Lunar and Planetary Science X

Press Abstracts
Tenth Lunar and Planetary Science Conference
March 19-23, 1979
PRESS ABSTRACTS

TENTH LUNAR AND PLANETARY SCIENCE CONFERENCE

March 19-23, 1979

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LPI Contribution 363
PREFACE

The Program Committee for the Tenth 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 X*.

For assistance during the conference, call the NASA Johnson Space Center News Center at 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 X*):

- **Non-Destructive \(^{26}\text{Al} \) Measurements on Antarctic Meteorites**

- **Archean Ultramafic Pyroclastic Deposits: The Use of Lunar Deposits to Resolve Some Terrestrial Problems**
  G. Heiken, page 528.

- **Highland Basalts? Spectral Data for a Southern Highland Plains Unit**
  C. M. Pieters, page 981.

- **Chemical Similarity Between Irghizites and Javan Tektites**
  S. R. Taylor and S. M. McLennan, page 1219.

This abstract volume was prepared by P. C. Robertson, Technical Editor, Lunar and Planetary Institute.
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M. H. Thiemens and R. N. Clayton

Terrestrial Basalts Revisited: The Importance of Planet Size
D. Walker, E. M. Stolper and J. F. Hays

Has the interest and excitement we felt during the first manned space mission to our Moon become just a casual interest in trips to Mars, Jupiter, Venus, and Saturn? For the public, the thrill of these new space probes wears off quickly, but scientists inherit the most exciting benefits of all—evidence of how the planets in our solar system formed. No other planetary body has given us such a large collection of different kinds of scientific information to solve these mysteries than our satellite, the Moon. Thus, the Moon may no longer be the most fashionable body in the sky, but it is our greatest hope. Important new facts continue to be discovered about the chemical composition of the Moon even though it has been more than two years since the last Soviet mission and more than 5 years since the last American mission. Of particular interest are the dark volcanic materials which fill most of the lunar basins. These rocks tell us about the composition of the interior and the conditions (pressure and temperature) under which the material formed. The chemistry of the soil and rock samples returned from a few isolated landing sites in these areas gives a very incomplete picture of subsurface and surface composition. However, chemical measurements from orbit by the X-ray and gamma-ray experiments extend this information to broad areas of coverage by the Apollo 15 and 16 spacecrafts. This remote sensing data also puts sample data into context by showing the relative abundance of the different compositions identified in the returned lunar soil.

There is new evidence based on the X-ray data taken from orbit that all five of the basins for which we have data may contain extensive early magnesium-rich basalts. In most cases, however, this material is buried by less-magnesian basalts which later flowed over them. If this is so, the high-magnesium flows are plentiful—but not on the lunar surface. Therefore, our returned surface soil collection probably does not contain a representative sample of the volume of this buried material.

One way the X-ray experiment which "sees" only the surface may be used to determine what lies beneath the surface layer is to measure the chemical composition of material uncovered and thrown out of a crater formed by meteorite impact. Such a crater, 23 km in diameter, is found in the basalt fill of the Crisium basin, the basin where the Soviets landed their Luna-24 spacecraft. This crater, Picard, shows that higher magnesium material has been excavated from below low-magnesium surface basalts in this basin. High-magnesium material on "benches" along the edges of the volcanic fill in the basin is evidence that these earlier subsurface basalts extend across the whole basin. We interpret this to mean that the center of the basin sank to some extent beneath the load of the early high-Mg fill and was later covered by lower-magnesium basalts, leaving the remains of the earlier fill exposed along the edges. (High-magnesium basalts refer here to basalts with an MgO content greater than 11% by weight.)

Similar evidence indicates that the Fecunditatis basin may also
High-magnesium basalts on the Moon

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contain extensive early magnesium-rich basalts. Two impact craters in this basin have excavated from depth material with higher concentrations of magnesium than the surrounding surface basalts. High-Mg material is also visible at the basin borders.

High-magnesium basalts are exposed in the Serenitatis basin as well. However, in this case, the unit is located toward the center of the basin rather than the border areas. Thus, a different interpretation of the history of basin filling is necessary.

The Smythii basin is the only one which does not appear to contain any low-magnesium mare basalts on the surface. Scattered patches of mare basalts which failed to completely flood the floor of this basin are characterized by magnesium values comparable to the high-magnesium ejecta at the Picard crater in Mare Crisium. Could it be that the limited volcanism in the Smythii basin was arrested after the high-magnesium basalts were emplaced?

Our studies show that early lunar volcanism—at least in the eastern maria produced high-magnesium materials that are largely buried by later flows. Random samplings of the early basalts by cratering suggest that they are widely distributed beneath the surface basalts and may comprise a large proportion of the volume of mare material on the Moon. If this is so, early high-magnesium basalts are underrepresented in the lunar sample suite and, perhaps, in models for the origin and formation of these mare rocks.

Acknowledgments—This work was supported by NASA grant NGR-21002-368
AN EXPLOSION CRATER COMPARABLE TO METEOR CRATER, ARIZONA
(CALCULATIONAL COMPARISONS OF EXPLOSION AND IMPACT CRATERING USING BARRINGER CRATER AS A PROTOTYPE), J. B. Bryan, D. E. Burton, and L. A. Lettis, Jr., Lawrence Livermore Laboratory, Earth Sciences Division, Livermore, CA 94550.

What mechanisms were involved in the formation of the Barringer Crater in Arizona? Scientists have been seeking the answers to this and related questions, hoping to gain a better understanding of the formation of the nearly 90 impact craters identified on the Earth as well as craters observed on the Moon and other planetary bodies. Information about original impact conditions is important to improving our understanding of early planetary history and geological events leading to the present structure of our Earth. Little evidence remains of the actual mass and velocity of impacting projectiles which produced these craters. Physical evidence of the meteorite seldom survives the effects of the violent impact and subsequent weathering at those accessible sites on the Earth.

In contrast, craters produced by chemical or nuclear explosives have well-known energies and geometries. Researchers have estimated the mass and velocities of impacting projectiles based on the similarities between impact and explosive craters. In the last two decades sophisticated computer programs have been developed that model the dynamic behavior of geologic materials induced by the intense shock waves from chemical and nuclear explosions. Adequate initial information, including measured geological material properties, and the location and energy released by the explosive source, enable these computer programs to accurately predict the dimensions of the resultant crater. Extending these computational tools to the study of impact cratering can produce valuable information about original impact conditions.

We have previously reported\(^1,2\) a computer simulation of the impact of the Canyon Diablo Meteorite forming the Barringer Crater which is approximately a mile in diameter. Assumptions included the vertical impact at 15 kilometers per second (about 34000 miles per hour) of a 30 m x 30 m (about 100 feet) cylinder of iron weighing 1.7 x \(10^8\) kilograms (about 180,000 tons) on a limestone earth surface. This impact has an energy equivalent to approximately 4.5 megatons (Mt) or 4,500,000 tons of TNT. Our results, summarized in Table I, are quite similar to the estimated pre-erosion dimensions for the Barringer Crater (Table II). In this impact cratering study the energy appeared to radiate from a point approximately 86 meters (280 ft) below the original ground surface.

Recently, we have substantiated this estimated depth by calculating a 4.5 megaton explosion crater assuming an 86 m depth of burial. The computer model for the surrounding media remained unchanged. The resulting crater has nearly the same dimensions as the impact crater calculation (Table I). Final crater profiles for the calculated impact and explosion craters are displayed in Figure 1.

Our studies have demonstrated that computer programs developed for explosive cratering studies can be adapted to the study of impact cratering. We have shown that the Barringer Meteor Crater could have been formed by the impact of a meteorite weighing 180,000 tons moving at 34,000 miles an hour, with an equivalent explosive energy of 4.5 megatons. A crater very similar to the size of Barringer could be produced by burying a 4.5 megaton explosive at a depth of 280 feet.
EXPLOSION CRATER COMPARABLE TO METEOR CRATER
J. B. Bryan, et al.

TABLE I. A Comparison of Calculated Impact and Explosion Final Crater Dimensions for Barringer Crater

<table>
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<th>Explosion</th>
<th>Difference</th>
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<td>Apparent Crater Radius, $R_A$ (m)</td>
<td>505</td>
<td>505</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>Apparent Crater Depth, $D_A$ (m)</td>
<td>179</td>
<td>178</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>Apparent Crater Volume, $V_A$ ($m^3$)</td>
<td>68,500,000</td>
<td>67,200,000</td>
<td>- 2%</td>
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<tr>
<td>Crater Rim Radius, $R_{RIM}$ (m)</td>
<td>606</td>
<td>616</td>
<td>+ 2%</td>
</tr>
<tr>
<td>Apparent Lip Height, $H_{AL}$ (m)</td>
<td>69.2</td>
<td>74.4</td>
<td>+ 8%</td>
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<tr>
<td>Apparent Lip Crater Volume, $V_{AL}$ ($m^3$)</td>
<td>132,000,000</td>
<td>138,000,000</td>
<td>+ 5%</td>
</tr>
</tbody>
</table>

$^{a}$Crater dimensions were extrapolated at 0.5 seconds using a slope stability angle of 40° and no bulking.

$^{b}$Impact velocity of 15 km/s, meteorite mass of $1.67 \times 10^8$ kg and kinetic energy of $1.88 \times 10^{16}$ J (4.5 Mt).

$^{c}$This was an approximation of a 4.5 Mt nuclear explosion buried at 86.25 m in limestone.
EXPLORATION CRATER COMPARABLE TO METEOR CRATER
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TABLE II. Dimensions of Barringer Crater Based on Field Measurements

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<th>Initial (pre-erosion)</th>
<th>Present (post-erosion)</th>
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<tr>
<td>Apparent Crater Radius, ( R_A ) (m)</td>
<td>511</td>
<td>518</td>
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<td>Apparent Crater Depth, ( D_A ) (m)</td>
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<td>150</td>
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<tr>
<td>Apparent Crater Volume, ( V_A ) (m³)</td>
<td>75,000,000</td>
<td>75,000,000</td>
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<tr>
<td>Crater Rim Radius (m)</td>
<td>578</td>
<td>593</td>
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<tr>
<td>Apparent Lip Height, ( H_{AL} ) (m)</td>
<td>67.5 ± 5.0</td>
<td>47.5</td>
</tr>
<tr>
<td>Apparent Crater Volume, ( V_{AL} ) (m³)</td>
<td>140,000,000</td>
<td>125,000,000</td>
</tr>
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\(^a\) Values in this table were reported by D. J. Roddy\(^3\)

\(^b\) Estimated values after the impact which probably occurred 20,000 to 30,000 years ago.

\(^c\) Average values based on recent field measurements.
EXPLOSION CRATER COMPARABLE TO METEOR CRATER

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REFERENCES


"Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore Laboratory under contract number W-7405-ENG-48."

Of the four satellites of Jupiter discovered by Galileo, Io is the closest to Jupiter and is therefore the one subject to the strongest gravitational force. One effect of this gravitational force is to cause a slight elongation on Io's shape. The amount and orientation of the elongation changes as Io circles its parent planet, and therefore the satellite experiences a pattern of cyclic stress and strain. A small fraction of the power that is used in producing this distortion will be dissipated; i.e., converted to heat. The heat released in this manner could be enough to trigger a runaway melting of Io's interior that would leave only a relatively thin solid mantle, over a molten core. The images of Io currently being taken from the Voyager spacecraft may therefore reveal evidence for a planetary structure and history dramatically different from any previously observed.

It has long been known that there is a special relationship among the orbital motions of three of the four Galilean satellites: Io circles Jupiter in nearly half the time as the next satellite out, Europa; and one-fourth the time as the third satellite, Ganymede. A consequence of this relation is that adjacent satellites always pass closest to each other at the same place in their orbits. Although it is not yet understood exactly how the motions of the satellites came to be this way, it is known that the gravitational attractions of the satellites for each other in these orbits cause the orbits to be slightly different from perfect circles. For instance, the distance between Io and Jupiter changes back and forth by about 1,800 km out of 422,000 km as Io goes around the planet. This is not a large amount; for comparison, the distance between the Earth and the Moon varies by 19,000 km out of an average of 384,000 km. Nevertheless, the small variability in Io's distance from Jupiter could have drastic consequences for the satellite's internal structure because of its effect on Io's tide.

The tide that we refer to here is not like the familiar ocean tides on the Earth. These tides are the response of the oceans to (mainly) the gravitational force of the Moon, as the Moon moves in its orbit. But the same force has a much less noticeable effect on the solid part of the Earth; it produces a very slight bulge in the planet, the alignment of the bulge being roughly along a line between Earth and Moon. The height of this solid Earth tide, as it is called, is only about 30 cm. In the same way, Jupiter causes a tide on Io, which is calculated to be nearly 10 km. But this does not mean that the surface of Io rises and falls this much every time Io circles Jupiter. Because Io keeps the same face to Jupiter, and the bulge is also almost aligned with Jupiter, the satellite would not change shape at all, except for the effects of Io's slightly non-circular orbit. The height of the tidal bulge depends on the distance between satellite and planet, and therefore it changes as the distance changes. (The non-circularity of the orbit also causes the bulge to oscillate slightly with respect to Io.). It is the dissipation of the energy associated with this flexing of the satellite that can lead to extensive internal heating.

Although we do not yet have much direct information about the nature of Io, we do know that it is roughly the same size and mass as the Moon. It is therefore likely that Io is made of stuff not very different from
lunar stuff. If this is so, the power required for the tidal forces to distort Io can be calculated. We expect that at least 1% of that power will be converted to heat. The calculation then tells us that, if Io was a completely solid body, the amount of heat released at its center would be about ten times the average amount released in the Moon. We know how much the Moon is heated from the Apollo experiments that measured the rate at which energy is lost from the lunar surface, and from models of the Moon's evolution based on other information from the Apollo program. (The Moon is not heated by tidal dissipation. It is presumed to be heated by the energy released by small amounts of radioactive elements like uranium; these elements are also expected to occur in Io, and would further add to the heating of that body.) We also believe that the deep interior of the Moon is presently at or at least close to its melting temperature. It therefore seems quite likely that the much higher heating rate calculated for Io would be enough to melt Io's interior.

But the heating rate due to tidal dissipation in Io could be much greater yet, because, if a planet (or satellite) has a "soft", liquid core, its solid outer shell will distort more under the same tidal force. The increased distortion leads to greater heating, which in turn leads to more melting and an even thinner solid shell. Thus, once melting in the interior has begun, it is likely to rapidly spread throughout the planet.

An analysis of the mechanisms that are known to transport heat out of planets reveals that they are not able to stop the run-away melting in Io until only a relatively thin solid surface layer remains. The thickness of this crust is difficult to predict, but it could be as thin as 20 km. (The radius of Io is about 1,800 km.) If this was the case, parts of the surface of Io might rise and fall by as much as 100 meters.

The consequences of the orbital dynamics of the inner three Galilean satellites are seen to be profound for Io, which might be the most intensely heated terrestrial-type body in the solar system. It is difficult to predict what Io's surface would look like, but one might speculate that widespread and recurrent volcanism would occur. (An unusual brightening of the satellite at infrared wavelengths has been observed from the Earth; lava erupting on the surface could produce such a brightening.) The appearance of craters produced by impacts with enough energy to penetrate the crust should be different from those on bodies with thick, solid mantles. Finally, it is quite possible that Io contains enough iron to form a core with a radius of as much as a third that of the satellite. Such a core would be molten, and therefore, by analogy with the Earth, Io might have a magnetic field of its own.

If the heating source described here is confirmed, Io would prove to be a much more dynamic, complex and interesting place than has hitherto been expected.
THE FORMATION OF COMPLEX IMPACT STRUCTURES; M.R. Dence and R.A.F. Grieve, Earth Physics Branch, Department of Energy, Mines & Resources, Ottawa, Ontario, Canada, K1A 0Y3.

Analysis of relatively fresh craters on the Moon, Mars and Mercury using spacecraft photography has shown a consistent pattern of crater shapes. In general the small craters have the form of a simple bowl with a prominent lip or rim. With increasing crater size the craters develop a flatter profile with the development of a mountainous central peak and broad, terraced rims. This change on the Moon takes place at crater diameters of about 15 km and is accompanied by a sharp decline in the rate at which crater depth increases with diameter. Similar changes at about the same diameter or somewhat smaller have been documented for craters on Mercury.

There is also a well-documented trend for central peaks to grow in height with increasing crater diameter but at a greater rate than the increase in crater depth. Thus at a diameter of about 150 km on the Moon the central peak roughly equals the depth of the crater below the surrounding surface.

However the trend does not continue. Instead of rising higher the peaks of still larger craters are replaced by a ring of hills which has been called a peak ring. In a few lunar craters between 140 and 175 km diameter, both peak rings and a central peak exist, but those larger than 175 km across have peak rings only. Craters with this shape are generally referred to as basins. A similar progression has been recorded on Mercury and on Mars, with the transformation to ring form occurring at about 100 km on those planets. The largest structures, greater than 350 km across on the Moon, possess multiple concentric rings, the most spectacular example being the 900 km Orientale Basin.

Similar changes in crater form have been observed on earth. More than 90 terrestrial craters have now been shown to satisfy the criteria for origin by meteorite impact. They range in size from less than 10 m to 140 km across, and in age from a few tens of years to almost 2 billion years. Obviously the great majority of the Earth's impact scars have been removed by the much faster rates of erosion on Earth compared with other planets, but the best preserved craters show the same progression of forms as observed on the Moon, Mars and Mercury. Analysis of the shapes of terrestrial craters shows that the change from simple, bowl shape to craters with central peaks takes place at smaller diameters than on the Moon and is dependent on the type of rock in which the craters are formed. Craters formed on Earth in sedimentary rocks, such as limestone and shale, change from bowl to central peak shape at diameters of approximately 1.5 km; those formed in crystalline rocks such as granite change at 4 to 5 km diameter. As on the other planets, a marked change in the ratio of depth to diameter accompanies the change in crater form.

As in the case of the Moon, with increasing crater diameter terrestrial craters show an increase in height of the central peak and a transformation to ring structure when the peak height approximates the depth of the crater below the original ground level. This takes place on earth at a much smaller diameter of between 10 and 30 km depending on rock type. The largest terrestrial craters appear to have multiple ring structure, as shown by the 70 km Manicouagan, Quebec, structure and the 100 km Popigai structure in north-
FORMATION OF COMPLEX IMPACT STRUCTURES

M.R. Dence and R.A.F. Grieve

central Siberia.

On Earth it is possible to look beyond crater form to an analysis of the underlying structure through surface mapping, deep drilling and geophysical studies. A consideration of the best documented cases shows that craters with central peaks are complex structures which involve uplift of strata in the center of the crater and that the amount of uplift increases steadily with increasing crater diameter, regardless of the rock type. On the other hand, in small, simple, bowl-shaped craters, rocks underlying the fragmented rocks (breccias) which partly fill the crater have been pushed downwards or outwards. This displacement is manifest at the surface as a rim of uplifted rocks surrounding the crater depression. In the largest simple craters, such as the 3.8 km Brent, Ontario, crater formed in the crystalline rocks of the Canadian Shield, the indicated amount of displacement is as much as 500 m. During the displacement, which takes place at speeds of up to 1 km/sec, adjacent rock masses are forced against each other, causing local crushing and frictional melting. The result is a significant lowering of the overall strength and internal friction of the displaced rock masses. In craters larger than Brent, or where the original rock types were weaker, the lubricating effect allows the crater floor to yield upwards under the pressure of the crater walls, thus initiating a central uplift.

The subsequent motion in the crater resembles the gravity waves produced when rain hits pools of water. The analogy was previously drawn by R. Baldwin and W.G. Van Dorn in discussions and analysis of the Orientale Basin rings, but had largely been passed over because there appeared to be no evidence for the extremely low strengths of lunar crustal materials required by the gravity wave idea. In the present concept the physical properties of the bulk of the displaced rock mass are little affected but the relatively small amount of crushed and melted lubricant allows the further motions to proceed. The amount of lubricant, the volume of rock so affected and the duration of the motions is greatest in the largest craters.

Interpreting the late motions in the crater as a gravity wave leads to the conclusion that in the larger craters central uplifts initially rose above their final physical height and then settled into an equilibrium position. Uplifts that rose well above the initial ground level, on settling formed a ring at the outer margin of the original peak, which may remain as a subdued residual peak. This change is most clearly shown on Earth by the crater pair at Lac à l'Eau Claire (Clearwater Lake) in the ancient crystalline rocks of north-central Quebec. The craters were formed simultaneously about 270 million years ago by two bodies which struck 40 km apart. The smaller east crater, 22 km across, has a well preserved central peak form which may have been defined by drilling. It closely resembles a crater of similar size at Boltysh in the Ukraine, which has been extensively drilled by Soviet investigators. The larger west crater, 32 km across, is shallower by about 300 m and has a clearly defined ring structure with a small residual central peak. The east crater is thus interpreted as an example in which the central peak did not rise above the original ground surface, whereas at the larger west crater the central peak rose higher and then collapsed to form the ring.

In yet larger structures the lubrication may persist to allow further motion in the center before final equilibrium is attained. Such additional vertical motions could generate additional rings. The structure will gradual-
FORMATION OF COMPLEX IMPACT STRUCTURES

M.R. Dence and R.A.F. Grieve

ly stabilize from the outside inwards with slumping and other adjustments taking place in the outer rings as motion continues in the center. The lubricating material fills all fractures and cavities between blocks to form an irregular network of veins of finely crushed and glassy material known as pseudotachylite. These veins are a prominent feature of the largest terrestrial craters.

The motions of the crater floor are visualized as taking place rapidly while material is still being ejected from the crater. Experiments and computer calculations show that in the first stage of crater growth the transient cavity has an almost hemispherical shape and deep excavation proceeds by ejection of highly shocked material along ballistic trajectories. Later, as the central uplift grows, ejection continues largely by the scouring of mobilized rock fragments and melt across the crater floor. Additional material sliding from the rising central peak will augment the scouring motion resulting in significant additional excavation in a broad region around the central zone of initial deep excavation. The excavation thus has the shape of an inverted sombrero as has been deduced from studies of terrestrial craters such as Flynn Creek, Tennessee.

Fragmental rocks within the final crater include a lower layer of material which moved across the crater floor but did not leave the crater, and higher levels of returned ejecta. Much of this is emplaced during the late motions when sheets of ejecta slide back towards the center. The result is a series of fragmental rocks which differ in their degree of deformation and initial depth of origin.

The picture of complex crater formation developed here places in context the relative dependence of crater form on size (energy), rock type and gravity. Unlike some recent models it does not require that the target rocks be layered to produce central peaks or ring structures; both are produced in terrestrial craters formed in essentially homogeneous rocks. Where the rocks are horizontally stratified peak formation may be modified and ring structure enhanced or localized. However contrasts in rock properties become less significant with increasing crater size and probably have little effect on the largest ring structures formed in the lithospheres of the planets.
COMPARISON OF DESERT FORMATIONS IN SOUTHWESTERN EGYPT WITH SIMILAR FEATURES ON MARS. Farouk El-Baz and Ted A. Maxwell, National Air and Space Museum, Smithsonian Institution, Washington, D.C. 20560

Study of photographs taken from space followed by observations in the field indicate that the Western Desert of Egypt provides a natural laboratory that is suitable for the interpretation of wind-blown features on Mars. Although many desert regions on Earth have been used to make comparisons with Mars, the Western Desert represents a unique analogy because of: (1) existence of dry valleys and lakes, which indicate a wetter climate in the geological past; and (2) present-day extreme aridity and the predominance of erosion and movement of surface materials by wind action. Both conditions are prevalent on Mars.

Numerous circular granitic mountains abound in the southwestern corner of Egypt (fig. 1), particularly near the borders with Libya and Sudan. The largest of these mountains is called Uweinat after the Arabic word meaning water springs, because of the natural groundwater wells on its southwestern side. To the northeast of Uweinat is the Gilf Kebir, a plateau that is topped with a layer of hard, iron-rich quartzite.

A joint American-Egyptian field expedition was planned to both the Gilf Kebir and Uweinat during September-October 1978. In addition to the maps and conventional navigation equipment, we used NASA satellite tracking signals to plot the route of the expedition and to locate sampling sites (fig. 1). The expedition started by air from Cairo to El Kharga. From this oasis, we used desert vehicles to travel southwesterly to Bir Tarfawi, westerly to Gilf Kebir, then southwesterly to Uweinat, and return. The traveled route totaled 2500 km.

Figure 1. Left, sketch map of Egypt showing the route of the expedition that was tracked by Nimbus 6 satellite; Right, Landsat view of the Gebel Uweinat-Gilf Kebir region in southwestern Egypt.
The southeastern border of the Gilf Kebir plateau exhibits deep canyons incised into the quartzite and the underlying fine-grained sandstone. These canyons were clearly formed by water erosion under wetter climatic conditions, which prevailed over 8,000 years ago. The canyons appear to be morphologically similar to martian canyonlands.

The Gilf Kebir canyon systems consist of branching distributary valleys that extend 10-30 km into the plateau. Field observations indicate that there are no drainage networks on top of the plateau. The heads of investigated canyons are characterized by steep cliffs with channels less than 30 m long on top of the plateau. In photographs taken from space, these canyon heads appear as flat-floored, circular depressions similar to the heads of tributary canyons on the south side of Ius Chasma of Mars (fig. 2).

The importance of cliff sapping (the undercutting of less resistant layers of rock and subsequent collapse of the cliff face) was suggested by Bagnold as early as 1933 (ref. 1). This idea is supported by the lack of drainage patterns on top of the plateau, and the possible presence of water springs half-way up the cliffs. Similar erosional processes may also apply to the martian cliffs (ref. 2).

The mouths of the Gilf Kebir canyons have been highly affected by wind activity. As on Mars, no deposits of the ancient stream channels exist as they do in more humid climates. The ancient running-water deposits of the Gilf Kebir canyons have long been buried by the wind-blown sand sheet that butts against the plateau edges.

From the area surrounding the Gilf Kebir to the Uweinat Mountain region, wind-blown features predominate. On the large scale, light- and dark-colored streaks occur everywhere. The light-colored streaks appear to be extensions of the longitudinal sand dunes of the Great Sand Sea to the north.
Orientations of these dunes and streaks indicate prevailing winds from the northeast.

In the Uweinat region, dark-colored streaks occur in the lee of topo-
graphic barriers; the largest streak is southwest of Uweinat itself (fig. 3). This mountain stands 1200 m above the surrounding sandy plain. Under the prevailing wind from the north-northeast, this mountain ring creates a flow pattern that is similar to those observed on Mars (ref. 3). This pattern is also similar to those generated by laboratory experiments to simulate the flow of wind around martian craters (refs. 4 and 5). The morphological similarities between the terrestrial and martian dark streaks are clearly illustrated in figures 3a-c.

Field investigations of the northern part of the Uweinat dark streak indicate that its surface is strewn with irregular chips of dark rock. These chips or flakes are usually a few centimeters in diameter. They appear to be fragments from the Uweinat Mountain rocks. Between the dark-colored chips are smaller, lighter-colored fragments and sand grains. However, the color of the larger fragments dominates, giving the area a dark color both in the field and in space photographs.

The importance of local material to dark streaks in southwestern Egypt is also demonstrated in the lee of Garet El-Meit hill (fig. 3d). This streak is composed of 5-7 mm granitic pebbles eroded from the hill itself. This surface is surrounded on either side by a light-colored sand sheet. Because of their large size, the dark pebbles of the streak are less likely to move about due to the more frequent sand-moving winds. Consequently, the shape of the streak will change mainly in response to the shifting of the light-colored sand on both sides.

Mariner 9 and the Viking orbiters photographed numerous, alternating light and dark streaks and streak bundles on Mars, particularly in the Cerberus and Elysium Mons regions. Similar streaks and streak bundles abound to the east of Uweinat Mountain. In both cases the streaks emanate from

Figure 4. (a) Streak and streak bundles east of Uweinat Mountain; dark areas are probably exposed rocks, and light areas are most likely sand deposits. (b) Streaks and streak bundles in the lee of craters and knobs in the Cerberus region of Mars.
Our study of light and dark streaks in the southwestern desert of Egypt indicates that: (1) the light streaks are depositional; sand dunes and/or sand sheets form most of the light streaks; (2) the dark streaks are erosional products of high mountains and hills; they represent virtually sand-free areas; and (3) the morphology of both light and dark streaks is controlled by the flow of the wind around topographic highs. These findings have significant implications to the interpretation of streaks on Mars.

The similarities between features of the southwestern desert of Egypt and wind-blown patterns on Mars are not limited to the views from orbit, but extend to small-scale surface features. In the Uweinat Mountain-Gilf Kebir region, numerous vistas were encountered that appeared very similar to views telemetered by the Viking landers. The distribution of blocks, rock size population, and sand accumulations behind larger rocks are very similar in both cases.

An additional feature that warrants special attention is the prevalence of pits or holes on exposed rock surfaces in the southwestern desert of Egypt. These hollows appear suspiciously similar to what are interpreted as "vesicles" in the rocks of Viking 2 landing site. Vesicles are formed in volcanic rocks as gases are trapped in a fast-cooling hot lava. Thus the martian rocks were interpreted as vesicular basalts.

In the dry, wind-dominated environment of southwestern Egypt, small pits are believed to have formed by wind vortices. The ability of the wind to create vortex pits has been established by laboratory studies (ref. 6). The wind in the Western Desert of Egypt is so fierce that it is quite capable of plucking individual grains from the rock fabric, thus creating small holes in their place.

Larger holes in the rock appear to form by the erosive action of sand grains, which become trapped in the smaller holes. Thus, once a pit is
formed it gets increasingly larger by the passage of time. These holes occur in all encountered rock types, including fine-grained and dense basalts, trachyte, granite, quartzite, sandstone, and in solid hematite. Because of this, it is possible that what are called "vesicles" in the martian rocks are wind-formed pits.

References
MICROCHARACTERIZATION OF "BROWNLEE" PARTICLES: FEATURES WHICH DISTINGUISH INTERPLANETARY DUST FROM METEORITES?, P. Fraundorf and J. Shirck, McDonnell Center for the Space Sciences, Washington University, St. Louis, MO 63130 USA.

Dust is a major constituent of the universe. In interstellar space, dust occurs as grains less than a thousandth of a centimeter in size, and causes reddening of starlight in the same way that dust and gas in the earth's atmosphere causes reddening of the sun as seen at sunrise and sunset. Dust between the planets, thought to be mostly from comets (1), gives rise to the phenomenon known as the zodiacal light, which is a glow in the sky seen after sunset. And anyone who has looked at the night sky has seen the arrival of interplanetary debris in the form of meteors or shooting stars. But outside of effects due to its physical presence, information on interplanetary dust may help our understanding of comets, meteorites, the early solar system, and the origin of interstellar dust.

Unfortunately, direct collection of interplanetary dust is difficult in space because the particles are traveling at very high velocities (often greater than 15 kilometers per second). At such velocities, impact onto a solid collection surface results in partial-to-total destruction of the particle, and the formation of a micrometeoroid crater - a miniature of the meteor crater in Arizona. Rather remarkably, the earth's atmosphere is a much better collector of interplanetary dust (e.g. ref. 2). First of all, the slowing-down process is much gentler because grains can be gradually slowed down by the atmosphere over distances of 40 kilometers or more. Although particles larger than 1/100th of a centimeter in size probably melt or vaporize, some particles which are around 1/1000th of a centimeter in size survive without severe heating (3). Secondly, the slowing down process and low settling velocity for such tiny particles (At 30 kilometers they fall at the rate of only 3 cm/sec.) concentrate the particles to volume densities a million times greater than would be found in space. Although over a billion particles (greater than 1/1000th of a centimeter in size) are collected by the earth's atmosphere each second, they are so widely dispersed that a stationary detector one meter on a side would on the average collect only one particle every 4 days by settling.

The most successful method so far for collecting these particles from the stratosphere was initiated by Brownlee et al (4) in 1974. A piece of plexiglass 4.5 cm on a side, coated with a thin film of high viscosity silicone oil, is mounted under the wing of a NASA U-2 aircraft. The collector, protected from contamination near the ground, is opened out into the airstream at an altitude of 20 kilometers. Particles down to a few ten thousandths of a centimeter in size stick on the collector and can be removed later for laboratory study. Although most of the particles are transparent aluminum oxide spheres from solid fuel rocket exhaust, a sizeable fraction of the remaining particles are black aggregates with compositions similar to those of "carbonaceous chondrite" meteorites (4,5,6) which for a variety of reasons are thought to be the most primitive materials left over from the initial formation of the solar system.

At least two important differences between these "Brownlee" particles (named after D. Brownlee who first discovered them) and meteoritic materials have already been reported. First, electron microscope secondary (reflected) electron images of these particles show them to be very open or porous aggregates of lumpy "nodules" which are typically 1/100,000th of a centimeter in size (4). This structure is quite unique and has not been found in other extra-terrestrial materials such as meteorites and lunar samples. The
structure is, however, consistent with those that have been inferred for many meteors or shooting stars. Secondly, large concentrations of helium have been measured in several of the Brownlee aggregates (3). This helium concentration is not typical of terrestrial materials, but has been found in other extra-terrestrial materials, such as lunar dust, which have been exposed to the sun for some years. One possible origin of the helium is direct implantation of helium from the expanding corona of the sun - the so-called solar wind.

This paper describes results of an ongoing effort directed toward the characterization of these particles, obtained from collectors supplied by D. Brownlee, using electron beam instruments. The results show that on the submicron scale there are two features that further distinguish the Brownlee particles from other extraterrestrial materials: (i) The particles are chemically heterogeneous on a smaller size scale, and (ii) the particles contain a "matrix" of amorphous material that coats or embeds many of the aggregate crystals and is probably responsible for the rounded lumpy appearance of the Brownlee particle "nodules" in secondary (reflected) electron images (Fig. 1). The two observations will be taken up in turn.

Chemical Heterogeneity - Quantitative chemical analysis of these aggregates has been limited by three factors: (a) Although the number of "chondritic" Brownlee particles collected to date numbers in the hundreds, they are so small that the total collected mass is still less than a millionth of a gram. (b) For 1/1000th centimeter particles, elemental analysis can be performed by measuring the x-rays produced under electron bombardment. However quantitative analysis is difficult because the spatial distribution of elements in the particle (the "geometry") produces changes in the amounts of detected x-rays. (c) The aggregates contain large concentrations of the light elements oxygen and carbon which are difficult to analyse in such small quantities. Clean techniques for crushing individual aggregates (6) and a high resolution electron microscope (JEOL 100CX TEMSCAN) with a low-contamination vacuum system have permitted us to analyse x-rays from small parts (or all) of the aggregates while minimizing uncertainties due to the geometry.

Figure 2 shows a secondary (reflected) electron image of a crushed piece from a Brownlee particle after 19 x-ray spectra have been taken at various locations (each marked by a tiny rectangle of contamination built up during data acquisition). The x-ray detector (which could not detect oxygen or carbon) indicated wide variations in detectable element composition across the piece. For example, the major detectable elements were magnesium and silicon in the lower, crystalline portion of the clump, iron-sulfur or iron-silicon in central regions, and iron only along edges of the upper portion. We have examined 5 Brownlee aggregates in this way, two in considerable detail. Figure 3a shows a secondary (reflected) electron image of a porous aggregate, much of which apparently "exploded" on crushing, dispersing tiny rounded clumps ranging in size from one millionth to two ten-thousandths of a centimeter. For all particles, it was difficult to predict the composition of adjacent clumps (on the 0.5 micron scale, or smaller) based on knowledge of neighboring compositions. This was true in many cases for adjacent crystals, as well as for interconnected polycrystalline or amorphous regions. Chemical variability on this size scale is not characteristic of meteorites. Even the fine-grained matrix material of carbonaceous chondrites appears to have "compositional grain sizes" on micron and larger scales, although single crystal sizes may be much smaller. This result suggests that, in spite of their gross similarity to
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Meteorites in chemical composition, Brownlee aggregates were assembled from grains which were smaller than those which collected to form meteorites.

Amorphous Coatings - Amorphous coatings on grains from Brownlee aggregates have been previously reported by us and others (7) when the grains are observed in the transmission electron microscope. In some cases, clouds of tiny microcrystallites appear to be embedded more or less uniformly in such amorphous material (6). The lumpy but reentrant nature of the surface of most Brownlee chondritic aggregates in secondary (reflected) electron images (e.g. ref. 4) further suggests that amorphous coatings are ubiquitous and may, in fact, form the cementing material that holds the grains together.

Matching secondary (reflected) and transmitted electron images of the same clump, shown in Fig. 3a and 3b, are consistent with this interpretation. In Fig. 3a, the secondary (reflected) electron image shows a generally rounded surface structure with little contrast from one part of the clump to the next. In comparison, the transmitted electron photo in Fig. 3b shows clearly that the clump consists of an opaque material pervaded by electron transparent regions. These transparent regions appear to be made up of low density, low atomic-number, amorphous material. The continuous, textured nature of the surface seen in Fig. 3a suggests that there was a continuous coating of amorphous material over the entire clump. Although not always so exaggerated, the different appearance of Brownlee particles in transmitted and secondary (reflected) electron images appears to be quite general: the former frequently showing sharp, angular fragments while the latter show rounded, lumpy surfaces. These results are not yet definitive, but they provide further support for the thesis that amorphous layers are an important part of Brownlee aggregate structure. Measurements with an electron microprobe (4), a scanning auger probe and an ion microprobe (8) have all indicated that, next to oxygen, carbon is probably the most abundant light element in Brownlee aggregates, as would be expected from their general chemical similarity to carbonaceous meteorites. Therefore this observation also suggests that carbon, perhaps in the form of hydrocarbons, may be a major constituent of the amorphous material in some Brownlee aggregates.

Discussion - It has often been suggested (e.g. ref. 9) that our sun, during early stages in the formation of the solar system, may have gone through one or more active phases capable of ejecting much of the very fine material (gas and dust) from the inner portions of the solar system. The finer scale of the chemical heterogeneity in Brownlee aggregates, in spite of their bulk chemical similarity to carbonaceous meteorites, suggests that just such a size segregation process may have operated in the early solar system, and that the Brownlee aggregates perhaps represent grains which aggregated at a location further out from the sun. Comets are known to lose a lot of volatile materials (in gaseous form) as well as dust as they are warmed up on their journey through the inner solar system. Thus the observation of porous amorphous coatings is certainly not inconsistent with a cometary origin for Brownlee aggregates. Finally, if the observations of a thick carbonaceous matrix for some Brownlee aggregates can be confirmed, they may help to shed light on the many remarkable properties already reported for carbon compounds of extra-terrestrial origin (e.g. refs. 10,11,12).
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REFERENCES

(3) R. S. Rajan et al. (1977) Nature 267, 133.
(4) D. E. Brownlee et al. (1976) NASA TM X-73, 152.
(11) R. S. Lewis et al. (1977) J. Geophys. Res. 82, 779.

FIGURE CAPTIONS

Figure 1: Secondary (reflected) electron image from particle U2-13-M8-16 showing the lumpy image characteristic of "nodules" comprising the surface of porous Brownlee aggregates. Field width is .000045 centimeters.

Figure 2: Secondary (reflected) electron image from particle U2-13-M5-1C after x-ray analysis of 19 locations. Note the tiny rectangles of contamination built up during data acquisition. Field width is .0003 centimeters.

Figure 3a: Secondary (reflected) electron image of a large clump from U2-13-M8-16. Note the continuous, textured surface. Field width is .0003 centimeters.

Figure 3b. Transmitted electron image of the clump shown in Figure 3a. Note the dense angular fragments (crystals) scattered throughout the clump's interior. Field width is .0003 centimeters.
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FIGURES

1

2

3a

3b
The geologic record of collisions by asteroidal and cometary bodies on the surface of the Earth is well established. Scars produced by the collisions have been recognized on all of the continental land masses --- huge craters up to 100 kilometers in diameter. The formation of such large geologic structures is an event of incredible, almost incomprehensible, violence involving energies equivalent to as much as that released by the explosion of a trillion tons of TNT, energies dwarfing that released by the largest known earthquakes.

With about three-quarters of Earth covered by oceans, the geologic scars on the continents represent an incomplete record of Earth's collisional history. Averaged over the long term of the geologic records, three impacts must have occurred in the ocean basins for each crater formed on the continents. Unlike the "localized" permanent craters formed on land, these pelagic impact events have left no obvious record of their occurrence, or at least none recognized to date.

The impact on Earth of an asteroidal body, say, 1 kilometer in diameter probably occurs three to four times each 10 million years, based on the most recent astronomical observations. Thus, a pelagic impact of such a size body is to be expected every several million years. Laboratory experiments of hypervelocity impacts into water, performed at the NASA, Ames Research Center, have indicated that initially a hemispherical cavity would be formed that subsequently collapses and then forms a huge central column, or central peak, of water, which then also collapses to form a smaller secondary crater, then a smaller central column, and so on. The formation of the initial crater and the collapse of the central column cause large waves to form and expand radially outward from the point of the impact. For a pelagic impact such waves would be tsunamis of potentially major (catastrophic) significance. For the 1 kilometer diameter body impacting with typical meteoritic velocity, it is estimated from the laboratory experiments that the transient crater in water could be more than 8 kilometers deep and, prior to collapse, could attain a diameter of 20 kilometers. With an average ocean depth of only 5 to 6 kilometers, the example impact event would probably also disturb (crater?) the floor of the ocean. Although intersection with the ocean floor introduces uncertainties in the analysis, it is estimated that the maximum height of the waves in the deep water of the ocean would be of the order of 300 meters at a distance of 100 kilometers from the crater collapse, and would decay to about 30 meters at a distance of 1000 kilometers. But if the waves approach the shores of lands, the decreases in water depth cause the wave heights to grow. Thus, instead of 30 meters heights at 1000 kilometer distances, waves as high as 300 meters could sweep onto the shores at 1000...
kilometers from the point of impact of the 1 kilometer diameter asteroidal body. Although the catastrophic inundation of islands and the shores of the continents by impact generated tsunamis may have virtually zero probability of occurrence in terms of man's lifespan, such events are relatively frequent on the terrestrial time scale and they represent potentially very significant events, both biologically and geologically, that remain to be explored in the geologic record.
DEEP-SEA MICROTEKTITES: CORRELATION WITH OTHER EARTH EVENTS AND IMPLICATIONS CONCERNING THE MAGNITUDE OF TEKTITE-PRODUCING EVENTS, B. P. Glass, M. B. Swink, and P. A. Zwart, Geology Department, University of Delaware, Newark, DE. 19711.

Tektites are naturally-occurring glass objects found on the Earth. They are often spherical, teardrop or dumbbell in shape and generally weigh a few grams. Tektites are found in several areas of the Earth's surface, called strewnfields. There are four major tektite strewnfields: Australasian, Ivory Coast (Africa), Czechoslovakian and North American (Fig. 1). Australasian tektites are found in Australia, Indonesia, Indochina and the Philippines. North American tektites are found in Texas and Georgia. Radiometric dating indicates that the Australasian, Ivory Coast, Czechoslovakian and North American tektites were formed and fell on the Earth's surface 0.7, 1, 14.7, and 35 million years ago, respectively. Although some investigators believe that tektites are from the moon (1), most scientists now believe that they were formed by the impact of a meteorite or comet on the Earth (2). Tektites are apparently Earth material that was melted and splashed out when large meteorites or comets hit the Earth's surface. The melted material cooled too quickly to crystallize and thus formed glass droplets. Tektites from Australia were apparently thrown out through the Earth's atmosphere and were remelted as they fell back down to the Earth's surface.

Microtektites (which are tektites less than one millimeter in diameter) belonging to the Australasian, Ivory Coast and North American tektite strewnfields have been found in deep-sea sediments (Fig. 1) (3, 4, 5). Microtektites are recovered from sediment cores that are taken by dropping metal pipes into the ocean floor or by drilling. The geographical distribution of microtektite-bearing cores indicates that the tektite strewnfields are much larger than previously thought. Likewise, the size of the strewnfields plus the calculated mass of microtektites in each strewnfield, indicate that the tektite-producing events were of greater magnitude than were previously believed. In addition, the microtektite layers are found to be associated with other events recorded in the sediment cores such as: reversals of the Earth's magnetic field, extinctions and first appearances of various microscopic marine organisms and possibly climatic changes.

Australasian microtektites have been found in thirty-three cores. They have recently been found in two cores from the northwest Indian Ocean (Somali Basin) and two cores from the eastern equatorial Pacific Ocean. This increases the known size of the strewnfield and changes its overall shape. Calculations, based on the number of microtektites found at each core site, indicate that the Australasian strewnfield contains approximately 100 million metric tons of tektite glass which is spread over about ten percent of the Earth's surface.

In most of the Australasian microtektite-bearing cores there is a fairly well-defined peak in microtektite abundance. In these cores the peak in abundance is generally within about 20 centimeters of the depth where the last reversal of the
Earth's magnetic field is recorded in the cores. (Reversals of the Earth's magnetic field are detected by changes in the direction in which the sediment is magnetized.) The last reversal of the Earth's magnetic field occurred about 0.7 million years ago. Prior to 0.7 million years ago the Earth's magnetic field was in a reversed orientation so that a compass needle would point south rather than north. This is called the Matuyama reversed epoch. From 0.7 million years ago until the present the Earth's magnetic field has had the present, normal orientation. This normal period from 0.7 million years ago until the present time is called the Brunhes normal epoch. The boundary between the Matuyama reversed epoch and the Brunhes normal epoch is called the Brunhes/Matuyama reversal boundary. On the average the peak in abundance of the Australasian microtektites is within about 6 centimeters of the Brunhes/Matuyama reversal boundary (Fig. 2). Thus it appears that the Australasian tektite fall may have coincided with the last reversal of the Earth's magnetic field about 0.7 million years ago.

Several authors have suggested that there was a major change in climate associated with the Brunhes/Matuyama reversal (e.g., 6, 7). Furthermore, Kean and Kennett (6) point out that the most conspicuous change in microfossils within the last 2.4 million years is at the Brunhes/Matuyama boundary where several species of microscopic one-celled marine organisms (two Radiolaria and one foraminifer) disappear and two new species appear.

Microtektites belonging to the Ivory Coast tektite strewnfield have been found in five cores from the Atlantic Ocean (Fig. 1). Recent discoveries of Ivory Coast microtektites in two cores from the North Atlantic and one from the South Atlantic show that the Ivory Coast strewnfield extends farther north and farther south, and is about four times larger than previously thought. Calculations indicate that there are about 10 million metric tons of tektite glass in this strewnfield.

The Ivory Coast microtektite layer is associated with a short period of time when the Earth's magnetic field had a normal orientation (called the Jaramillo geomagnetic event). The Ivory Coast microtektite layer may be associated with the beginning of this event about 0.95 million years ago. The extinctions of several species of microscopic one-celled marine organisms are closely associated with the Jaramillo event (e.g., 6).

North American microtektites have been reported from one site in the Gulf of Mexico and two sites in the Caribbean Sea. North American microtektites have now been found in cores from several sites across the equatorial Pacific and from one site in the Indian Ocean (Fig. 1). This indicates that the North American strewnfield extends at least half-way around the Earth. Calculations indicate that there is over one billion metric tons of glass in this strewnfield.

The North American microtektite layer is apparently not associated with a reversal of the Earth's magnetic field, but it is associated with the extinction of several species of one-celled marine organisms called Radiolaria (8). In addition, there is evidence (9, 10) for a sharp drop in temperature at
MICROTEKTITES AND METEORITE IMPACT

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about the same time (i.e., 35 million years ago) which may correlate with both the North American tektite event and radiolarian extinctions.

If it is correct that tektites were produced by the impact of a meteorite or comet on the Earth's surface, then it appears that these impacts were responsible for spreading 10 million to one billion metric tons of glass up to at least half-way around the Earth. In addition, these impacts may have triggered reversals of the Earth's magnetic field and produced climatic changes which may have been responsible for extinctions and first appearances of various species of microscopic one-celled marine organisms.

REFERENCES:
Figure 1. Tektite strewnfields and location of cores containing microtektites. Circles and stars indicate location of cores searched for Australasian microtektites. Triangles and squares indicate locations of cores searched for Ivory Coast and North American microtektites, respectively. Solid symbols indicate microtektite-bearing cores and open symbols indicate cores that do not contain microtektites.

Figure 2. Correlation between Brunhes/Matuyama reversal boundary and Australasian microtektite layer in ten cores from the Indian Ocean. Black indicates normally magnetized sediment and white indicates reversely magnetized sediment. Scale to the right of each core indicates number of microtektites per 8 cm$^3$ sample.

One of the principal conclusions of the Viking mission to Mars was that the surface environments at the two landing sites are very hostile for life as we know it, and the prospects that life may exist on Mars seem to have been somewhat dimmed by the Viking results.

While the surface environments at the two Viking sites may be hostile to life as we know it, this may not be true at other locations on the planet. In fact Earth-based telescope observations and Viking orbiter data indicate that at least one area, Solis Lacus (Lake of the Sun), may have a very different surface environment: an environment that would appear to be quite hospitable to at least some forms of life known to exist on Earth.

The single most hostile element of the Viking site environments was the remarkably high desiccation state of the soils. The soils were absolutely dry. At the landing site in Chryse Planitia, for example, soils had to be heated to 350° and 500°C before any detectable water was given off. Heating at 50° and 200°C was not enough, and at the high-temperature heatings the amounts of water that were driven off corresponded to only a few thousandths of a gram of water per gram of soil. At the Viking-2 landing site in Utopia Planitia there was only slightly more water, with some detectable water being driven off at temperatures as low as 200°C. No detectable water came off at temperatures lower than this, however, and it indicates that at both sites only chemically-bound water was present in the samples. There were no detectable traces of ice or any other weakly-bound forms of H₂O that could be utilized by organisms in the soil. That is a remarkably high desiccation state for a natural soil, particularly when we know that H₂O frost forms on these soils every night.

Apparently much of the martian surface is as highly desiccated as the Viking landing sites. Dr. Thomas McCord, Roger Clark (both at the University of Hawaii) and I recently published (Journal of Geophysical Research, December 1978 Issue) Earth-based telescope measurements of martian soil composition (reflectance spectra) and we found that the average surface soil all across the planet is highly desiccated, with all but the most strongly bound H₂O removed from the soil by the highly desiccating martian environment.

The fact that the surface material is so highly desiccated is understandable in light of laboratory studies of vacuum-drying and freeze-drying, as well as my own work on desiccation by ultraviolet sunlight. It suggests that there is probably not a widespread occurrence of near-surface ground ice or water in the martian topsoil, except possibly at high latitudes near the polar caps.

While this may be generally true for the planet as a whole, remote sensing data indicate that there is at least one region where there may be a reservoir of weakly-bound H₂O that extends to within a few centimeters of the surface. That region is Solis Lacus, located at -25° latitude and 85° longitude, which is a relatively high elevation region on the southeast slopes of the giant Tharsis volcanic bulge.

During 1973 Solis Lacus was the site of origin of a huge dust storm. During the second day of the storm Dr. McCord, Gary Johnson (his graduate student), and I took some images of the planet at several colors using a special instrument developed by Dr. McCord for use on Earth-based telescopes. We discovered in the blue-color images a huge ring of ground haze and frost surrounding the central dust cloud. We published our findings in ICARUS in
1977 and argued that the H₂O in these frosts and hazes had been evaporated out of the central Solis Lacus region at the onset of the storm and it condensed as frost and haze in the colder regions surrounding the storm system. The solar heating at the time of the storm was higher than at any other time of the year, but it was capable of evaporating only the most weakly bound forms of H₂O (water, ice, frost, or weakly adsorbed H₂O) and only from the uppermost few centimeters of topsoil. In order to form the amount of frost and haze that we saw, there was at least several hundredths of a gram of H₂O per gram of soil evaporated from Solis Lacus. Therefore unlike the highly desiccated soils that apparently comprise most of the surface, the soils in Solis Lacus apparently contain appreciable quantities of weakly-bound H₂O.

We are not the only ones to have seen such phenomena in the Solis Lacus region. They were reported during 1971 and 1956, in both cases at the onsets of great dust storms, and in both cases they occurred in the vicinity of Solis Lacus even though during 1971 the dust clouds were well to the east. The fact that these phenomena in the past preferentially appeared in this region even when the dust storms were in other regions suggests that an unusually large reservoir of H₂O may be stored in Solis Lacus. The reservoir apparently extends to within a few centimeters of the surface and replenishes the large evaporative losses produced by the highly desiccating surface environment.

This is further supported by Earth-based telescope measurements of the composition of the Solis Lacus dust clouds during the 1973 storm. The observations were published in ICARUS in 1977 by Dr. McCord, Douglas Mink, Carle Pieters and I and in a subsequent publication by Dr. Kristine Andersen (my graduate student at the time) and I the data were interpreted as indicating that the dust cloud material was more hydrated than the rest of the surface material. This provided independent evidence that there is an anomalous reservoir of H₂O in the Solis Lacus region.

Additional supporting evidence was provided by two Viking orbiter experiments, the Water Vapor Mapper and the Infrared Thermal Mapper experiments. The Water Vapor Mapper revealed that during late Southern Winter, when the atmospheric water vapor abundances were showing rapid increases in the southern hemisphere, there was an anomalously large water vapor abundance over Solis Lacus. The Infrared Thermal Mapper revealed that Solis Lacus cools at an anomalously slow rate after sunset and in the predawn hours the temperature of Solis Lacus was significantly higher than the surrounding terrain. Again this is consistent with a water reservoir in that region, since damp soils can conduct heat better than dry soils and as a result they retain more heat and cool more slowly.

Biologically speaking there couldn't be a more interesting spot on the planet for there to be an anomalous H₂O reservoir. It is one of the warmest spots on the planet during the summer, reaching daytime temperatures as high as 290°K, i.e. above 65°F. In fact, the daytime temperatures in Solis Lacus exceed the melting point of ice from late southern winter to late southern summer, which is over half of the year. This raises the possibility that liquid water may exist near the surface. It is well known that liquid water is not stable at the martian surface due to the low surface pressures; however it is stable under 1-2 cm of topsoil.

Furthermore when you consider the amounts of salts in the soil revealed by the Viking Inorganic Analysis experiment the possibility that liquid H₂O may exist near the surface is enhanced. These salts can lower the freezing point of water by as much as 30-40 °C, thus extending the length of the year during which the H₂O can be stable as a liquid. In fact it extends the period to almost the entire year.
MARS: EVIDENCE FOR AN OASIS...

R. L. Huguenin

It should also be pointed out that such a near-surface source of liquid H₂O should prevent the formation of the oxidants that were observed during the Viking biology experiments, and so Solis Lacus might indeed be a hospitable spot for at least some life forms on an otherwise quite hostile planet.
Meteorites can be conveniently divided into two broad groups: the primitive meteorites and the differentiated meteorites. The primitive meteorites are those that have escaped planetary processes such as melting and still contain a chemical record of the time when the solar system was a cloud of gas and dust. Among the primitive meteorites are a class of stony meteorites called chondrites and possibly some iron meteorites. On the other hand, the differentiated meteorites have experienced melting and crystallization processes and only poorly record events that occurred in the solar nebula. Among the differentiated meteorites are most iron and stony-iron meteorites and the stony meteorites called achondrites.

The basaltic achondrite group of differentiated meteorites is a group of meteorites of diverse types. It includes the eucrites which are basalts similar to the common basalts on earth, the diogenites which are composed almost entirely of the mineral pyroxene, the howardites which are mechanical mixtures of eucrite-like and diogenite-like material and the mesosiderites which are similar to the howardites but contain about 50 percent by weight of iron-nickel metal. All of these four meteorite types are thought to have crystallized in the crust of an asteroid about 400-800 km (240-480 mi) in diameter. Two other meteorite types which may be related to the four types listed above are the main-group pallasites (composed of approximately equal parts by weight of the mineral olivine and iron-nickel metal) and the IIIAB iron meteorites. The pallasites and IIIAB irons are believed to have been formed in the core of an asteroid that was on the order of 400 km (240 mi) in diameter [1].

Because the variations in chemistry and mineralogy of these meteorites can be understood as having arisen during melting and crystallization processes and because the isotopic composition of oxygen in their minerals are similar [2], it is possible that all of these six meteorite types were formed in the same parent body asteroid. These meteorites make up about one-third of all irons and about 4/5 of all achondrites and stony-irons, hence, they strongly influence our thoughts concerning asteroidal differentiation (melting and crystallization).

Early theories of asteroid differentiation suggested that the eucrites, howardites, diogenites, pallasites and irons formed in an asteroid that was once totally molten [3]. Separation of the liquid metal from the silicate liquid and fractional crystallization resulted in a zoned asteroid. The irons formed the core of the asteroid and the basaltic eucrites crystallized as the crust. In between the zones of pallasites, olivine (not represented by any known meteorites), diogenites and howardites. More recent research has shown that the eucrites are not the product of the fractional crystallization of a large magma body, but rather are quenched (that is, rapidly crystallized) primary melts similar to the basalts on earth [4]. This melting took place very early in the history of the solar system. The ages of these basalts are about 4.5-4.6 billion years (e.g. [5]).
In an attempt to better understand the nature of the differentiation processes which occurred on asteroidal sized bodies, a suite of igneous materials were separated from four howardites and six mesosiderites for study. Techniques used include microscopic examination to determine the textures of the rocks, electron microprobe analysis to determine mineral compositions and instrumental neutron activation analysis (INAA) to determine the chemistry of the rocks. In addition to these igneous clasts, several samples of eucrites and diogenites were studied by INAA.

By considering the various models which are capable of explaining the resulting geochemical data from these meteorites, it is possible to infer certain characteristics for their parent asteroid and the heating process which caused melting:

1. The parent asteroid was not uniform in composition. A basaltic fragment from the howardite Petersburg has a ratio of the elements lanthanum (La) to lutetium (Lu) equal to 1.4 when compared to the ratio in chondritic meteorites. The eucrites (basalts) Pasamonte and Bereba have a ratio of lanthanum to lutetium equal to 1.0 compared to chondritic meteorites and yet, the concentration of lutetium in these two eucrites is identical to that in the basalt from Petersburg. All of these samples are believed to represent primary melts (that is, they have not lost any material during crystallization). During melting, both lanthanum (La) and lutetium (Lu) are concentrated in the magma. Therefore, as the percent of melting increases the ratio La/Lu decreases and the concentrations of La and Lu in the melt decrease. Since the amounts of Lu in Bereba, Pasamonte and the Petersburg clast are the same but the ratios of La to Lu are different, one must conclude that the melts were produced in separate regions of the asteroid that were slightly different in composition. This conclusion is supported by the ratio of iron to magnesium in these three basalts. This ratio in the Petersburg clast is lower than that observed in any of the primary melt eucrites and further points to differences in composition of the source regions.

2. The amount of melting varied from region to region. Several researchers have attempted to match the concentrations of many elements in eucrite meteorites with those calculated from melting models (e.g., [6], [7]). This modeling has shown that the range of melting necessary to produce all observed eucrites is about 5-20 percent. In addition, the chemistry of the diogenite meteorites suggests that they were formed from magmas produced by more than 20 percent melting [4]. The mesosiderite meteorites contain large crystals of the mineral olivine. The composition of some of these olivines suggest that they may have crystallized from a magma that was a 100 percent melt of a region of the parent asteroid. Therefore, it appears as though heating of the asteroid was not uniform. Some areas were only heated enough to produce a small amount of melt (about 5 percent) whereas other areas were able to completely melt.

3. Multiple generations of basalts were produced from a single source region. The ratios of the elements lanthanum to lutetium and samarium to europium in the basaltic fragments from the Patwar and Vaca Muerta mesosiderites and a fragment from the howardite Jodzie are unlike those in primary melt eucrites. Yet the textures of the first two rocks suggest that they were formed as quenched primary melts. Modeling of melting processes suggests that all
three of these samples may have been formed in a source region that had previously produced a basaltic magma. The unusual concentrations of some elements in these three rocks is due to the earlier formed basalt having removed most of the lanthanum, lutetium, samarium and europium and other elements as well. It is not possible to decide whether the chemical data are the result of two separate melting episodes or whether there was only one melting event with basaltic magmas being removed at two different times.

4. Remelting of earlier formed igneous rocks. The diogenites and some eucrites are cumulates, that is, they were formed by the accumulation of minerals crystallizing from a magma. Among cumulate samples, the diogenite Tatahouine [7] and a fragment from the mesosiderite Clover Springs show unusual abundances of a group of elements called the rare earth elements (or REE). Attempts to model the concentrations of REE in these two samples show that they were most likely formed as a result of two crystallization episodes. This requires that after the first crystallization event, a portion of the resulting cumulate was remelted and crystallized again, causing the unusual concentrations of the REE. To be able to accomplish this, the heating of the asteroid must go through at least two heating and cooling cycles.

The above observations suggest that the heating of the asteroid was variable both from region to region on the asteroid and with time. The simplest interpretation of such heating variations is that the heat source was external to the asteroid and that energy was not uniformly applied to the asteroid's surface. Because only the outer region of the asteroid is heated, rapid loss of heat to space occurs when the heat source is temporarily removed. The magmas that were formed can then crystallize and are available for remelting if the heat source is reactivated. Internal heating, such as by the decay of radioactive elements, is less capable of producing the observed temperature variations. This is because the overlying thick layer of rocky material provides a heat insulation which keeps the internal temperature more uniform.

One possible external heating mechanism is heating by rapid accretion. Accretion is the process by which planets and asteroids grow in size by accumulating loose debris from space. Because the infalling debris releases some of its gravitational energy as heat, if an asteroid can accrete at a rapid enough rate it may be possible to raise the temperature of the outer regions of the asteroid to the melting point. Because accretion is a relatively random process, significant variations in heating of the asteroid can occur.

Problems with this model include the following: (1) Not all large asteroids appear to have been melted. The accretional heating mechanism should affect all asteroids of the same size in a similar fashion. (Note that this problem applies to almost all possible heat sources, external and internal.) (2) Iron cores are unlikely to be formed by external heating of the asteroids. Yet, most iron meteorites appear to have been formed in cores. Where did they come from? and (3) The assumptions normally used to model asteroid accretion lead to insignificant heating, even for the largest asteroids. Is it possible to generate a realistic accretion model that results in melting of asteroids?
ASTEROID DIFFERENTIATION

David W. Mittlefehldt

References:


The Lunatic Asylum at Caltech has made a substantial advance in unraveling the early history of the moon covering the first half billion years. This ancient epoch began with the formation of the moon about 4.5 billion years ago followed by its transformation into crust and mantle. During this period, the moon was subjected to a heavy bombardment with meteorites which ended in a major episode some 3.9 billion years ago when a swarm of giant meteorites collided with the moon. This last major bombardment episode, called the "terminal lunar cataclysm," has almost totally erased direct evidence of the preceding history. The problem of precisely when the moon and its solid crust were formed and what happened during the first 600 million years is of great importance in the evolution of the terrestrial planets.

The major terminal bombardment at about 3.9 billion years, which must have affected both the earth and the moon, has left its scars in the form of huge circular basins which can clearly be seen on the lunar near side. These basins were subsequently flooded by volcanic rocks. Most of the older rocks returned from the moon are called breccias, which are compacted, heated, and often partially melted fragments from pre-existing rocks.

Dating experiments by several different techniques have been carried out on a large number of breccias and have nearly always yielded ages very close to the time of the cataclysm at 3.9 billion years. Some rocks were found to be significantly older than 3.9 billion years and in a very few cases ages up to 4.5 billion years have been measured. Until now it has not been clear what these intermediate ages meant, whether they reflect crustal formation or early bombardment, or whether they were artifacts resulting from mixing of rocks with a variety of different ages. In general, the terminal bombardment obliterated or badly obscured records of specific previous processes. This overprint by the terminal lunar cataclysm posed an almost "opaque" barrier impeding studies of the oldest and most important period of lunar evolution. It became essential to separate the effects of the terminal bombardment in order to clearly identify and date early processes on the moon.

A few rocks returned by the Apollo 17 mission have yielded age data which are exceptions to the scenario outlined above. Applying two different high precision age dating techniques to one of these rocks, F. Oberli, J. C. Huneke, and G. J. Wasserburg were able to obtain a precise impact age of 4.17 billion years by both methods. This is so far the closest agreement of results derived from two independent dating methods for a rock which predated the terminal cataclysm. The time of 4.17 billion years represents the clear imprint of a major impact event on the moon 300 million years before the terminal lunar bombardment. The approach used here may permit a reliable means of establishing the times of major impacts in the moon's early history.

One of the two dating methods also allows the calculation of the time when the rock was originally formed. The resulting age is 4.5 billion years. This is identical to the ages obtained from similar calculations on rocks which were subjected to the terminal cataclysm. The repeated occurrence of the 4.5 billion year age for both Apollo samples with widely different impact ages and some fragments from the Luna 20 mission suggests that the earliest lunar crust was formed at that time. We conclude from our results that it now appears possible to separate the times of impacts and the time of original formation of ancient lunar crustal rocks.
A NEW HETEROGENEOUS ACCRETION MODEL FOR THE INNER PLANETS, ESPECIALLY THE EARTH; J. V. Smith, Dept. of the Geophysical Sciences, The University of Chicago, Chicago, Ill. 60637

The origin of the Earth and other planets from the presumed gas cloud of the original solar nebula involves a sequence of complex processes. A new model described here utilizes the dramatic advances in planetary exploration of the inner planets, typified by the Apollo missions to the Moon and the Viking mission to Mars. The oldest surviving rocks on Earth are only 3.8 billion years old, leaving some seven hundred million years to be accounted for by study of lunar rocks and meteorites. The present model could not have been justified on the basis of information known just ten years ago, and may need drastic revision or even rejection as planetary exploration proceeds. It utilizes ideas developed by many scientists, especially those working in the lunar science program.

Following the theoretical studies of many scientists, accretion (i.e. growth by capture of material) of a planet is assumed to occur by condensation of gas to dust, then of dust to clods, and so on to large planetesimals up to hundreds of kilometers or miles across, as envisaged by Urey, Safronov, Hartmann, Wetherill, etc. Well-known theoretical calculations, reviewed by Grossman and Larimer, show that if the dust remains in equilibrium with the surviving gas, noble metals condense first, followed by calcium, aluminum and titanium in mixed oxides, then magnesium silicates and iron, nickel metal, and so on to the more volatile elements. Some iron reacts at low temperature with oxygen from the gas to form iron oxide, and some reacts with sulfur to form iron sulfide. Some silicate reacts to form hydrated silicate at low temperature. The Clark-Turekian-Grossman model for direct addition to planets of these materials in the above order of condensation is rejected because of problems in explaining the origin of meteorites if planetesimals of various compositions had not developed.

Small bodies jostle each other resulting in circular orbits. By chance, a few bodies capture their neighbors. Initially only nearby material is captured, but as bodies grow they can pull in other bodies from greater and greater distances. Some of these other bodies are captured by direct collision, but some just miss capture and are sling-shotted into non-circular orbits. Another group of bodies disintegrates. In each "feeding-zone" of a planet, one lucky planetesimal ultimately eats up all the other material. In the zones next to the Sun and Jupiter, the planetesimals are accelerated by gravitational forces from the Sun and Jupiter to high speed and capture is difficult. Considerable amounts of collision debris are generated, and in the feeding-zone for Mercury the lighter silicate debris may be preferentially captured by the Sun thereby leaving an extra amount of heavy iron-rich debris to be captured by Mercury. Mars grows slowly because of the high speed of planetesimals accelerated by Jupiter, and the asteroids do not assemble into a single planet. A great mass of material is sling-shotted by Jupiter and the other giant planets into the inner solar system. When such material hits a small planet (Moon, Mercury and Mars) at high speed, most debris is lost because of the low gravitational force, but material hitting a large planet (Earth, Venus) is completely captured. The first feature of the new model is this heterogeneity of accretion with time, starting with nearby material and ending for the larger planets with material which originally condensed near Jupiter. The feeding zones for the inner planets must overlap, especially for Earth and Venus. The Lewis model of planetary accretion is rejected because it does not consider this time variation of accretion. However condensation tends to proceed to lower temperature with...
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increasing distance from the Sun before the remaining gas is blown away by the solar wind.

Asteroids, meteorites and comets provide only fragmentary and distorted evidence on the planetesimals of the inner solar system, but two general factors seem important in conjunction with evidence from the planets themselves. (i) The mineralogies of the iron and stony meteorites require a wide range of oxidizing to non-oxidizing conditions. Reflectance spectra of C-type asteroids, particularly of water-bearing Ceres, indicate oxidizing conditions at least in the outer part of the asteroid belt next to Jupiter. Many iron and stony meteorites (e.g. enstatite meteorites) were formed under non-oxidizing conditions. The original sites for condensation and accretion of their parent planetesimals are unknown, and following Hutchison and Wasson it will be assumed that some mechanism, as yet unidentified, produced non-oxidized planetesimals in the inner solar system. Perhaps the rare E-type asteroids are survivors which were fortuitously deflected outwards into the asteroid belt from the inner solar system. Hence it is suggested that accretion of the inner planets begins with non-oxidizing material and ends with oxidized material, the fraction of the latter being greater for Earth and Venus than for the Moon, Mercury and Mars. Following Turekian, increasing oxidation involves conversion of iron metal to iron oxide (FeO), and conversion of part of the mineral pyroxene (approx. MgSiO₃) to olivine [approx. (Mg,Fe)₂SiO₄]. (ii) Early melting of Mercury and Mars, as advocated by scientists who have recognized volcanic surface features dated by analogy with the Moon, cannot be achieved by plausible concentrations of radioactive heat-producing elements (uranium, thorium, potassium) unless the planets accreted from hot material. Many meteorites crystallized from liquid rock, or were heated while solid to 900-1200°C. S-type asteroids may have crystallized from a liquid, and Vesta certainly has. Accordingly it is assumed that the inner planets began accretion from planetesimals at near-melting temperature, and that melting of each planet began promptly in spite of the then trivial collisional heating from capture.

A third crucial factor for planetary models is the well-known evidence that the outer part of the Earth (now sampled to a depth of 200km (125 miles) from rock fragments brought up in kimberlite pipes) has too high a concentration of noble metals (gold, iridium, etc.) and transition metals (e.g. nickel, cobalt) to have been in equilibrium with Fe,Ni-rich metal, such as is presumed to occur in the Earth's core. Coupled with new evidence for present-day emission of He³ (i.e. helium with three mass units) and other noble gases from the mantle, it is assumed that accretion of the Earth is completed by addition of oxidized volatile-rich material which is prevented from complete reaction with the core by slowness of convection through the mantle. This does not rule out an earlier episode of complete melting and possible fission (i.e. splitting into two parts) to produce the Moon (or even complete volatilization, as in the Ringwood model), but does imply that such processes were confined to a stage before the Earth was (say) 5/6ths of its final volume. It implies that the Earth's mantle of silicate was mostly crystalline and fairly rigid during the last stage of accretion, in spite of the massive energy input from the heat of impact of incoming planetesimals and the energy produced when iron sinks to form the Earth's core. Three factors which could reduce the Earth's temperature at this stage are: (i) slow accretion rate (e.g. 100 million years for accretion of 99.9% mass), (ii) continual transfer of radioactive heat-producing elements (U, Th, K) into volcanic rock at the surface where the heat can escape more easily than if trapped at depth, and (iii) removal of the atmosphere by the solar wind to allow heat loss from hot volcanic rock rather than from a cold layer in the upper atmosphere.
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Fig. 1 shows suggested stages of development of the Earth, which is represented by a pie-shaped slice. At an early stage (a), melting produces a liquid core rich in iron, nickel and sulfur and containing most of the noble metals including gold. The Mg-rich silicate crystallizes mainly into pyroxene to form a mantle with the atomic ratio of metal atoms (M) to silicon near 1. The surface is volcanic with a basaltic composition rich in the elements silicon, magnesium, calcium, aluminum and titanium. Incoming planetesimals may either hit the surface or disintegrate before hitting the surface or be sling-shot away to return again later. The planetesimals are assumed to have already melted into a core of material and a silicate mantle. After impact, the Fe,S-rich material sinks as big globs. Off-center collisions by big planetesimals may rotate the Earth and cause a piece to fly off into orbit. Alternatively, the Moon may begin to grow from accretion of orbiting debris. Probably the Moon grows by a combination of interrelated processes, thereby rendering obsolete the old simple models of simultaneous accretion with the Earth vs. capture of a fully-formed Moon vs. fission from the Earth. Most, if not all, uranium, thorium and potassium should end up in the basaltic surface of the Earth, thereby removing the radioactive elements from the inside. The Earth is not oxidized at this stage.

At an intermediate stage when the Earth is (say) five-sixths grown, incoming planetesimals are tending to come from the Mars side of the Earth rather than the Venus side. They tend to be oxidized, and to contain more olivine (M/Si = 2) than earlier planetesimals. All collision debris is captured by the Earth, but most is lost by the Moon to fall on the Earth. The Earth's mantle is hardening but is unstable because of sinking bodies rich in Fe and S. Increasing pressure causes conversion of silicate to dense phases of which the perovskite structure of (Mg,Fe)SiO$_3$, the periclase structure of (Mg,Fe)O and the garnet structure of Mg, Ca, Al, Cr, Si-rich material are representative. [Perovskite is best known as the mineral of composition CaTiO$_3$, but at high pressure, Ti can be replaced by Si and Ca by Mg and Fe. Periclase has the same structure as common salt with Mg replacing Na and O replacing Cl].

Nowadays (c), part of the Earth's core has crystallized thereby releasing heat to drive the dynamo for the magnetic field. The inner core is solid iron-nickel alloy, while the outer core is a liquid containing iron, nickel, sulfur, phosphorus, carbon, noble metals, and perhaps nitrogen. If the mantle has not attained a state of equilibrium, it might be zoned chemically from an interior with M/Si less than the exterior. Accretion and melting processes might have yielded the radial variation shown for Fe/Mg and (Mg+Fe)/Si but convection or "bubbling" of the mantle might have changed these variations. Furthermore the interior might be non-oxidizing and the exterior oxidizing and richer in volatile elements. This suggestion is complicated by problems caused by the change of oxidation state of iron with high pressure. In the uppermost mantle, the rocks are mainly peridotite and eclogite, some of which contain diamond. [Peridotite is a rock containing olivine, pyroxenes and either garnet, spinel or plagioclase. Eclogite contains garnet and pyroxene]. With increasing depth, pyroxene transforms to garnet and olivine to the β-structure. [The β-structure is like olivine except for the method of placing adjacent atoms]. Ilmenite and perovskite structures are important at greater depth, and even denser structures further down.

Loss of hydrogen from water vapor in the upper atmosphere yields free oxygen which can oxidize the Earth's surface. Highly speculative is a suggestion that an inward wave of oxidation is converting elemental carbon into carbon dioxide which is leaking out to the surface, causing local melting on its way. Also speculative is a suggestion that the surface plates
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[i.e. blocks of the Earth's surface which participate in plate tectonics] are hardening and will drive deeper into the mantle in future millenia thereby triggering release of Na-rich material which is deduced to occur abundantly in the lower mantle.

For Mercury, the model predicts iron-poor or iron-free silicates and the surface may not be "anorthositic" (i.e. dominated by feldspar rich in calcium and sodium) as currently proposed.

Venus should have a similar history to the Earth, except for capture of all its orbiting debris, and effects caused by a higher surface temperature (470°C). Perhaps Venus lost nearly all its hydrogen because of poor retention in silicates rendered unstable by the high temperature, and the inward wave of oxidation may be stronger than on Earth. Sulfur could be stable in sulfates and feldspathoid minerals at the surface. The mantle could contain less iron than the Earth's mantle if the planetesimals in the feeding zone of Venus were less oxidized than in the Earth's zone.

Predictions for Mars are uncertain because it may lie near the transition from non-oxidized to oxidized planetesimals, and because of Jupiter's slingshotting of planetesimals. A simple assumption is that Mars tends to resemble S-type asteroids. If so, its core would contain Fe,Ni and S rather than an earlier suggestion of magnetite (Fe3O4).

Full details with extensive credits to other scientists (including ideas from Ringwood, whose model of cool accretion and late volatilization of the Earth is the antithesis of the present model) are given in the Hallimond Lecture for the Centenary of the Mineralogical Society of Great Britain and Ireland, published in March 1979 issue of Mineralogical Magazine, available by mail from Mineralogical Society, 41 Queen's Gate, London SW7 5HR, England. Supported by NASA (Lunar and Planetary Science Programs) and NSF (Geochemistry).

Press enquiries answered at 312-753-8110 after March 26, (9am-4pm preferred). Glossy prints available.
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Fig. 1. Three stages of development of the Earth. (a) Early stage of accretion from hot differentiated planetesimals. A S-rich core is growing from diapirs sinking through a reduced pyroxene-rich mantle. Most or all U,K goes into basaltic liquid. The Moon may result from fission or disintegrative capture. (b) Later stage in which mantle is hardening and planetesimals are more oxidized. High-pressure minerals are forming in the lower mantle. (c) Present stage with solid inner core, and complex high-pressure mineralogy in mantle. Is an oxidation wave moving inwards?
ANCIENT SOLAR WIND IN LUNAR MICROBRECIA

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The moon has several unique features which make it especially suitable as a monitor of the space environment over the history of the solar system. In contrast to the earth, it has no atmosphere and no magnetic field, so that atoms and ions which impinge upon the moon either from the sun or from interstellar space are able to reach the rocky surface and become embedded in mineral grains. In contrast to the meteorites, which have also been exposed to solar and cosmic radiations, the moon's location within the solar system over its entire life is known. Also, its sub-surface layers provide samples which were exposed at the surface at earlier times, and which therefore provide an historical record of the activity of the sun and the cosmic rays. Another important advantage of lunar samples over meteorites is that the latter have suffered substantial mass loss during their fiery passage through the terrestrial atmosphere.

It is known from measurements on lunar igneous rocks that the moon as a whole is strongly depleted in the very volatile chemical elements that usually constitute the atmospheres of the larger planets: hydrogen, carbon, nitrogen and the noble gases (helium, neon, argon, krypton and xenon). However, the lunar soil, which is a layer averaging about five meters (16 feet) in thickness, is found to contain substantial quantities of these volatile elements. Since the soil is derived primarily by the grinding up of underlying rock by meteoric impact, its volatile elements must be derived either from impacting projectiles or from some other extralunar source. By far the most abundant volatile elements in the lunar soil are hydrogen and helium. These are rare elements in meteorites but are the predominant elements in the sun. Hydrogen and helium, in the form of positively charged ions, are also the principal constituents of the solar wind, the constant flow of particles from the sun outward into the solar system. Thus the solar wind is the obvious source of hydrogen and helium in lunar soils. By comparing the solar abundances of carbon, nitrogen and the noble gases with the solar abundances of hydrogen and helium, we can conclude that the principal source of these elements in the lunar soil is also the sun.

Because of the continual stirring action of meteorite impacts, the lunar soil does not provide a simple continuous stratigraphic sequence akin to the layers of sedimentary rocks exposed on earth in the Grand Canyon. As a result, the core samples taken by the astronauts at depths of as much as 2.5 meters (8 feet) show evidence of a complicated history of deposition and erosion. Nevertheless, samples taken from greater depths have generally had their surface exposures at earlier times, and samples from the bottom of the regolith may be composed of particles which were on the lunar surface shortly after the major rock-forming processes occurred some 3.5 to 4.0 billion years ago. In the present work, we present results which indicate that certain samples from the Apollo 11 mission were derived from a region deep within the soil layer, and as such they provide a sample of the solar wind as it existed 3.5 billion years ago. We find a substantial difference between the composition of the ancient solar wind and the present-day wind, which implies the occurrence of solar processes which were not anticipated on the basis of our theoretical and observational understanding of how the sun works.
ANCIENT SOLAR WIND
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The experiments involve the determination of the relative abundances of the two stable isotopes of nitrogen, $^{15}\text{N}$ and $^{14}\text{N}$ in lunar soils. In previous studies it was shown that the ratio $^{15}\text{N}/^{14}\text{N}$ in present-day solar wind is about 12% greater than the ratio in nitrogen of the terrestrial atmosphere. Earlier evidence also showed that nitrogen in soils from the deepest drill cores (and hence of greatest age) had $^{15}\text{N}/^{14}\text{N}$ ratios about 10% lower than the atmospheric value. In our research, we have found a group of Apollo 11 samples with even lower ratios: about 19% below the terrestrial standard. Thus the combined evidence indicates at least a 31% increase in the $^{15}\text{N}/^{14}\text{N}$ ratio in the solar wind over a period of 3-4 billion years. This variation presumably reflects an increase in the amount of $^{15}\text{N}$ in the surface layers of the sun. This observation, along with the recognition by Fireman of production of radioactive $^{14}\text{C}$ in the surface of the sun, constitutes evidence for a substantial amount of nuclear processing in the outer part of the sun, or a substantial mixing of matter between the inner and outer parts, both of which were unexpected.

No deep drill cores were taken during the Apollo 11 mission, in which sampling techniques were much more "primitive" than in the Apollo 15, 16 and 17 missions. However, the moon itself apparently has a process for excavating a deep soil sample, whereby the lower soil layers are compressed against the underlying "hard" basement rock by an impacting meteorite, producing newly formed rocks which are deposited on the surface. These "instant rocks" are the "soil breccias", or Apollo 11 type D rocks, which were considered the least interesting of the lunar sample types when they were returned in 1969. We have also measured in these samples the amount of $^{15}\text{N}$ produced by nuclear interaction of the high energy cosmic rays, which originate outside our solar system, with the atoms in the lunar soil. The cosmic ray effects penetrate to depths of two or three meters and produce a set of characteristic reaction products which allows a determination of the length of time during which a sample resided within that depth interval. The Apollo 11 soil breccias have such a "cosmic ray exposure age" of about 2.5 billion years. This age is two to three times greater than had been found for any other lunar samples, again attesting to the great antiquity of these samples.

Finally the cosmic ray exposure age determined by the $^{15}\text{N}$ method is compared with the age determined from the amount of $^{21}\text{Ne}$ (another cosmic ray produced nuclide) which has been measured in many lunar samples. It is found that the amounts of $^{21}\text{Ne}$ are systematically low, and more so for older samples. Apparently significant amounts of neon leak out of the mineral grains over long periods of time. Neon is lost preferentially to nitrogen since the former is chemically inert, whereas the latter is strongly bound, probably as a nitride ion. A consequence of this neon loss is that the time-scale for turnover of the lunar soil by impacts should be substantially longer than previously thought, and that the probability of retrieving very old soils, and perhaps longer undisturbed sequences, is greater than believed until now.

Basalt magma (molten or partially molten lava) appears to have erupted on all of the terrestrial planets: Mercury, Venus, Earth, the Moon, Mars, and some of the asteroids. Basalts on the Earth have been extensively studied for well over a century, but it has only been in the last ten years, with the advent of lunar exploration and growing interest in basaltic meteorites, that enough information is available for us to begin to look for systematic differences between basalts on different planets and to try to understand what controls the types of basalts which have erupted on each planet. Can we say from study of basalts from the Earth and the Moon and of certain types of meteorites what types of basalts will be found on Mercury or Mars or Venus? Mercury is between the Earth and the Moon in size, much closer to the Sun than the Earth, Moon, or presumably the asteroidal bodies from which meteorites have come, and it probably differs considerably in composition from other planets. From this list of differences between Mercury and the planets from which basalts have been studied, one might be pessimistic about predicting anything about its basalts. However, it appears that the size of a planet may be the most important factor in determining certain of the characteristics of its volcanism. Although the only way to be really sure of the types of basalts on Mercury is to actually go there, it is nevertheless possible to make a number of predictions about what will be found there simply on the basis of its size. These predictions may be of help in planning for the actual exploration of the other planets. When the interior of a planet begins to melt, the composition of the resulting liquid — or "melt" — is determined by what minerals are present. Furthermore, since the chemical reactions are sensitive to pressure, the depth at which the reactions occur is important as well. Once melt escapes from the area within a planet where it is produced and begins to rise to the cooler surface regions, it cools and decompresses. If it rises fast enough, no change in the chemistry of the melt occurs and a "primary" magma erupts. However, if the ascent is slow or is interrupted by stagnation in shallow magma reservoirs before eruption, cooling at low pressures may cause some crystallization to occur. This process — fractionation — can cause the melt chemistry to change and the resulting composition is determined by the pressure(s) at which the fractionation occurs. Magmas then erupted are said to have experienced secondary differentiation. A survey of observed basalt compositions shows the extent to which the process has occurred in the Earth, the Moon and the asteroids.

The composition of the most voluminous eruptions on the Moon, known as Fra Mauro basalts, suggests that they originated as partial melts of the lunar crust (1) which then underwent secondary differentiation; (2) the control was at low pressure.

An investigation of the basalts from the parent body of the eucrite meteorites (possibly asteroid 4 Vesta) showed that control was also encountered at low pressure for these samples; (3) however, there was very little compositional variation in the suite, indicating that the effects of secondary differentiation were small.
BASALTS AND PLANET SIZE


Recently the basaltic rocks erupted at the submarine ridges of Earth's ocean basins have been recognized as the most voluminous eruptives on Earth. They are similar in this respect to the Moon's Fra Mauro basalts and the eucrite parent planet's basalts. Professor M. J. O'Hara, of the University of Edinburgh, showed over ten years ago that these compositions showed strong effects of secondary differentiation at low pressures. (4) This conclusion has been recently confirmed (5,6,7). The important point is that control was at low pressure on all three bodies despite the great range in their sizes (~100 km for EPB; ~6000 km for Earth). With this as background, it would be surprising if the majority of basalt samples from Mercury, Venus and Mars did not also show a major chemical control by saturation equilibration at low pressures, since this condition seems to be the rule on the planets sampled so far.

There are significant differences among the planets, however, which appear to be determined by planet size. In contrast to the Moon and eucrite parent body, where the saturating minerals were plagioclase feldspar, olivine, and low-calcium pyroxene, the terrestrial ocean-ridge basalts equilibrated at low pressures with high-calcium pyroxene instead of low-calcium pyroxene. This difference is due to Earth's layer size and the greater pressures it develops at depth compared to the Moon or eucrite parent body. The primary melts produced by melting planetary interiors have a higher high-calcium/low-calcium pyroxene ratio as pressure increases (4,8). Both lunar Fra Mauro basalts and terrestrial ocean ridge basalts may be produced by melting as deep as ~60 km down. But this depth corresponds to a pressure of ~20,000 atm. on the Earth as compared to only ~3,000 atm. on the Moon. Consequently the terrestrial melts are much richer in high-calcium pyroxene than their lunar counterparts. Lunar basalts can be generated from regions under ~20,000 atm. pressure at depths of ~400 km. Indeed, these are found in the mare basins and have a higher high-calcium/low calcium pyroxene ratio, but the volume of these eruptives is inferior to the highlands volcanism. The eucrite parent planet appears to have been small enough so that melts with important high-calcium pyroxene were not generated.

A number of other properties of eruptives appear to be related to planet size: Earth>Moon>Eucr.ite. A. Hotness — A larger planet has a stronger gravity field and higher internal pressures. The temperature at which melting of planetary material begins increases with pressure. Consequently, when melting begins beneath the cool surface layer of a planet it must do so at a higher temperature on a bigger planet. We might expect bigger planets to erupt hotter magmas. The earth erupted komatiite lavas as hot as ~1600°C in the Archean period; the Moon, ultramafic glasses (~1400°C); and the eucrites erupted relatively cool (~1200°C). B. Endurance — Larger planets have better thermal insulation since they have lower surface area/volume ratios, so they may be expected to remain active longer. This expectation is confirmed by a survey of "closure ages" for basaltic volcanism in the size series eucrite (~4.6 b.y.), Moon (~2.5 b.y.), Earth (still active). Crater chronologies suggest (9) that Mercury and Mars fit this series according to their size. C. Variety — The larger pressure range within, the greater endurance of, and the
possibly higher level of volatile enrichment in larger planets may lead to more variety of eruption products. Terrestrial volcanics show much variety reflecting depth of melting, previous depletions of the source regions, and variable volatile enrichment, among other factors. The Moon produced a pedestrian series of rocks by comparison; while the eucrites are positively barren of variety. D. Fractionation — The stronger gravity field of a large planet is more effective at separating crystals from melt once primary melts leave their source region. We might expect secondary differentiation to be more efficient on a large planet. As many as 1/4 of the eucrites are unaffected by secondary differentiation. However, the incidence of primary magmas on the Moon is only measured in percent, while the proportion of erupted magmas which are primary on Earth is <1% — reflecting efficient secondary differentiation.

It is easy to imagine any number of circumstances which could upset these correlations. Yet the observation that properties A - D do correlate with planet size suggests that planet size is a useful index of eruption character. Other possible general controls such as the details of planet chemistry (or the distance from the sun which may be related to planetary chemical differences) do not seem to exert a strong influence on these properties.

Exceptions to these general rules would be provided by the shergottite, nakhlite and chassignite meteorites if they should prove to come from asteroid-sized objects as is generally assumed. Their high-calcium pyroxene, young, fractionated character is consistent with larger parent bodies. The possible discrepancy would be resolved if they came from a large body. This question and the generality of the size correlations await the exploration and sampling of the rest of the solar system planets.

References: