Papers presented at the
Third Annual
Summer Intern Conference

August 13, 1987
Houston, Texas

1987 Summer Intern Program for Undergraduates
Lunar and Planetary Institute
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* Presented at the August 5, 1987 Intern Seminar.
MARTIAN CRATER INTERIORS: RELATIONSHIPS WITH EJECTA, DIAMETER, LATITUDE AND TERRAIN
Tracy L. Bradley, Department of Geology, University of Alberta, Edmonton, Canada. Advisor: Nadine G. Barlow, Lunar and Planetary Institute.

BACKGROUND
Initial investigation clearly demonstrated the 'fluidized' nature of martian craters as opposed to the ballistic craters seen on the moon and Mercury. Further analyses led to the idea that some relationships may exist between such crater characteristics as interior morphology with terrain, latitude, diameter, and ejecta (Ref 1-4). A study entailing 1558 craters was conducted by Mouginis-Mark (Ref 1) in which he determined a relationship existing between ejecta and terrain. A later study, however, by Mouginis-Mark and Cloutis (Ref 2) contradicted these earliest findings. In 1986, Horner and Greeley determined a slight correspondence existing between ejecta morphology and elevation for the ridged plains. Despite any early indications of trends, though, the databases are insufficient to draw firm conclusions because of their limitations, both in crater numbers and areal extent. The database used for this study, compiled by N.G. Barlow and S.K. Croft, contains over 42 000 craters visible on the Viking 1:2M photomosaics. All craters greater than 8.0 km in diameter were mapped by latitude and longitude, terrain unit, ejecta type, interior morphology, relationship to tectonic features, and degree of ellipticity (Ref 5; Table 1). This data is archived in a computer data management system for ease of access and manipulation of the data. The presence of such a complete database now enables the full investigation of possible relationships between crater characteristics.

ANALYSIS
Manipulation of the database entailed setting certain parameters and manually tallying the number of craters satisfying those conditions. The resulting crater numbers were normalized (1) to the total number of craters satisfying the stated conditions, (2) to the total number of craters displaying interior features and satisfying the specified parameters, and (3) to the total number of craters with the particular interior morphology considered. The intersection and union of various crater characteristics were then graphed in the form of percentage bar-histograms. Histograms were chosen as the analytical tool because any relationships or trends existing in the data would be clearly displayed graphically. Approximately 1600 histograms were plotted for the 3819 craters displaying interior morphology, the majority of which yielded little to no correlation. Of the few which showed some relationship, chi square statistical tests were applied and the results were found to be statistically viable.

RESULTS
The major results obtained from this study are as follows:
(1) Central peak craters (Pk) were found to be distributed fairly evenly amongst all terrains and latitudes, therefore showing no presence of an underlying control to their formation. There appears to be, however, a slight increase in crater numbers with an increase in diameter size as well as a general concentration in the heavily cratered southern hemisphere (between -5° and -40°).
(2) Flat floor deposits (FD) have a tendency to occur on younger terrains: 65% of all FD craters lie within the sparsely cratered plains (Pls) and mottled plains (Mot) located in the northern hemisphere.
(3) In accordance to previous studies, it was found that 63% of all peak rings (PR) occur on the older heavily cratered uplands (CrP) and have a higher concentration at larger diameters.
(4) Flat floor pristine craters (FP), on the other hand, dominate younger terrains and higher latitudes (Table 2).
(5) Both flat floor deposits and flat floor pristine craters decrease with increasing diameters.
(6) There is no apparent relationship between complex craters (Cx) with latitude, diameter, and ejecta.
(7) Most Pk craters display diverse (Di) or radial lineated (Rd) ejecta and are greater than 120 km.
(8) 72% of all pancake ejecta (Pn) show flat pristine floors (FP) - Table 3.
(9) In terms of increasing diameter, summit pits (sP) dominate up to 45 km, symmetric pits (SY) up to 65 km, followed by asymmetric pits (AP); results confirming a previous study by Croft and Awwiller (Ref 6).
(10) The majority of all ejecta craters (60% of all Un, 40% of all SL, Di and ML craters, 30% of all Pn, and 28% of all DL craters distribution) have Pk interior structure.

CONCLUSIONS
A complete analysis of martian cratering can now be done through the use of a recently developed global-wide database. The relationships between crater interiors in correlation with diameter, terrain, latitude, and ejecta can be investigated thoroughly. It is through the careful analysis of such characteristics that the regional variations in volatile content can be defined. This particular study is only one of many possible ways of analyzing the data. The use of other related data, such as thicknesses of the mantling material, will add additional insight into their study. The next step after the extensive statistical analysis is to look at the global picture with a geological insight and determine the reasons for obtaining such results.

TABLE 1

<table>
<thead>
<tr>
<th>INTERIOR MORPHOLOGY:</th>
<th>EJECTA MORPHOLOGY:</th>
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<tbody>
<tr>
<td>ST-symmetric pit</td>
<td>SL-single lobe</td>
</tr>
<tr>
<td>AP-asymmetric pit</td>
<td>DL-double lobe</td>
</tr>
<tr>
<td>Pf-summit pit</td>
<td>ML-multiple lobe</td>
</tr>
<tr>
<td>Pk-central peak</td>
<td>Rd-radial lineated</td>
</tr>
<tr>
<td>Pr-peak ring</td>
<td>Di-diverse/complex</td>
</tr>
<tr>
<td>FP-flat floor pristine</td>
<td>Un-unclassifiable</td>
</tr>
<tr>
<td>FD-flat floor deposits</td>
<td></td>
</tr>
<tr>
<td>Cx-complex</td>
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TABLE 2

LATITUDE DEPENDENCE OF FD

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<th>20</th>
<th>30</th>
<th>40</th>
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<th>90</th>
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<tbody>
<tr>
<td>FD</td>
<td>0</td>
<td>5</td>
<td>10</td>
<td>15</td>
<td>20</td>
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<td>30</td>
<td>35</td>
<td>40</td>
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TABLE 3

INTERIOR MORPHOLOGY DEPENDENCE - PN (LEPH)

REFERENCES
The 18 June Space Surveillance Center Catalog (SSCCAT) contains 6807 objects which are in orbit around the Earth, 636 of which will cross the space station's orbit. Results of analysis of the distribution of these objects, characterized as payloads, rocket bodies or debris particles, according to inclination, eccentricity, perigee and radar cross section (RCS) are presented. It is assumed that the altitude of the space station will be 500 km and that the orbit will have an eccentricity of zero and an inclination of 28.5°. This research represents one step in a feasibility study for the space station's Debris Impact Avoidance System (DIAS).

Introduction: As the U.S. prepares to inaugurate new space initiatives—the space station, a revitalized shuttle program and possibly SDI—scientists are becoming increasingly concerned with the hazards posed by orbital debris. Four years ago the US Space Command monitored 4,000 Earth orbiting objects, approximately 10 cm in diameter and larger, for the North American Aerospace Defense Command (NORAD). Currently the SSCCAT contains close to 7,000 objects which are in orbit, over half of which are due to more than 80 satellite breakups. The cause of many of these breakups, deliberate or intentional, is predominantly explosions due to either propulsion failures or ASAT testing. A smaller fraction may be due to on-orbit collisions. While NORAD can detect about 200 objects from an explosion, hundreds of additional centimeter-sized objects are also generated. It is estimated that an additional 30,000 objects between 1-10 cm, as well as trillions of paint flakes and aluminum oxide dust particles, are created in fragmentations and contribute heavily to the debris environment (1).

Space Station Debris Environment: Extracting only those objects contained in the SSCCAT having a perigee ≤ 500 km and at the same time an apogee ≥ 500 km yields 636 artificial satellites which will cross the orbit of the space station. In looking for concentrations of objects according to eccentricity and inclination, the entire population has been divided by perigee into ranges incremented by 50 km including one region below 150 km (Fig. 1). The distribution of objects increases with perigee with the exception of the region between 400 km and 450 km. The distribution of payloads, rocket bodies and debris among each region is disimilar and is different from all of the cataloged orbiting objects (Fig 2).

Approximately 12% of all objects in each 50 km incremental region considered are payloads. A "payload" designation implies only that the satellite is intact. It does not imply that the satellite is serving a purpose, as only 5% of all orbiting payloads in the SSCCAT catalog are functioning. Functional or not, the number of intact payloads in a specified region shows what percentage of the debris population is not a partial indicator of an untracked debris environment.

Population Statistics: Although this study takes into account only those 636 objects which have been found to cross the station's orbit, additional members belong to the population. In addition to the SSCCAT, the US Space Command publishes a listing of objects which are not included in the main catalog. These objects are identified by a numerical designation commencing with 80 000. Using the same procedure to determine which objects will intersect 500 km, 164 additional objects are found to belong to the 80 000 series.
Theoretically, this increases the number of objects intersecting 500 km by 25%. It must be emphasized, however, that perigee, apogee, inclination, period and RCS values for the 80 000 series are not always reliable. In addition, many of the objects in this series may not even exist. Highly eccentric or highly inclined orbits characterize many of these objects, which accounts for the low probability of their detection. Although, the orbital parameters of the 80 000 series are not exact, the number of these objects alone is case enough to justify their consideration in any analysis.

Origin of Orbital Debris: Although the U.S.S.R. has put more objects into orbit around the Earth in recent years, approximately 80% of all launches, the lifetimes of these satellites are very short. In 1985, 119 Soviet satellites were launched but only 48 were operational a year later (2). The debris responsibility is shared equally by the U.S. and U.S.S.R. and this distribution had been determined to be consistent among the 636 objects intersecting the space station. For objects crossing the space station's orbit, the U.S. accounts for 46.88% of all debris and rocket bodies, the U.S.S.R. claims 44.74%, while all other countries share the responsibility for the remaining 8.38%. The breakup of the P-78 satellite (Solwind) during 1985 which generated several hundred trackable pieces and countless smaller fragments, presently accounts for 13.4% of all trackable objects in the space station vicinity. No other single satellite debris population in the space station environment was found to be as heavily represented as Solwind.

The 10 fragmentations with the greatest number of associated cataloged debris particles in the space station environment include: Cosmos 1813, January 1987; Cosmos 1260, Aug 1982; Cosmos 1174, Apr 1980; Cosmos 397, Feb 1971; Cosmos 374, Oct 1970; Cosmos 375, Oct 1970; Cosmos 252, Nov 1968; Cosmos 249, Oct 1968; Himwari, Jul 1977 and Solwind, Sept 1985. Alleged ASAT testing accounts for seven of the satellite breakups. The cause of the other three fragmentations were Cosmos 1813, unknown; Cosmos 1260, deliberate fragmentation; Himwari, hypergolic explosion.

Eccentricity, Inclination and RCS Distribution: The objects which intersect the space station's orbit are not distributed uniformly according to eccentricity, inclination, altitude or any other parameter. Analysis of the eccentricity and inclination of each artificial satellite by creating statistical SAS programs delineates the concentration of objects.

The eccentricity of all 636 objects was calculated to look for evidence of non-zero values. The objects were incremented from 0.0 to 0.9 by 0.1. Almost half of the objects considered were determined to have an eccentricity of zero; one-third of all objects have an eccentricity between 0.6 and 0.7--due to U.S.S.R. Molniya (communication) satellites, various Cosmos fragmentations and rocket bodies (Fig.3). Many of the highly eccentric objects are also highly inclined. Below 250 km, essentially all objects are considerably inclined. Between 250 km and 400 km both circular and very eccentric orbits are found. There is a large concentration of 11 payloads found at e=0.1 between 350 and 400 km. Above 400 km the environment is dominated by low eccentricities. In the 450 to 500 km region, a significant payload population, five Molniya satellites at e=0.7 and six Cosmos satellites at e=0.0, are found.

Most U.S. hardware is located at inclinations -30° while U.S.S.R. satellites are generally distributed at inclinations between 60° and 70° (Fig.4). In addition, a large concentration of objects between 450 and 500 km have an inclination -100°--primarily due to debris from Solwind. Approximately seventy percent of all artificial satellites have inclinations near these values. The remaining objects are distributed randomly. There is a peak in the distribution between 250 km and 300 km at 30° and between 350 km and 400 km at 70°.
One half all the objects analysed have RCS values less than one square meter (Fig 5) and almost 75% have RCS values below five square meters. Of all the objects in this region 4% do not have determined RCS values. The population of large objects (>1 square meter) is substantial and correlates with the fact that there is a greater percentage of rocket bodies, which have large RCS values, found at these lower altitudes. The existence of so many large objects may need to be taken into account in the design of DIAS. In addition, the presence of a population of objects with large RCS values means that there is a large percentage of objects which are likely targets for small debris particles.

Debris Decay Rate: Granted space is self-cleaning to a certain extent, however, the rate of input of orbital debris far exceeds the rate of decay. After one year only 10% of the 636 objects studied were determined to have decayed. If the current annual launch rate (100/yr) continues, the additional contribution of debris to very low Earth orbits will increase the risk of a debris collision with the space station or other large scale space operations. At present, the rate of deposition and the rate of decay show no signs of attaining equilibrium.

Conclusion: Orbital debris poses many potential hazards to the space station. Many questions remain to be answered. In what manner can the population in the space station environment be anticipated to increase? At what rate has it increased over the last 10 years? How do large objects in this region deteriorate? Is there a significant untracked population associated with Cosmos 1813, 1174 and 1260, Solwind and Himwari debris clouds? What is the collisional probability (flux) that the space station may be impacted? What will be the effect of atmospheric drag and the solar cycle on debris--on the space station? Is the natural meteoroid population a threat? How might any of these statistics be anticipated to change? Artificial satellites may render the near-Earth environment useless for space operations in the future unless solutions to controlling the debris environment are found.

Distribution of Payloads, Deb and R/B Intersecting the Space Station's Orbit

![Bar chart showing distribution of payloads based on eccentricity and inclination.]

**fig 3**

![Bar chart showing distribution of payloads based on inclination.]

**fig 4**

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<th>RCS (square meters)</th>
<th>Frequency</th>
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<td>0</td>
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**fig 5**
Massif-type anorthosites are almost always spatially associated with orthopyroxene-bearing acidic intrusives known as the mangeritic-charnockitic series. The tectonic setting of the silicic magmatism and of the associated anorthosite massifs has long been controversial. The silicic rocks were once believed to represent late-stage differentiates of a parent magma that produced the anorthosites (Philpotts, 1969), however, geochemical evidence and field observations are inconsistent with this claim (Ashwal, 1980; Buddington, 1939). It has been suggested, instead, that the mangeritic-charnockitic suites represent anatectic melts produced from the latent heat of crystallization of the anorthosite bodies (Ashwal, 1978). Several workers (e.g. Mclelland, 1986) favor an "anorogenic" setting in which silicic melting takes place in the lower crust in an extensional regime.

We studied mangeritic-charnockitic rocks from the Diana and Stark Complexes in the Adirondack Mountains of New York in an effort to characterize their geochemistry, to compare their characteristics with other Adirondack samples, and to provide possible constraints on tectonic setting. Twenty-four samples were analyzed for major element and selected trace element abundances using X-ray fluorescence. Instrumental neutron activation analysis was employed for rare earth element (REE) and trace element determination. We also examined thin sections of Diana samples, but none were available for Stark Complex rocks. Stark samples were kindly provided by J.W. Valley and J.M. Mclelland.

The Diana Complex is located near a major shear zone (the Carthage-Colton line) associated with the boundary between the granulite terrane of the Adirondack highlands and the amphibolite terrane of the northwest Adirondack lowlands (Buddington, 1939; Hargraves, 1969). Rocks of the Complex have been highly deformed and most are mylonitic. Metamorphic grade is upper amphibolite to lower granulite facies. The Diana Complex is notable for its compositional layering, and has been interpreted by Buddington (1939) as an overturned, gravity-stratified, intrusive syenitic gneiss sheet. The gross composition varies from pyroxene syenite gneiss in the northwest to hornblende quartz syenite gneiss in the southeast. Locally, layers rich in pyroxene and Fe-Ti oxides occur within the syenite and are apparently conformable. The Stark Complex is a similar body of quartz syenitic rocks some 30 km northeast of the Diana Complex, but compared to Diana, Stark is less deformed (Brock, 1980). Pyroxene - Fe-Ti oxide layers have not been identified in the Stark Complex. In both complexes, the dominant lithology is pyroxene- and/or hornblende quartz syenite gneiss. Plagioclase is a minor phase except in local layers. Rocks from both complexes are unusually rich in accessory minerals (zircon and apatite), and constitute up to 5% of some samples.

For the Diana Complex, Si02 ranges from 59.2% to 65.9%, although the oxide-pyroxene cumulate (sample DC-4) has about 38% Si02. Stark Complex samples show a larger range of Si02 (61.4 - 71.1), and therefore, may be slightly more evolved. Chondrite normalized REE abundances of the Diana and Stark Complexes are shown in Figures 1 and 2. The smooth and nearly straight trending patterns
of most samples are parallel and characterized by conspicuous negative Eu anomalies. For Diana samples, REE abundances correlate very well with P2O5, and to a lesser degree, with Zr, suggesting that accessory phases apatite and zircon largely control REE abundances. An extreme example is represented by sample DC-4, which contains 2.5 wt.% P2O5 and over 2500 ppm Zr. Stark samples show no such correlations, but instead, Th correlates with REE, suggesting control by monazite or some other Th-rich accessory phase. These data collectively imply that the LIL-rich accessory minerals behaved as cumulate phases, although we cannot constrain whether gravitational accumulation or other processes were responsible. Two Diana samples (DC-6 and DC-7) are unusually plagioclase-rich (50-60 modal %) and have distinct positive Eu anomalies, indicating probable plagioclase accumulation.

The Diana and Stark Complexes have remarkably similar REE patterns, although Stark has slightly higher total REE, consistent with its somewhat more evolved character (e.g., higher SiO2). Another major mangerite-charnockite body of the Adirondacks (the Tupper-Saranac Complex) also has similar REE characteristics (Haskin and Seifert, unpublished data). The coherence in these patterns strongly suggests a similar origin for the three mangeritic-charnockitic complexes. The lack of variation of light REE among these samples indicates that insufficient spread in Sm/Nd exists to attempt age determinations by the Sm-Nd method.

The application of trace elements to the petrogenesis of granitic rocks is quite complex considering the various processes and starting materials involved in the generation of acidic melts. Geochemical discriminators of tectonic setting for granitoid rocks have been suggested both for major elements (e.g., Batchelor and Bowden, 1985) and trace elements (e.g. Pearce et al., 1984). McLelland (1986) has used major element discrimination diagrams to propose an "anorogenic" origin for silicic plutonic rocks of the Adirondacks. However, for the Adirondack granitoids studied here, the Pearce-type trace elements discrimination diagrams are inconclusive. It is interesting that in terms of REE, the Adirondack samples (Figs. 1,2) are more akin to "collisional-type" granitoids (Fig. 3) than "anorogenic" granites (Fig. 4). We believe that a more thorough compilation of trace element (REE, etc.) and isotopic data for granitoids from different tectonic settings, especially those from well established collisional and rift-related terranes should be carried out before geochemistry can be used effectively as an indicator of tectonic setting.

References

Figure 1. REE abundances of the Diana Complex.

Figure 2. REE abundances of the Stark Complex.

Figure 3. REE abundances of collisional-type granites of the Himalaya (Debon et al., 1986).

Figure 4. REE abundances of Proterozoic anorogenic granites (Anderson, 1983).

The following is a continuation of the study of high-resolution thermal data of Mars collected by the Viking 1 and 2 Orbiters. Past studies have included the regions contained in 30°S to 30°N latitude and 45°W to 225°W longitude. The regions now examined are the Oxia Palus (0° to 30°N, 0° to 45°W), and Margaritifer Sinus (30°S to 0°, 0° to 45°W) quadrangles. The purpose of this study is to examine specific geomorphic features as they correspond to the recorded thermal data, in particular, aeolian features, craters, and outflow channels.

The Oxia Palus quadrangle is regionally characterized by a series of outflow channels and scattered craters, and it contains Chryse Planitia, the landing site of Viking Lander 1. The Margaritifer Sinus quadrangle is characterized by more heavily cratered terrain, and highlighted in the Northwest subquad by chaotic terrain at the lower end of Vallis Marineris, the origin of the outflow channels in the upper quadrangle (1). Both quadrangles have regionally higher thermal inertias than much of the planet (2,3).

Measurements from both Viking orbiters were used, and were subject to several constraints (range < 1500 km, emission angle < 60°, consideration of quality, and hour between 19H and 5H for nighttime sequences, and between 10H and 14H for daytime sequences, where H is 1/24th of a Martian solar day and is referenced to midnight). A series of adjustments were made to the data, then, in order to more accurately interpret their significance. In response to timing errors during data collection, trends in thermal inertia were matched to specific geologic features, producing a positional shift affecting the entire sequence. Following this, the recorded thermal inertias were visually compared to regional values for thermal inertia and adjusted accordingly. An elevation correction was also incorporated into this procedure, but this made only a minimal difference owing to the consistent nature of the topography throughout both quadrangles.

Several important observations of have been made from this entire process. Wind streaks, which have been studied on other parts of the planet (4), have shown comparable values of thermal inertia in this region. This may indicate that the same grain-sized material collects on the lee side of craters both in regions of high and low thermal inertia.

Also in agreement with previous studies (5,6,7,8), craters in both quadrangles showed a significantly higher pattern of thermal inertia than in their surroundings, indicating a collection of aeolian material in the interior of the crater. Values for these observed thermal inertias are consistent with particles of medium to coarse sand size (5).

Lastly, and most significantly, several data sequences crossed outflow channels in the upper quadrangle, and an increase in thermal inertia on the channel floor was clearly seen. The sequence that crossed the upper reach of the Ares Vallis (Fig. 1) showed a pattern for thermal inertia consistent with the contours of the channel. On examination, no aeolian material was visible within this portion of the channel, which may indicate that the variation in thermal inertia is a result of the channel itself, and not any aeolian material inside of it, as has been observed before. Previous studies of Martian channels have indicated both that no channel features were seen that did not contain aeolian material (9), and that only regional increases were observed in areas containing outflow channels (2). In the first case, only
nighttime sequences were examined, where this study examines both day and nighttime sequences, and it is actually in the daytime sequences where these channels are observed. In the second case, only medium spatial resolution data (30 by 30 km) was examined, while this study examines high spatial resolution data (2 by 5 km). Further, the lower reach of the Ares Vallis (Fig. 2), was crossed by two sequences, both indicating an increase in thermal inertia, but a slightly smaller increase than at the upper reach, which may be interpreted as the decrease in particle size for deposits along the length of the channel, which is in agreement with sedimentological conditions.

A statistical treatment of the data collected for these two quadrangles reveals two significant results. These regions can be characterized by a combination of medium albedo features and high thermal inertia, where previous studies (6,7,8) have shown an inverse correlation between albedo and thermal inertia; high albedo/low thermal inertia, medium albedo/medium thermal inertia, low albedo/high thermal inertia. And, in agreement with our findings, the channel's median value for thermal inertia (T.I.-9), is one thermal inertia unit higher than the surrounding plains' median value (T.I.-8). (The units of thermal inertia are $10^{-3}$ cal cm$^2$ sec$^{-1/2}$ K$^{-1}$). The entire range of thermal inertia values observed over this region was between 4 and 18.

In conclusion, these results seem to indicate that for the first time in studies of this sort, the regions in question, known to be of relatively high thermal inertia, are free from the blanketing, wind-blown dust found in other regions, and are therefore more successfully subject to correspondence between specific geological features, namely outflow channels, and variations in thermal inertia.


Figure 1. Figure 2.
SODIUM AND POTASSIUM IN THE ATMOSPHERE OF MERCURY
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Recent detections of sodium and potassium emission features in the atmosphere of Mercury at or near their solar Fraunhofer lines in Mercury's reflectance spectrum are attributed to resonance scattering of sunlight from sodium and potassium vapors at rest with respect to Mercury.1,2 Data collected from observations conducted at the Kitt Peak National Observatory in December 1986, February, and April 1987, using the McMath Telescope complex, were analysed. The spectral information obtained were processed into data images and used in the investigation of the abundance of both sodium and potassium. The motion of the sodium atoms in the planet's atmosphere was also studied.

Data Acquisition
A. E. Potter† and T. H. Morgan discovered sodium D line emission in the spectrum of Mercury in January, 1985, and potassium emission in November, 1985 using ground-based telescopes and spectrometers. The rapid orbital motion of Mercury enabled frequent observations of the planet at varying locations on its orbit with changing radial velocities and radiation pressure. Temporal and spatial variations in the intensities of the emission were observed and continuous measurements of the emission led to research on the diffusion pattern of the elements in the atmosphere.

The spectral information mentioned earlier were collected with the spectrograph aligned along the celestial north-south or east-west axes. The slit lengths exceeded the apparent diameter of the planet, and the sky background was subtracted from the composite spectra. These spectra were obtained during daytime and contained emission from the atmosphere, reflected light from the surface, and terrestrial water and oxygen absorption lines. The emissions coincided with the bright disk of the observed planet. Moreover, the Doppler shifts of the resonance lines as well as the solar spectrum correspond to the radial velocities of Mercury relative to the Earth and the Sun.3

Numerical Analysis
The equivalent widths of the sodium D₁ and D₂ lines were calculated by measuring the area bounded by the emission line profile and the area computed was used to determine the equivalent width relative to the solar continuum outside the sodium Fraunhofer lines. This area involved is proportional to the intensity of the D line. Each line of the pair (D₁ and D₂) was observed under similar situations using the same instrument at the same time and the ratio of the area under their respective emission lines is equal to the ratio of the total intensities.4 For the observations from December 1986 through June 1987, the baseline of the emission peaks were estimated by curve fitting. A computer program employing third to fifth order equations was used to extrapolate the continuum on either side of the emission line.

The D₂ to D₁ oscillator strength ratio is around 2.0 for optically thin sodium vapor.5 The north-south and east-west scans made in December 1986 near maximum radiation pressure and in February and April 1987 near minimum pressure yielded ratios between 0.1 and 8.0. It is believed that the sodium D lines were observed under varying atmospheric conditions with different background noise. D₂/D₁ can be further corrected by observing both emission lines together so that the data obtained will have identical background signals and observing time will be reduced by half. To determine the sodium column density of this optically dense vapor, detailed radiation transfer calculation6,7,8 was necessary. Assuming a mean temperature of 500 K, which corresponds to the surface temperature about 45° away from the subsolar point, Morgan and Potter analyzed the spectral data collected within the last year and discovered a decrease of sodium abundance with increasing solar radiation pressure. Further research showed that under high radiation pressure, sodium is displaced towards the terminator, and a north-south asymmetry may also exist.
The distribution of atmospheric potassium was studied using the same techniques except that there is one emission line and only the area under that emission profile need to be calculated. The Fraunhofer line is located at 7699Å and its abundance was calculated from the equivalent widths given by Chamberlain. The observations gave a Na/K abundance ratio of approximately 200. The weak potassium emission lines in the spectra were only detectable near the poles and suggest a concentration of the element in that region of the planet as opposed to the minimum column density around the poles and the equator detected in November 1985. This phenomenon is not yet understood and larger ensembles of the data need to be obtained from prolonged exposures (around sixty minutes) of the spectrograph to the planet to improve the signal to noise ratio.

Sources and Sinks
The Na/K abundance ratio is determined by the relative velocities of their supply (source) and loss (sink) processes. There are on average a total of around 3.7*10^28 atoms of sodium and 4*10^26 atoms of potassium in the sunlit atmosphere. The average loss rate was estimated to be at least 2.5*10^22 atoms sec^-1 thus implying a supply of stronger magnitude. Source mechanisms are believed to include photo-sputtering and vaporization by meteoroid impact. Of the two processes, the later provides a continuing and major source of sodium. Sodium vapor is produced by the impacting meteorites and the regolith. The supply rate depends on the spatial mass density, velocity distribution, and sodium abundance of the meteorite as well as the elemental abundance of sodium in the regolith.

Both sodium and potassium are alkali metals with similar chemical and physical behaviors. Since the production processes of the two vapors are similar, the high abundance ratio between them must be a result of fractionation of sodium versus potassium. Possible sinks are photoionization and thermal escape assisted by radiation pressure. H. A. Zook calculated the mean impact velocities of the meteorites to be 3.5*10^6 m sec^-1 and the escape velocity of Mercury is found to be 4.25*10^3 m sec^-1. The atoms released are initially at very high kinetic temperatures in the range from 2500 K to 5000 K. These high-velocity atoms, especially those along the terminator, could spend sufficient time above the Mercurian surface to be swept off the planet by radiation pressure. It was also suggested that radiation pressure might push some of the sodium to the dark side of the planet and thus reduce the amount of sodium visible on the observed sunlit side. This explains the decrease in sodium abundance with increasing radiation pressure mentioned earlier regardless of the fact that sodium and potassium have high atomic weights and thermal escape should be negligible. The maximum radiation pressure for sodium along the orbit of Mercury is 1.62 m sec^-2 and is 2.52 m sec^-2 for potassium. The resulting critical velocities for sodium and potassium are 60 m sec^-1 and 46 m sec^-1 respectively so that the fraction of atoms of each species with sufficient escape velocities are about the same. Solar wind can sweep away ions produced by photoionization and is a major sink process of atmospheric gases. The photoionization rate of potassium is 40% higher than that of sodium so that potassium is more readily lost than sodium and should account largely for the high sodium to potassium abundance ratio.

Diffusion of the gases. Discussion
With a knowledge of the above source and loss processes, an attempt was made to study the diffusion of sodium in Mercury's atmosphere. The study, if successful, should also apply to the motion of the potassium atoms. Since sodium and potassium have appreciable atomic masses, the atoms are expected to approach a Maxwellian distribution in statistical equilibrium because multiple-phonon exchanges are highly probable. H. A. Zook (1987) assumed that sodium atoms do not adhere to the Mercurian surface and their velocity distribution should be that of a Maxwell Boltzmann gas at the surface temperature. A classical diffusion equation in spherical coordinates was used to relate the rate of flow of sodium atoms with time across a vertical column normal to the surface with the flux of the particles due to diffusion and mass flow. This flux is a differential equation involving the drift velocity of the particles as well as the diffusion coefficient of the gradient of particle flow. The diffusion coefficient calculated from statistical mechanics was further modified through consideration of the effect of radiation pressure. These values, with both time and angular dependence, are used in the on-going development of a FORTRAN program to compute a 201 by 401 array of the column density as a function of time and the angle between the subsolar point and the axis of the column. The output of the program is expected to provide insight on the planetary distribution of sodium and potassium.
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SCANNING ELECTRON MICROSCOPE STUDY OF METALLIC IRON ASSOCIATED WITH LUNAR AGGLUTINATES

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INTRODUCTION: Lunar agglutinates are glassy aggregates of glass, minerals and iron that are formed when a small meteorite hits soil particles on the lunar surface. The high velocity impact melts some of the soil and mixes it with unmelted soil. As the agglutinate forms, outgassing occurs creating vesicles. Fine dust particles become imbedded in the surface giving it a cinder-like appearance. Agglutinates are not formed on the Earth because the decelerating effect of the earth's atmosphere on micrometeorites prevents the high velocity impacts of these small objects on the earth's surface (1).

Agglutinates can be used to determine lunar soil maturity. Previous studies have shown that a high agglutinate content corresponds to a high FMR index \( I(s)/FeO \), and that agglutinates are the primary carrier of the single-domain iron responsible for this FMR signal (1,2). Agglutinates may be a valuable source of metallic iron, oxygen, aluminum and titanium when a lunar base is established.

The purpose of this study was to catalog the different types of metallic iron found in agglutinates, to determine whether carbon is present in agglutinates and where it is located, and to determine whether the metallic iron is from the reduction of FeO or from meteoritic sources.

PROCEDURE: Thirteen whole agglutinates from soil 10084,853 were handpicked, cleaned, mounted and coated with gold-palladium. In addition, a polished thin section of soil 10084,853 was ion etched to enhance agglutinate structure then was coated with gold-palladium.

Photomicrographs were taken of all the samples on either the ISI SR 50 or the JEOL CF 35 scanning electron microscopes (SEM's) in the JSC Solar System Exploration Division electron microscope laboratory. Qualitative analysis was done on the samples by means of the PGT energy dispersive x-ray analysis system (EDAX). A beryllium window detector was used to analyze elements heavier than sodium (\( z = 11 \)); thin window and open window detectors were used to analyze the lighter elements, such as carbon and oxygen.

RESULTS AND DISCUSSION: Based on morphology and size, four main types of iron can be differentiated in the lunar agglutinates: blebs, chains, ameboids and particles. Blebs are isolated hemispherical mounds of iron which are found on many smooth, glassy surfaces. They are occasionally found on some rough surfaces. Blebs are commonly larger than 150 nm. Chains are trails of small iron droplets that are also hemispherical mounds. Individual iron droplets within the chains get progressively smaller from the beginning of the chain until the drops are no longer visible. The droplets are mostly smaller than 150 nm. Chains are common morphological features on smooth, glassy surfaces both where blebs are present and where blebs are absent. Ameboids are asymmetrical iron mounds which are interconnected and often starfish shaped. They are less common than the blebs and chains but are often found in the same areas. The average size of ameboids is larger than 150-200 nm. Parts
or irregular forms are considered to be all other iron or carbon-rich particles which are generally larger than 150 nm. Most have irregular shapes although many are rectangular or mound-like. Few were molten. Irregular particles are often found in the same area with the other feature types.

Three likely sources of the metallic iron found in agglutinates are, 1) impact-induced reduction of FeO by solar wind implanted carbon and hydrogen, 2) iron from the impacting meteorite and 3) iron derived from pre-existing regolith iron including indigenous lunar iron.

Carbon is associated with much of the metallic iron found in the agglutinates. The maximum solubility of graphite in solid iron is approximately 2%. Carbon solubility increases in liquid iron as the temperature increases. At a temperature of about 1500 degrees Celsius, 5% by weight carbon can dissolve in liquid iron (Fig. 1) (3). If the liquid was quenched the carbon would be dispersed throughout the solid iron. If significant carbon and metallic iron are sufficiently heated iron carbide will form, possibly in the eutectic form. Iron carbide can contain up to 7% by weight carbon. Thus carbon is likely to be associated with the iron droplets as both carbon in solution and iron carbide.

On the agglutinate surfaces, carbon is associated with all of the feature types. Figure 2 shows the percentage of features containing carbon.

Several sources for the presence of carbon in agglutinates have been suggested. Solar wind is believed to be a major source of carbon in the lunar regolith (4,5,6). Meteorites are another possible source of available carbon (4,5,6). Very little carbon is considered to be indigenous to the moon. The total carbon content of a lunar soil can also be a soil maturity indicator (7).

Meteoritic iron commonly contains 3 to 5% nickel (8). Indigenous lunar iron also contains some nickel. If no nickel is present in an iron feature associated with an agglutinate, then it is unlikely that that feature was derived directly from meteoritic iron. These iron features may have formed by direct reduction of iron in the silicate melt. Detectable nickel was found in 38% of the blebs, 5% of the chains and 30% of the ameboids (fig. 4).

Some sulfur is indigenous to the moon and some is present in meteorites. Most of the sulfur found in the agglutinates was associated with the iron as troilite (FeS) mounds. Very small amounts were found in some blebs and ameboids (fig. 5). Reduced iron would not be expected to contain any significant amount of sulfur.

CONCLUSION: Three distinct types of iron were found both on the surface and in the interior of the agglutinates. These are blebs, chains and ameboids. In addition, many iron-rich irregular particles were found on the surface. It is not certain at this time how many different types of particles exist.

No definite conclusion as to the origin of the metallic iron can be reached at this time. It is possible that the chain-type metallic iron is from carbon-reduced or hydrogen-reduced FeO because of the negligible amount of nickel and sulfur present. The blebs and ameboids have a higher nickel and sulfur content than the surrounding glass which may mean they are of meteoritic origin (Table 1).

Carbon was found in the iron blebs and chains, and in small carbon-rich fragments adhering to the agglutinate surface.
Quantitative analysis was not done on these samples so it is not certain how much carbon is present in each feature.

The carbon associated with the iron blebs and chains may be present as carbon in solution with the iron, although this carbon should not exceed a few percent in the iron. Carbon may also be present as iron carbide. Iron carbide contains about 7% carbon by weight. The source of the carbon may be either solar wind or from micrometeorites. The presence of carbon-rich fragments resembling interplanetary dust particles on the surface of an agglutinate suggests that carbon derived from micrometeorites may not be uncommon.

| TABLE 1: PERCENTAGE OF AGGLUTINATE SURFACE FEATURES CONTAINING VARIOUS ELEMENTS |
|-----------------------------------|-----------------|-----------------|-----------------|-----------------|
|                                   | BLEB  | CHAIN  | AMEBOID  | PARTICLE | GLASS |
| FE                                | 100   | 100    | 100      | 92        | 100  |
| SI                                | 97    | 100    | 100      | 100       | 100  |
| AL                                | 70    | 100    | 100      | 92        | 100  |
| MG                                | 68    | 91     | 80       | 83        | 100  |
| CA                                | 92    | 100    | 100      | 92        | 100  |
| TI                                | 73    | 82     | 100      | 87        | 100  |
| C                                 | 32    | 38     | 0        | 39        | 60   |
| S                                 | 38    | 9      | 20       | 4         | 20   |
| NI                                | 38    | 5      | 30       | 0         | 0    |
| O                                 | 24    | 38     | 0        | 39        | 60   |
| K                                 | 3     | 5      | 20       | 22        | 20   |
| CR                                | 11    | 5      | 30       | 26        | 20   |
| P                                 | 5     | 9      | 0        | 0         | 0    |
| NA                                | 3     | 0      | 0        | 4         | 0    |

Figure 1: Solubility of Carbon
REFERENCES

HYDROGEN ABUNDANCE IN LUNAR SOIL
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As plans for an operational space station and lunar base are being formulated, the possibility of utilizing lunar resources is being recognized. Use of these materials may significantly reduce the costs of operating these facilities. One of the necessary resources is hydrogen, which is found in the lunar soil. It must be determined whether it will be economically feasible to extract and utilize this hydrogen in the reduction of ilmenite for iron metal and oxygen and in the production of water and fuel. It is necessary to determine both the abundance and distribution of hydrogen in lunar soils so that sites and processes may be chosen and developed efficiently.

Soil samples from three cores from Apollos 16 and 17 and twelve breccias from Apollos 11 and 17 were analyzed using a vacuum pyrolysis technique (1). Samples were heated at 900°C (three minutes for soils, a total of nine minutes for breccias), and the liberated hydrogen was injected directly into a VALCO Model 1000 gas chromatograph equipped with a helium ionization detector. The carrier was 92 ppm nitrogen in helium. Standard curves were obtained using a standard gas of 99.2 ppm hydrogen in helium. The response was linear in the range of interest (10-700 ng).

A general trend was observed in the hydrogen content of soils and breccias. It was found that breccias tended to be enriched in hydrogen relative to lunar soils. It had been previously observed that basalts generally had lower hydrogen concentrations than lunar soils (2). These observations help in the interpretation of the data obtained, and may be significant in the choice of the location of a lunar base which would use hydrogen as a resource.

A strong correlation between hydrogen abundance in the cores and the $I_s/FeO$ maturity was noted. It was also observed that fine-grained soils usually contained more hydrogen and were more mature than coarse-grained samples.

The Apollo 16 Deep Drill Core was collected on the Cayley regolith at Station 10, the site of the heat flow experiment included in the Apollo Lunar Surface Experiment Package (3). A good correlation between hydrogen content and $I_s/FeO$ maturity was apparent in the lower two-thirds of the core (Fig. 1). The soil was very immature towards the lower end of the core. It has been suggested that this section was not exposed at the lunar surface for a significant length of time (4). The exact reasons for the poorer correlation in the upper part of the core are unknown. A partial explanation may involve the fact that the upper sections of the core were disturbed sometime during the lunar core collection and transfer process (5).

The Apollo 17 Deep Drill Core was collected approximately 650m southeast of Camelot Crater in the Taurus-Littrow Valley at the ALSEP site (5). There was an excellent correlation between the hydrogen abundance and $I_s/FeO$ profiles (Fig. 2). The core may be divided into three sections. The upper 107 cm is coarse-grained (6) with the most immature soil located in the 20-60 cm zone (7). The center section, about 76 cm, is fine-grained and more mature. The lowest section contains medium-coarse to very fine grains (6). The hydrogen abundances reflect these variations within the core.

The 79002/1 double drive tube was collected about 70m south of the Van Serg Crater in the Taurus-Littrow Valley (8). The $I_s/FeO$ and hydrogen abundance correlation
is excellent (Fig. 3). The upper part of the core is characterized by dark grey, loosely packed material with soil breccias and clods prevalent. The lower part of the core is lighter in color and basalt and glasses are dominant (8). The hydrogen concentration in this section of the core is lower than that of the upper section, agreeing well with the previously mentioned observations.

If an efficient and economical extraction process can be developed, it may be possible to utilize the hydrogen present in lunar soils and breccias in the support of a lunar base and space station. Even if the amount is insufficient for use as a propellant, there may be an adequate supply for industrial and life support uses. One proposed use of hydrogen is in the reduction of ilmenite to iron and oxygen products (9):

\[
\text{FeTiO}_3 + \text{H}_2 \rightarrow \text{Fe} + \text{TiO}_2 + \text{H}_2\text{O} \rightarrow \text{H}_2 + \frac{1}{2} \text{O}_2
\]

cycle electrolysis

Future study will serve to evaluate the feasibility of utilizing lunar hydrogen as a supporting material.

PALEOCLIMATIC RECONSTRUCTION AND NEOTECTONIC INVESTIGATION OF THE PLUVIAL LAKES OF THE EASTERN GREAT BASIN, USA. Stephan J. MoJzsis, Department of Geology, Boston University; Bruce G. Bills, Lunar and Planetary Institute, Houston.

The Quaternary Period (1.8 My ago to present), is exemplified by periods of extreme climatic fluctuations in the form of repeated glacial/pluvial and interglacial/interpluvial episodes. Lake Bonneville was the largest of the late Pleistocene (0.7 My and younger) lakes in the Western Hemisphere that was of non-glacial origin during the time of the Wisconsinan ice age (Currey, 1986). Bonneville had a profound affect on the topography of the Eastern Great Basin, dominating the hydrography and applying hydro-isostatic downwarping to the region (Gilbert, 1890; Crittenden, 1963; Currey, 1982). The primary purpose of this report is to provide information of fundamental importance to paleoclimatic reconstruction of events and neotectonic analysis in the Great Basin based upon study of the pluvial lakes west of the Bonneville Basin as sensitive tilt and climate meters.

Lake Bonneville, which covered much of NW Utah, parts of SE Idaho and NE Nevada during it's height, was first studied by Gilbert (1890) who recognized the changing nature of the lake over time by mapping the paleoshoreline features that remained from the last pluvial interval and deducing the hydro-isostatic downwarping of the crust in the region. Since that time, much information has been compiled regarding Lake Bonneville, and it's affect on tilting in the Great Basin. Little work has been done however, in linking the processes that are observed to have occurred in the Bonneville Basin with those seen in the many small pluvial elements of the Basin and Range Province.

Nineteen lakes have been identified in the Eastern Great Basin that were contemporaneous with Lake Bonneville. Four of these (Spring, Maxey, Franklin(-Ruby) and Clover) were chosen for the present study because of their: 1) excellent preservation of shorelines, 2) close proximity to the Bonneville Basin, 3) sufficient size to contain recognizable features, 4) closed lacustrine/climate sensitive systems, and 5) accessibility of data in topographic and air photo coverage.

PRIMARY GOALS:

The objective of this study has been to link the shoreline features of the paleo-lakes of the Eastern Great Basin to known, datable lacustrine stillstands represented by beach ridges in the Bonneville Basin.

Another goal is to determine the extent to which the Bonneville load depressed the crust, in regions beyond it's own shorelines, to cause tilting. Tilting that makes itself evident in the analysis of ancient beach ridges present in these small pluvial lakes.

Lastly, since many of these small lakes in the Great Basin had no drainage outlet, fluctuations in the lake area should serve as sensitive climate indicators that may shed new light on the climate of the late Pleistocene.

SOURCES OF INFORMATION:

Paleoshoreline segments other than those of maximum extent (Mifflin and Wheat, 1979; Snyder and Langbein, 1962) for the pluvial lakes west of the Bonneville Basin have not been compiled. Previous studies examined the climatic implications of the highest shorelines of these valleys. Shoreline continuity of different ages for the Spring Valley, Ruby Valley and Clover Valley basins had to be undertaken.

1) A preliminary field reconnaissances was made to the Bonneville Basin of Utah and Lakes Spring and Maxey in NE Nevada.
2) Depositional and erosional segments of shorelines of specific ages were differentiated and mapped from aerial photographs. Close to 100 HAP photographs provided complete coverage of the area of interest.

3) Hundreds of sites of particular major shoreline groups were measured stereoscopically and topographically for elevation determination, and plotted according to their specific coordinates.

4) Shorelines plotted and drafted on the topo maps were digitized and the lake surface areas of four major lake level stillstands were established.

5) Cross-sections through the thalweg of Lakes Spring and Maxey were carried out from information provided on 7.5 min. topo quads, and parallax measurement of aerial photographs.

6) A total of 40, 7.5 min. topo quads were used that covered the shoreline exposures of Lakes Spring, Maxey, Franklin, Ruby and Clover.

**METHODOLOGY:**

1) Geomorphic and sedimentologic interpretations were made of the unique shoreline development of the north end of Lake Spring. (see photo). Interestingly, prevailing southerly winds at time of deposition resulted in wave action and longshore transport onto the shallow slope of the north shore (avg. grade=0.04%) that created beach ridges of unusual clarity and exaggeration.

2) Reconstruction of lake level fluctuation history (figure 2) of Lake Spring was possible by identifying, mapping and surveying five distinctive major shorelines. These shorelines can be placed into three “packets”: three high shorelines, one low shoreline and one intermediate.

3) Correlation has been made between the five major shorelines in Lake Spring and Comparable events of known age seen in the Bonneville Basin.

4) An elevation profile along the thalweg of the basins of Lakes Spring and Maxey was plotted (with vert. scale exaggerated for ease of identification - see figure 3).

**RESULTS**

We identified the massive intermediate shoreline of Lakes Spring and Maxey (figs.3,4,photo) with the Stansbury[STANS] Oscillation (figure 1). The three highest major shorelines correspond to the Keg Mountain Oscillation [KMO]. The highest shoreline can be correlated with the pre-KMO [PRKMO] transgression, the second highest with the post-KMO [PTKMO] transgression and the third regressive shoreline is representative of the mid-KMO [MIKMO] minimum. The lowest well developed shoreline corresponds to the Gilbert [GILB] Oscillation.

Points of elevation for each of the PRKMO (~17000yrs), PTKMO (~15000yrs), STANS (~23000yrs) and GILB (~11000yrs) equivalent shorelines of Lake Spring and their coordinates allowed us to calculate the tilt experienced by each shoreline by the Bonneville downwarping at time of deposition. This was done by applying a plane to the points and measuring the amount of tilt from the horizontal. Results have fitted extrapolations made based on the tilting observed in the Snake Valley arm of Lake Bonneville.

Interpretations of the PRKMO, PTKMO, MIKMO, STANS and GILB shorelines were applied to the basins of Maxey, Franklin-Ruby (one system in much of their history) and Lake Clover. Lake Maxey was shown to have regularly spilled over into it’s neighbor to the north, Lake Spring. This meant that after the STANS level, Spring’s drainage basin area increased dramatically with the addition of Maxey. This explains why Spring was observed to have occupied a significantly larger fraction of it’s drainage basin (27%) than Maxey (17%).

**CONCLUSIONS:**

It can be seen that shorelines present within the pluvial lakes of the Eastern Great Basin illustrate that the region shared the same climatic
fluctuations as the Bonneville Basin (as expected due to their close proximities to each other). Also, the major shorelines present in these small lakes correspond convincingly with those observed and dated in Lake Bonneville (that were not due to threshold controls, but by climatic factors). Tilting of the paleolakes of northeastern Nevada lessened as the load of of Lake Bonneville went down and the climate became dryer. Additionally, tilting of the basins is observed to decrease as a function of distance away from the depocenter of the Bonneville Basin downwarping. Lake Maxey, throughout a significant part of its history, overflowed into Lake Spring resulting in the differences in their pluvial hydrologic index values. The lower still stand of the PTKMO with respect to the PRKMO indicates a change in the evapotranspiration:precipitation ratio of the climate from ~17000yrs to ~15000yrs ago that was not previously recognized.

photo 1: north shore of Lake Spring showing shoreline development.
References:


PETROGRAPHIC ANALYSIS OF PLANAR FEATURES IN QUARTZ AT THE PROPOSED UVALDE IMPACT SITE. Diane Nielsen, Cornell University, Ithaca, NY. Advisor: V. L. Sharpton, Lunar and Planetary Institute, Houston, TX.

Introduction. The Uvalde (Bee Bluff) structure in South Texas is listed as a probable impact crater in the literature [1] based largely on structural evidence [2]. The suspected target rocks are Eocene Carrizo sandstones and El Indio calcareous shales. The ~2.5 km diameter impact site is topographically expressed by a low arcuate ridge consisting of folded and faulted sandstone (Fig. 1). We have undertaken a detailed petrographic analysis of sandstones and breccias from the impact area to determine the occurrence and characteristics of deformation features in quartz which are diagnostic of impact cratering.

Observations. Table 1 summarizes the prominent petrographic characteristics observed in our samples. Some of the samples contain severely fractured grains (Table 1), similar in appearance to sandstone samples from Meteor Crater, Arizona. The fractures are conchoidal and stained uniformly with hematite. Up to three percent of the quartz grains in the sandstones and the breccias contain single or multiple sets of planar cleavages and lamellae. These features are visually similar to those documented at known impact craters [3,4,5,6]. The planar cleavages are usually hematite-stained, straight to slightly curved, and constitute parallel to sub-parallel sets of features (Fig. 2). The planes may or may not have decorations. Sets of planar cleavages with 3 to 5 planes per set have variable separation distances, whereas sets with abundant planes have fairly constant separation distances. The lamellae are very closely-spaced features (<10 µm) and are typically unstained, straight, parallel, undecorated, and are most often observed as single sets (Fig. 3). They generally extend over the whole grain, whereas the cleavages often do not. The maximum number of sets of planar features found in a single grain is four.

Quartz overgrowths in crystallographic continuity with the sand grains are evident in several samples (Table 1). The original grain boundaries are marked by conspicuous hematite bands. Planar features present in such grains never cross the original grain boundaries (Fig. 2). Many of the fractures, however, do, suggesting that the fractures either postdate the planar features, or that they have subsequently propagated.

Using a universal stage, we measured the attitudes of planar features with respect to the optic axes in various sandstone samples in the impact area (Fig. 4). The majority of the cleavages have attitudes that are consistent with rational crystallographic orientations. The planar cleavages show a strong peak corresponding to the r,z(1011) crystallographic planes, and a subordinate peak about π(1012). The lamellae show a maxima between 20-30°, the ω(1013) orientation, and a lesser peak at r,z.

Analysis. The r,z crystallographic orientations are characteristic of shock pressures between 50 and 100 kbar, which is in the lower range for shock deformation features in quartz [5,7]. Planar features occurring along the π and ω crystallographic planes are indicative of higher pressures, between 100-380 kbar [5]. Sub-parallel cleavages are also indicative of low shock pressures [4].

To test whether the planar features observed originated from a local shock event, control samples in the same sandstone unit were collected 15 km and 135 km east of the crater (Table 1). Planar features were found in all
three samples taken 15 km east of the crater. The frequency and general characteristics of these features were comparable to those from within the impact area. Of the two samples collected 135 km away from the crater, we found five grains with planar features.

Discussion. The characteristics and attitudes of planar features observed in samples from the Uvalde structure are similar to those found in weakly shocked facies at several well-studied impact craters [3,4,5]. The occurrence of planar features away from the proposed impact area suggests, however, that alternative explanations for the features must be investigated. The frequency of intersecting sets of planar features and the attitudes of the planes with respect to the c-axes of the grains is not consistent with the characteristics of tectonic (Boehm) lamellae [5]. It has been recently suggested that explosive volcanic eruptions are capable of producing shock pressures high enough to create planar features in quartz [8], but these features are infrequent in number and rarely occur as multiple sets [9]. In addition, there is no evidence for Eocene volcanism in south Texas.

The scarcity of planar features 135 km from the impact area argues against a shocked source area for the sands. A larger impact structure or multiple impacts could be responsible for the occurrence of features 15 km to the east of the proposed site, but no topographic or structural evidence has been found to support this conclusion. We have found no indication of high levels of shock such as diaplectic glass or multiple sets of lamellae like those found in the floor rocks of the Lake St. Martin crater. In addition, we have found no occurrence of impact breccias at the impact site. The breccias we analyzed have calcareous matrices, abundant hematite, and altered clasts, suggesting that these breccias are of sedimentary origin (Table 1). We cannot discount the possibility that severe diagenetic effects related to the formation of extensive caliche deposits may have produced planar features in quartz that resemble weakly shocked quartz grains. Numerous studies of sandstones, however, have not documented such a phenomenon and the characteristics of deformational shock features in quartz are believed to be unique to the cratering process [6]. The absence of breccia dikes and indicators of higher levels of shock metamorphism do not preclude an impact origin, as the samples we have studied would be associated with the weakly shocked ejecta facies.

Conclusion. Our analysis supports an impact origin for the Uvalde structure, but significant uncertainties regarding the occurrence of planar features away from the structure and the absence of indicators of higher levels of shock remain. Retrieval and analysis of buried floor materials is necessary to confirm an impact origin.

TABLE 1

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<thead>
<tr>
<th>Sample Location</th>
<th>Lithology</th>
<th>Remarks</th>
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<tbody>
<tr>
<td>U1</td>
<td>Brown quartz sandstone</td>
<td>Large well-rounded quartz grains in a matrix of hematite and small quartz grains</td>
</tr>
<tr>
<td>U2</td>
<td>Brown quartz sandstone</td>
<td>Quartz and hematized clasts in a calcite matrix</td>
</tr>
<tr>
<td>U3</td>
<td>Brown quartz sandstone</td>
<td>Large hematized clasts and polyphase quartz grains in a calcite matrix</td>
</tr>
<tr>
<td>U4</td>
<td>White quartz sandstone</td>
<td>Calcite matrix</td>
</tr>
<tr>
<td>U5</td>
<td>Brown quartz sandstone</td>
<td>Quartz grains and hematized clasts in a calcite matrix</td>
</tr>
<tr>
<td>U6</td>
<td>White quartz sandstone</td>
<td>Pure quartz sandstone, well fractured, abundant overgrowths</td>
</tr>
<tr>
<td>U7</td>
<td>Red quartz sandstone</td>
<td>Graded bedding, well-rounded highly fractured quartz grains</td>
</tr>
<tr>
<td>U8</td>
<td>Brown quartz sandstone</td>
<td>Friable, calcite matrix</td>
</tr>
<tr>
<td>U9</td>
<td>Calcaceous rock</td>
<td>Extremely friable, infrequent quartz grains</td>
</tr>
<tr>
<td>U10</td>
<td>Red quartz sandstone</td>
<td>Well fractured, abundant overgrowths, some semimatrix-fractured</td>
</tr>
<tr>
<td>U11</td>
<td>Red quartz sandstone</td>
<td>Well fractured, abundant overgrowths</td>
</tr>
<tr>
<td>U12</td>
<td>Brown quartz sandstone</td>
<td>Hematized quartz-rich clasts in a planar calcite matrix</td>
</tr>
<tr>
<td>U13</td>
<td>Orange quartz sandstone</td>
<td>Extremely oxidized, some very large quartz grains, accessory Feldspar</td>
</tr>
<tr>
<td>U14</td>
<td>Red quartz sandstone</td>
<td>Well fractured, accessory Feldspar</td>
</tr>
<tr>
<td>U15</td>
<td>Red quartz sandstone</td>
<td>Friable, accessory Feldspar</td>
</tr>
<tr>
<td>U16</td>
<td>Brown quartz sandstone</td>
<td>Well fractured, well-rounded quartz grains</td>
</tr>
<tr>
<td>U17</td>
<td>Red quartz sandstone</td>
<td>Friable, well-rounded quartz grains, accessory Feldspar</td>
</tr>
</tbody>
</table>

Fig. 1. Sample location map (after Wilson and Wilson, 1979).

Fig. 2.

Fig. 3.

Fig. 4. Histograms of measured angles between quartz c-axes and poles to the planar features.
REFRACTORY DUST PARTICLES FROM THE ANTARCTIC DEEP FREEZE

Aurora Pun, California State University, San Francisco, CA, and Michael E. Zolensky, NASA/Johnson Space Center, Houston, TX.

INTRODUCTION The National Aeronautics and Space Administration (NASA/JSC) is actively engaged in the collection and study of interplanetary dust particles (IDP's). These particles are collected from the stratosphere by high-flying aircraft, the ice cap of Greenland and deep sea sediments. Recently, IDP's have also been found in pre-industrial aged Antarctic ice (Zolensky and Webb, 1987). The importance of this discovery lies in the fact that the terrestrial age of these Antarctic IDP's is far greater than other IDP's, and that the possibility of contamination of these IDP's from industrial operations is eliminated.

Approximately one hundred pounds of this pre-industrial aged polar ice was collected from the Far Western Ice Field (FWIF) (76° 54'S, 157° 01'E) and the Allan Hills Main Ice Field (ALHA) (76° 41'S, 159° 17'E) in South Victoria Land, Antarctica. The ice from these localities has been tentatively dated to be <100,000 yrs. and 700,000 yrs. old, respectively (Nishizumi, 1986).

The present study concentrated on the discovery and examination of IDP's which were composed of minerals with refractory compositions. Such minerals are composed predominantly of oxides and silicates of calcium, aluminum and titanium. Since these minerals have high condensation temperatures, they would be the most likely particles to survive the heating, melting and evaporation of early nebular solid material during the proposed T-Tauri stage of the sun (Grossman and Larimer, 1974). Therefore IDP's composed of refractory minerals are presumed to be among the most primitive and least altered particles available for analysis, potentially revealing important information about the early state of the solar nebula.

METHODS The FWIF and ALHA ice was melted and sieved through a series of sequentially stacked nucleopore filters with pore sizes ranging from 1 to 10 micrometers (Zolensky and Webb, 1987). Filters containing particles >10 micrometers were examined using an ISI-SR-50 Scanning Electron Microscope (SEM), and a JEOL 35CF SEM equipped with a PGT System IV Energy Dispersive Spectrometer (EDS) for the collection of chemical analyses. Particles rich in Al and/or Ca were transferred from the filter and placed on holey carbon substrates. These particles were examined with a JEOL 100C Scanning Transmission Electron Microscope (STEM) using Selected Area Electron Diffraction (SAED), which revealed the mineralogy of each particle.

DISCUSSION We examined eight particles from one ALHA filter in detail. The size, surface morphology and mineral composition of these particles are listed in Table 1. The chemical composition of each of these particles is listed in Table 2.

Particle 18 contains kaolinite, $\text{Ti}_4\text{O}_9$ and $\text{Ti}_5\text{O}_9$. These titanium oxides have been previously reported to be found in IDP's (Rietmeijer and Mackinnon, 1987). Kaolinite is a common aqueous alteration product of glass, which is often found in refractory IDP's (Zolensky, 1987). Therefore, the discovery of kaolinite within potential refractory IDP's may be an indication of pre-existing glass. If this were so, there is uncertainty as to whether the alteration episode which produced the kaolinite was terrestrial or pre-terrestrial.
Particles 705A, B, C, and D are fragments from the same large particle. 705A, B and D contain kaolinite and a variety of titanium oxides. 705D also contains ZrTiO₄, which has never been found in any natural material. The titanium oxides found in these particles are from the same family of phases, characterized by the formula Ti₉O₁₉⁻₁ (n⁻⁴ to 10), and have not been found on the earth. Only two titanium oxides from this family have been previously reported from natural material, and this was within Ti-rich chondritic IDP's (Rietmeijer and Mackinnon, 1987). Particle 705C may contain only kaolinite. Further study of these important particles, as well as a remaining large section of particle 705, is necessary in order to determine whether other phases are present within them. Sufficient mass from the parent particle 705 remains for isotopic and other analytical analyses to also be performed.

Particle 27 is composed solely of apatite and particle 42 is solely kaolinite. Both minerals are common terrestrial minerals, although they are also found in extraterrestrial materials. Particle 703V contains calcite and perovskite, minerals found in terrestrial carbonatites but rarely in extraterrestrial material. Thus, there is no compelling evidence that particles 27, 42 and 703V are IDP's.

CONCLUSION Of the eight Antarctic ice-melt particles selected for detailed characterization in this study, four were considered to be probable refractory IDP's. These four particles contain kaolinite and titanium oxides, some of which have been reported to be in other IDP's (Rietmeijer and Mackinnon, 1987). However, many of these titanium oxides have never been reported from natural material, and none have been reported from terrestrial rocks. Detailed mineralogical and (upcoming) isotopic analyses of these unusual phases promises to reveal important details regarding the early history of matter in the solar nebula. The presence of kaolinite within these same materials hints at these potential IDP's suffered an episode of aqueous alteration. We therefore recommend that additional work be performed on these and additional particles from old Antarctic ice.

REFERENCES
### TABLE 1

<table>
<thead>
<tr>
<th>Particle Number</th>
<th>Morphology</th>
<th>Number</th>
<th>Mineral Types</th>
<th>Titanium Oxides</th>
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<tbody>
<tr>
<td>18, 13x13</td>
<td>Fluffy anhedral, Equidimensional</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27, 30x70</td>
<td>Platy subhedral, Irregular</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>42, 25x30</td>
<td>Subhedral, Equidimensional</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>703V, 20x35</td>
<td>Platy subhedral, Irregular</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>705a, 55x55</td>
<td>Platy anhedral, Irregular</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>705b, 25x30</td>
<td>Platy subhedral, Irregular</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>705c, 25x30</td>
<td>Platy subhedral, Irregular</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>705d, 20x35</td>
<td>Platy anhedral, Irregular</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Size, morphology, shape, and mineral composition of eight Interplanetary Dust Particles.

### TABLE 2

<table>
<thead>
<tr>
<th>Particle Number</th>
<th>Major Elements</th>
<th>Minor Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>Si, Ti, Al</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>Ca, P</td>
<td></td>
</tr>
<tr>
<td>42</td>
<td>Al, Si, Cl, Ca</td>
<td>K, S</td>
</tr>
<tr>
<td>703V</td>
<td>Ca, Ti</td>
<td>Si, Fe</td>
</tr>
<tr>
<td>705A</td>
<td>Al, Ti</td>
<td></td>
</tr>
<tr>
<td>705B</td>
<td>Ti, Al</td>
<td>Si</td>
</tr>
<tr>
<td>705C</td>
<td>Al, Si</td>
<td>Ti, Ca, K, Fe</td>
</tr>
<tr>
<td>705D</td>
<td>Si, Al, Ti</td>
<td>Ca, Fe, Zr</td>
</tr>
</tbody>
</table>

Table 2. Qualitative EDS chemical composition of eight refractory Interplanetary Dust Particles.
AC ELECTRICAL CONDUCTIVITY MONITORING OF NUCLEATION AND CRYSTALLIZATION IN THE DIOPSIDE-ANORTHITE SYSTEM. Kevin Righter, Bryn Mawr/Haverford College, Haverford, PA 19041; Advisor: Gordon A. McKay, NASA-JSC, Houston, TX.

INTRODUCTION

Measuring the electrical conductivity of silicate melts as a method of studying their kinetic behavior was suggested and described by Lindstrom (1). Such a capability is useful for three reasons: 1) nucleation is a submicroscopic process and therefore difficult to observe, 2) nucleation is transient in nature, since it depends on small variations in melt density, composition, defect concentration and other characteristics; as a result, incubation times (the time between undercooling and nucleation), for a given composition subjected to the same conditions, will be of random length, 3) crystal-melt interface processes and diffusion processes in a crystallizing melt are of interest to experimental petrologists but difficult to study using traditional methods (2). Tsuchiyama (3) performed isothermal crystallization experiments on compositions in the diopside-anorthite system. Tsuchiyama’s method required quenching, preparing a thin section, and analyzing each of many experimental charges. In situ conductivity monitoring methods can detect nucleation and crystallization without quenching, thin sectioning, or analysis. This study duplicates various aspects of Tsuchiyama’s work, and demonstrates the potential for using conductivity to monitor crystallization kinetics in silicate systems.

EXPERIMENTAL DESCRIPTION

A simple electrical circuit was devised that would allow measurement of two voltages, one across a reference resistor, and the other across a conductivity cell, in order to calculate the conductivity of the experimental charge in the cell (Figure 1). An experimental apparatus was assembled to support a conductivity cell, which included a central electrode, an outer electrode and an experimental charge (Figure 2). The cell was seated in the hot-spot of a one atmosphere vertical furnace with a programmer/controller.

RESULTS

Nucleation, or the onset of crystallization, is easily detectable using the described conductivity monitoring apparatus and circuit. Resistance profiles of isothermal crystallization experiments (Figure 3) consist of five parts: A) initial superheating above the liquidus temperature, B) rapid cooling (1000°C/hr.) to a sub-liquidus temperature, C) incubation period, D) crystallization curve, and E) approach to equilibrium. In 13 identical isothermal crystallization experiments with a Di\textsubscript{80}An\textsubscript{20} composition (liquidus temperature of 1330°C (3)), which included an initial superheating at 1360°C for 5 hours, followed by an undercooling of 70°C below the liquidus, nucleation and crystallization are readily detectable as abrupt changes in resistance. Resistance increases from 79 (± 1.5) to 1300-2200 Ohms when nucleation and crystallization occur. This change in resistance occurs in a range of 7 to 18 minutes. After its initial abrupt increase, resistance gradually decreases over several hours to an equilibrium value of 600-700 Ohms.
Experiments with $\text{Di}_{80}\text{An}_{20}$ also indicate that incubation time is of random length (Table 1, and Figure 4). Incubation times obtained via conductivity measurements are in good general agreement with those of Tsuchiyama (3), in which samples were superheated for 3 hours at 1360°C and undercooled to 70°C below the liquidus. However, data obtained from multiple runs of one experimental charge have longer incubation times (020b-020f). Perhaps cycling of experimental charges destroys more nuclei than the standard superheating procedure. The construction of Tsuchiyama’s nucleation probability curve required approximately 150 separate experimental runs. The method of conductivity monitoring reduces the number of experimental runs necessary for such a construction to only a few.

Contrasting crystal growth rates between $\text{Di}_{69}\text{An}_{31}$ and $\text{Di}_{80}\text{An}_{20}$ in isothermal crystallization experiments are readily discernible when observed with the conductivity monitoring apparatus. Slower crystal growth is evident in a sample of $\text{Di}_{69}\text{An}_{31}$ (liquidus temperature of 1300°C (4)) which underwent an initial superheating of 1480°C for 1.5 hours and an undercooling to 30°C below the liquidus (Figure 5). An approach to equilibrium requires approximately 6 days. Extremely rapid crystal growth occurs in a sample of $\text{Di}_{80}\text{An}_{20}$ (Figure 3, D). However, this rapid growth was followed by a more gradual approach to equilibrium. Studies of crystal growth as a function of initial superheating, undercooling and cooling rates, are easily performed with the conductivity monitoring apparatus.

The AC electrical conductivity monitoring apparatus described can be used to readily study incubation times for nucleation, and study crystal growth rates in silicate systems. Such studies can be done more efficiently and more quickly than traditional methods allow.

REFERENCES

3) Tsuchiyama, Akira (1983) Crystallization kinetics in the system CaMgSi$_2$O$_6$-CaAl$_2$Si$_2$O$_8$: the delay in nucleation of diopside and anorthite, American Mineralogist, 68, 687-698.
**FIGURE 1**

Conductivity Monitoring Experimental Circuit

\[ \sigma = C_{\text{cell}} \left( \frac{V_2}{V_1} \right)^{-1} \]

- Signal Generator
- **IEEE 488 GPIB Connectors**
- AT&T P/C with Lotus 123, Measure, and N.I. GPIB
- Indicators V1, V2, V3

**FIGURE 2**

Conductivity Monitoring Experimental Apparatus

- 0.02 in. Pt Wire
- 0.02 in. Pt 70Rh 30 Wire
- Type S Thermocouple
- Central Electrode 0.008 in. Pt 70Rh 30 Weight
- Notches cut in support rod to stabilize electrodes
- Double strand, twisted, 0.008 in. Pt 70Rh 30 Wire
- Conductivity Cell
- Experiment
- Single strands form 0.125 in. circular loop for conductivity cell
- Outer Electrode

**FIGURE 3**

Composition DI 80

**FIGURE 4**

Incubation Times for DI 80

**FIGURE 5**

Composition DI 69

### Table 1: Incubation Times for DI 80 An 20 Composition

<table>
<thead>
<tr>
<th>Run#</th>
<th>( T_1 ) (Hrs.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>012</td>
<td>3.1 ± 0.25</td>
</tr>
<tr>
<td>013</td>
<td>1.8 ± 0.1</td>
</tr>
<tr>
<td>014</td>
<td>1.8 ± 0.1</td>
</tr>
<tr>
<td>015</td>
<td>0.4 ± 0.1</td>
</tr>
<tr>
<td>017</td>
<td>0.8 ± 0.15</td>
</tr>
<tr>
<td>018</td>
<td>0.4 ± 0.15</td>
</tr>
<tr>
<td>019</td>
<td>0.3 ± 0.025</td>
</tr>
<tr>
<td>020a</td>
<td>0.8 ± 0.1</td>
</tr>
<tr>
<td>020b</td>
<td>8.2 ± 0.1</td>
</tr>
<tr>
<td>020c</td>
<td>10.0 ± 0.1</td>
</tr>
<tr>
<td>020d</td>
<td>6.3 ± 0.1</td>
</tr>
<tr>
<td>020e</td>
<td>62.0 ± 0.1</td>
</tr>
<tr>
<td>020f</td>
<td>17.5 ± 0.1</td>
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</table>
The primary aim of the MARSTHERM project is to develop a software package to thermally model the Martian surface and subsurface, but to be flexible enough to be used for other planets, asteroids, and comets. To achieve this versatility, the code has been constructed with ease of understanding as a prime goal. It is hoped that the clarity of the code will encourage its users to adapt the framework to their more specific needs.

The MARSTHERM thermal model is written in well documented, system independent FORTRAN 77 and uses the method of finite differences to compute the diurnal and seasonal temperature variations at and below the Martian surface. The code avoids the use of special functions found only in some systems--this increases the portability of the software and the ease with which MARSTHERM may be adapted to suit the needs of individual projects.

Throughout the development of MARSTHERM, efforts have been made to minimize the amount of cpu time required to complete the calculations. However, there is another equally important, but conflicting, consideration. The explicit finite difference technique currently being used has a very strict convergence criterium:

\[ \frac{DT(I)}{DZ(I)}^2 < 0.50, \]  

but to prevent oscillations,

\[ \frac{DT(I)}{DZ(I)}^2 < 0.25, \]

where I is the compartment's location below the surface. This stability requirement prevents arbitrarily large DT's. If DT is small then many iterations must be performed before even one year has been analyzed. Additionally, the accumulation of internal round off errors becomes unacceptable as the number of iterations increase. Thus, to avoid this double peril, it becomes necessary to reduce the volume of calculations to a more manageable level.

Fortunately, the stability requirement can be satisfied if DT increases in accordance with the DT-DZ relation. This allows the conflict to be dealt with in a two fold manner. First, the use of a non-constant spatial grid permits fewer sampling points far below the surface, where thermal variations are less frequent and less severe. This grid system still allows for a dense packing of compartments near the surface so that the diurnal variations, which penetrate to a depth of approximately 25 cm, can be carefully analyzed. Second, the use of a non-constant time grid allows the deeper compartments to be iterated less frequently than the upper compartments. This format yields a significant reduction of the number of iterations required to achieve the desired results. As the code now stands, the spatial scaling factor is 1.13 (beginning with the fourth compartment) and the temporal scaling factor is 4; these values result in an 88% savings in cpu time over the constant space-constant time interval scenarios.

The code tests each compartment to determine the largest multiple of 4*DT that can be used between iterations, where DT is the standard unit of time based on the surface compartment’s stability requirements. The result is a system of
compartments which slowly increase in thickness as a function of depth; these compartments are arranged into 6 discrete time levels such that the deepest layers are evaluated only once for every 1024 times that the topmost layers are iterated.

The actual calculation of the heat flow is handled in 3 mutually dependent subroutines. The surface temperature is calculated from information provided by the subroutine which calculates the position and distance of the sun based on the current position of the planet in its orbit. Other factors that are considered include: planetary obliquity, rotation, surface emissivity, albedo, etc. It is from the resulting energy balance equation that the surface temperature can be determined:

\[ S(1-A)\cos(i) + K\left[\frac{dT}{dZ}\right]_{z=0} + FF + L\frac{dm}{dT} + e\sigma T^4 \quad (3) \]

where \( S \) is the solar flux (W/m\(^2\)) at the current position of Mars, \( A \) is the albedo, set to a default of 0.25 (Kieffer, 1977), Angle \( i \) is the angle of incidence for the incoming sunlight, \( k \) is the thermal conductivity, \( \frac{dT}{dZ} \) is the temperature gradient evaluated at the surface, \( FF \) is a correction factor based on the solar insolation (2% of the total), \( L \) is the latent heat of fusion of \( CO_2 \), \( \frac{dm}{dT} \) is the rate of change of the mass of \( CO_2 \) condensed on the surface, \( e \) is the emissivity of the surface, \( \sigma \) is the Stefan-Boltzman constant, and \( T \) is the current surface temperature.

Once the surface temperature has been calculated, the heat flow through the regolith is determined by solving the one dimensional, time dependent heat conduction equation:

\[ \frac{dT}{dt} = k(\rho c) \frac{d^2T}{dz^2} \quad (4) \]

where \( T \) is the temperature, \( k \) is the thermal conductivity, \( \rho \) is the density, and \( c \) is the specific heat. It is at this point that the finite difference technique designed by Sundqvist and Veronis (1979) is utilized to solve the partial differential equation. The technique is based on a Taylor expansion of \( T(t+dt) \) and \( T(t-dt) \). Solving for \( \frac{dT}{dt} \) yields:

\[ \frac{dT}{dt} = \frac{[T(t+dt)-T(t)]}{dt}. \quad (5) \]

From this relation the second derivative follows:

\[ \frac{d^2T}{dz^2} = \frac{dT}{dz_{i+1/2}} - \frac{dT}{dz_{i-1/2}} / 0.5[\frac{dz_i}{dz_{i+1/2} - dz_{i-1/2}}, \quad (6) \]

where,

\[ \frac{dT}{dz_{i+1/2}} = \frac{T_{i+1} - T_i}{dz_i}, \quad (7) \]

and,

\[ \frac{dT}{dz_{i-1/2}} = \frac{T_i - T_{i-1}}{dz_{i-1}}. \]

It is based on this procedure that the thermal model is built and later stored.
The format of this output is determined by the needs of the current user. By altering just a few lines, the data written to the disk file can be changed to include other compartments, all compartments, different intervals etc. Two examples of such results are shown in Figures 1 and 2. Figure 1 illustrates the temperature variations for all compartments down to 6 meters for four $L_e$ values. Figure 2 displays the temperature variations over the course of one Martian year at five depths.

As stated before, MARSTHERM is intended for general distribution as a research and educational tool. There will be periodic updates of MARSTHERM based on interest, input from others, and general advances of sophistication. Plans for future improvements include: the incorporation of alternative finite difference techniques (including the Crank-Nicolson implicit method) to increase speed of operation and reduce errors, a more generalized code to accept the input data files necessary to model other solar system bodies, and the development of a version capable of simulating climatic timescales of tens of millions of years to analyze the effects of time dependent orbital parameters. It is hoped that MARSTHERM, in its present and future incarnations, will continue to provide useful results to all who use it.

REFERENCES


Mare ridges are important structural landforms frequently observed on the lunar nearside, the plains of Mars, and on Mercury. Their origin is tectonic but the exact mechanisms of formation and relevance to the evolution of planetary surfaces are poorly understood [1]. It has recently been proposed from analysis of terrestrial analogs that mare ridges are thrust faults [2]. However, the morphological diversity of lunar mare ridges suggests to us that no single mechanism is responsible for all ridge formation. To provide constraints on the attitudes of faults associated with ridge formation and to understand the regional tectonic environment, we have initiated a detailed analysis of the relationship between ridge morphology, topographic offset, and regional slope. Detailed regional and local topographic profiles with 20X vertical exaggeration were generated from Lunar Topographic Orthophoto Maps (1:250,000 with 100 meter contour intervals) and Apollo 15, 16, and 17 metric stereophotographs. Topographic profiles across Mare Serenitatis along 21°, 23°, 25°, and 27° latitude show a consistent eastward regional slope (figure 1). Topographic profiles across the entire mapped nearside maria along 27° and 30° latitude reflect an overall doming, with Mare Serenitatis sloping to the east and Oceanus Procellarum sloping to the west. Limited profiles generated from widely separated map quadrants along 10° and 30° longitude infer a general slope to the south across the southern half of the nearside maria.

The low viscosity of mare lava and the high eruption rates associated with lunar volcanism dictate initial horizontal emplacement of mare units within a basin [3]. Thus, topographic variations on mare surfaces are presumed to result from post-emplacement tectonic activity. Evidence for post-mare deformation can be seen between Dorsum Smirnov and Aldrovandi in eastern Serenitatis, where a distinct volcanic unit boundary extends north-south across the eastward sloping surface (AS15-0396 metric). The average total decrease in elevation of 430 meters in an eastward direction across the basin is interpreted as an expression of deep-seated structure. Current models for regional and global stress fields, however, are insufficient in explaining the pronounced tilt of Mare Serenitatis. Recognized mechanisms responsible for the tectonic evolution of lunar mascon basins include global thermal contraction and axisymmetric, load-induced compression centered within the basin [4]. The systematic regional tilts across mare basins suggest an additional tectonic component has influenced nearside mare surfaces. The eastward regional slope of Serenitatis and the westward regional slope of Oceanus Procellarum indicate a broad, axisymmetric structural control that is centered between the two basins and one which may coincide with the center of the proposed Procellarum (Gargantua) impact basin [5,6].

It is clear from topographic profiles that ridges are associated with the regional tilting of mare surfaces. The surface of Mare Serenitatis is broken by ridges into vertically offset sections whose slope direction is
generally the same as that of the entire basin. Two tectonic models can account for the pattern of vertical offset and tilt that is observed within Serenitatis. The first calls for a series of imbricate thrust faults dipping to the east and requires significant overthrusting of surface features associated with the ridges. The second model calls for steep, westwardly dipping basement faults that would produce vertical offsets showing vertical translation of pre-existing features with little or no deformation.

Fault attitudes have been approximated by constraining the amount of vertical and horizontal offsets associated with ridges. The topographic profiles document the amount of vertical offset associated with ridge formation, while the amount of horizontal displacement can be deduced from the amount of shortening observed across originally circular impact craters adjacent to mare ridges. Thorough examination of Lunar Orbiter and Apollo metric, panoramic, and hand-held photos produced very few examples of horizontal displacement across pre-existing, intersecting features. In almost all cases, horizontal displacement is unresolvable in the highest resolution photography available. Vertical displacements of up to 200 meters with little apparent horizontal displacement indicate near vertical fault planes in most cases. In rare instances, it is possible to follow the fault scarp into large deformed impact craters. An example is the 2.5 km crater south of the steeply offset Dorsa Aldrovandi in eastern Serenitatis (AS17-2318 pan). Based on the lateral displacement of the fault trace with depth in the crater, we estimate the dip of the fault plane to be greater than 60° to the west. These analyses clearly indicate that mare ridges are often associated with displacements on steeply dipping faults with minimal overthrusting, and disfavor suggestions that all ridges are thrust faults.

Our results favor the second tectonic model and suggest that the regional tilting and associated ridge formation expresses deep-seated, high angle faults. If the Procellarum basin structure is controlling the regional tilt of the nearside maria, then the zone of discrete offsets and slopes within Mare Serenitatis could be associated with steep, inwardly dipping faults shown to occur in large multi-ring basins [7].

REFERENCES
Figure 1 - Topographic profile across Mare Serenitatis along 21° N. latitude. Vertical exaggeration is 20X. Elevation marks have been placed every 500 meters.