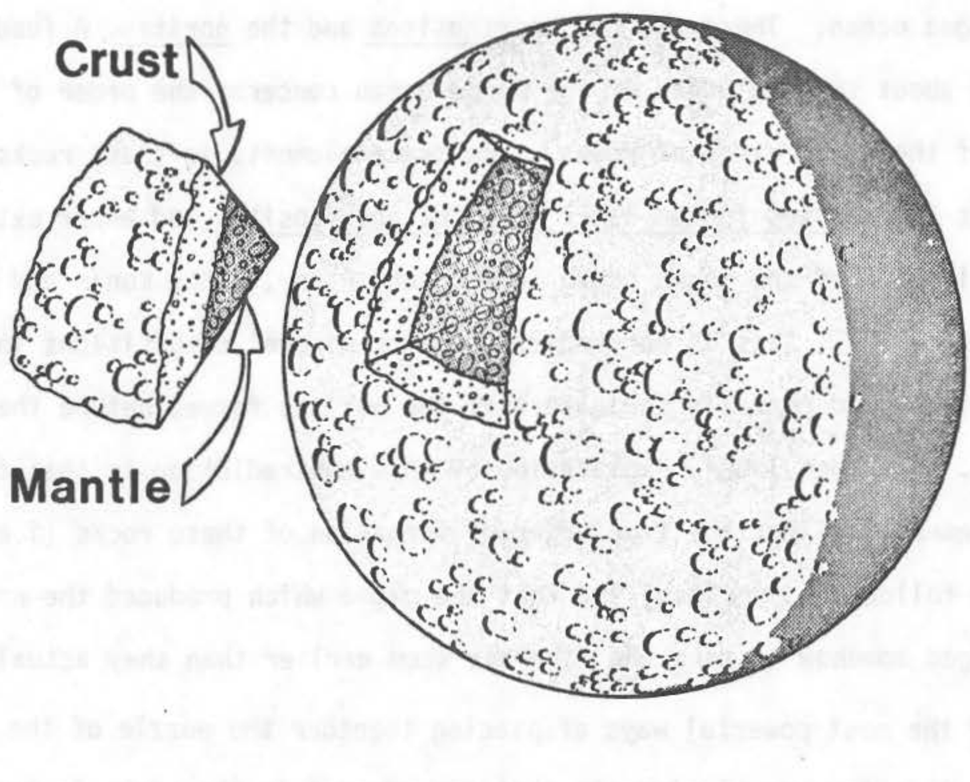


Figure 1. Cross section sketch of the Moon's crust and mantle. The crust is about 100 km thick.

CRYSTALLIZATION SEQUENCE

Marc D. Norman

Ever since the Apollo astronauts brought back samples of Moon rock, lunar scientists have been trying to figure out exactly how the Moon's crust was made. This has not been easy because the rocks are very difficult to study. Most of them are mixtures formed over the ages by many asteroids and large meteorites crashing into the Moon. Because rocks formed by this continuing bombardment are mixtures of other, pre-existing rocks, they cannot directly tell us anything about the original lunar crust. Recently, though, a few rocks have been recognized which probably actually represent pieces of the original lunar crust formed by the "magma ocean". These rocks are being intensely studied by many lunar scientists using a variety of techniques, for if we can understand the Moon's crust, we might also be able to understand the even more complex crust of the Earth.

Two kinds of rocks from the Moon's crust probably crystallized from the lunar magma ocean. These are the <u>anorthosites</u> and the <u>norites</u>. A fundamental question about the evolution of the magma ocean concerns the order of formation of these two kinds of rocks. The trace elements in these rocks indicate that the <u>norites formed later than the anorthosites</u> and after extensive crystallization of the magma ocean (Norman and Ryder, 1980, Lunar and Planetary Science XI). This is contradicted by the mineral compositions in these rocks which would normally indicate that the norites formed before the anorthosites. The most likely explanation of this contradiction is that the trace elements reflect the true order of formation of these rocks (i.e. anorthosites followed by norites) and that the magma which produced the norites was changed somehow to make the minerals seem earlier than they actually were.

One of the most powerful ways of piecing together the puzzle of the ancient lunar crust is to measure elements that are present in the rocks in trace (very small) amounts, usually less than 0.1%. Every rock from the Moon's crust that has been analyzed so far has had some trace elements in it, but because the minerals which make up the rocks cannot accept these elements into their crystal structure, the amounts of these elements in the rocks are very small.

There are,however, certain trace elements which are especially important because they are removed from a magma only by specific minerals. Many of these minerals are not common in the lunar crust but are believed to have crystallized from the magma ocean in large amounts.By using the right trace elements the effects of these minerals can be determined.

By looking at several trace elements, some of which go into certain minerals and some of which do not go into any minerals well at all, the evolution of the magma ocean can hopefully be understood. Titanium (Ti), scandium (Sc) and samarium (Sm) are three trace elements in particular that reveal some fundamental information about the rocks of the lunar crust.

Titanium is only removed from a magma in large amounts by the ore mineral ilmenite.When ilmenite crystallizes it reduces the amount of titanium left in the magma. Other minerals which crystallize after ilmenite will have less Ti in them because there is less in the magma.Ilmenite also contains a large amount of iron and will sink out of the magma ocean.

Scandium is selectively taken up by the iron-magnesium mineral pyroxene. Pyroxene will also settle out of the magma ocean,reducing the amount of scandium that is left for later minerals.Both ilmenite and pyroxene probably crystallized from the magma ocean in large amounts but at different times.The fact that both of these minerals are heavy and will sink to the bottom of the magma ocean explains why there is so little Ti and Sc in the lunar crust.

Samarium is one of a number of trace elements that are not removed from a magma in large amounts by any major mineral. As minerals do crystallize, the amount of liquid magma becomes smaller, and the relative concentration of Sm in the magma becomes progressively larger, just as water becomes saltier when ice crystallizes from it.

Normally these three elements-Ti, Sc and Sm-behave very similarly in nature and it is hard for a magma to separate them from one another unless either ilmenite or pyroxene crystallizes.

Since the absolute amounts of Ti, Sc and Sm in a rock can vary for a number of different reasons, it is often more useful to look at the relative abundances of the trace elements. That is, the ratios of Ti to Sm (Ti/Sm) and Sc to Sm (Sc/Sm) can be used to get a clearer picture of the effects of ilmenite and pyroxene crystallization from the magma ocean. For example, rocks formed after ilmenite has begun crystallizing will have a lower Ti/Sm ratio than rocks formed before the appearance of ilmenite because ilmenite removes Ti from the magma but does not take out Sm.

The anorthosites (rocks composed of only the aluminum-rich mineral plagioclase) and the norites (rocks with roughly half plagioclase and half pyroxene) probably crystallized from the magma ocean.These rocks are not mixtures of other rocks and their trace elements are believed to reflect the conditions at that time of their formation. These two types of rocks have been known about for some time but recent examination of their Ti/Sm and Sc/Sm ratios revealed new information about how the lunar crust was formed.

The anorthosites have mineral compositions which seem to indicate that they crystallized very late in the history of the magma ocean. Yet their Ti/Sm ratio is very similar to the ratio that we suspect the magma ocean started with. Since Ti had not been removed from the magma ocean when these rocks formed,they must have existed before ilmenite had started to crystallize.The Sc/Sm ratio of the anorthosites is somewhat lower than what the magma ocean started with, so we can conclude that some pyroxene had already crystallized and sank before the anorthosites were formed.

CRYSTALLIZATION SEQUENCE

Marc D. Norman

The norites have mineral compositions which seem to indicate that they crystallized before the anorthosites. If this were true, the Ti/Sm ratios of the norites should be the same as those of the anorthosites.The Sc/Sm ratios of the norites should also be as high or higher than those of the anorthosites. Surprisingly, the Ti/Sm and Sc/Sm ratios of the norites turn out to be lower than the ratios of the anorthosites,suggesting that both ilmenite and pyroxene had settled out of the magma before the norites but after the anorthosites were formed. This leads to a striking contradiction. The rocks whose minerals suggest they crystallized first (the norites) show trace element ratios that have been affected by large amounts of both ilmenite and pyroxene crystallization. Yet the anorthosites, with minerals that would normally indicate formation after the norites have trace element ratios that have not been affected by ilmenite and only slightly affected by pyroxene.

The apparent contradiction between the mineral compositions and the trace element ratios points to a major lack of understanding of how the magma ocean operated during the early history of the Moon. The best guess to explain this contradiction is that the trace element ratios accurately reflect the order of formation of the two sets of rocks; that is the norites really did crystallize later and after extensive ilmenite and pyroxene crystallization.If this is true then the magma which produced the norites must have been modified,making the minerals seem earlier than they actually were

A major goal of lunar science has always been to seek out the hard questions and find ways of answering them. When the riddle of the two sets of rocks from the Moon's crust has finally been solved, mankind's understanding of his Earth and the solar system will be greatly improved.

COMETARY IMPACT CALCULATIONS: FLAT FLOORS, MULTIRINGS AND CENTRAL PEAKS, John D. O'Keefe and Thomas J. Ahrens, Seismological Laboratory, California Institute of Technology, Pasadena, California 91125.

We have carried out a series of computer calculations which are meant to describe in detail what happens when a cometary nucleus collides with a planetary surface at speeds up to 45 km per second or approximately 100,000 miles per hour. The collisions of cometary nuclei with the surface of the earth and the other planets and the craters which result have been the subject of much speculation in this century particularly since the time of the Tunguska explosion of June 30, 1908 in central Siberia. At that time intense shock waves in the atmosphere were recorded, worldwide, from what was apparently produced by an energy source explosion comparable to that of several hundred megatons of TNT. Data gathered since that time demonstrate that the Tunguska explosion demolished a pine forest over an area in the order of 2,000 km^2 and yet produced virtually no crater or left much physical evidence except for a few scattered magnetite and silicate spherules of presumed extra terrestrial origin which were discovered only 20 years ago. Although other, more exotic, explanations for the Tunguska explosion have been proposed, the lack of a well defined meteorite crater and the spherule discoveries appear consistent with our calculations for cometary impact in which we assume a comet nucleus is like a dusty snowball. This is a model astronomers have developed based on observations of the very luminous tails, millions of kilometers long, developed by comets as they approach the sun and lose their frosty covering. Comets apparently form at the very outer reaches of the solar system. Virtually all new comets, as they come into the solar system, provide a dazzling display arising from the boiling away of their ices and occasionally breakup into several pieces and then again depart the solar system on very nearly parabolic orbits; some, like Halley's comet, become trapped in an orbit around the sun and eventually, because of the gravitational perturbations of the planets, are swept up and impact the earth and/or other planets at speeds ranging from 5 to 72 kilometers per second. In contrast to the Tunguska explosion site, most meteorite impact craters show relatively deep penetration and in many cases shattering and melting of the target rock. Analysis of the shattered rubble (breccia) found within and surrounding the crater often yields meteorite fragments. In some cases where shock melted rock occurs, chemical analysis indicates an anomalous enrichment in a characteristic meteoritical elemental assemblage such as nickel, iridium, silver and gold. In the case of exceptionally shallow craters, where little evidence for penetration of a meteorite or geochemical traces of a meteorite can be found, impact of a icy cometary nucleus, has also been suggested. Thus comets are the "disappearing" bullets of planetary surfaces!

Solid ice cometary nuclei may represent material which has been in periodic orbit about the sun and hence in time, has lost its exterior of presumably porous ice. Our results for the impact of solid ice impactors on a rocky planetary surface demonstrate that over the range of impact speeds appropriate produce ordinary bowl-shaped craters (Fig. 1), similar to those obtained in calculations in which a silicate meteorite impacts a silicate planetary surface (Fig. 2). In contrast, new comets, which we model as having a mean density of between one-tenth and one-hundredth that of solid ice, essentially snowballs, upon impacting silicate planetary surfaces are completely vaporized. Surprisingly the one-tenth normal density projectile produce shallow craters whereas the one-hundredth density projectiles do not produce a real crater, instead a broad flat-floor depression results which has circular rings and in some cases, depending on the strength of the rock assumed in the calculation results in a central peak (Figs. 3 and 4). In the case of a porous ice cometary projectile, the ice does not penetrate into the planetary surface to any degree and instead, the shockwave that is induced upon impact of the snowball (comet) vaporizes the ice. The escaping vapor cloud in attempting to expand in all directions exerts a relatively long duration pressure on the surface of the planet. We propose that the low density projectile, acting on the denser and more viscous planetary material gives rise to a Rayleigh-Taylor instability. Basically, the Rayleigh-Taylor instability phenomenon produces ripples at the interface between two fluids which sometimes results in the nearly uncontrolled interfingering of fluids. This occurs when a low density fluid (in this case, ice) attempts to accelerate downward a high density fluid (silicate planetary surface). This phenomena has not previously been considered by scientists studying impact processes and we believe many of the rippled surfaces of flat-floor craters which can also be produced by surface and above surface chemical explosive detonations may have a similar origin. In this, and other cases, the energy source for the central peak may also be the elastic rebound of the planetary surface.

The Rayleigh-Taylor instability may give rise to some of the ring structures seen in many of the larger craters on planetary surfaces which have been explored during the last decade. On the terrestrial planets, some of these large ancient multiring structures have diameters approaching 1000 km. These are seen on the ancient cratered terrane of Mercury (Caloris basin), on the backside of the moon in the form of the Orientale and Al-Khwarizmi basins, and recently a 1200 km diameter multiringed crater, named Gilgamesh, has been observed on the lunar-sized ice-covered satellite of Jupiter, Callisto, (Fig. 5).

We are currently in the process of carrying out computational studies of the effect of changing the planetary material properties such as viscosity and strength on the growth rate and wavelength of the Rayleigh-Taylor instabilities which may control crater ring structures.

COMETARY IMPACT

O'Keefe et al.

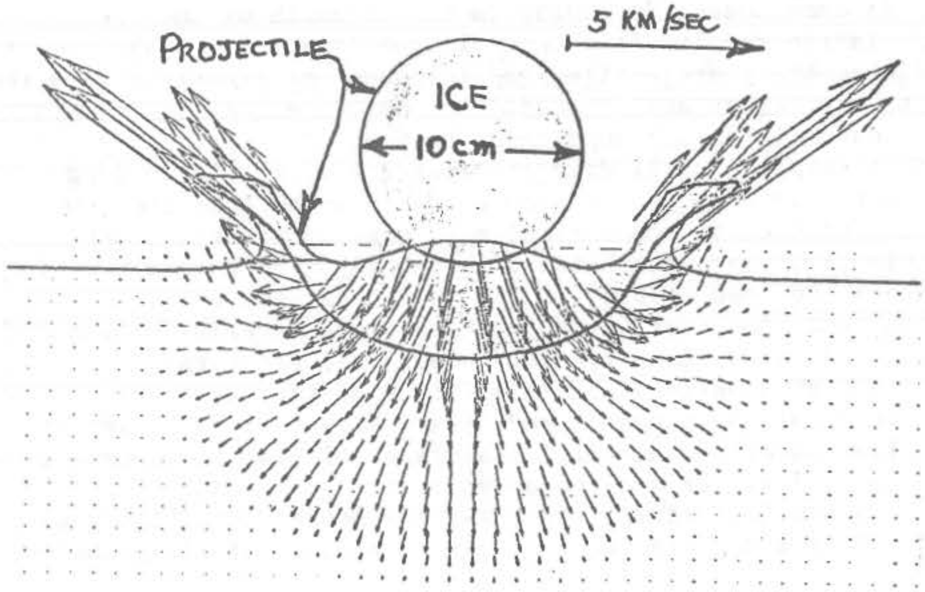


Fig. 1 Particle velocities calculated for different portions of the impact induced flow. The length of each vector is proportional to the velocity of the material at the position of its' tail. Both the original spherical and solid ice projectile and the calculated deformed projectile is shown after impact with a silicate rock. Model calculation was carried out for impact of a 10 cm diameter projectile at 5 kilometers per second. Flow shown occurs 23 microseconds after impact.

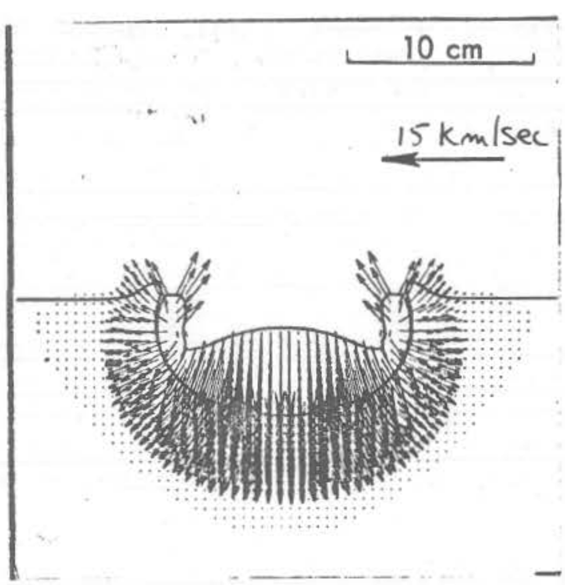


Fig. 2 Same as Fig. 1, except projectile is also a silicate rock, originally a 10 cm diameter sphere, which impacted at 15 kilometers per second. Flow field shown is 8 microseconds after impact.

COMETARY IMPACT

O'Keefe et al.

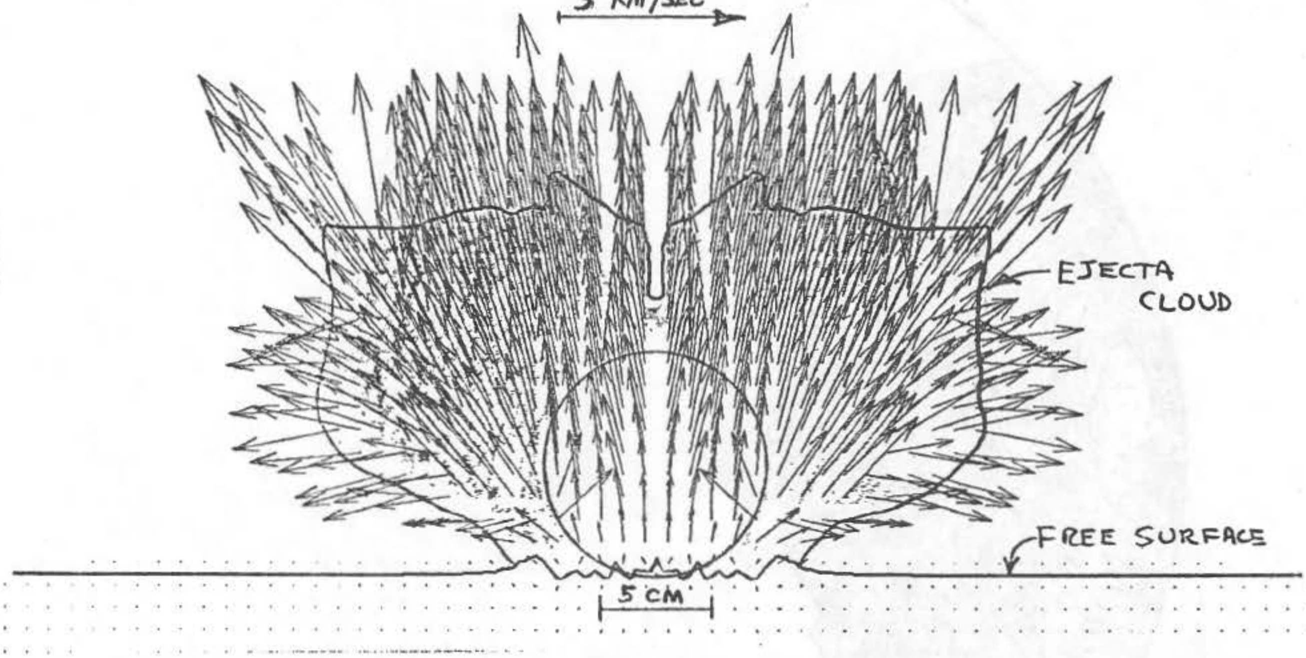


Fig. 3 Same as Fig. 1, except projectile is very porous (snowball) having one-hundredth the density of solid ice. Impact is also at 5 kilometers per second but the entire projectile has vaporized. Note lack of a real crater and ridges in affected planetary surface. Flow field show occurs at 50 microseconds after impact.

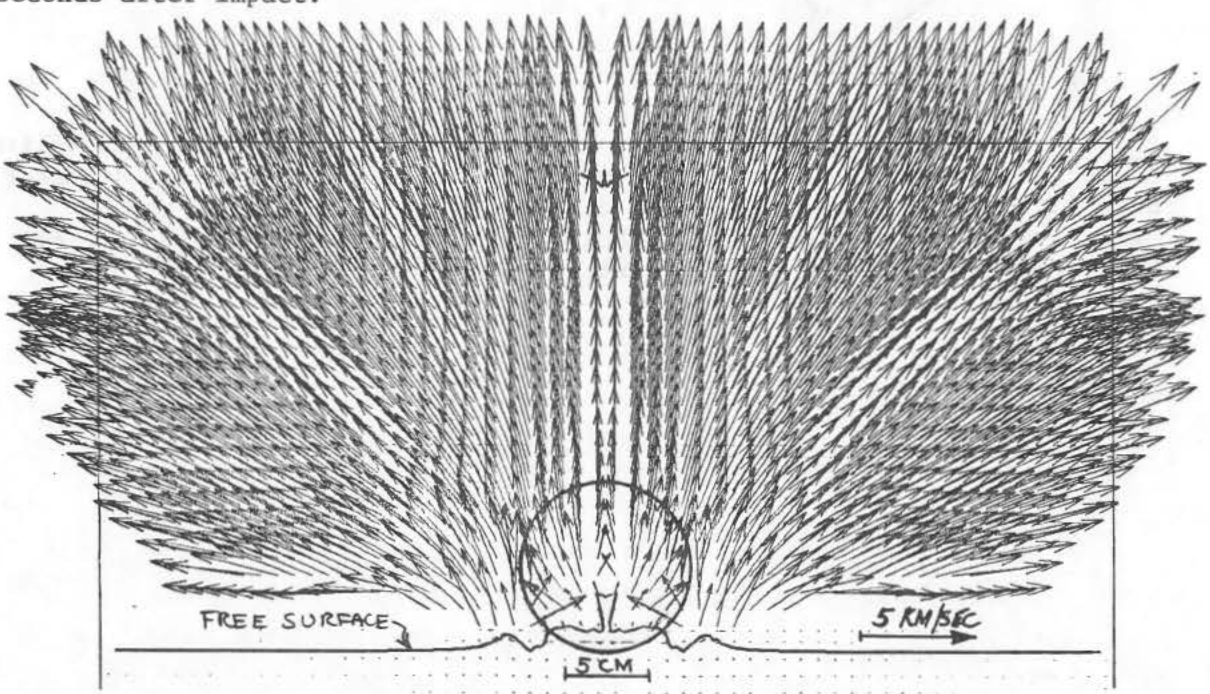


Fig. 4 Same as Fig. 3, except projectile impact occurs at 15 kilometers per second and the flow field, in which the vaporized projectile is moving faster than in Fig. 3 is shown 34 microseconds after impact. Note formation of central peak at projectile-planetary surface interface.

Fig. 5 Sketch of crater Gilgamesh, on the surface of Callisto, a satellite of Jupiter. The circular ridges around the crater have a maximum diameter of about 1,200 km. Callisto has a diameter about 40% greater than the earth's moon and its' exterior is believed to be largely composed of ice. (Taken from Voyager Imaging Team Initial Report)

TIDAL DISSIPATION, ORBITAL EVOLUTION AND THE NATURE OF SATURN'S INNER SATELLITES, S. J. Peale,* JILA, U. of Colo. & NBS, Boulder, CO 80309, P. Cassen and R. T. Reynolds, NASA-Ames, Moffett Field, CA 94035.

Because the gravitational field of a planet is not uniform across a satellite of finite size, the nominally spherical satellite is distorted by the field into an egg shape with the largest dimension aligned with the direction to the planet. This distortion is larger for larger planetary mass, smaller separation of planet and satellite and for larger satellites.

If the satellite rotates relative to the line joining the planet and satellite, different points on the satellite are sequentially toward and away from the planet. A point fixed on the equator of the satellite would then be raised and lowered relative to the center of the satellite twice each rotation period. The moon has a similar effect on the earth which we experience as the twice daily tide, which is most obvious in the oceans but also occurs on the land. Just as flexing a piece of metal makes it hot at the point of bending, the flexing of the solid satellite heats its interior. In the process of this heating the tidal bulge is carried in the direction of the relative rotation away from the direction toward the planet such that the long axis of the "egg" is no longer aligned with the direction toward the planet. But the gravitational field of the planet tries to pull the tidal bulge back into alignment and in the process slows the relative rotation of the satellite. This process continues until the satellite rotates relative to the stars with the same period as its orbital motion around the planet. It would thereby keep the same face toward planet at all times. The earth's moon has reached this state of "synchronous" rotation such that we see only one face. The satellites of both Jupiter and Saturn, except those which are very distant from their respective planets, have suffered the same fate as our moon and are rotating synchronously with their orbital motion.

If these satellites were in circular orbits, the tidal bulge would be fixed in the satellite, there would be no tidal flexing and therefore no heating. However, most satellites are in eccentric orbits where the distance to the planet varies and, because the orbital motion is not uniform whereas the rotation is uniform, the planet appears to move back and forth in the "sky" of the satellite by an angle which increases as the orbital eccentricity increases. This causes the tidal bulge to increase and decrease in size as the separation between the bodies varies and to move back and forth on the satellite as it follows the motion of the planet in the satellite's sky. So in an eccentric orbit tides again flex the satellite and heat the interior even though the rotation is synchronous with the average orbital motion.

Since Jupiter is so massive and its nearest large satellite Io is relatively close, tidal heating due to Io's orbital eccentricity has apparently been sufficient to melt the satellite almost entirely. However, Saturn's

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close satellite Mimas, although closer to Saturn than Io is to Jupiter and having an orbit five times more eccentric than Io's, has not been heated significantly by the tides. This is because Mimas is only about 1/10 the size of Io and is therefore distorted much less by Saturn's field than Io would be in the same position. The change in the gravitational field of the planet is much greater across the bigger diameter of the large Io and distorts that satellite much more than a similar field on Mimas. Saturn's mass is only about 1/3 that of Jupiter but this is more than compensated by Mimas' smaller orbit. So the reason for the much smaller tidal heating of Mimas is mainly its small size. Similarly, tidal heating of the remaining satellites of Saturn has also not been important. Titan, although very large and in an eccentric orbit, is too far away.

The energy which is deposited in a synchronously rotating satellite by tidal flexing due to orbit eccentricity must come from the energy of its orbital motion. This tends to decrease the average radius of the orbit but more importantly to reduce the orbital eccentricity. So the heating of such a satellite tends to destroy the eccentric orbital configuration which causes the heating in the first place. The large heating rate in Io would have reduced Io's orbital eccentricity to a very small value were it not for the existence of orbital resonances among the first three Galilean satellites where the orbital periods of Europa and Io and separately Ganymede and Europa are nearly in the ratio of 2:1. The orbital resonances are thus necessary to maintain Io's orbit eccentricity at a reasonable value in order to melt the satellite by tidal heating. Mimas is also in an orbital resonance with Tethys but of a different type which does not force the eccentricity to be maintained. Hence, the tidal heating in Mimas, although small, has still been decreasing the eccentricity of its orbit for essentially the entire age of the solar system, 4.6×10^9 years. The rate at which this eccentricity is reduced is proportional to the rate of tidal heating which in turn depends on the properties assumed for Mimas.

But the eccentricity of Mimas' orbit is about 0.02 which is the fractional increase in the separation from Saturn from the average separation when Mimas is at its maximum distance from Saturn. This eccentricity is reasonably large and represents the remnant from a primordial value which probably did not exceed 0.1. The rate of tidal heating depends on the fraction of the maximum elastic energy stored in the distorted planet which is converted to heat in each cycle of oscillation. The elastic energy is like that stored in a stretched spring which can be converted into energy of motion if the spring is released and ultimately into heat if the motion is stopped by friction. A less rigid satellite will be distorted more and store more energy for a given distorting gravitational field and hence there is the potential for more rapid tidal heating in the less rigid satellite.

Water ice and ices of some other compounds are stable at Saturn's distance from the sun, so it is possible that Saturn's satellites are made mostly of ice rather than rock-like materials as in our own moon. Ice is much less rigid than rock, so an ice-like Mimas would heat considerably faster than a rock-like Mimas if the fraction of stored energy converted to heat in each cycle of oscillation were the same for each case. The time required for Mimas' orbit eccentricity to reach about 1/3 of its initial value is about 3×10^8 years if the rigidity of ice is assumed and a fraction of stored energy lost in each cycle was like that in the earth. But since the reduction has been going on for 4.6×10^9 years, we would expect to see Mimas' eccentricity much smaller than the current value of 0.02. Only if the fraction of stored elastic energy converted to heat in each cycle were much smaller than that in the earth could the present orbital eccentricity of an ice-like Mimas have survived the tidal damping over 4.6×10^9 years. It seems unlikely that ice could heat so little as it is flexed. A rock-like Mimas with its higher rigidity would store less maximum tidal energy so heating properties like those in the earth are entirely compatible with the currently observed eccentricity.

So it appears that even though tidal heating has not altered the interior temperatures of any of Saturn's satellites significantly, it places constraints on the evolution of the orbital eccentricity of Mimas that favor a rocky structure for that satellite and by association for the other nearby satellites rather than one dominated by ices. Of course these calculations do not exclude the possibility that any rock-like inner satellites could still have substantial layers of ice on the surface.

FORMATION OF BOWL-SHAPED CRATERS. Andrew J. Piekutowski, University of Dayton Research Institute, 300 College Park Avenue, Dayton OH 45469.

Man has long made the heavens above him an object of his observation and wonderment. Ever since Galileo first looked at the moon and inner planets with his telescope more than 350 years ago, earthbound man has observed and studied the surface features of these heavenly bodies. In recent years, manned and unmanned exploration of the moon and the planetary exploration missions of the Viking, Pioneer, and Voyager spacecraft have greatly increased his exposure to that very small part of the universe around him. Photographs obtained during these missions have shown,in greater and greater detail, the surfaces of the moon, Mercury, Venus, Mars and its moons Phobos and Deimos, and the moons of Jupiter and Saturn. In these photographs there has been a surface feature common to all these bodies. This feature is a circular depression we call a crater.

The origin of these circular depressions or craters has been a topic for discussion and study ever since these features were first observed. Some of the craters were clearly volcanic in their origin. Within the last 25 years or so, experimental investigations and studies have lead scientists to believe, and argue rather convincingly, that most craters were produced by the collision of meteoroids, asteroids, or other cosmic bodies with the planetary and lunar surfaces. At the same time, theories were developed and used to explain ways in which the planets and other bodies in our solar system began to form approximately 4 1/2 billion years ago. Through a process called accretion, larger bodies in the solar system grew by capturing the smaller bodies which collided with them until eventually the larger bodies became the planets and moons we observe today. Fortunately for Earth's inhabitants, the rate of accretion and crater producing collisions has reduced dramatically. The accretion process is still going on today and its effects are most commonly observed when the ashes of small meteoroids or shooting stars fall to Earth after their fiery entry into our atmosphere.

Numerous and violent collisions of large bodies with Earth have occurred at irregular intervals within the last several hundred million years, however. At least 33 meteorite impact sites have been confirmed in the United States and Canada with numerous other probable impact sites being identified in both countries. Impact sites have also been identified in similar numbers on Earth's other land masses. Processes of erosion and land building have severely altered or destroyed the records (craters) of most terrestial impact sites. Consequently, craters are generally not usually an easily recognized feature of the Earth's surface.

Although the effects of erosional processes have been observed on other planetary surfaces, craters left by impacting bodies are quite often the most dominant features of these surfaces. Numerous studies have been performed in which these craters have been counted, their depths and diameters measured, their approximate ages determined, and their characteristic features cataloged. Results of these studies and companion experimental studies has shown that the study of the form, or morphology, of craters can reveal much about the nature of the surface which was impacted and the size and energy of the impacting body and, in effect, add to our knowledge of the planet or moon being examined.

Craters have been separated into classes according to the various features they exhibit, both within the crater and in the region surrounding the crater. Results of these classifications show that the simplest class and largest number of impact craters are bowl-shaped craters. It is not hard to understand, then, why the word crater, first used centuries ago, was derived from the Greek word for cup or bowl.

A number of investigators have developed models which are used in attempts to describe the very complex processes associated with the formation of impact craters. Other investigators have developed models which are used to describe how craters might grow and how material thrown out of the crater (called ejecta) might be deposited around the crater. As yet, however, there have not been any models for the crater formation process which would permit a detailed and quantitative description of the dynamic processes which occur during the formation of even the simplest class of crater--the bowl-shaped crater.

Recent experiments at the University of Dayton Research Institute have made use of an experimental technique which permits the various processes associated with crater formation to be photographed using high-speed movie cameras. In these experiments, small high-explosive charges are detonated in a special test container filled with a cratering medium, usually a clean sand. Although the crater formation process initiated by the impact of a meteoroid or other body traveling at speeds of up to 70,000 or 80,000 miles per hour is not identical with that initiated by the detonation of a high explosive, the processes are similar in terms of the crater structural forms (morphologies) and deformations. From the standpoint of cost and technical feasibility, further study of the mechanics of formation of various lunar and planetary structures must continue to rely heavily on information and results obtained from small-scale impact and explosion cratering experiments.

In the experiments currently being performed at UDRI, small high-explosive charges are being used in a special test container to form bowl-shaped craters in various materials, usually sands. one wall of the test container is constructed of a thick piece of clear plastic and serves as a window through which the crater formation process is observed. By using high-speed movie cameras and colored tracers in the cratered materials it is possible to record, on film, the entire crater formation process. Detailed study and analysis of the changing crater profile and the motions of the tracers located in and around the crater permits a picture of the crater formation process to be obtained. The crater formation sequence shown in Figure 1 is an example of the

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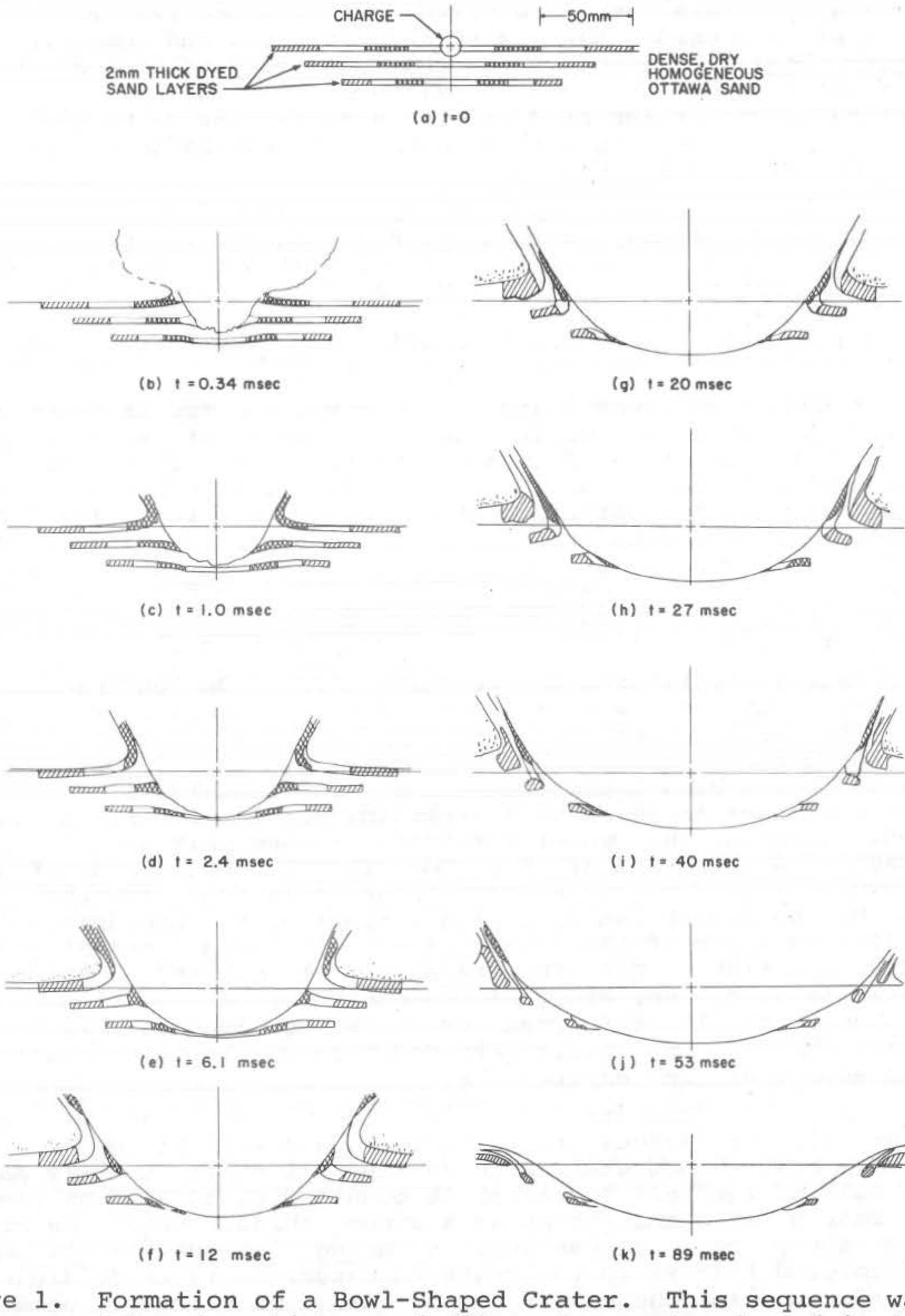

Figure 1. Formation of a Bowl-Shaped Crater. This sequence was taken from high-speed films of a crater formed in dry, densely-packed sand. The size of the crater and the location of dyed sand tracer layers are shown for various times after detonation of the explosive charge.

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kind of information which can be generated from these films. A number of other measurements related to the formation of bowl-shaped craters are also being made from films of similar experiments.

A description of the rate of growth of bowl-shaped craters formed in one of the cratering media is presented in Figure 2.

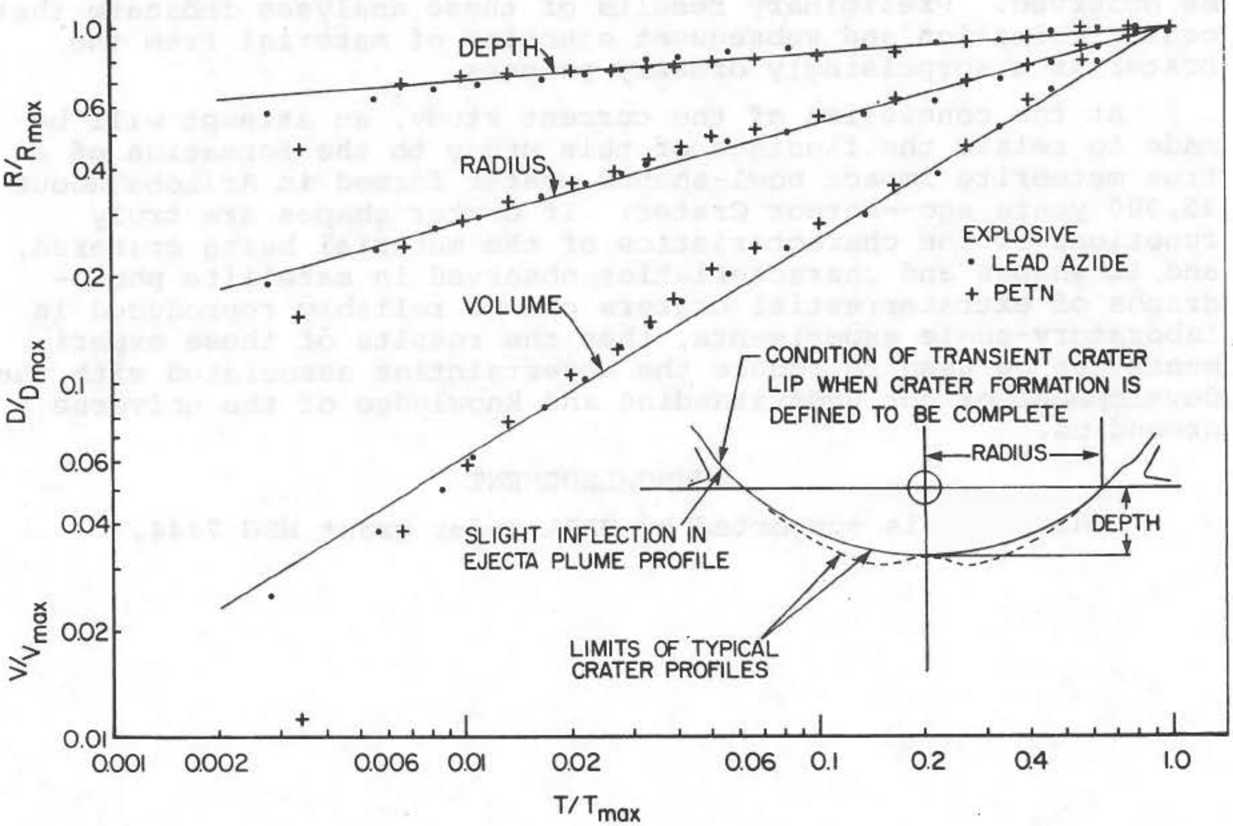

Figure 2. Rate of Growth of the Volume, Depth, and Radius of Bowl-Shaped Craters Produced by the Detonation of Small High-Explosive Charges in Ottawa Flint Shot.

In Figure 2, the ratio of instantaneous crater volume, depth, and radius to maximum crater volume, depth, and radius is plotted as a function of the ratio of the time after detonation to the time required to form the crater. Two explosive materials, lead azide and pentaerythritol tetranitrate (PETN), were used to produce the craters. Although both explosive charges yielded the same heat energy, the final volumes of the craters formed in identical media differed by a factor of 1.8. Data presented in Figure 2 indicate that processes which control the the shape of the crater are independent of the source which motivates formation of the crater but are very dependent on the properties of the material being cratered, since both craters grew in an identical fashion. Further work to verify this preliminary conclusion is being performed, using several sizes of explosive charges, depths of burst, and cratering media.

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Considerable detailed information about the motion of material in the region around the crater and changes in its physical properties is being obtained from analyses of the motions of a large number of individual colored sand grains placed in the test beds. These colored sand grains are placed in a grid pattern which extends from very near the explosive charge to those regions where little or no effect of the explosion is likely to be observed. Preliminary results of these analyses indicate that crater formation and subsequent ejection of material from the crater is a surprisingly orderly process.

At the conclusion of the current study, an attempt will be made to relate the findings of this study to the formation of a true meteorite impact bowl-shaped crater formed in Arizona about 25,000 years ago--Meteor Crater. If crater shapes are truly functions of the characteristics of the material being cratered, and if shapes and characteristics observed in satellite photographs of extraterrestial craters can be reliably reproduced in laboratory-scale experiments, then the results of these experiments can be used to reduce the uncertainties associated with the development of our understanding and knowledge of the universe around us.

ACKNOWLEDGMENT

This work is supported by NASA under grant NSG 7444.

CORE FORMATION DYNAMICS AND PRIMORDIAL PLANETARY DYNAMOS. D.J. Stevenson, Dept. Earth & Space Sciences, U.C.L.A., Los Angeles, CA 90024.

The Earth is known to have a partially liquid core made mostly of iron. The other Earth-like planets (Mercury, Venus and Mars) probably have iron cores also, and even the Moon may have a small iron core. The way in which these planets formed about 4.6 billion years ago is not yet well understood, but one view accepted by many scientists is that they formed nearly homogeneously as an approximately uniform mixture of iron (initially solid) and silicates (the minerals which make up most of the surface rocks on these planets). The puzzles my work seek to resolve are these: If these planets formed as a jumble of silicates and iron, how did they evolve to their present state of iron in the center and silicates on the outside? How quickly did this happen? What impact might this process have had on the chemical and physical evolution of the Earth-like planets and the Moon, the presence of magnetic fields in these bodies and perhaps even the formation of the Moon? My main conclusions are as follows. Formation of an iron core was rapid, in the Earth and Venus, and may have occured because of the "catastrophic" fracturing of a cold, rigid primordial central region. This probably happened whilst the planets were still growing by accretion (the incorporation of smaller bodies which hit the surface of the planet). Even at this stage, a large magnetic field would be generated within these planets by the dynamo process responsible for the present magnetic field of the Earth. On the surface of the growing Earth, this field might have been many times larger than the present field, perhaps large enough to have played an important role in the formation and early evolution of the Moon (if, as seems likely, the Moon formed in Earth orbit). The Moon could have also generated its own field as its small iron core formed slowly (because of smaller gravity). This might conceivably explain the enigmatic measurements of remnant magnetism in the Apollo moonrocks.

It needs to be stressed that the ideas expressed here are speculative in nature, since the available data are not yet sufficient to single out one of several competing theories. In what follows, I shall attempt to provide some insight into the considerations which led me to the above conclusions. The problems addressed here have been puzzled over for many years. One well known theory of core formation in the Earth proposed by Elsasser in 1963 runs as follows: during or after the formation of the Earth by accretion (a process which may have taken about ten million years), the temperature inside the Earth reaches the melting point of iron (which is lower than the melting point of the silicates). The liquid iron then accumulates into a global layer within the Earth by percolating through channels between silicate grains. Enormous blobs of iron, hundreds of kilometers across, can then spontaneously form and begin descending towards the center of the Earth. They descend because they are heavier than the surrounding silicates and because the hot silicate rock can deform and flow viscously. (This viscous behavior of silicate rock is an essential part of understanding present day plate tectonics on Earth and the way in which flows deep down can ultimately cause mountain building, earthquakes and continental drift at the Earth's surface). If the silicate rock of the primordial Earth could flow as readily as the same rock deep within the present Earth, then the iron core could have formed in only a thousand years. However, there is a difficulty with this theory: the innermost regions of the primordial Earth may have been cold and therefore unable to flow, since radioactive heating would have only just begun and since this material was incorporated when the Earth-to-be was much smaller. (At that stage, the Earth-to-be had less gravity and therefore had less heat generated by the accretion--less collisional heating). If this is the case, then the iron blobs proposed by Elsasser are much too large and sink much less rapidly than previously supposed. I estimate that the time for core formation by this method could be as long as one hundred million years (compared to previous estimates that are as short as one thousand years). Another theory, proposed in the Soviet Union by Vityazev in 1973 encounters similar difficulties.

Clearly, the mechanism of core formation which is quickest will be the one that "wins". My theory (many ideas for which were already in Elsasser's work or in the work by Tozer around 1965) runs as follows: already, when the Earth-to-be is only about the size of the present Mars, the energy released by accretion is sufficient to melt the iron in near surface regions. An iron layer forms, as in Elsasser's theory, but instead of giant "blobs" of iron forming, the entire "rigid" central, cold region of the Earth-to-be moves upwards (just as a piece of light material, such as wood, bobs to the surface of a newly thawed lake or pond, having previously been held under by the rigidity of the ice). The liquid iron is displaced downwards, but the planet becomes pear-shaped because the rigid, primordial region cannot smear itself out uniformly. Gravity abhors a non-spherical shape, however, and sufficiently large stresses are exerted on the rigid region such that it will fracture into numerous "rockbergs". These rockbergs, which may be around one hundred kilometers in size, contain both iron and silicate and float at the top of the newly forming liquid iron core. This can take place in a matter of hours and is thus "castastrophic" on a geologic timescale. Meanwhile, the planet continues to grow by accretion and add iron to the core. The rockbergs take a long time (tens of millions of years) to equilibrate with their surroundings because they are cold and must be heated by thermal conduction (a slow process). The rest of the Earth is convecting vigorously.

Even when the layer of iron first forms, it is being stirred with sufficient vigor that a magnetic field can be generated by the dynamo process. In this mechanism, the motion of a liquid metal in a magnetic field can, by the process of electromagnetic induction, amplify any existing field. A "seed" field is needed, but any stray or interplanetary field (even if it is much smaller than the present field of the Earth) is sufficient. The energy source for this amplification is ultimately gravitation. The stirring of the iron was much more vigorous then than it is now in the Earth's core, so the field could have been larger. It

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could have been large enough to have had an important dynamical effect on the partially-ionized gas and particulate cloud surrounding the still-accreting Earth. In 1960, Hoyle proposed that hydromagnetic torques could be responsible for transferring most of the Sun's angular momentum to the orbital angular momentum of the planets. Although this idea is not favored for the solar system as a whole by most scientists, it may work for the Earth-Moon system: the orbital motion of the newly-forming Moon could have been derived from the rotational motion of the Earth by means of magnetic coupling. A magnetic field of about ten gauss is required (the present Earth field is around one half of a gauss).

Once the Moon formed (perhaps within the magnetosphere of the Earth, thereby undergoing some of the processes Io is subjected to within the Jovian magnetosphere), it could also separate into iron and silicate components. However, the small gravity of the Moon is inadequate for rapid core formation. The iron layer initially forms below the magma ocean (from which the lunar highlands formed), then slowly sinks towards the center of the Moon. Even though this layer is initially only a few kilometers thick, dynamo generation may be possible, driven by the gravitational energy released as chunks of silicate float upwards. The remnant magnetism of lunar rocks has an uncertain origin but might be explainable by an internal field generated in this iron layer. As the layer sinks, the surface magnetic field decreases (because the surface is increasingly far from the electric currents responsible for the field); this is consistent with the observed trend in the Apollo moonrocks for the oldest rocks to have the largest remnant magnetism. When the iron reaches the center of the Moon, dynamo generation ceases (there is no more gravitational energy release possible) and the field turns off. This can explain the absence of a measurable global field for the present Moon. In recent years, Runcorn has strongly advocated an internal dynamo but has proposed hypothetical superheavy elements as an energy source. Recent measurements on meteorites suggest that the required amount of superheavy elements was not present in the early solar system. The scenario I propose does not require any "ad hoc" assumption such as superheavy elements.

Any scientific theory must be testable to be useful. How can the ideas described here be tested? On the Earth, most of the evidence concerning very early events has been obliterated. The oldest rocks ever found are only 3.8 billion years old and formed about 700 million years after the formation of the Earth. However, a number of people have analyzed lead isotopes, to establish when the core may have formed. The idea is that some of the Earth's lead will dissolve into the iron during core formation whereas uranium (the source of some lead isotopes because of natural radioactivity) does not. This analysis suggests that the core formed within about one hundred million years of Earth accretion. This is a rather weak test of the theory. Recent evidence from Australia (the work of McElhinny and Senanayake at Australian National University) shows that the Earth had a magnetic field at least 3.5 billion years ago, but this is also a rather weak test.

Perhaps the Moon will provide a better test, since it has preserved at least a partial record of the earliest events which

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took place. Future work will be aimed at quantifying the above speculations concerning the way in which the Moon formed (in particular, the role of a large magnetic field), the possibility that the surface of the Moon was heated by electrical currents (a process which has been suggested for the present Io), the possibility that the remnant magnetism of the lunar rocks can be explained by a sinking, vigorously stirred layer of iron, and even the possibility that the crustal asymmetry of the Moon (the fact that the far side of the Moon has a thicker crust than the near side) can be related to the upward displacement of the cold, primordial central region relative to the heavier, liquid iron layer above. The early Moon could have been slightly pear-shaped.

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