Papers presented at the
Fourth Annual
Summer Intern Conference

August 18, 1988
Houston, Texas
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1988 Summer Intern Program for Undergraduates
Lunar and Planetary Institute

Co-sponsors: Lunar and Planetary Institute
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PROGRAM OF PAPERS PRESENTED AT THE FOURTH ANNUAL SUMMER INTERN CONFERENCE

Lunar and Planetary Institute
August 18, 1988
Houston, Texas

MORNING SESSION
9:00 A.M. - 12:15 P.M.

Chairman: Bruce Bills

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VARIATION OF MARTIAN RAMPART CRATER EJECTA LOBATENESS IN COMPARISON TO LATITUDE, LONGITUDE, TERRAIN, AND CRATER DIAMETER. Nathan Bridges, Department of Geology, University of Colorado, Boulder. Adviser: Nadine G. Barlow, Lunar and Planetary Institute

Introduction
The appearance of lobate ejecta patterns around Martian craters was first discovered from Mariner 9 images. Entrainment of subsurface volatiles, most likely H₂O, in the Martian regolith causing fluidization of the ejecta (1), aerodynamic drag effects on ejecta (2), or a combination of these two have been pointed to as causes of the rampart morphology. The rampart ejecta morphology is distinguished by a distinct distal ridge surrounding the ejecta. Three classes of rampart craters are defined: 1) single lobe, consisting of only one ejecta lobe surrounding the crater, 2) double lobe, consisting of two ejecta lobes surrounding the crater, and 3) multiple lobe, consisting of three or more lobes. Of the craters on Mars ≥8km that display an ejecta morphology, 50.9% are single lobe, 6.6% are double lobe, 11.8% are multiple lobe, and the others are unclassifiable or do not have a rampart ejecta (3). Single lobe craters tend to have smaller diameters than double lobe craters which, in turn, tend to be smaller than multiple lobe craters. At this point in the project, only single lobe craters have been examined.

In this study the degree of lobateness of rampart ejecta was studied. In particular, we wanted to see if the degree of lobateness correlated in any way to latitude, longitude, terrain, crater diameter, and various combinations of these variables. All single lobe craters larger than 8 km (n = 1960) were mapped as were their surrounding ejecta pattern. The perimeter and area of the ejecta were computed using a Summagraphics ID - RS 232 digitizer. We next computed the lobateness of each crater ejecta from the formula (5):

$$\Gamma = \frac{\text{(ejecta flow front perimeter)}}{((4 \pi \text{(flow area)})^{1/2}}$$

where $\Gamma = 1$ for a circular ejecta and greater numbers indicate more lobate ejecta. Few craters in our analysis had a $\Gamma > 1.4$

The lobateness of all the craters was loaded into a Microrim R-BASE 4000 file that also contained the craters' latitude, longitude, diameter, and type of terrain they were located on. Using the R-BASE file enabled us to compare lobateness to these different variables. Histograms of our data came from Harvard Graphics.

Results
Between 8 and 33 km diameter lobateness increases with increasing diameter (figure 1). Above 33 km the lobateness is variable. Due to the few single lobe craters at these diameters, the results for $D > 33$ km are probably not significant. This data confirms work done by previous researchers (5).
(4) has found that ejecta morphologies with greater lobateness increase poleward, while (5) found they decrease. Our research, on the other hand, confirms that of (6) and (7) that found no lobateness trends for single lobe rampart craters toward either the equator or poles. Except for 50-60° S, the predominant lobateness in the southern hemisphere is 1.1-1.2 (45.0%). In the northern hemisphere, except from 30-50° N, the dominant lobateness is 1.0-1.1 (49.2%). The reason for this planetary dichotomy is not clear. It is not a result of a greater percentage of large craters in the southern hemisphere since the size of craters is distributed evenly over Mars. Differing compositions and/or depths of the regolith and/or cryosphere may be a factor. A dependence on terrain types, which are not found in equal abundance in both hemispheres, is also possible.

Based on cratering statistics, terrains can be grouped by relative times of formation. The only terrain which is classified as end of heavy bombardment is the ridged plains, with the greatest percentage (41.4%) of craters having a lobateness of 1.0-1.1. Of the craters in the heavy bombardment terrains, the greatest percentage (44.4%) have a lobateness of 1.1-1.2. 60% of the terrain units on Mars formed during the heavy bombardment period (8). Post heavy bombardment terrain craters are dominant (48.1%) in the 1.0-1.1 lobateness range. Though younger (post HB) terrains have less lobateness, it is difficult to find a time mechanism that would affect lobateness. Since all craters studied here have ejecta blankets and probably are therefore relatively young, the lobateness probably is related to the composition of the terrains, not their age. Of the individual terrain types, the greatest proportion of single lobe craters (49.6%) are found in the cratered plains. These craters are dominant in the 1.1-1.2 lobateness range, except from 0-20° N. This could possibly be due to less regolith in this region. A summary of lobateness for the individual terrains is given in table 1.

In addition, a study was done to see whether lobateness varies with longitude. 3/4 of the 10° longitude bins had lobateness' of 1.1-1.2, while the rest were 1.0-1.1. There are no apparent planetary features to account for these longitudinal variations.

Maps were made showing lobateness with a resolution of 10° X 10°. The only trend observed was the greater lobateness in the southern hemisphere.

Conclusions Lobateness is found to increase with increasing diameter of the crater up to 33 km after which data becomes scarce. Higher lobateness ejecta are concentrated in the southern hemisphere. Contrary to conclusions reached by some researchers, lobateness does not show a trend with latitude. We also found no correlation to longitude. Terrains formed after heavy bombardment had less lobate crater ejecta than heavy bombardment terrains. Though this is the most comprehensive study yet done of ejecta lobateness, future work on double and multiple lobe ejecta is necessary.
VARIATION OF CRATER LOBATENESS
BRIDGES, N.T.

References

Table 1

<table>
<thead>
<tr>
<th>Terrain</th>
<th>Lobateness</th>
<th>Age</th>
<th>n</th>
<th>Comments</th>
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<tr>
<td>Aureole</td>
<td>100%</td>
<td>1.0-1.1</td>
<td>PHB</td>
<td>3</td>
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<tr>
<td>Basin Floor</td>
<td>55.6%</td>
<td>1.1-1.2</td>
<td>HB</td>
<td>27</td>
</tr>
<tr>
<td>Channel</td>
<td>50.0%</td>
<td>1.1-1.2</td>
<td>PHB</td>
<td>5</td>
</tr>
<tr>
<td>Cratered &amp; Fra</td>
<td>79.1%</td>
<td>1.0-1.2</td>
<td>PHB</td>
<td>43</td>
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<td>Dissected Upl</td>
<td>42.9%</td>
<td>1.2-1.3</td>
<td>HB</td>
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<td>Equatorial Lay</td>
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<td>1.2-1.3</td>
<td>PHB</td>
<td>3</td>
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<td>Exhumed Upland</td>
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<td>Fretted Terr</td>
<td>45.5%</td>
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<td>Hellas Vol Pin</td>
<td>41.4%</td>
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<td>HB</td>
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<tr>
<td>Intercrater Pl</td>
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<td>1.0-1.1</td>
<td>PHB</td>
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<tr>
<td>Rigid Plains</td>
<td>41.4%</td>
<td>1.0-1.1</td>
<td>EHB</td>
<td>232</td>
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<td>Volcanic Pins</td>
<td>60.0%</td>
<td>1.1-1.2</td>
<td>PHB</td>
<td>25</td>
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<tr>
<td>Volcanic Cons</td>
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<td>1.2-1.3</td>
<td>HB/PHB</td>
<td>4</td>
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<tr>
<td>Uplands</td>
<td>32.1%</td>
<td>1.1-1.2</td>
<td>HB</td>
<td>186</td>
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</table>

Table showing the percentage of the dominant lobateness class in each terrain classification. n is the number of craters sampled. HB = heavy bombardment, EHB = end of heavy bombardment, PHB = post heavy bombardment.

Figure 1 Histograms showing the percentage of each lobateness range within a particular diameter range. Notice that lobateness increases with increasing diameter. Above 33 km lobateness varies, probably due to the few craters in this category (n = 33 total).
PLEONASTE SPINELS IN APOLLO 14 BRECCIAS; D. T. Collins, University of Houston, Houston, TX., and Arch M. Reid, Lunar and Planetary Institute/University of Houston, Houston, TX.

INTRODUCTION

The Fra Mauro Formation, covering large areas of the near side of the moon, has been interpreted as material excavated by the large impact that formed the Imbrium Basin (1). The Apollo 14 mission was targeted in the Fra Mauro Highlands, 550 km south of the Imbrium Basin; its objective was to obtain samples of Imbrium ejecta that presumably represent lithologies derived from substantial depth in the lunar crust. The site was selected in pre-mission mapping to be near the relatively young, 370 meter wide, Cone Crater whose ejecta should represent, and facilitate reconstruction of, the Fra Mauro stratigraphy.

The Apollo 14 samples are interesting for a number of reasons including the occurrence of pink to purple spinels that have been classified as chromian pleonastes. The paucity of this phase in other Apollo missions suggests that an unusual part of the lunar geology has been excavated by the Cone Crater event (see Fig. 1).

Although it is a minor component of the lunar samples in which it occurs, the wide range of possible compositions makes spinel a potentially significant petrogenetic indicator of its parent lithology. The objectives of our research are:

(1) To establish the compositional ranges of the spinels and their associated phases.
(2) To apply these data to the task of determining the nature and petrogenesis of the source rock(s) from which the spinels derive.

METHODS

Our method of study involved a literature search which compiled a collection of publications pertaining to Apollo 14 spinels; systematic examination of the Apollo 14 breccia thin sections in the Curatorial Facility at the Johnson Space Center; and detailed analysis of twenty spinel-bearing clasts showing significant mineral assemblages. The spinels and their associated phases were analysed using the Cameca microprobe at the Johnson Space Center (accelerating voltage 15 kV, beam current 30 nA, using mineral standards).

SPINEL COMPOSITIONS

The spinels analysed occur as solid solutions intermediate between true spinel (MgAl2O4) and hercynite (FeAl2O4); substantial chromium (Cr2O3, 7.3 to 10.3 wt. pct.) and minor titanium (TiO2, 0 to 1.5 wt. pct.) are also present.

Two types of zoning are evident in the pleonastes studied, primary and secondary (3). Primary zoning is present in most grains and is observed optically as a gradational change from pink cores to red rims. Microprobe analysis of grains representative of this type zoning
indicate a gradual change in composition from magnesium rich cores to iron rich rims. In most cases this zoning is symmetrical and independent of contact with the matrix and/or associated phases; we therefore interpret it as a growth phenomenon which was present before brecciation of the source rock (see Fig. 2).

**CROSS-GRAIN TRAVERSE**

![Cross-gain traverse graph](image)

Fig. 2 Primary zoning.

Secondary zoning occurs as distinct outer rims, much darker in color than the cores, and in some instances opaque. Microprobe traverse across such grains confirms the suspected sharp compositional contrast between core and rim, with the rim showing significant enrichment in iron and titanium. Since this zoning is commonly present where the spinel contacts the matrix, and absent where in contact with crystalline phases in the rock clast, these rims are apparently the result of reactions with the breccia matrix (see Fig. 3).

**CROSS GRAIN TRAVERSE**

![Cross-gain traverse graph](image)

**CROSS-GRAIN TRAVERSE**

![Cross-gain traverse graph](image)

Fig. 3 Plots showing abrupt nature of the shift to Fe and Ti rich rims in secondary zoning.

Pleonaste spinels that show secondary overgrowths are separated from the matrix by narrow reaction coronas of plagioclase of average composition An 90. The plagioclase appears to be the result of reaction between the spinel and the matrix phases where iron and titanium from the matrix pyroxenes and oxides are added to the spinel rim producing a narrow zone adjacent to the spinel overgrowth relatively enriched in plagioclase components.
ASSOCIATED PHASES

Most pleonaste spinels occur as isolated grains within the breccia matrix. Where the spinel occurs in a lithic clast, the primary phase assemblage can be determined. This interpretation is complicated by the range of textures encountered in spinel-bearing clasts. A majority have undergone extensive deformation and texturally are cataclasites; some appear to have recrystallized, and at least one clast has melted, then cooled rapidly resulting in a fine grained quench texture enclosing relic pleonaste and small secondary euhedral olivines. The most abundant assemblages are pleonaste with plagioclase and/or olivine; to date no assemblages including pyroxene or cordierite have been recognised in our study. The plagioclase is low potassium and highly calcic in the range An 79-95 with the majority of compositions being An 90-95. The olivine is forsteritic and ranges from Fo 67 to a maximum of Fo 90; fluctuations in olivine Mg/Mg+Fe ratios are accompanied by similar trends in the pleonaste included in the same assemblage (see Fig. 4). Thus, the pleonastes occur primarily in a spinel troctolite assemblage characterised by very magnesian olivine, and very calcic plagioclase. More detailed study of minor phases in the troctolite is in progress at this time.

![OL VS. SP FRACTIONATION TRENDS](image1)

**OL VS. SP FRACTIONATION TRENDS**

**PI VS. OL FRACTIONATION TRENDS**

![PI VS. OL FRACTIONATION TRENDS](image2)

Fig. 4 Plot showing crystal-liquid fractionation trends in coexisting spinel, olivine, and plagioclase.

CONCLUSIONS

The Apollo 14 pleonaste spinels are primarily, though not exclusively, derived from a suite of spinel troctolites largely disaggregated by impact processes, and modified by extensive deformation, recrystallization, and in some instances melting. Plots of coexisting spinel, olivine, and plagioclase (Fig. 4) indicate systematic trends generally consistent with crystal-liquid fractionation processes. The limited data set for coexisting olivine and plagioclase shows a decrease in An content of plagioclase with decreasing Fo content of coexisting olivine in four of the five clasts, with one anomalous clast in 14305 that has much more sodic plagioclase. The "pink spinel troctolites" are most readily explained as a related series of early cumulates derived from a high magnesium, high aluminum magma. However, the one anomalous assemblage in Fig. 4 indicates that a second series of troctolite clasts may also be present. Further research is aimed at determining the composition and significance of minor phases that occur in the lithic clasts; at searching for other spinel-bearing lithologies and other troctolites with more sodic feldspar; and at exploring the simplistic cumulate model, both to test its validity and to investigate the relationship of spinel troctolites to other non-mare rocks.

REFERENCES

(4) Cameron K.L. (1972) Lunar Science VI, p. 115
Slope failure morphologies are used to constrain the values of physical properties for martian surface material. Morphology can indicate both flow rheology and initiating mechanisms of a slope failure. For example, debris strength can be determined from the slope angle of the failure. Slope failure, in turn, is dependent on cohesion, specific weight, and angle of internal friction of a material. These values are calculated for two martian slope failures, and compared to terrestrial data. The study sites are located in the summit calderas of Olympus Mons and Ascraeus Mons, two large basaltic constructs within the Tharsis region. The morphology of the deposits and failure surfaces indicates that the failures acted as debris flows, as defined by Young (1), and are thus treated as such in this analysis.

Olympus Mons, the largest volcano in the solar system, is centered at approximately 18N, 133W. Its complex summit caldera is roughly 75 km in diameter and composed of several smaller, coalescing calderas. The study slump failure is on a scree slope in the southwestern caldera (Figure 1). Dimensions and volume of the slump were calculated using shadow measurements on Viking orbiter images 474S21, 474S22, and 474S24 (Table 1). The slope of the caldera escarpment at the slump site consists of a lower scree slope topped by steep bedrock outcrops; the slope of the latter was determined from shadow measurements to be 39°. The slope of the scree surface is assumed to be 33°, which is consistent with terrestrial basaltic screes on cinder cones (2,3).

The second slope failure is on Ascraeus Mons, centered at approximately 11N, 104W. A slump was induced in the scree on the southeastern portion of the caldera escarpment when a meteorite impact removed part of the scree, oversteepening the slope and causing failure. The depth of the impact crater is calculated as 100m using the depth/diameter equation of Pike (4). The depth of the flow channel, and consequently the change in slope angle caused by the impact, are obtained by equating the volume of material entering the crater to that exiting the channel, and filling a portion of the crater. The values obtained are 18m and 3°, respectively.

Debris strengths are calculated using a method after Johnson (5), in which the strength variable is determined by comparing two ratios: a) the ratio of the half-width of the plug (non-shearing) portion of the flow to the half-width of the flow, and b) the width/depth ratio of the flow. The strength variable, slope angle, and flow dimensions are used to calculate debris strengths (Table 1). The following assumptions were made: density of 2200 kg/m³; slope angle of 32°; plug-width to half-width ratio of 1; a noncircular flow channel; and Bingham behavior of the debris. The values represent the upper bound for this method. The angle of internal friction was determined using slope stability analysis for a planar failure surface (6). Two separate analyses were made; the first assumed zero cohesion, and the second assumed a cohesion of 17500 kgf/m². The latter value, chosen arbitrarily, covers the range of cohesion values found in natural screes. The cohesion of solid basalt is 100,000 kgf/m, for comparison.

Terrestrial debris flows occur in many sizes, and the martian flows lie within the range of terrestrial dimensions and flow volumes. The study flows are larger than many well known terrestrial debris flows, but they are smaller than the volume of the Socompa debris flow in the Andes, one of the largest recorded (8). The slopes for the martian flows are also similar to the terrestrial data. Terrestrial scree slope angles range from 25-38° (1) with 27.2° given as that for basalt talus (9). The study screes must be less steep than 39°, the overall slope of the entire escarpment,
and steeper than $24^\circ$, determined using a scaled drawing of the flow. The angle of internal friction obtained from the first analysis is the estimated angle of repose of the scree slope. The second analysis gives a slightly lower value of $24^\circ$. These values are lower than the average angle of internal friction for terrestrial basalts, however, the accuracy of these angles are only as good as the estimate for the angle of repose of the scree slope. The values for martian debris strengths are slightly greater than those for terrestrial debris flows, which is not surprising because large terrestrial debris flows incorporate substantial amounts of water, much more than is likely in the martian cases. The martian flows are relatively volatile-poor, as evidenced by the short length of the flow and its steep front, measured at five places to average $18^\circ$ with a range of $12^\circ$ to $26^\circ$. Many terrestrial debris flows and martian landslides incorporate atmospheric and regolith volatiles and are characterized by much longer flow runouts than the Olympus debris flow. Perhaps the apparent lack of volatiles is related to the extreme elevation of the Olympus caldera.

In summary, values obtained for the physical properties of two slope failures on Mars are comparable to the values for terrestrial debris flows. The volumes, debris strength, and slope angle all closely relate to their terrestrial counterparts. The angle of internal friction calculated is slightly lower than that for earth.

REFERENCES

Table 1: Summary of Results

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<th>DIMENSIONS (m)</th>
<th>VOLUME (m$^3$)</th>
<th>SLOPE ANGLE (Deg)</th>
<th>DEBRIS STRENGTH (N/m$^2$)</th>
<th>ANGLE OF INTERNAL FRICTION (Deg)</th>
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<td>474521</td>
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<td>(Socompa)</td>
<td>15 (Socompa)</td>
<td>(range)</td>
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<tr>
<td></td>
<td>27.2 (9)</td>
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<td></td>
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Figure 1: Debris flow in southwestern caldera at the summit of Olympus Mons. Viking orbiter image 474S24; neutral gain filter; rectilinear version. Scale bar is 5km.

Figure 2: Impact-induced debris slide on the southeast wall of Asraeus Mons summit caldera. This is a specially processed version of a portion of Viking orbiter frame 401B20. Scale bar is 5km.
HYDROGEN EXTRACTION FROM LUNAR SOIL: TWO METHODS APPLICABLE TO A LUNAR PROCESSING FACILITY. Mark L. Houdashelt, Colorado State University; Roberta Bustin, Arkansas College; Everett K. Gibson, NASA Johnson Space Center.

INTRODUCTION:

The development of a lunar base is a major stepping stone in the advancement of mankind into space. A settlement on the moon will most likely precede any further manned exploration or colonization of the solar system. However, the speed with which this goal is achieved will depend greatly upon the cost of providing necessary resources to meet the energy, transportation and life support needs of the base’s inhabitants.

Hydrogen will be a critical resource for lunar activity, as a fuel for transportation to and from the moon and as a necessary component for water production (1). Recent research has found that hydrogen is present in much of the lunar soil in sufficient quantities to make its extraction a viable alternative to transport from Earth (2, 3). If a means of removing this hydrogen from the soil could be developed which would be readily applicable to the lunar environment, the requirements of a lunar facility could be more easily met.

Since the hydrogen present in lunar soil is a surface phenomenon implanted by the solar wind, it is readily removed by heating the soil (4). We explored two such methods of hydrogen extraction which make use of energy supplies available to a lunar colony. Solar energy will be prevalent on the moon, and excess thermal energy will be produced by a nuclear reactor, the most likely source of the initial power required for the base.

PROCEDURE:

Lunar soil samples were heated under vacuum and analyzed using gas chromatography (5). Hydrogen concentrations received by heating a soil for five minutes in a resistance wire furnace were used for comparison and evaluation of the efficiency of the two methods studied. Attempts were made to achieve similar experimental conditions for all three types of heating by using similar sample sizes (9 - 12 mg.), heating times (5 min.) and sample temperatures (900°C.).

Solar energy was employed to heat the soil samples by constructing a solar furnace made up of a large Fresnel lens (28.5 in. X 37.25 in.). A simple frame was built for this lens which allowed it to be tilted and rotated for focusing.

Hydrogen extraction was achieved by placing the sample in an alumina tube and heating it at the focal point of the lens at an external temperature of approximately 1100°C. for five minutes. To do this under vacuum, a quartz valve assembly was placed between the sample tube and the experimental apparatus which allowed the evacuated sample chamber to be removed, heated and replaced.
Alternatively, a hot gas was used to heat the soils, since the excess thermal energy produced by a nuclear reactor can be transferred to a flowing gas. Studies of He, Ar, CO₂, N₂ and steam showed that helium absorbed the greatest amount of heat and held it for a sufficient length of time to adequately heat the samples. Thus, soils were heated by passing helium at 1000° C. over the tip of the alumina sample tube. The required temperature was achieved by flowing helium through a quartz tube extending through three resistance wire furnaces, each at 1000° - 1100° C.

RESULTS AND DISCUSSION:

A comparison of hydrogen concentrations measured for three lunar soils is illustrated in Figure 1. Soil 15021,2 is a mature surface soil collected 25 meters west of the Apollo 15 landing site. 60051,15 is an Apollo 16 submature soil. 73141,8 was collected by Apollo 17 and is a submature soil found 15 cm. below the lunar surface.

The solar furnace and the heated helium produced comparable results for hydrogen extraction from lunar soils, and these results correlated well with the reference values. This indicates the possible applicability of each method to actual resource management on the moon. The studies done, however, are merely prototypical, with the true merit of each method still requiring examination on a larger, mass production-type scale.

Before either of these methods can be used for mass hydrogen extraction, efficiency studies are necessary which show the percentage of a soil's total hydrogen content released as a function of heating temperature and heating time. We believe that temperatures lower than the 900° C. used here will be adequate and the heating time required will decrease when the soil can be heated directly, as the alumina sample tube was found to slow sample heating.

To make the solar furnace adaptable to the moon, a larger heating zone is necessary. Although temperatures as high as 1600° C. could be achieved under proper conditions at the focal point of the Fresnel lens, the temperature zone providing sufficient energy to heat the soils properly was very small (1/2 inch in diameter). The temperature here was also significantly influenced by atmospheric conditions and the time of day, and it was found to decrease dramatically in the focal plane as one moved out radially from the focal point. A less dramatic, but significant, drop was also observed as one moved out of the focal plane along the lens axis.

We believe that conditions on the moon will allow for a larger area to be sufficiently heated to make a solar furnace viable for hydrogen extraction. The lack of an atmosphere will allow consistent, continual, direct heating of the soil with about 40% greater solar flux than the maximum flux experienced on Earth (6, 7). Additionally, a larger Fresnel lens could be used. Of course, the 14-day lunar sun cycle limits the productivity of this method.
The main considerations involved in scaling up the heated helium scheme concern heat transport and heat retention of the gas. We found helium to lose heat rapidly upon expansion and upon leaving the heating area inside the furnaces. Could helium be transported from a nuclear reactor to a soil processing plant while retaining sufficient heat to extract the hydrogen from the soil? We believe so.

CONCLUSION:

A solar furnace and a hot gas furnace each show promise as a method of extracting hydrogen from lunar soils. The applicability of each method to an actual lunar base depends upon the ability to properly control the heating of lunar soil on a much larger scale than that studied here. These preliminary investigations, however, indicate that further study of each method would be beneficial, since the economic ramifications are substantial.

REFERENCES:

SEARCH FOR INTERPLANETARY DUST TRAPPED WITHIN ANCIENT POLAR ICE
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Michael Zolensky, NASA Johnson Space Center, Houston TX 77058

INTRODUCTION Interplanetary dust particles (IDPs) have been studied intensively in an attempt to gain insight into the formation and evolution of the solar system. IDPs with refractory compositions, that is particles containing heat resistant minerals rich in aluminum, calcium and titanium, are particularly interesting because they are probably the first phases to have condensed from the early solar nebula [1] and, therefore represent the most primitive extraterrestrial material available for study. In addition, they most likely would have survived the hypothesized super-luminous phase of our sun, and may therefore contain remnant presolar or interstellar matter that was shielded from destruction by these refractory phases [2]. For these reasons, we focused our attention on the chemical and structural characterization of refractory grains.

NASA currently supports the collection of IDPs in the stratosphere. However, the earth's atmosphere is becoming increasingly polluted by man made orbital debris [2], and it is often difficult to distinguish between the products of aerospace activities and refractory IDPs. For this reason, we decided to search for refractory particles from pre-industrial aged Antarctic ice samples, thus eliminating the possibility of contamination by man made materials.

The particles discussed in this paper came from ice collected at the Allan Hills main ice field (76°41'S, 159°17'E), in Antarctica. Ice samples from this site range in age from 66,000 to 295,000 years old [3], and therefore contain no artificial contamination. Only the cleanest ice was collected, carefully packaged to prevent contamination, and shipped to the Johnson Space Center for melting and filtering under ultra-clean conditions.

METHODS Filters containing particles >10 µm in size were examined in a JEOL-35CF scanning electron microscope (SEM) equipped with a PGT energy dispersive X-ray spectrometer (EDX) for chemical analyses. Since these filters contained thousands of particles, a detailed analysis of each one would have been impossible in the limited amount of time available. Therefore, aluminum, calcium and titanium element maps were made to facilitate the identification of grains with refractory compositions. The most interesting grains were then picked off the filters, crushed between clean glass slides, and mounted onto holey carbon membranes on beryllium grids for study in a JEOL 100CX analytical electron microscope (AEM), also equipped with an EDX attachment. Mineral identifications are, thus, based on electron diffraction and EDX analyses.

RESULTS The analysis of the filters revealed 111 particles containing significant concentrations of aluminum, calcium or titanium. The particles showed considerable morphological variation, from single, euhedral grains to aggregates of tiny crystals, and ranged in size from approximately 10 µm to 60 µm. We have begun the characterization of one particle, #5066, which contained major titanium and oxygen, and minor aluminum and silicon. We also continued the detailed characterization of particle #705, which was picked off a different filter last summer.
All pieces of this particle (705 M, N, P and Q) contain titanium oxides (titanias) and kaolinite as their main constituents. Other parts of particle 705 contain titanium carbide [2]. The titania phases in this particle are characterized by the formula Ti$_2$O$_{2n-1}$ (n=3-10), and are called Magnéli phases. 705P also contains a single, 2 um sized grain of wüstite (FeO).

DISCUSSION and CONCLUSIONS We have studied particle 705 in considerable detail, and believe that it contains extraterrestrial and, possibly, pre-solar material because: (1) Magnéli phases are known from only one restricted terrestrial locality, (2) titanium carbide and wüstite are unknown from natural terrestrial localities, and (3) Magnéli phases and wüstite have been found in some chondritic IDP's, where, as in particle 705, they are associated with kaolinite [2]. Magnéli phases provide us with an indication of the $P_0^2-T$ conditions in the early solar nebula (Fig.1).

Particle 705 is unique in that it contains TiC. Formation of TiC requires temperatures of about 1200°C at probable total pressures ranging from $10^{-5}$ to $10^{-9}$ atmospheres, and a carbon/oxygen ratio >1.5. Since the presently accepted carbon/oxygen ratio of the solar nebula is much less than 1.5, TiC should not have condensed from the solar nebula. Therefore, particle 705 may contain remnant interstellar matter. The Magnéli phases most likely formed within the early solar nebula by oxidation of the outermost titanium carbide crystals. Isotopic studies that should determine the origin of particle 705 are presently being performed. Further study of this particle and the search for others like it will provide us with invaluable information concerning stellar evolution and the early history of our solar system.

Figure 1: Phase stability range for particle 705 as constrained by its mineralogy and the probable total nebular pressure.
LATE PLEISTOCENE PLUVIAL LAKES FRANKLIN, AND GALE, EASTERN NEVADA; PALEOCLIMATIC AND NEOTECTONIC IMPLICATIONS

Susan E. Hubbard, Whitman College, Walla Walla, WA
Bruce G. Bills, Lunar and Planetary Institute, Houston, TX

Lake Bonneville was the largest of the late Pleistocene pluvial lakes in the Great Basin. Its sediments and shorelines have preserved a valuable record of major climatic change and significant neotectonic activity. Over the last 30-40 years a greater understanding of that record has emerged (figure 1) [1,2,3]. Most of the major pluvial lake oscillations have counterparts in isotopic variations recorded in deep sea sediments [4] and ice cores from Greenland [5] and Antarctica [6]. Thus, the climate of the Great Basin is largely responding as part of a global system. Furthermore, Lake Bonneville was large enough (380 m maximum depth, 51,000 km² maximum area) that it significantly deformed the crust beneath it [1,7,8]. The highest shorelines in the center of the basin are as much as 70 m higher than their peripheral counterparts. The well known loading history and excellent preservation of the response make this a classic location for studying the Earth's response to stresses that are imposed on time scales intermediate between seismic (seconds to hours) and tectonic (millions of years) periods [7,9,10].

The primary objective of the work reported here was to use some of the smaller lakes that formed immediately to the west of Lake Bonneville (figure 2) in an effort to further delineate their climatic and neotectonic environment. The small lakes provide several potential advantages. They provide an independent record of presumably similar climatic events with (in most cases) less overprinting by internal lacustrine dynamics. These lakes were too small to produce measurable crustal deformation, but their shorelines act as sensitive tiltmeters which will record hydro-isostatic and seismotectonic activity since their formation. Of particular interest is the possibility of extending the mapped deflection field of Lake Bonneville beyond its own shores.

After a preliminary survey of aerial photographs and Landsat TM images of all 18 lakes in the study area we selected two for more intensive study. Lakes Franklin and Gale were selected, at least in part, because of the complexity of the visible shorelines and the possibility of significant interbasin hydrologic interaction. Snyder et al. [11] suggested overflow from the north end of Gale into the southeast extremity of Franklin and overflow from the northeast extremity of Franklin into the southwest corner of Lake Clover. On the other hand, Mifflin and Wheat [12] discounted the possibility of overflow into Clover and were ambivalent about the overflow from Gale.

Lake Gale was situated in Butte valley, which does not presently support a perennial lake. The Lake Gale shorelines can be loosely grouped into three subsets: an upper series of two or three very faint shorelines above the present drainage divide; a middle set of two well defined shorelines; and a few lower shorelines defining a series of very shallow closed basins along the valley floor. Only the middle set of shorelines can be individually identified around the complete perimeter of the lake.

The middle shorelines also are readily identifiable on topographic maps, and show an elevation decrease of two to three meters from north to south over a distance of 70 km. No east-west deflection is apparent from the maps, but this is not unexpected as the center of rebound for the Lake Bonneville load is to the NNE, and the east-west baseline in Lake Gale is only 20 km.

The main body of Lake Franklin was situated in Ruby valley, which presently supports two small perennial lakes, and an eastern arm of the lake extended through Dry Lake Flats into the extreme north end of Butte Valley. Lake Franklin has a few shorelines that are identifiable throughout the basin, and a large number of shorelines that are highly visible in low gradient areas, but almost completely absent in higher gradient areas. Measurements on the highest well defined shorelines show an elevation decrease of almost three meters from north to south over a distance of 80 km.
PLEISTOCENE LAKES
Hubbard and Bills

The highest shoreline of Lake Franklin encloses an area that comprises a larger fraction of its drainage basin area (38%) than the highest shorelines of the surrounding pluvial lakes (Clover, 35%; Gale, 22%, Hubbs, 29%, Newark, 22%). In contrast, Lake Gale’s areal fraction is at the low end of the regional range of values. These disparities provide some support for the postulated overflows from Gale to Franklin and from Franklin to Clover as envisioned by Snyder et al. [11].

Several sets of data corroborate the Gale-to-Franklin overflow: the highest shorelines in Lake Gale are faint and apparently above the present drainage divide; the well developed shorelines in Lake Gale are very near the reconstructed threshold elevation; the present drainage divide between the Franklin and Gale systems is formed by a small mound of material that has slumped off the east flank of a well developed channel which presumably marks the course of the overflow stream. A possible scenario might be: gradual rise of Lake Gale until the paleo-drainage divide at the toe of the Taylor Creek fan was reached; spillover and relatively rapid downcutting of a few meters until an equilibrium was attained; eventual regression below the threshold. The configuration of the Taylor Creek fan suggests that prior to overflow, Taylor Creek sometimes drained to the north into Lake Franklin and sometimes to the south into Lake Gale. At present, Taylor Creek is deeply incised into the northern flank of its older fan, and drains north. A fairly fresh looking fault scarp [13] cuts the older parts of the fan but predates the incision.

The postulated overflow from Franklin to Clover is not well supported. The highest identifiable shoreline of Lake Franklin is at least 10 m below the present threshold elevation. There is also no indication of an overflow stream channel. There may well have been significant groundwater flow into Lake Clover, but apparently no surface flow.

A fairly clear neotectonic signal has been recorded in the tilting of the shorelines of Lakes Gale and Franklin. However, the extent to which that signal is related to isostatic rebound from the Lake Bonneville load is obscured by the presence of possibly coeval faulting. The interaction of the Franklin and Gale hydrologic systems has also added considerable "noise" to the climatic record encoded in the shorelines. An independent determination of the chronology of these lakes will be required before either the neotectonic or the paloeclimatic records found here can be utilized.

References

Figure 1
Surface elevation history for Lake Bonneville. After Currey and Oviatt, 1985.

Figure 2
Outlines of late Pleistocene lakes in the Great Basin. Lake Bonneville is the largest. Lakes Franklin and Gale are highlighted. After Snyder et al., 1964.
EXPERIMENTAL AND THEORETICAL INVESTIGATIONS INTO THE PARTITIONING OF TRACE METALS IN THE FE-NI-S AND FE-NI-S-P SYSTEMS; P.E. Janney, University of New Hampshire.

Studying the thermodynamic mechanics of the Fe-Ni-S and Fe-Ni-S-P chemical systems is necessary to understand iron meteorite formation and core formation processes of the terrestrial planets. This study's objective was to gather experimental data and use this and previously obtained data to develop and test a model that predicts the distribution coefficient \( D = \frac{X_{\text{sol}}}{X_{\text{liq}}} \) of trace metals in these chemical systems.

Previous experiments (1) were conducted at fairly high temperatures (1200-1600\(^\circ\)C), so the new experiments were conducted at lower temperatures (950-1050\(^\circ\)C) in order to widen our data base. These experiments consisted of 200 mg samples made up of FeS\(_2\), Fe, Ni, P, Ge, Au and Ge powders. Once mixed, the samples were placed in alumina crucibles which were placed in silica tubes and sealed under vacuum. These samples were prepared in groups of three, each "doped" with a weight percent of a different trace element (Ge, Au or P). These samples were placed in a furnace for 5 to 10 days. When removed the samples were quenched in water and the sample retrieved. The sample was then mounted in epoxy and polished until smooth. Most of the samples formed two or more phases during heating. The phases we have observed are "liquid" (frozen upon quenching, S-rich, trace metal poor), metal (concentrates trace metals Ge and Au), troilite (FeS) and shreibersite (Fe\(_3\)P), Fe\(_3\)Ge and S-rich and P-rich immiscible liquids. The samples were analyzed using the JSC electron microprobe. Several points were analyzed in each phase of each sample in order to get a reliable average.

The new and old data were combined and used in modeling efforts. I modeled only the Ge distribution coefficients because of limited time and because John Jones was modeling coefficients for other elements. A paper by D. Malvin and J. Jones (2) presented a way to predict the distribution coefficients of minor and trace constituents as a function of the mole fraction of the nonmetal(s) present in the liquid:

\[
\ln D(\text{tr}) = -B \ln (1 - 2\alpha X_S) + C_S \quad \text{in the Fe-Ni-S system}
\]
\[
\ln D(\text{tr}) = -\beta \ln (1 - 2\alpha X_S - 4\alpha X_P) + C_{SP} \text{ in the Fe-Ni-S-P system}
\]

\[\alpha = 1.09, \quad \beta \text{ is the slope of the line where } x = \ln(1 - 2\alpha \ldots) \text{ and } y = \ln D(\text{tr}) \quad \text{and } C \text{ is the y intercept of this line. The model agrees well with the data, the average error is 10.26\% for the Fe-Ni-S system and 10.7\% in the Fe-Ni-S-P system. The figure below shows the regression for the Fe-Ni-S system.}
\]

In order to be certain that this is the best predictive method possible, we tested it against two other models. One is the same as the above model except that the constant "\(\alpha\)" = 1.00 instead of 1.09 and therefore drops out of the equation. The second is a polynomial model, which is the traditional metallurgical approach. We limited it to a second-order expression (\(\ln D(Ge) = a + bx + cx^2\), \(x = X_S \text{ and/or } X_P\)) and for simplicity a computer picked the
best fitting equation. The following table summarizes the error results of both models.

<table>
<thead>
<tr>
<th>MODEL</th>
<th>MEAN ERROR-FE-NI-S</th>
<th>MEAN ERROR-FE-NI-S-P</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-\ln(1-2\alpha x_s-4\alpha x_p)$</td>
<td>±10.26%</td>
<td>±10.7%</td>
</tr>
<tr>
<td>$-\ln(1-2x_s-4x_p)$</td>
<td>±15.6%</td>
<td>±12.7%</td>
</tr>
<tr>
<td>$a + bx + cx^2$</td>
<td>±15.57%</td>
<td>±49.97%</td>
</tr>
</tbody>
</table>

The original $-\ln (1-2\alpha x_s-4\alpha x_p)$ model proves to be the most accurate method of prediction by a significant margin.

In conclusion, the objectives of this project seem to have been met. We have developed and tested the most accurate mathematical model currently available for predicting distribution coefficients of trace metals and minor constituents in the Fe-Ni-S and Fe-Ni-S-P systems. We have also gathered a significant amount of data in chemical systems and under temperatures rarely studied before. Of course, the investigations will not stop here. This has been only a small part of a larger study intending to "map out" in compositional and thermal space the chemical systems involved in planetary core and iron meteorite formation, and to mathematically parameterize these systems in order to understand the thermodynamic mechanisms controlling them.

ACKNOWLEDGEMENTS
I gratefully acknowledge the help of my advisor, John Jones, who guided me through experimental technique and theoretical background, and who trusted me enough to let me make mistakes and learn from them.

REFERENCES:


(2) Jones J.J. and Malvin D.J.(1987-88) to be submitted to Metallurgical Transactions, "A Nonmetal Interaction Model for the Segregation of Trace Metals During Solidification of Fe-Ni-S, Fe-Ni-P and Fe-Ni-S-P Alloys"
GEOCHEMISTRY OF METAMORPHIC GARNETS FROM THE EARTH'S CRUST AND MANTLE

Celeste D. Maag, Summer Intern, Lunar and Planetary Institute
Advisors: A.V. Murali and L.D. Ashwal

Garnet is an important mineral in many petrogenetic processes. It is common in a variety of crustal metamorphic rocks and is likely to be present in the mantle. Garnet has been suggested as a residual phase left behind during the formation of several magma types, including kimberlite, basalt, calc-alkaline magmas, Archean tonalites, and granites, imparting a distinct geochemical signature to these melts. Partition coefficients for garnet have been determined both experimentally and empirically, but these have focused on garnet as a product of magmatic crystallization. We have begun a systematic trace element geochemical study of garnet in its more common environment of formation- as a product of metamorphic crystallization or recrystallization.

We made purified garnet mineral separates from a wide variety of lithologies, including metagabbros (Parry Sound, Ontario; Gore Mountain, N.Y.; Morin, Quebec), metasediments (gar-biot-sill schist, Sturbridge, MA; gar-biot schist, Quabbin Reservoir MA), and metamorphosed granitic rocks (charnockite, South India; quartz monzonite, central MA). We also separated garnets from a variety of mantle xenoliths (lherzolite, harzburgite, eclogite) from kimberlites in South Africa (Roberts Victor, Kimberley, Weltevreden) and Kentucky (Hamilton Branch) and included three samples of Cr-poor garnet megacrysts from the kimberlites at Shaffer, Wyoming and the Lace and Kaalvalli pipes of So. Africa. All separates were hand picked under a binocular microscope to ensure purity. Whole-rock powders for all samples were prepared using an alumina shatterbox. The samples were analysed for trace element and a few major element concentrations using standard instrumental neutron activation (INAA) techniques.

Chondrite-normalized rare earth element (REE) patterns for the garnet separates are quite variable, and the differences can be correlated with lithology. Garnet megacrysts from kimberlites show low REE levels (2 - 40x chondrites) with typical progressive enrichment in heavy REE. Mantle xenolith garnets show generally similar patterns, but some show larger depletions in light REE. One sample (harzburgite, Weltevreden, So. Africa) has garnet with REE abundances higher than its whole-rock, a light REE enriched pattern, and a small positive Eu anomaly. Garnet separates from metagabbros show light REE depleted patterns with abundance levels depending on the REE levels of their protoliths. Garnets from metasediments and metagranitoid rocks show high total REE levels (La to 200x, Lu to 700 x chondrites), and conspicuous negative Eu anomalies.

Garnet/whole-rock partition coefficients (Kd) for our samples also depend on lithology, and are similar to garnet/liquid Kd values determined both experimentally and empirically. This suggests similar partitioning of REE into garnet regardless of whether the parent reservior is a liquid (silicate melt) or a solid (metamorphic rock). Most of our garnet samples show smooth increases in Kd from light to heavy REE, but Kd patterns for granitoid garnet show conspicuous negative Eu anomalies. Similar behavior was found by Irving and Frey for igneous garnets in dacite-ryholite, and these workers considered this to be either an sampling artifact (excess plagioclase phenocrysts in matrix separates) or an effect of high oxygen fugacity. We suggest that the relative rejection of Eu by granitoid garnets may have a crystallochemical explanation- such garnets are poor in CaO (grossular
component) compared to garnets crystallized or recrystallized from mafic or ultramafic melts or protoliths.

Our data suggests further that other trace elements can be used to discriminate garnet protoliths. Distinct groupings are evident for garnets from mantle, metagabbro, metasediment, and metagranitoid protoliths on ternary plots of Co-Sc-Cr and FeO-Sc-Cr.

One aspect of our study was to investigate the potential of garnet as a carrier for siderophile elements such as Ir. Preliminary data indicates that Ir concentrations in all of our garnet separates are below detection limits (1 ppb). However, INAA data for mineral separates of garnet, Cr diopside and olivine from a phlogopite-garnet lherzolite (Kimberley, So. Africa) show that olivine has high concentrations of Ir (7 ppb), and may be the major host for Ir in the Earth’s mantle.

References

GEOCHEMISTRY OF 15205 KREEP BASALT CLASTS. Bill Moss, Auburn University, Auburn Al.

Apollo KREEP basalts have been one of least understood rock types on the lunar surface. The origin of KREEP basalts still remains unclear as to when and how in lunar evolution they formed. Studies on lunar rocks have shown KREEP to be a moon-wide phenomena, yet it has only been found as fragments in lunar rocks. This study focuses on 15 KREEP basalt fragments picked from sample 15205 and analyzed by INAA and Fusedbead Microprobe. The data acquired show linear arrays on Eu vs. Sm and Sc vs. Sm plots, thereby suggesting a fractional crystallization sequence or heterogenity within a single basalt flow. After analysis of the data a single basalt flow is the preferred hypothesis.

Sample 15205 is a regolith breccia lithified by impact into immature lunar soil (Ryder, pers com). The sample was obtained from a 1 m boulder at collecting station 2 of the Apollo 15 landing site. The outer surface is covered with a dark green-brown glass, which is cross-cut by glass filled microfractures (1). 75% of the rock is composed of clasts of green-glass, mare basalts, and KREEP Basalts. Dymek (1) suggests 20% of the clasts are KREEP, although Ryder (2) suspects a higher percentage of KREEP basalt clasts present. The clasts are contained in a fine grained matrix of glass and mineral fragments.(!)

The textures observed in 15205 KREEP basalts range from subophitic-intergranular to intersertial. The grain sizes range from fine grained to medium coarse. The minerals in the fine-grained samples average less than .5mm in size, while those in coarse grained samples average 1.0-1.5mm. Plagioclase is the dominant mineral, occurring as subhedral acicular prisms which may or may not be bent. Orthopyroxene is also present, occurring as either subhedral prisms or intergranular material. Mesostasis comprises the remainder of the clasts, being found as cryptocrystalline interstitial material.

The samples taken for analysis were hand-picked from the surrounding 15205 matrix at Johnson Space Center. Sample weights ranged from 7.06 mg to 79.26 mg. The larger samples were split for INAA and fusedbead microprobe analyses, while the smaller ones could only be studied by INAA. The INAA procedure consisted of irradiating the lunar samples for 20 hours at the University of Missouri reactor in Columbia with a flux of $4.9 \times 10^{13}$ n/cm$^2$sec. Radioassays were then taken 4 days, 1 week, and 3 weeks after irradiation. Data reduction and compilation were performed on a DEC MicroVAX using TEABAGS and FEAT programs. Fusedbead microprobe analysis consisted of melting the sample into a homogeneous glass, which was later thin-sectioned and analysed in an electron microprobe at 15 kv, wide beam raster.

INAA data are given in TABLE 1, together with means and standard deviations. Fusedbead microprobe data are given in Table 2. Samples show surprising little variation. As the REE plot shows, all of the compositions are KREEPY, including the matrix and glass (FIGURE 1). These two samples and one basalt clast (161B) differ somewhat from the other basalts as shown in FIGURE 2, and have been excluded from the mean calculations. Variations in the other 12 basalt clasts are small but analytically significant. -The REE and other incompatible elements vary from the mean by 15%, while major elements and compatible trace elements exhibit smaller variations. These variations form roughly linear arrays on two-element correlation plots (FIGURE 2). Two possible interpretations of these data are that they result from
sampling different portions of the same flow, or by fractional crystallization of a basaltic magma.

Lindstrom & Haskin (3,4) compared compositional variations in mare basalts to the heterogeneity observed in single flows of terrestrial basalts. Using the present data this comparison can be done for KREEP basalts. Standard deviations of the major and minor elements in the 12 KREEP basalt samples are very near those for a vertical section in a single Icelandic basaltic flow (4). Standard deviations for some elements in the KREEP samples scarcely exceed the Icelandic Basalt, which should be expected considering the small sizes of the clasts. Figure 2 helps to explain these greater standard deviations. A Eu vs. Sm plot shows which samples deviate from the average due to a probable bias of plagioclase in the sample. This can be done due to the fact that Eu is concentrated in plagioclase and Sm is concentrated in the mesostasis. By the same reasoning Sc vs. Sm shows which clast could have a higher percentage of pyroxene present due to Sc affinity for pyroxene. These sampling biases could account for the greater standard deviations observed for the KREEP clasts.

Simple modeling calculations can be used to evaluate the variations in mesostasis component of the basalts. For an incompatible element the Rayleigh equation reduces to

\[ \frac{C_q}{C_0} = \frac{1}{f} \]

where \( C_q \) is the concentration of the element in question at the time of quenching, \( C_0 \) is the concentration of the element in the initial liquid, and \( f \) is the fraction of liquid or % of mesostasis in the sample. Using the average basalt composition for initial liquid and assuming that the liquid is quenched at 25% mesostasis, we can calculate the composition of mesostasis (\( C_q \)). For La the average basalt composition of 75ppm yields a mesostasis concentration of 300 ppm. The range of basalt compositions (65-85 ppm La) can be used to calculate the range in hypothetical mesostasis components in the basalts, 22-25%. This range of variation is comparable to that seen in single terrestrial basalt flows.

Some of the clasts vary outside the acceptable deviation of the linear trend for reasons not described above. Split 161 is a green glass that was removed from the outer surface of basalt clast 161B. It is undoubtedly of impact origin, having high siderophile element contents (Co, Ni, Ir, Au). Though KREEPy in nature it deviates on the two plots, probably due to mixing with mare components as suggested by the high Fe and Sc. Sample 142B is matrix material. Although it deviates from the trend in FIGURE 2, it definitely has a KREEP-rich composition, showing that 15205 KREEP basalt is the major component of the matrix. Some other components are also present but the analysis doesn't show the higher Fe and Sc to be expected from observed mare clasts. 148 was recognized macroscopically to contain some matrix material. This mixed clast plots very close to the two trends and it is unknown how much matrix contamination the sample had. 161B plots on the pyroxene deficient side on the Sc vs. Sm plot and on the plagioclase enriched side of the Eu vs. Sm plot, thereby suggesting a sampling problem. However, compatible elements plotted against noncompatible elements show 161B to be distinct from the other basalt clasts, and suggest it could be of a different flow.

Compared to other Apollo 15 pristine KREEP basalt data available from the literature, our data show a smaller variation than the overall range, and some hints of other trends. The large variations could result from other flows being present, or from interlabatory biases. Detailed comparison of the Apollo
15 KREEP basalt suite can only be done after eliminating any interlabatory biases.

Analysis of 13 15205 KREEP basalt clasts have shown them to exhibit little variation in composition. Only one basalt clast (161B) has shown any real deviation and may be of a different flow unit. Though the hypothesis of fractional crystallization cannot be ruled out, a more parsimonious hypothesis would be that they are from a single basalt flow.


**TABLE 1**

**TABLE 2**

**15205 MICROPROBE DATA**

<table>
<thead>
<tr>
<th>SAMPLE</th>
<th>1428</th>
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<th>1673</th>
<th>1675</th>
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<tbody>
<tr>
<td>Na2O</td>
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**FIGURE 1**

**FIGURE 2**
IN SEARCH OF: ANDEAN "ACTIVE" VOLCANOES; Tracy K. Porter, Dept. of Geology, Brown University, Providence, RI 02912, Peter W. Francis and Shanaka L. deSilva, Lunar and Planetary Institute, Houston, TX 77058.

"The identification and global mapping of all active and potentially active volcanoes is an important science objective." - International Decade for Natural Hazard Reduction [1].

The Central Andean volcanic province (between 14° and 26° S) has the highest density of volcanoes in the world, but the exact number of active volcanoes is unknown - 16 have previously been cataloged [2,3]. The importance of such a catalog cannot be ignored: it establishes a database from which further research on volcanic activity can be done; by knowing the location of active volcanoes, people living near them can be warned of an impending eruption, and their lives saved. Thematic Mapper (TM) data has been used for the first time to search the Central Andes for active and potentially active volcanoes; to date, over 70 have been identified. A new catalog is obviously needed, and is the object of this study.

The Andes are well-suited for TM study; the arid climate and high elevation - average 4000 meters - create a relatively cloudless environment with minimal atmospheric scatter, which allows the surface geology to be seen easily. The TM sensor records the Earth's surface at seven wavelengths, six of which have a pixel resolution of 30 meters. These seven bands correspond to three visible wavelengths and four infrared wavelengths [4]. The Digital Image Processing System at the Lunar and Planetary Institute assigns red, green and blue filters to any combination of three selected bands. In this study, bands 7 (short infrared), 4 (photographic infrared) and 2 (visible wavelength) were merged to produce a false-color composite image that best emphasizes the fresh andesitic lavas, hydrothermally altered rocks and ignimbrites of the area.

A volcano is catalogued if it shows evidence of activity within the past 10,000 years; e.g., if one or more of the following is visible on the TM data:

1) a pristine summit crater; i.e., one that shows little or no evidence of chemical erosion (other than hydrothermal activity) or mechanical erosion.

2) pristine, low-albedo lava flows. Fresh andesitic lava typically has a low albedo in TM bands 7, 4 and 2, as well as in visible wavelengths. Well-preserved flow ridges and lava levees are also frequently indicative of young lavas.

3) fumarolic activity. Fumaroles are generally too small for TM resolution. Without eye-witness reports, fumarolic activity can sometimes be identified on TM images by the presence of unglaciated hydrothermally altered rock.

4) evidence of activity since the last period of glaciation; i.e., lava flows superimposed onto glacial moraines.

Interpreting glacial features was an important aspect of this study because the lack of radiometric data from young Andean volcanoes requires the use of an alternate dating method. C14 dates of the Peruvian Quelccaya ice cap moraines show that the last great expansion of the ice in South America occurred approximately 10,000 years ago. There was also a minor advance 600 years ago, during the "little ice age" [5]. Moraines from the 600 years BP advance are identified by their high altitude and crisp morphology, indicating a small, recent advance. The 10,000 years BP moraines are generally the largest fresh moraines that are visible on TM images. The moraines left by advances older than 10,000 years are almost completely eroded or buried under ignimbrites and lava flows, and are of little use in the search for active volcanoes.

South of about 24°, the Andes are more arid; there are fewer moraines, and they do not extend as far as the northern moraines do. An added complication is that Andean glaciers at any latitude prefer to move down the southern slopes. In many cases, there are lava flows on the northern flanks of a volcano, but all the moraines are on the southern slopes. The elevations of the flows and the moraines are then considered: if the terminus of the lava is at or below the elevation of the terminal moraines, the flow is presumed to have been emplaced since the moraines were formed.

Glacial moraines and lava flows are not always noticeable in TM images unless the data is enhanced. TM data is stored as Brightness Values (BV) ranging from 0 (black) to 255 (white); values in between are unique shades of gray. Typically, the "raw" TM image has only a few BV's, which makes
the image dark and murky. "Stretching" causes all BV's to be used, enhancing the contrast, and "filtering" sharpens the edges of flows and moraines. The two processes combined result in sharper, brighter images, and leads to hardcopy products that are the basis for further study. Large amounts of snow and ice in an image can create difficulties: when the image is stretched, snow and ice attain a BV of 255, and any textural detail under the snow (such as fresh lava flows) is lost. This can be overcome by studying the snow-covered areas in the "raw" form and the rest of the image in the processed form. These processed TM images will be included with the entries in the new catalog for the first time.

The new catalog will also contain a number of entries for young, monogenetic volcanic features. Although these will not erupt again and hence are not truly "active volcanoes," they are much younger than 10,000 years and represent some of the most recent activity in the area. These include large dacite flows, such as Cerro Chao in Chile (22°07'S, 68°09'W) - probably the largest flow of its kind in the world - and Cerro Chascon in Bolivia (21°53'S, 67°54'W), a small torta (a flat-topped dacite dome). There are also monogenetic centers which produced large ash falls, such as Cerro Quemado in Bolivia (18°37'S, 68°54'W) and Huaynaputina in Peru (16°35'S, 70°52'W).

In the past, mountains which were not even thought to be volcanoes have erupted violently. Therefore, the importance of an updated, correct catalog cannot be ignored. Such a catalog would establish a standard database for further research on the Andean volcanoes. It will collect in one publication basic facts such as elevation, location, past and present volcanic activity; and in addition to TM images, it will include sketch maps and ground photographs where available. Moreover, it will enable the hazard potential of the volcanoes to be further assessed. In the Central Andes, many villages and cities are located at the bases of active or potentially active volcanoes. If El Misti (16°18'S, 71°24'W) were to erupt, for example, the city of Arequipa, Peru - and its inhabitants - could be obliterated.

References

A Catalogue of the Apollo 15 4-10 mm Coarse-Fines.
Sherman, S., (1) and Ryder, G. (2). 1. Boston Univ. 675 Comm. Ave, Boston, Ma. 02215. 2. LPI, 3303 NASA Rd. 1, Houston, Tx. 77058

Catalogues of subsets of lunar samples are important for providing information on what a sample is, what is known about it, how much of a sample there is, and what has been done to it. This information is useful both for synthesizing knowledge about the moon and for planning further research, such as chemical analysis.

This project is to produce an updated version of the catalogue the Apollo 15 4-10 mm coarse-fine particles which Benjamin Powell completed in 1972, very shortly after the Apollo 15 samples were first inspected. The revisions that we made provide a detailed summary of what is presently known about all the particles. The catalogue contains chemical and petrographic data that has been obtained from the particles, as well as Powell's original observations. It provides a basis for the planning of research projects including possible allocations of the particles to be used for future work.

The relatively large size of the 4-10 mm particles permits more than one type of analysis to be performed on each sample, whereas the other fines are too small for much multiple analysis work. Another characteristic about the 4-10 mm fines is that they are few enough that a catalogue is a realistic project but there are enough to provide a reasonably representative population.

Studying the regolith of a lunar landing sight is necessary for understanding the geology of the site. The soil fragments are a source of information on the existing rock types that occur at a particular area of the moon, and can provide insight to the bedrock or to the identification of exotic particles.

The major geologic objectives of the Apollo 15 mission were to observe and to sample the Apennine Front, Hadley Rille and the Mare plain of Palus Putredinis (1). Regolith samples were obtained by the methods of scooping, trenching, or coring. Apollo 15 was the first mission to have the Lunar Roving Vehicle (LRV) which enabled a geographically more extensive sample return, 77 kg of samples were retrieved. The LRV made three traverses, covering a total of 27.9 km (see Fig. 1).

![Fig. 1 Apollo 15 traverse map. EVA is an acronym for Extravehicular Activity (2).](image-url)
Sieve Procedures and Number Allocations: Three paired rake and soil samples were obtained from the Apollo 15 mission. The samples from each station were placed in a sieve mesh stack in the order of pan, 1 mm, 2 mm, and 4 mm, 10 mm, and the lid. The top was covered with a thin layer of sample, then shaken with a circular motion until the material had all passed through the sieves. The particles which remained on the 4 mm mesh were classified as the 4-10 mm coarse-fines. (Meyer 1987).

The bulk soil samples were given the number 15XY0. Part of each 15XY0 was sieved to give 15XY1 = < 1 mm, 15XY2 = 1-2 mm, 15XY3 = 2-4 mm, and 15XY4 = 4-10 mm. These 5 digit numbers are the generic numbers. All paired rake and soil samples were assigned the numbers: 15100-15199, 15300-15399, and 15600-15699. The exceptions are the rake samples, which are numbered 15315-15392 and 15605-15689 for which 15340, 15341, 15342, and etc. are rocks.

Preliminary Classification Procedures: A preliminary catalogue on the Apollo 15 4-10 mm coarse-fines was done by Benjamin Powell in 1972. Powell examined the fragments through the windows of the nitrogen atmosphere processing cabinets using binocular microscopes. Each sample was examined in bulk, and then separated into several subgroups (which we list in the revised catalogue as groups) on the basis of macroscopically observable lithological differences. The classifications were based on textures and/or mineralogical compositions. This technique was limited by the resolution of the microscope. Powell acknowledged the difficulty of this technique, and estimated that the placement of a particle in a given subgroup (group) to be about 75-90 % accurate, on the average.

Many coarse-fine samples have since undergone more division. Instead of simply having the generic number and within that subgroups of particles that are lithologically similar, individual particles have been selected and renumbered. Some of these individual particles have been further subdivided by having pieces removed from the particle and renumbered. Potted butts, probe mounts, and thin sections have been made from these "splits"; others have been used for chemical, isotopic, and other analyses. Principal investigators (PI) seek allocations of these individual particles and subsamples for their research.

Current Revision Procedures: The first step carried out was to get computer print-outs of the "genealogy" and "generic listings" for all the Apollo 15 4-10 mm coarse-fines. The genealogy is a tree which lists each individual particle weight, a description of it, what form it is in, and the order of the subdivisions from the subgroups (groups) all the way to the thin section/probe mount. The "generic" listing is an account of all the particles that make up the whole sample. It lists the present location of the particle ex. Return Sample Vault (RSV) or if a (PI) has it in his/her possession, the weight, a description of what form it is in now, e.g. granules and the immediate parent number.

The generic listing, the genealogy, Powell's catalogue, and a file, which is called a data pack, were used as references for the recording of the 4-10 mm coarse-fine history. A data pack is a file which was created when the samples were first returned; it contains information on a generic, such as subdivisions of the particles, allocations of the particles to PIs and discrepancies that occurred. A new genealogy, arranged in the form of a "tree", was devised, the purpose being to update as well as to clarify the previous system of recording genealogy. The tree was set up with four headings: groups, individual particles, subsamples, and thin sections/probe mounts. The new generic listing is a combination of Powell's original macroscopic observations and identification, the old generic, the datapack information, any published data, and microscopic description. Because of the research done on the coarse-fines there have been changes and refinements in the original classifications of some of the particles. For example, Powell did not (discover) identify the KREEP basalts correctly, because without the benefit of microscopic work and INAA it can be very difficult to distinguish mare basalts from KREEP basalts. In the 16 years since Powell's catalogue
was written there have been advances in the understanding of certain processes, such as impact melting. The updated catalogue contains chemical data and petrographic work on these rock types. The petrographic work entailed examining all the thin sections and writing descriptions of them. Some of the thin sections have published data which was used as a supplement to our descriptions. However, many of the thin sections have little, if any, published petrographic or chemical data. There have also been changes in the terminology used, for example regolith breccias were originally classified as microbreccias. Particle group photographs, photomicrographs, and prechip/postchip pictures are included in the catalogue.

Common Rock Types: Some of the more common rock types in the Apollo 15 4-10 mm coarse-fines are listed below along with a short description and example. A list of some of the rarer rock types identified are granulite breccias, green glass clods, and troctolites.

Mare Basalts
The Apollo 15 mare basalts have low TiO₂ and are either quartz-normative or olivine-normative. The ages of both types are ~3.35 b.y. (3). The quartz-normative mare basalts generally have a porphyritic texture and a mineral composition which includes pigeonite and some have tridymite. Olivine is very rarely present. Olivine-normative mare basalts are coarse to fine-grained, with intergranular, subpoikilitic-poilititic textures. Minerals are pyroxenes, olivines, plagioclases, and opaques. An e.g. is 15104.2.

KREEP Basalts
The textures are subophitic to interstitial. Minerals are plagioclase, low-Ca pyroxenes, opaques (ilmenite is fairly common) sometimes cristobalite, and a glassy mesostasis. All of the KREEP basalts from the Apollo 15 mission were coarse-fines except for two that are rock samples. The name is an acronym for Potassium Rare Earth Elements Phosphorous; they have the highest REE of particles in Apollo 15 coarse-fines. An e.g. is 15304.5.

Regolith Breccias and Agglutinates
The regolith breccias have porphyritic, cataclastic textures. The groundmass is generally brown glass and sometimes plagioclase. Commonly there are yellow, green, and sometimes orange and even red glasses which are present as spherules or as broken fragments. The clasts are fairly fine-grained, and have an array or types: mare basalt, norite/anorthosite, and mineral clasts of pyroxene, olivine, and plagioclase. An e.g. is 15304.1.

An agglutinate is a combination of rock, mineral, and glass fragments held together by glass. The glass is black in hand sample, brown in thin section and is heterogeneous. There are many vesicles, different shapes and sizes (Meyers, 1987). An e.g. is 15224.3.

Impact Melts
Impact melts consist of a matrix of melt produced by impact and encloses clastic material. The textures are poikilitic to equigranular or glassy. The grain size is commonly fine-grained. An e.g. is 15314.26.

Anorthosites/Norites
Both anorthosite and norite are part of the gabbro family. A Norite is primarily composed of plagioclase and orthopyroxene, and anorthosite has ~90% plagioclase and minor amounts of pyroxene and/or olivine. The textures are cataclastic, (poikilitic, porphyritic, medium-grained, etc... look up) Some of the coarse-fines have an anorthosite percentage of plagioclase but the pyroxene is orthorhombic and therefore the classification is a noritic anorthosite. An e.g. is 15224.6.

Conclusion
The purpose of this catalogue is to make it as easy as possible for anyone interested to find information on the Apollo 15 4-10 mm coarse-fines. The coarse-fines relatively large size, compared with the finer fines, makes them valuable for research. This catalogue will be helpful to anyone who is interested in studying these particles.

References
(1) Powell, B.N. (1972). Apollo 15 coarse-fines (4-10 mm): Sample classification, description, and inventory. NASA Publ. MSC 03228
CADMIUM ADSORPTION IN CLAY LINER MATERIAL AMENDED WITH THE ZEOLITE CHABAZITE
Kelly Taylor, University of California, Riverside.

Land disposal of municipal and industrial wastes has resulted in the contamination of soils and groundwater with various heavy metals such as Cu, Zn, Ni, Pb, and Cd. One common method of containing such heavy metals is the use of clay liners in hazardous waste dumps. These methods, however, may not effectively prevent leaching of heavy metals into groundwater.

Zeolites are hydrated aluminosilicates of alkali and alkaline earth cations with unique cation exchange, adsorption, and hydration-dehydration properties which make them attractive for use as slow-release fertilizers, as ion-exchange sieves, and as traps for heavy metals in soils (Ming and Mumpton, 1988). The use of zeolites as amendments to clay liners may increase the adsorption potential of the liners for heavy metals; however, these zeolite starting materials must be characterized before they can be effectively used for environmental problems.

In this study, chabazite, a naturally occurring zeolite, was investigated to determine its effectiveness as an amendment in clay liner materials to increase adsorption of Cd from solution. Few studies have examined the adsorption of heavy metals onto the exchange sites of chabazite. Mondale et al. (1978) found that a chabazite-rich tuff from Bowie, Arizona effectively removed Cu$^{2+}$, Pb$^{2+}$, and Zn$^{2+}$ from aqueous solutions; however, they did not examine the adsorption potential for Cd$^{2+}$. The general selectivity sequence of chabazite for monovalent and divalent cations, including several heavy metals, is:

\[ \text{Tl}^+ > \text{K}^+ > \text{Ag}^+ > \text{Rb}^+ > \text{NH}_4^+ > \text{Ba}^{2+} > \text{Sr}^{2+} > \text{Ca}^{2+} > \text{Li}^+ \] (Breck 1974, page 536).

Several researchers have suggested the addition of zeolites to soils contaminated with heavy metals such as Cd, Pb, Zn, and Cu (Fujii, 1974); however, the addition of zeolites to clay liner materials in municipal and industrial waste disposal sites has not been examined. The purpose of this study is to examine the potential adsorption of cadmium by clay liner material amended with the zeolite chabazite.

MATERIALS AND METHODS

Characterization of Materials.

Ca-rich chabazite from Bowie, Arizona was sieved to <30 µm and treated with 1 M NaOAc buffered to pH=5 to remove carbonates. Clay liner material from Galveston County, Texas (Beaumont Formation clay) was also treated to remove carbonates. After pretreatment, the chabazite and clay liner materials were dialyzed to remove excess salts and freeze-dried.

For mineralogical analysis, slurries of Mg-saturated clay (2-0.2 and <0.2 µm) from the clay liner material and chabazite were pipetted onto glass slides to prepare preferentially oriented aggregates for X-ray diffraction (XRD) analysis. Following initial XRD analysis, Mg-saturated clays were glycerol solvated and X-rayed again. All samples were scanned from 2° to 45° 2θ using a scan speed of 1° 2θ/minute on a Philips X-ray diffractometer with monochromatic CuKα radiation obtained with a graphite crystal monochrometer. Morphological characteristics of chabazite were examined with a ISI-SR-50 scanning electron microscope. For scanning electron microscopy (SEM) analysis, samples were evenly dispersed over adhesive copper tape, cemented to 20 mm Al stubs, and grains were coated with approximately 20 nm of Au-Pd.

Cation exchange capacities of the treated chabazite and clay liner material were determined by displacing native cations with 0.1 M RbCl and analyzing by atomic absorption spectroscopy.

Cadmium Adsorption.

Clay liner material was amended with 0%, 5%, 10%, 25%, 50%, 75%, and 100% of the zeolite, each sample weighing a total of one gram. Samples were shaken with 100 ml of -10^{-2} M CdCl$_2$·2H$_2$O solution for 72 hours at 150 rpm and 25°C. Once shaking was completed, pH of the soil-solution mixture was measured. The samples were centrifuged and the supernatant measured for Cd, Ca, Mg, Na, and K by atomic absorption spectroscopy.
TABLE 1. Native cations and cation exchange capacities for clay liner material and chabazite used in Batch equilibrium exchange experiments.

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RESULTS

Characterization of Chabazite and Clay Liner Material.

X-ray diffraction indicated nearly monomineralic chabazite from the Bowie, Arizona deposit. The clay liner material (<30 µm) consisted primarily of smectite along with kaolinite, mica, and quartz. The individual crystals of chabazite occur as small (<1 µm in diameter) cube-like rhombohedra.

Native cations and total cation exchange capacities (CEC) for the clay liner material and chabazite are given in Table 1. Chabazite has a CEC approximately seven times greater than the clay liner material.

Cadmium Adsorption.

The clay liner material showed increasing adsorption of Cd\(^{2+}\) from the solution with increasing percent of chabazite added (Figure 1). Ca\(^{2+}\) and Mg\(^{2+}\) were de-adsorbed from the clay (Figures 2 and 3), while Na\(^+\) was de-adsorbed from the zeolite (Figure 4). The equivalents of ions adsorbed were approximately equal to the equivalents of ions de-adsorbed, clearly showing the occurrence of the exchange.

The 100% chabazite system removed nearly 64% of the total Cd\(^{2+}\) from the 10\(^{-2}\) M CdCl\(_2\)-2H\(_2\)O solution. On the other hand, the clay liner material only removed about 13% Cd\(^{2+}\) from solution. An addition of 5% chabazite by weight to the clay liner material increased the Cd\(^{2+}\) removed from solution to about 17%.

**FIGURE 1.** Cadmium adsorbed by clay liner material amended with chabazite (Initial solution=10\(^{-2}\) M CdCl\(_2\)-2H\(_2\)O, 1g clay/chabazite mixture, 0.1 L solution, 25°C).

**FIGURE 2.** Calcium de-adsorbed from clay liner material amended with chabazite (Init. sol.=10\(^{-2}\) M CdCl\(_2\)-2H\(_2\)O, 1g clay/chab. mix., 0.1 L sol., 25°C).
FIGURE 3. Magnesium de-adsorbed by clay liner material amended with chabazite (Init. sol.=10^{-2} M CdCl_{2}·2½H_{2}O, 1 g clay/chab. mixture, 0.1 L sol., 25°C).

FIGURE 4. Sodium de-adsorbed from clay liner material amended with chabazite (Init. sol.=10^{-2} M CdCl_{2}·2½H_{2}O, 1 g clay/chab. mix., 0.1 L sol., 25°C).

DISCUSSION

Clay Liner Materials.

The results of this study show that chabazite has a great capacity for adsorbing Cd from solution. Zeolites such as chabazite may be equally effective in removing other heavy metals such as Ni, Pb, Cu, and Zn. This indicates that the addition of zeolites will increase the life and effectiveness of clay liners used in waste impoundments and disposal facilities. Water seepage through clay liners amended with zeolites and zeolite stabilities and selectivities in clay liners are worthy of further research.

Controlled Ecological Life Support Systems.

Zeolites also may be useful in controlled ecological life support systems (CELSS) on planetary bases and the space station. The absorption capabilities of zeolites make them potentially useful as ion-exchange filters in water recycling processes to remove heavy metals.

REFERENCES


PETROGRAPHIC ANALYSIS OF SHOCKED QUARTZ IN THE CENTRAL UPLIFT OF THE MANSON STRUCTURE, IOWA

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Introduction. The Manson Structure, located in northwest central Iowa, is a 35 km wide zone of disturbed and displaced Paleozoic and Mesozoic sedimentary rocks surrounding an uplifted core of Proterozoic crystalline basement. As the structure is covered by glacial deposits, samples of involved lithologies are limited to preserved cuttings from numerous water wells in the region, and two cores extending to a depth of ~ 450 feet in the center of the crater, one of which (Manson 2-A) penetrated and retrieved crystalline basement material [1]. An impact origin was suspected primarily on the basis of the intense disruption of strata and the unusual central core of basement rocks that have been structurally uplifted more than 6 km. This hypothesis was strengthened when multiple sets of planar features in quartz grains from Manson were discovered [2]. These features have not been studied in detail, however, and many important aspects of their expression had not been documented prior to the present study.

The purpose of this project is to characterize planar features in quartz within the central uplift sampled by Manson 2-A, with an emphasis on documenting variations in shock expression with depth and lithology. There are three quartz bearing crystalline lithologies: Proterozoic granitic gneiss, a late-stage Proterozoic granite, and an impact-induced, chloritized "micro-breccia" consisting primarily of gneiss and granite clasts. The mineralogy and petrology of the these rocks have been described in Dryden [3] and Hoppin and Dryden [4]. A total of 12 thin sections, spanning the length of Manson 2-A and sampling the three major lithologies were examined. The location of these samples within the core is shown in Figure 1.

Procedure. Using standard universal stage techniques, quartz grains containing planar deformation features were mapped and characterized in terms of such descriptive parameters as continuity, sharpness, degree of curvature, spacing and decorations. Quantitative analysis included documenting the number of planes per set, sets per grain, and the optical attitude of each set. Attitudes were measured using two procedures. In both methods, the poles to all sets deformation planes and the optic axis of each quartz grain were plotted on a stereo-net. These data were then rotated to a c-axis vertical orientation. The first procedure involved measuring only the angle between the c-axis and each planar set and then plotting the frequency distribution of these data. The second method involved overlaying a template of all rational crystallographic orientations (c-axis vertical orientation) onto the data for each quartz grain and then rotating the template to get a best fit to the planar elements. Although more time consuming, the advantage to the second method is that the angular separation between multiple sets of planar features is retained whereas in the first method it is not. Thus more confidence can be placed in the assignment of deformation features to crystallographic planes. Accuracy of measurements was within ± 2.5°.

Results. Of the 705 sets in 188 grains analysed, only 8 appeared undecorated. The planar features are generally sharp and moderately continuous across the grain, although intra-grain domains, defined either by variations in extinction angle or bounded by fractures, commonly showed distinct sets of planar features not present in other regions of the grain. Spacing between features within a set varied between 0.1 and 4 µ in the granite and 0.2 and 10 µ in the gneiss and microbreccia, with the most common spacing 0.4 - 0.5 µ. Planar elements were usually perceivable within an angle of 30° to 60°; however, in many cases, the position of best focus of the plane was noticeably off center of this angle (~ 10°).

Up to 75 individual parallel planar elements constitute a set. Although it might be expected that larger grains would contain more elements per set our results indicate that large grains usually contain fewer planar features than the smaller grains do. This could be related to the fact that the surface area to volume ratio decreases as grain size increases and suggests that planar elements originate as grain boundary deformations.

The number of sets per grains is an important characteristic which distinguishes impact-produced planar features from other mechanisms such as tectonic deformation (Boehm lamellae) and volcanic processes. In both tectonic and volcanic mechanisms the vast majority of quartz grains contain only one set of lamellae with Boehm lamellae rarely having up to three. In contrast, shock lamellae are typically multiple sets with up to 11 individual sets reported [2]. Figure 2 summarizes the results of our measurements. Up to 8 sets were detected in a single grain and grains averaged between 3 and 4 sets. Less
than 10% of the grains measured contained single sets. The marked contrast between these results and those of non-impact mechanisms provide clear indications of the impact origin of the Manson Structure.

Another feature diagnostic of shock-induced planar elements is the high percentage of sets that correspond to rational crystallographic planes [2]. Using our second method, described above, we found that over 95% of the measured sets correspond within \( \pm 0.5^\circ \) of crystallographic orientations (Figure 3) with approximately 17% oriented along the \( \pi \) direction. Only about 3% of the sets were basal features, all of which were located within the gneiss samples.

Our comparison of the two techniques for determining optical correspondence of the planar elements indicates that the first and most expedient method is sufficient for most purposes. Figure 4 shows our results for the total population of quartz grains using the first method and can be compared with Figure 3. Variations in bin size (Figure 4 is \( 2^\circ \); Figure 3 is \( 10^\circ \)) accounts for the major differences in these two histograms.

The orientations of planar elements shown in Figure 4 are somewhat unusual for impact structures in that the modes associated with the most commonly observed orientations are only about 30-50% above the background, and the background appears to have a skewed but continuous distribution similar to that of tectonic lamellae. Comparison of the histograms for each of the three lithologies indicates that the gneiss (Figure 5) is the primary contributor to the background pattern. The granitic samples produce a histogram (Figure 6) with a relatively flat background and strong peaks; the micro-breccia samples produce a histogram (Figure 7) that appears like a mixture of the two other lithologies. The lithological variations and the unusual characteristics of the gneiss samples lead us to believe that the orientations of the shock features produced by the Manson impact event were control by a preexisting, tectonically-induced micro-fabric produced in the gneiss. Further work is required to substantiate this hypothesis, however, if true, this would have profound implications for the recognition of shocked lithologies in previously metamorphosed terrains.


Figure 1
2 SETS PER GRAINS
MANSON CORE 2A

705 Sets in
188 Grains

Maximum = 8 Sets
Mean = 3.75 Sets

Histogram of the Number of Sets Recorded per Grains

3 ORIENTATIONS
MANSON CORE 2A

705 Sets in
188 Grains

4.7% Unfitted
Planes

Histogram of Crystallographic Planes

4 ORIENTATIONS MANSON CORE 2A

705 Sets in
188 Grains

Histogram of Measured Angles Between Quartz C-Axes
and Poles to the Planar Features

5 ORIENTATIONS GNEISS

402 Sets in
109 Grains

Histogram of Measured Angles Between Quartz C-Axes
and Poles to the Planar Features in
M2A 189/207/258/400/438/458

6 ORIENTATIONS GRANITE

215 Sets in
52 Grains

Histogram of Measured Angles Between Quartz C-Axes
and Poles to the Planar Features in
M2A 93-99/379/432½/448

7 ORIENTATIONS MICRObreccia

83 Sets in
27 Grains

Histogram of Measured Angles Between Quartz C-Axes
and Poles to the Planar Features in
M2A 192 AND M2A 387