Papers Presented at the

12th annual

Summer Intern Conference

August 15, 1996
Houston, Texas

1996 Summer Intern Program for Undergraduates
Lunar and Planetary Institute
Papers Presented at the

Twelfth Annual
SUMMER INTERN CONFERENCE

August 15, 1996
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1996 Summer Intern Program for Undergraduates
Lunar and Planetary Institute

Sponsored by
Lunar and Planetary Institute
NASA Johnson Space Center
TWELFTH ANNUAL SUMMER INTERN CONFERENCE PROGRAM

AUGUST 15, 1996—LPI BERKNER ROOM

Morning Session
Chair: Paul D. Spudis

9:00 a.m. KATHERINE A. HERRELL Advisor: Graham Ryder
A Petrographic Study of Olivine Characteristics and Variations Among the Apollo 15 Olivine Normative Mare Basalts

9:20 a.m. MARK F. JOHNSON Advisor: Carl Allen
Multi-Spectral Mosaic Building Using Clementine Images

* KEVIN B. JONES Advisor: Paul M. Schenk
Stereo Topography of Io and Ganymede from Voyager Imagery

9:40 a.m. KENTARO KANEDA Advisor: Gordon A. McKay
Synthetic and Natural Nakhla Pyroxenes: Minor Elements Composition

10:00 a.m. Break

10:30 a.m. PETER T. LETH Advisor: Allan H. Treiman
Geology of the Reull Vallis Region of Mars: Evidence for Mid-Noachian Sheet Floods

10:50 a.m. CELINDA A. MARSH Advisor: Robert R. Herrick
Ereshkigal and Kunhild: Large Volcanoes, Low Gravity Anomalies, and a Geologic History

11:10 a.m. PIMOL MOTH Advisor: Deborah Domingue
Spatial and Temporal Variations in Io's Surface Composition

11:30 a.m. Lunch

* Presented at the August 6, 1996, Intern Seminar
Afternoon Session
Chair: Michael E. Zolensky

1:00 p.m. KEIKO NAKAMURA  Advisor: Michael E. Zolensky
    Dark Inclusions in CV3 Carbonaceous Chondrite Meteorites

1:20 p.m. CRAIG B. PAMPLIN  Advisor: Richard V. Morris
    Sulfur Analysis of Tephra from Mauna Kea Volcano, Hawaii and Goldfield, Nevada: Implications for Acid Sulfate Weathering on Mars

1:40 p.m. PATRICK S. RUSSELL  Advisor: Gary E. Lofgren
    Chondrule Precursor Aggregates and Clastic Rims in Ordinary Chondrites

2:00 p.m. Break

2:30 p.m. AMER SMAILBEGOVIC  Advisors: Don A. Morrison and Paul D. Spudis
    Moon Down Under: Clementine’s Multispectral Look on the Apollo Basin Characteristics

2:50 p.m. ANNE E. TAUNTON  Advisor: David S. McKay
    Scanning Electron Microscopy of Terrestrial and Extraterrestrial Samples: A Study of Bacteria and Nannobacteria

3:10 p.m. Adjourn
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Scanning Electron Microscopy of Terrestrial and Extraterrestrial Samples: A Study of Bacteria and Nannobacteria

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A Petrographic Study Of Olivine Characteristics And Variations Among The Apollo 15 Olivine-Normative Mare Basalts; Katherine A Herrell, University of Texas at Austin

INTRODUCTION: The lunar mare plains are volcanic landforms composed of basalt, an igneous rock consisting dominantly of the silicate minerals pyroxene and plagioclase feldspar. Some basalts also contain significant amounts of olivine, which is the first phase to crystallize. One group of basalt samples collected at the Apollo 15 landing site is olivine-normative. These Apollo 15 olivine-normative basalt samples all have the same crystallization age and isotopic characteristics within analytical uncertainty [1]. Early workers [2] proposed that the individual samples were related to each other by the separation of olivine from the parent magma. Work by Ryder and Schuraytz [3] has confirmed in detail the olivine control of the chemical variation (Fig. 1). However, identification of the chemical process has not led to understanding of the physical process by which the differentiation actually took place. At the Apollo 12 site, a corresponding group of olivine-normative basalts has the characteristics of representing a single thick flow in which olivine crystallized and sank [4]. However, for the Apollo 15 olivine-normative basalts the relationship is not as easily explained: there are no glassy samples; there is a lack of olivine as large phenocrysts; and there is a considerable range in rock textures.

In the present study the characteristics of the olivine itself are being studied in an effort to constrain possible crystallization histories of each sample. Variations in size, shape, abundance, and composition of olivine can shed light on how and where the olivines crystallized. With consideration to other rock characteristics, such as grain size of other minerals, we will further understand the cooling histories and recognize how the process of olivine separation was physically carried out. A specific goal is to assess if the olivine separation took place in surface flows or in subsurface magma chambers, and whether each sample, or each subgroup of samples with identical compositions, represent separate extrusions and flows.

SAMPLES: 25 samples of the olivine-normative basalts were analysed in order to establish the chemical variations that exist among them [3,5]. The samples ranged in texture from fine-grained, vesicular and non-vesicular rocks to coarse-grained, vesicular and non vesicular rocks. Thin sections corresponding to each sample, in some cases multiple thin sections, were used to study the petrography of the olivines. Presently I have viewed 14 of the 25 samples (see Table 1), each sample section representing a part of the chemical and textural range.

METHODS: Mosaics: For 14 of the samples (Table 1) I made large scale photo mosaics of the thin sections, each 4 by 6 inch photograph corresponding to a 1.38 by 4.15 mm thin section area. This allowed me to compare the samples on an identical scale, magnified 76 times for easier mapping of grains. From the mosaics, I numbered and mapped out olivine crystals larger than .20 mm. For calculating average grain size, I measured the longest crystal dimension. On a data sheet, I recorded the measurements and categorized the olivine shapes. Inclusions of chromite and trapped liquid and zoning, optically characterized by changes in birefringence colour within the grain, were also recorded.

Image Processing: I scanned slides taken of the mosaics into a PC computer. From the scanned images, I graphically mapped out the olivines in order to obtain pixel images of the olivine area and the total rock area. From these images, I calculated the modal % of the olivines within each thin section. This number I compared with the normative % of olivine expected in the sample.

Inspection of Rock Slabs: Olivine distribution and size maps were made from rock slabs of 7 samples. The slabs are large, relatively planar, sawn surfaces and kept under clean conditions in the Lunar Laboratory at Johnson Space Center. I identified the olivines in the rock by using a binocular microscope and mapped them on a scaled photograph taken of the slab. The sizes of the longest olivine dimensions were recorded using a representative scale within the microscope eyepiece. This was to check that the small area sampling of thin sections correctly represented the distribution of sizes and abundances of the olivine crystals in the rock on a macroscopic level.

Electron Microprobe Analyses: Using standard techniques, quantitative chemical data for the olivine grains of thin section 15556,133 was taken by using both electron microprobes at Johnson Space Center. The sample was cleaned and coated in carbon. The cores and rims of the olivine crystals were analyzed to obtain the ratio of Mg to Fe, the proportions of minor elements, especially Ca and Cr, within the olivine and to map how the olivines were compositionally zoned.

RESULTS: Table 1 is a summary of the samples and some results. Many details, such as the shapes of grains and the presence or absence of chromite inclusions, cannot be shown in such a summary. The sequence of grain size shown in the table is based on groundmass plagioclase grain size and was compiled for these samples by B.
Schuraytz. Much of the data still has to be synthesized into meaningful comparisons among samples and their genetic differences, e.g. the differences between normative and actual olivine abundance in the larger grains, and the differences of the calculated maximum olivine composition and the actual maximum olivine compositions. Below is a summary of general olivine characteristics seen in the samples.

**Olivine sizes:** There was no obvious size variation among samples. The average long dimension of the crystals ranged from .5 to 1.5 mm. There were a few larger olivines of the 2mm range, one 3mm, present in the slab samples. There were no olivine megacrysts or large phenocrysts found.

**Olivine shapes:** Shapes of the olivines in the samples included: subhedral boxy, round, triangular grains; equant grains; holey and embayed grains; skeletal and irregular grains. In a few larger grained samples, tiny euhedral grains included in the plagioclase and pyroxene were present. Some grains were multi-grained, forming dual cores, aggregates, and chains of olivine. For most of the rocks there was no great distinction in the shapes among samples; the olivines tended to be somewhat irregular. Regular euhedral and subhedral grains were rare.

**Olivine abundances:** The abundances of the olivine found in the samples compared to the amount of normative olivine chemically calculated tended to be on the ratio of 1 to 2 or larger. There was considerably less olivine found then expected. In sample 15556, olivine abundances seemed to be affected by the size of the vesicles. The section containing the largest vesicles seemed to also have the least amount of olivine for that sample.

**Zoning:** In all samples zoning was present in most of the grains. In some fine-grained samples, the optical zoning was very apparent, represented by distinct colour variations from the core of the crystal to the rim. In some coarser-grained samples, optical zoning was less distinct or not apparent. Chemically though, these grains still showed zoning. The Mg to Fe ratio of the olivine cores ranged from Fo74-Fo60. The maximum Fo value for most samples was found to be less than the expected Fo value.

**Inclusions:** Chromite, other oxide inclusions, large liquid inclusions and dotted liquid inclusion cores were also identified in particular samples.

A brief comparison of olivine characteristics in 15556, a fine-grained vesicular, Mg poor rock to 15555, a coarse-grained Mg rich rock is described below:

- Olivines in 15556 have cores that are very similar to those that should crystallized from a liquid of a 15556 composition (Fo68). The olivine cores in sample 15555 are more Mg rich than the olivines in 15556, but they contain less than the expected Fo value (Fo72,Fo74). Very few cores in 15555 are even as Mg rich as Fo72.
- The modal % of olivine calculated for 15556 is only about 4% less than the calculated olivine normative %. The modal % of olivine for 15555 was less than half the normative % (4-7% vs. 15-16%).
- The sizes of the olivine grains are relatively similar. The grains in 15555 were slightly larger than 15556 (.1.1mm vs. 1.3mm).
- The shapes of the olivines were generally irregular. Holes, embayments, and multiple grains occurred in both samples.
- The zoning in 15556 was more distinct in more grains than the zoning in 15555.
- Liquid inclusions were more abundant in 15556 than in 15555. Chromite inclusions seemed consistent for both samples.

**DISCUSSION:** The olivines in these samples seem to number fewer and are smaller in size and variation than expected for an olivine controlled magma flow of their composition. Neither the sizes nor the shapes of the olivine crystals were found to greatly vary throughout the suite, the average maximum dimensions of the crystals remaining relatively homogeneous and the shapes, generally irregular. Euhedral and subhedral crystal faces were rare, occurring only as tiny grains in the groundmass or as inclusions within larger pyroxene and plagioclase grains of the larger grained samples. There is not an apparent increase in the number of olivines appearing in the rocks, even as grain size of the groundmasses drastically increases. There is no sign of phenocryst growth and settling, either in the thin sections or the rock slabs. There is some variation of olivine abundance in 15556 that suggests some movement of olivine crystals that might be related to vesiculation. If 15556 was produced from 10-15% olivine separation from a liquid like 15555 (as chemistry suggests) then there should be rocks with that much olivine cumulated in them. We have not seen these olivine accumulations. It looks as if numerous separate magma extrusions occurred, and these extrusions lacked phenocrysts. The far side of Hadley Rille shows bedded layers of numerous thin flows, yet only two main groups of mare basalts were found at this site. One of these is the olivine-normative group. This model fits with subsurface olivine separation but it is still unclear as to why no magmas erupted with big olivine phenocrysts as seen in Hawaii [6].
### Table 1. Summary of data for Apollo 15 Olivine-normative basalt samples studied

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<tr>
<th>Chemical</th>
<th>MgO</th>
<th>Sm</th>
<th>Thin Probe</th>
<th>Mosaic</th>
<th>Mode Ol</th>
<th>Norm Ol</th>
<th>Max Fo</th>
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Thin sections listed in [ ] do not correspond with chemical differences.

*"s" = probe data available for this sample from Shervais et al. (1990); all other probe data this study and Ryder and Schuraytz unpublished.

* size for simplicity here is average of 5 largest grains.
MULTI-SPECTRAL MOSAIC BUILDING USING CLEMENTINE IMAGES

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Advisors: Carlton C. Allen, PhD., SN2, Johnson Space Center, Houston, TX
Cassandra Coombs, PhD., Dept. of Geology, College of Charleston, SC

INTRODUCTION

Since the dawn of space flight photographic images have enhanced mankind’s understanding of the makeup of the lunar surface. The recently acquired CLEMENTINE images have taken this evolutionary process to its next level. We now have the ability to produce multi-spectral images with resolution heretofore unobtainable. When these images are compared with high resolution Apollo images and, more importantly, “ground-truthing” from the Apollo lunar samples, the utility of this process becomes evident. The multi-spectral values from the sample areas can be compared to those from unsampled areas and lunar soil makeup can be predicted with reasonable accuracy.

Harrison “Jack” Schmitt and Gene Cerman of the Apollo 17 lunar mission discovered orange and black colored soil during their exploration of dark mantle deposits on the eastern edge of Mare Serenitatis. This soil has been identified as volcanic glass and is rich in iron oxide (FeO). Iron oxide has been found to be an important source of extractable oxygen. The exact location of this deposit of volcanic glass is well documented. It is theorized that comparison of the multi-spectral data obtained from CLEMENTINE images will allow scientists to predict the soil make-up of similar areas of unsampled dark mantle deposits found around the southern rim of Mare Serenitatis, especially in the vicinity of the crater Sulpicius Gallus.

The process of assembling large mosaics from CLEMENTINE images is still in its early evolution. Currently ISIS, a software program from the USGS, is used to decompress, merge, coregister, and mosaic multiple CLEMENTINE images. Other image processing programs such as ENVI by RSI hold the potential to increase the utility of ISIS and allow “quick-and-dirty” image subsetting, band ratio calculations, and principal component analysis.

With these computer tools selection of future manned and unmanned lunar landing sites is made more efficient and productive. Sites near or on large deposits of oxygen extractable soil can be plotted and considered. The need to traverse extensive and potentially dangerous tracts of lunar landscape is reduced or eliminated.

METHODS

These mosaics cover large areas of interest on opposite sides of Mare Serenitatis. The images were taken by the UV/VIS camera on the CLEMENTINE spacecraft using filters in the 415nm, 750nm, and 950nm range. The Taurus Littrow mosaic encompasses an area bounded by 25 - 30E and 15 - 30N. This mosaic utilized 222 raw CLEMENTINE images spanning six orbits and one-and-one-half latitude bins. The Sulpicius Gallus mosaic encompasses an area bounded by 5 - 12E and 15 - 30N with an inconsequential loss of data between 7 - 9E and 15 - 20N. Here 288 raw images were utilised from five orbits and one-and-one-half latitude bins. The raw images were converted to ISIS usable cube files and merged using the ISIS “Calmrg” calibration/merging program. The UV/VIS calibration program dated July 6, 1996 was used to calibrate the images. Following calibration, matchpoints between images and between orbits were found for the 750nm (B Filter) images using the “Matchpoint” program.

The remaining 415nm (A Filter) and 950nm (D Filter) images were coregistered with the B Filter images and photometrically corrected before they were built into individual mosaics. These mosaics were then ratioed in the following manner; B/A, which was assigned the color red, B/D, which was assigned the color green, and A/B, which was
assigned the color blue. These ratios have been determined to be most useful in mapping pyroclastic deposits [1]. The images resulting from this ratioing were 'stretched' and converted to raw images and then to multi-spectral mosaics.

OBJECTIVES

It is theorized that a comparison of these multi-spectral mosaics will show similarities in the make-up of pyroclastic deposits found around the rim of Serenitatis. At the very least, these mosaics will allow accurate mapping of boundaries and areas of mixed and pure volcanic glass. As these mosaics consist of first-month, second-month, and 'zero-month' orbits, an accurate deduction of soil make-up can only come from comparison of similar 'month' orbits; in effect, apples must be compared to apples.

A secondary benefit of building large mosaics is the ability to study large areas initially and then create subsets of smaller areas of interest which do not have to be 'restretched'; in other words, the reflectance values of the subset will be identical to the same area in the larger mosaic.

It is also possible that as more large area mosaics are constructed using this method of band ratioing, similar patterns of deposition on other areas of the lunar surface may be discerned. In the area of lunar landing site planning, this could greatly reduce search time, as more accurate geologic mapping would be possible.

APPLICATION

Initial color mosaics of the Taurus Littrow and Sulpicius Gallus dark mantle deposits have been completed, and support tentative comparisons of the color and hence chemical composition. The deposits immediately surrounding the Apollo 17 site appear as dark purple on the mosaics while the deposits around Sulpicius Gallus are deep red in color. This color difference implies differences in major element abundances, particularly TiO2. Refinement of the color calibration is still in progress. Because of the unavailability of the July 6th version of the UV/VIS calibration program, the Sulpicius Gallus mosaic was calibrated using the previously available program which was found to be flawed and required correction [2]. A new mosaic using the July 6th UV/VIS calibration program is currently under construction. The results of this mosaic will allow more accurate comparison of the two sites.

REFERENCES


STEREO TOPOGRAPHY OF IO AND GANYMEDE
FROM VOYAGER IMAGERY

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INTRODUCTION

Voyagers 1 and 2 passed through the Jovian system in 1979, returning images of Io, perhaps the most volcanically active body in the Solar System, and Ganymede, covered with impact craters and patches of dark terrain cut by swaths of bright, grooved terrain. No altimetry data or direct measurements of topography on Io or Ganymede were gathered, however. Prior to this study, only limited topographic information for these two satellites had been obtained, using shadow lengths [1], photoclinometry [2], and limb profiles. Some areas of Io and Ganymede were imaged several times from different angles as the Voyagers passed. In 1995, stereo topographic mapping of areas on Io using Voyager images was attempted with limited success by Davenport and Schenk [3], but errors due to inadequate geometric calibration were discovered. Portions of the geometric calibration procedure were updated by the U. S. Geological Survey in Flagstaff in an effort to correct these errors. This study was intended to evaluate the validity of these updates and to begin the complex job of mapping extensive areas of Io and Ganymede topographically, something which had not previously been possible. Goals were to describe the general topography of shield volcanoes on Io and to extract quantitative values for shield volcano slopes for later use in constraining lava rheologies.

METHODS

Areas on Ganymede and Io were mapped topographically using automated stereo topography software, which takes a registered stereo image pair as inputs and outputs a digital elevation map (DEM), as well as maps of height errors and correlation coefficients calculated during processing.

Targets for topographic mapping within the multiply-imaged areas on Ganymede and Io were chosen based on scientific interest and the availability of images suitable for stereo topography processing. Sets of three or more different suitable images were selected for each chosen target area. The selected images of each target feature were registered to one another using five match points to tie each frame to every other frame in the set. Following registration, the images in each set were reprojected onto a common orthographic grid. These reprojected images were used as inputs to the stereo topography software. This software analyzes a pair of images by taking a subsection (the size of which can be varied) of one image and, using a subpixel registration algorithm, locating the same subsection in the second image. The offset of this location from the predicted location is interpreted as parallax, from which a height is calculated.

The software outputs a DEM and maps of estimated height errors in the DEM and correlation coefficients showing how well the subpixel registrations matched. These error and correlation coefficient maps were used to mask off areas of the DEMs containing large errors or low correlation coefficients, interpreted as areas of potentially bad topographic information. After this masking, some small areas of clearly invalid topographic data occasionally remained. These areas were masked off manually. Elevations in the masked areas were interpolated from surrounding valid data. Most DEMs showed a regional tilt across the mapped areas. The tilts were not consistent in magnitude or direction for DEMs of the same target area produced using different image pairs. These tilts were artifacts of slight misregistration between images interpreted by the software as parallax, and were manually removed by subtracting an oblique plane from each apparently tilted DEM.
GANYMEDe RESULTS

Ganymede was chosen for verification of this method of stereo topographic mapping for two reasons: its assumed flatness and its detailed, textured surface which allows mapping of continuous regions. Mapping of continuous regions is not possible on Io where smooth, featureless plains are extensive.

An area near the south pole and an area surrounding the impact crater Isis were selected as target areas on Ganymede. All three DEMs of the Isis region yield consistent topographic information. The four Ganymede south polar DEMs contain almost entirely consistent topographic information. Two small areas are inconsistent, appearing as topographic domes in two DEMs and basins in the other two. The cause of these inconsistencies has not yet been identified, but they are probably due to reseau marks mislocated during image processing.

The Isis region of Ganymede contains large areas of both dark and grooved terrain. On each of the three independent Isis DEMs, the dark terrain shows up as a relatively high plateau surrounded by lower swaths of grooved terrain (Figure 1). Two swaths of grooved terrain are estimated from the DEMs to be approximately 0.3 and 0.5 km below the surrounding dark terrain plateaus.

Figure 1. Isis region of Ganymede. Left: Orthographic reprojection of Voyager 2 image (0666 J2-001, clear filter). Right: DEM showing computed topography.

The floor of the impact crater Isis is estimated to be 1.1 km below the rim crest. This estimate is consistent with shadow length and photoclinometry measurements for this crater [4]. Crater elevation is one of the best checks on the accuracy of this stereo topography determination technique. Two other, smaller recent craters in the Isis region have floors estimated at 1.2 and 1.0 km below their respective rim crests.

The four DEMs produced of the area near the south pole of Ganymede show features similar to those visible on the Isis DEMs. A large impact crater in the region has an estimated depth from rim crest to floor of 0.8 to 1.0 km. A smooth area embaying the grooved terrain in this region is estimated to be 0.4 km below the terrain.

IO RESULTS

Agni, Dingir, Maasaw, and Ra Paterae, four prominent shield volcanoes on Io, were selected as target areas for stereo topographic mapping.

Based on measurements from three DEMs of Ra Patera, the rim of Ra rises between 3.0 and 3.5 km above the surrounding plains (Figure 2). Seven radial profiles constructed from these DEMs show that the flows of Ra Patera slope between 5.2° and 13.3° near the rim crest, 0.3° to 0.6° from just below the rim crest to the flow termini, and average a slope of 0.9° from rim crest to flow termini.

Measurements from a single DEM show the rim crest of Maasaw Patera to be approximately 1.3 km above the surrounding plains. Measured along three radial profiles, Maasaw slopes between 5.1° and 7.3° near the rim.
crest, 0.2° to 0.4° from just below the rim crest to the flow termini, and between 0.6° and 1.2° from rim crest to flow termini. Dingir Patera, based on measurements from one DEM along three radial profiles, rises about 1.6 km above the surrounding plains, and slopes between 0.6° and 0.8° from rim crest to flow termini. From a single DEM, the Agni Patera rim crest is estimated to be 1.7 km above the surrounding plains. Along three radial profiles, the mean slope of Agni Patera is estimated to be between 1.5° and 3.3° from rim crest to flow termini.

Figure 2. Ra Patera region of Io. Left: Orthographic reprojection of Voyager 1 image (0043 J1+000, blue filter). Right: DEM showing computed topography.

DISCUSSION AND CONCLUSIONS

The internal consistency of the Ganymede DEMs and the quantitative consistency of estimated impact crater depths with previously published values illustrates that the stereo topography software produces valid results. The two small discrepancies noted in the Ganymede south polar DEMs indicate there are some minor residual anomalies that remain to be corrected.

The topographic expression of the bright terrain relative to the dark terrain in the Isis area was an unexpected finding. The difference in elevation between areas of bright and dark terrain had not previously been accurately measured.

The average slopes of volcanoes on Io were found to be similar to those of many shield volcanoes on Venus (0.2°-1.2°) and to some on Mars, but were shallower than those of some prominent terrestrial shield volcanoes, such as the island of Hawai'i (3-5°) [5]. These results will be useful in future efforts to understand the rheology and composition of lavas on Io.

This mapping of Io and Ganymede represents the first successful use of stereo topographic mapping techniques at this scale in the outer Solar System. Stereo topographic analysis has the advantage over other limited methods of elevation determination such as shadow length measurements and photoclinometry of being able to analyze extended areas. This makes the generation of DEMs of large areas of images possible.

Acknowledgments. The author thanks Paul M. Schenk for his instruction and the opportunity to work on this project, and Brian Fessler for his limitless assistance with computer programs and problems.

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SYNTHETIC AND NATURAL NAKHLA PYROXENES: MINOR ELEMENTS COMPOSITION. Kentaro Kaneda (Mineralogical Inst., Fac. of Sci., University of Tokyo 113, Japan), Advisors: G. Mckay (SN4, NASA-JSC, Houston, TX 77058), L. Le (Lockheed Martin, 2400 NASA Rd. 1, Houston, TX 77058)

INTRODUCTION: The SNC meteorites, which are of Martian origin, have four groups (Shergottite, Nakhlite, Chassigny, ALH84001). Nakhlite is one of the three nakhlites which are known as Ca-rich achondrites together with angrites. It is mainly composed of cpx, olivine and mesostasis which contains principally radiating plagioclase, alkali feldspar, pigeonite and opaque minerals [1]. Pyroxenes in Nakhlite show cumulate texture [1], [2] and rarely have pigeonite exsolution lamellae. Therefore, Nakhlite is believed to have been quenched after accumulation.

The pyroxenes have igneous elemental zoning, especially with respect to Mg, Al, Ti and Fe, which would preserve information about the formation process of Nakhlite and the composition of the Martian magma from which it was formed. A series of crystallization experiments were performed over a range of cooling rates using a synthetic Nakhlite composition. By comparing the compositions and textures of pyroxenes from these experiments with natural pyroxenes in Nakhlite, we hope to provide additional constraints on the formation of Nakhlite.

EXPERIMENT: Experimental starting material NJ3 was made by mixing of our earlier synthetic compositions, NJ2 and NL1 [3] (Table 1). A series of experiments were then performed to determine its liquidus temperature. 125 mg pellets of NJ3 were placed on 8 mil Pt/Rh loops, fused ~1350 °C for 48 hours in a gas mixing furnace at fO2=QFM (quartz-fayalite-magnetite buffer), then quenched to room temperature. Pellets were then placed back in the furnaces at fixed temperature for 48 hours, then quenched. Oxygen fugacity was monitored using a solid oxygen electrolytic zirconia cell in an external reference furnace [4].

After the liquidus temperature was determined, homogenized charges were put back in the furnaces slightly below the liquidus temperature, then cooled linearly or non-linearly to ~200 degrees below their liquidus temperature, and quenched to the room temperature. The cooling rate, quench temperature and duration of these experiment are shown in table 2 and fig.1. These quenched charges contained small amount of glasses, zoned pyroxenes, and spinel.

Pyroxenes and melts were then analyzed with the Cameca Camebax Electron Microprobe, and the pyroxenes were compared with Nakhlite Pyroxene. The Cameca SX100 Electron Microprobe was used to acquire elemental maps of the pyroxenes to study zoning patterns.

RESULTS: Average glass compositions show no significant difference among experiments of NJ3, except volatile elements such as Na, P and K. These elements were depleted during the experiments.

The liquidus temperature was determined at 1185 °C after a series of isothermal experiments were performed ranging from 1178 °C to 1190 °C. Crystals were found in NJ3-654A at ~1186 °C at QFM and NJ3-656B at ~1178 °C and none was found in NJ3-656A at 1190 °C. Pyroxene core compositions in NJ3-654A have resemble those in NJ3-656B, except for Al2O3 and TiO2.

Pyroxenes in NJ3-657, which was cooled at 2 °C/hr, have the closest composition to Nakhlite Pyroxenes, with Al2O3 within a 0.01% difference in average composition. These pyroxenes also have similar crystal shapes with small glass inclusions (parental melt inclusions) similar to those seen in Nakhlite. However, pyroxene compositions in the NJ3-658 experiment, which was cooled non-linearly from 1186°C to 1003°C, were significantly different from Nakhlite pyroxene composition. Many glass inclusions were found in these crystals and thus they were difficult to analyze.
Pyroxenes in NJ3-659, cooled at 4°C/h, were also different in composition and texture from Nakhla pyroxenes. Crystals have bar or needle shapes and no euhedral-subhedral pyroxenes were found. However a great percentage of crystals have glass inclusions. NJ3-660, cooled non-linearly from 1181 °C to 850 °C, also has many glass inclusions in its pyroxenes. This sample was not analyzed quantitatively but was mapped with the Cameca SX100 Scanning Electron Microprobe. Evidently, some pyroxenes in NJ3-657 are sector zoned.

NJ3-657, -658, -659 and -660 contain small euhedral opaque minerals. EDS spectra indicate they are composed of Al, Ti, Fe and O. These compositions were not analyzed, however they are probably Ti-magnetite.

**DISCUSSION:** Fig.2 shows a Al$_2$O$_3$ vs. TiO$_2$ plot of pyroxene core compositions from Nakhla and our experiments. Pyroxene Al$_2$O$_3$/TiO$_2$ appears to be a function of cooling rate. Al$_2$O$_3$/TiO$_2$ in pyroxene from the isothermal experiments range from 4 to 5. Al$_2$O$_3$/TiO$_2$ in the experiments cooled at 2°C/Hr range from 2.6 to 3.2. Al$_2$O$_3$/TiO$_2$ in Nakhla pyroxenes range from 3 to 4. If the Al$_2$O$_3$/TiO$_2$ of pyroxene does relate to cooling rate, the Nakhla cools at < 2 °C/Hr. Currently experiments at 1.5 °C/Hr are being carried out to test this hypothesis.

Although Al$_2$O$_3$/TiO$_2$ is similar in the experiments and Nakhla, the pyroxene compositions are slightly different. The CaO and MgO contents are high in the experimental pyroxenes and the FeO is lower. This is probably due to the loss off Fe to the Pt loops during the experiment [5]. Experiments will be carried out on very thin (i.e., 4 mil) Pt wire in order to avoid this experimental problem.

**CONCLUSIONS:** Cooling rate effect the minor elements such as Al and Ti very strongly. Figure 2 shows that pyroxenes grown with rapid cooling rates contain high Al in the cores and rims. Each experiment was carried out for a different duration. Comparison between rims may not have any crucial meaning. Therefore, we should focus on the cores. Major element compositions of the cores seem to change according to cooling rate. However, the cores might have almost the same compositions of major elements and just have different sizes. That will not affect above conclusion, because no correlations can be shown between MgO content and Al$_2$O$_3$ or TiO$_2$ content in the cores.

The cores in 657 have almost same range of the content of Al$_2$O$_3$ contained in the cores of Nakhla pyroxenes. Actually some 657 pyroxenes show sector zoning like Nakhla pyroxenes.

**ACKNOWLEDGMENT:** I gratefully acknowledge Dr. V. Yang, J. Wagstaff for the use of, and help with, the Camebax electron microprobe, and Dr. T. McCoy, Dr. V. Lauer, and Dr. B. Hanson for the help with Deltech furnaces.

**REFERENCE**

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hc: homogenized charge (average)

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Fig. 1

Fig. 2
Geology of the Reull Vallis Region of Mars: Evidence for Mid-Noachian Sheet Floods

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Allan Treiman
Lunar and Planetary Institute, Houston, Texas

Detailed geologic study of the Reull Vallis uncovers a complex history. The region seems to have undergone at least two stages of flooding which have exposed a thick sedimentary sequence of possibly volcanic origin.

The geology of the Martian surface cannot be determined by conventional field mapping and sampling. Rather, one must rely on interpretation of satellite images. This method is somewhat limited, since image resolutions are often on the order of 200 meters/pixel, preventing us from seeing anything but large regional features. We also do not have samples from any specific site on the surface. Although we do know exactly what rock types the SNC meteorites are, we have no way of telling where they came from on Mars.

Viking Orbiter images of the Reull Vallis (41.6°S, 258.3°W) show a complex scene which includes horizontal rock strata exposed in the valley walls, parallel remnants of plains mantle units and an apparently anomalous re-entrant structure which we call the Pomona Vallis (44°S, 258.5°W) (see Figure 1). These features reveal an intricate history, including a large sheet flood, possibly originating from the Pomona Vallis, which stripped and scoured Reull Vallis and its surroundings.

![Figure 1: Overview of Reull Vallis Region (MDIM; lat=[-47,-37], lon=[253,268]; frame width=700km).](image)

**Methods**

To determine the geologic history of the Reull Vallis region, we first assembled a photo mosaic of orthographically projected images (VO frames 329S21-31; 235m/pixel) and mapped topographic units. This allowed us to locate time-stratigraphic contacts between different units, and to obtain a broad view of the surrounding terrain. Red, green and blue filter images that were cleaned and radiometrically and geometrically corrected with PICS and ISIS software packages, were then registered together to obtain full color images for the upper Reull Vallis/ Pomona Vallis region (VO frames 126A08,16,22,24; 160m/pixel) and the lower Reull Vallis/ Harmakhis Vallis region (VO frames 124A45,51,56,57; 140m/pixel). We then used TVSTEREO (PICS) to determine point elevations stereogrammetrically in and around Reull Vallis, and Z (a.k.a. AUTOSTEREO; P. Schenk) to produce topographic maps for the Pomona Vallis region (VO frame pairs 124A73/329S21 and 124A73/126A24). Shadow lengths were measured to get approximate heights of several mountains.

**Results**

**COLOR**

The Martian surface in and around the Reull Vallis is nearly monochromatic, as if the surface were composed of a single reddish material. Almost all color differences seem to be brighter and darker variants of the same rusty hue, caused perhaps by changes in slope and solar illumination. Only the dark wind streaks on the leeward sides of minor topographic rises (e.g. craters and hills) have significantly different color. The colors of the streaks are consistent with mixtures of the reddish material with <20% dark gray material (visible albedo ~5%). The basement units of the plains sequence exposed in the valley walls appear to be more yellowish than other materials, but the difference is not significant.

**STRATIGRAPHY**

From our geologic mapping, we can outline the following units in the history of Reull Vallis.

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<td>Hesperian</td>
<td>upper northern plains fluvial deposit</td>
<td></td>
</tr>
<tr>
<td></td>
<td>middle impact ejecta blankets</td>
<td></td>
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<tr>
<td></td>
<td>lower</td>
<td></td>
</tr>
<tr>
<td></td>
<td>upper plains mantle unit</td>
<td></td>
</tr>
<tr>
<td>Noachian</td>
<td>middle two thick basement units of the plains sequence (exposed in valley walls)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>lower Hellas crater rim massifs, mountains</td>
<td></td>
</tr>
</tbody>
</table>

![Figure 2: Stratigraphy of Reull Vallis region](image)

The sequence was used to construct a detailed geologic history (see below).
TOPOGRAPHY

Stereo photogrammetry of Reull Vallis was disappointing. From AUTOSTEREO we produced large scale topographic maps of Pomona Vallis with some success. Elevations seemed reasonable on a regional sense, but small scale topography showed abundant errors (e.g. multi-km elevation changes between adjacent pixels) and artifacts (N-S stripes of shadow measurements. Manual TVSTEREO spot elevation traverses across the Valles seemed reasonable to within ±2km, but apparently random otherwise. The causes of the errors in both stereo programs are unknown, although it may be related to errors in the pointing vectors of the Viking images (i.e. the directions that the cameras were pointed).

A GEOLOGIC HISTORY OF THE REULL VALLIS REGION OF MARS

Geologic history of the Reull Vallis starts with the Hellas Basin impact event in the Early Noachian, since all previous morphology was either destroyed by the impact or covered by its ejecta blanket. Based on the distribution of ejecta and rim uplift, the basin likely formed by the impact of a southeast trending (S60E) low angle bolide of enormous size [1]. Currently the rugged massifs of the crater rim unit have vertical relief of up to 4km, as determined by shadow measurements.

The Beds:

By the Middle to Late Noachian [1] the low-lying areas of the pre-Reull landscape had been covered by a thick sedimentary sequence, including at least two widespread, thick (~1km each) layers now exposed as two distinct steps in the Valley walls (especially Pomona; see Figure 3) and an overlying, thin (~200m) mantle unit which is currently found in dissected fragments west and northeast of Reull Vallis. The nearly complete burial of two large craters of 120km and 100km diameters, just southwest of Reull Vallis, indicates that the sedimentary sequence is 2-3km thick, based on known depth/diameter relationships for Martian impact craters [2]. In addition to Pomona Vallis, the thick layers are also exposed clearly in a 40km long stretch of Reull Vallis about 100km downstream from Pomona, and in a 50km long stretch of Reull just before its terminus near Harmakhis. Although layers cannot be traced continuously from one exposure to another, all exposures show similar stratigraphy, lithologic properties and weathering patterns which suggest that the same laterally-extensive layers are exposed in each of these localities. Their fluted weathering pattern on north facing slopes suggests that they are loosely lithified and friable, possibly consistent with volcanic ash (see Figure 3), although the exact origin and nature of this sequence, whether volcanic, aeolian or fluvial, is not known. Emplacement as volcanic ashfall or ash flow tuff during multiple episodes of eruption of Hadriaca Patera is possible, considering that the steplike form on the western Hadriaca caldera rim could be interpreted as resulting from a series of caldera collapse and eruption stages [3]. Shortly after lithification, regional compression and/or subsidence of the sequence produced a series of east/west trending wrinkle ridges. By the beginning of the Hesperian a small fluvial stream channel may have developed roughly in the current location of Reull Vallis, along the extreme western flank of the Hesperia Planum highlands, next to the eastern Hellas Rim.

The Flood:

In the Early to Mid-Hesperian, a large near-catastrophic flood, emerging roughly 120km southwest of the north-trending bend in the proto-Reull Vallis, may have scooped out Pomona Vallis. The waters subsequently roared downhill toward Hellas Planitia, focusing their strength along the proto-Reull Vallis, deepening and widening the valley to roughly its current breadth and depth. Evidence in the form of a large erosional field suggests that the waters also flowed over the plains southwest of Reull Vallis in a sheet flood which stripped and plucked the wrinkle ridges and upper mantle unit of the plains sequence. As far as 400km west of Pomona Vallis, remnants of the mantle deposit are aligned parallel to slight topographic undulations and the inferred direction of flood flow (west), indicating that even though the remnants are not streamlined, the unit was likely plucked out of the ground as the flood passed laterally. By ~300km west of Pomona Vallis in the erosional field, valleys and streamlined landforms become more common, while masses of the mantle deposit become rare. These observations are consistent with increasing flow velocity as the flood descended over topographic lips on its way towards the Hellas basin floor. The flood, however, was likely not as catastrophic as those which emptied from Ares and surrounding valleys into Chryse Planitia, since streamlined flood plain features are not as well developed.

Evidence that Pomona Vallis was the source of the flood is circumstantial. The Vallis sits near the highest and easternmost edge of the eroded surface which radiates downstream toward Hellas Planitia [4]. The above-mentioned parallel ridges and undulations all converge on this edge. While there is no obvious chaotic terrain on the floor of Pomona Vallis, as there is in many catastrophic outflow channel heads, its floor is
much more lumpy and uneven than the smooth, lineated floor of the main Reull Vallis. A few bean-shaped lumps on the floor of Pomona Vallis are parallel to the valley walls, suggesting that some erosive agent flowed down-canyon. Also, Pomona’s position as a short and abrupt tributary of Reull Vallis suggests that it has a separate, younger origin.

The cause and source of water for the Pomona Vallis flood are uncertain, although the melting of large blocks of ground ice by some external source, such as coeval volcanism in Tyrrhena Patera, has been suggested [1,5]. The catastrophic release of confined, high pore-pressure groundwater, emerging as an enormous artesian spring initiated by some disruption event such as meteorite impact or crustal faulting, is also possible.

Figure 3: Pomona Vallis (MDIM; lat= [45-43]), lon= [257,260]; frame width = 120km).

Following the catastrophic Pomona Vallis flood, the then-fluvial Reull Vallis entered its fretted channel stage [6-8], probably in the Mid-Hesperian. Promoted by subsurface groundwater sapping, debris in upper Reull Vallis could have begun to flow slowly downslope. At a rate as small as a few millimeters per year, the debris flow could have swept down-valley, slowly obliterating all evidence of a previous fluvial history, such as canyon bottom stream channels, streamlined basement features (e.g. teardrop/medialemniscate islands) and narrow V-shaped cross-sections, in much the same way that terrestrial valley glaciers alter mountainous terrain. The mouth of Reull Vallis may have filled with debris at one time, but subsequent debris flows from highland massifs have since covered the region. Reull Vallis today is a classic fretted channel: broad (~20km), deep (~1.5km), and boxy with few tributaries and with numerous longitudinal ridges and/or medial streaks which parallel the valley.

Throughout the Hesperian, meteorite bombardment of the Reull Vallis region continued. Several impact craters (2km-30km in diameter) and their ejecta blankets overlie the stripped mantle and plains sequence west of the Vallis. Around the end of the Hesperian, a large fluvial flow from an undetermined source in the Dao Vallis/Hadriaca Patera region closed off the lower end of Reull Vallis and laid a thick (volcanic or sedimentary?) deposit over the lower northwestern limits of the Pomona flood plain. This surface appears to be younger than the stripped plains to the south because it has fewer impact craters. In the Early Amazonian a catastrophic flood from Harmakhis Vallis created a large (60km wide) outflow channel head and streamlined topography (e.g. teardrop islands) downstream. Harmakhis Vallis shows no signs of fretted terrain, perhaps because of the distance of its head from the highlands or its relatively young age.

The Early Amazonian was also characterized by frequent debris apron formation from the Noachian basin rim massifs. One debris apron overlies both the Reull Vallis terminus and the Late Hesperian northern plains flows. These lobate debris aprons are interpreted as talus, emplaced by either ice creep [5] or rapid debris avalanches, perhaps triggered by meteorite impacts.

Evolution of the Reull Vallis landscape continues to this day. Plastic flows from slopes near the convergence of Pomona and Reul Valles appear to be infilling the Valles. The absence of impact craters on its floor and the lack of a depositional fan at its mouth suggests that debris in Reull Vallis may have only recently stopped flowing. The transient wind streaks suggest a present-day wind direction from the northeast (N70E), which agrees well with the Mars general atmospheric circulation model [1]. The current monochromatic surface is likely due to a thick (few-mm?) dust cover, distributed during dust storms [6].

Conclusions

The Reull Vallis region has experienced a complex geologic history, more so than has previously been inferred. No one theory suffices to describe all observed features in and around Reull Vallis. The landscape has been affected by several episodes of flooding, deposition and erosion. Pomona Vallis is interpreted to be the source of the large sheet flood, since all flood features (mantle stripping and streamlined islands), appear to originate from this area.

Acknowledgments

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References

Ereshkigal and Kunhild:
Large volcanoes, low gravity anomalies, and a geologic history

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Introduction: Ereshkigal and Kunhild are two large volcanoes located at 21N, 85 E, and 19N, 80E, respectively. They are located just north of Aphrodite Terra on the surface of Venus. These two volcanoes have free air anomalies a little above 20 mgals [1]. These are much lower than gravity readings for volcanoes of similar size on Venus. For example, Beta Regio has a free air anomaly of 240 mgals [1]. When the isostatic anomaly is calculated for the Ereshkigal and Kunhild area at an assumed crustal thickness of 30 km, the result is around 0-10 mgals, indicating that Ereshkigal and Kunhild are probably isostatically compensated. Other large volcanoes and volcanic rises have much larger isostatic anomalies, and are widely interpreted to be dynamically-supported hot spots [2] [3] [4] [5]. If Ereshkigal and Kunhild are isostatically compensated, they may be the surface manifestation of an extinct hot spot. To test this hypothesis an in-depth examination of the geologic history of Ereshkigal and Kunhild was conducted.

Datasets used to determine this geologic history include: compressed-once Mosaiced Image Data Record (MIDR) at 225 m per pixel and full resolution MIDR data at 75 m per pixel, F-maps (a data product from Magellan data produced by the USGS), altimetry data from Magellan, and Digital Elevation Models (DEMs) created using the Magellan Stereo Toolkit program.

Summary of Regional History: The sequence of unit formations is diagrammed in Fig. 1. The oldest visible features in the study region are several deformed regions (labeled DZ in Fig. 2) including two fold belts to the northwest and southwest of Kunhild, upraised extensional rifts to the south of both volcanoes, and an old corona to the northeast of Ereshkigal. A series of plains deposits then covered most of the area. After this first plains formation, extension continued, causing long (1300 km and more), thin, straight, and regularly spaced extension fractures trending north-south throughout the eastern half of the exposed plains units. Fracturing and folding continued, and these older plains units will be referred to as fractured plains (FP). A single younger plains unit, with no clear way to compare its age with the volcanoes, is of a darker color and embays all of the nearby units (EP). Several small shields formed between the formation of the fractured plains and Kunhild or Ereshkigal. Around this time a radar-bright shield field formed in the east (SF). The next major event in this region was the formation of Ereshkigal, a volcano with a topographic expression that is approximately 250 km wide and 390 km long. Ereshkigal contains two distinct flow units, two tectonic events, and many corona-like deformation features. Ereshkigal clearly has a dark outer flow covering fractured plains to the north, but to the south there are many flows of indistinct colors that could be from Ereshkigal or Kunhild, or the bright shield field to the southeast of Ereshkigal (E1). Since Ereshkigal’s second flow unit fills in a central low and embays many of the corona-like deformation features (folds and radial extension fractures), some collapse of Ereshkigal must have occurred before this flows deposition (E2). Kunhild erupted after Ereshkigal, embaying and encircling Ereshkigal’s flank with parts of its three flow units. Kunhild’s topographic uplift is around 250 km in diameter and its surrounding flows have a diameter of approximately 900 km. A group of calderas cluster on Kunhild’s summit and a collapse occurred between the second and third flows. The wide depressed ring around Kunhild’s summit is around 180 km wide and its floor is 620 m below the rim. The third flow filled in the central depression, and flowed outward to cover the brighter second period flows and out across the southern flank of Ereshkigal to eventually curve in reflection of Ereshkigal’s shape and meet with some of Ereshkigal’s flows (K3). This is yet another corona-like feature of Ereshkigal, since outer moats are a common feature around coronae. It is interesting to note that Kunhild’s flows appear to embay and fill the center of the Lullin impact crater, to the north of this younger large volcano. Kunhild’s oldest flow (E1) embays all the features its edges touch. Sometime after Kunhild had encircled Ereshkigal’s flank, Ereshkigal went through its second period of tectonic movement. The second tectonic period is evident because the edges of the Ereshkigal’s inner flow are tilted to the south where the flow edge is approximately 860 m lower than the flow edge to the north. In fact the highest point on Ereshkigal is not its summit, but the rim left from the first collapse to the northwest. The event definitely occurred
C. Marsh and R. Herrick: Ereshkigal and Kunhild

after Kunhild’s formation because the topographic data shows that a notch in the lowest part of Ereshkigal’s rim has developed that the inner Ereshkigal flow would have flowed out of, or Kunhild’s embaying flows would have flown in through. Also, radial deformation marks from the lowest area in Ereshkigal’s second tectonic movement cut across the lava flow that encircled Ereshkigal’s southern and eastern flank. This last tectonic events did not affect the topography beyond Ereshkigal, which may indicate it was an internal collapse. It is difficult to determine whether the many corona-like deformation features around Ereshkigal were caused by the first collapse or this second event, except when they cross or are covered by the dark inner flow of Ereshkigal. The only younger volcanic event, a group of dark, small, shield volcanos, lies directly between Kunhild and Ereshkigal and clouds the timing between the formation of many of the corona-like features on Ereshkigal and the majority of Kunhild’s flows (SF). A 42.8 km diameter impact crater, Parra, formed on the northwest flank of Kunhild [6]. Other impact craters dot the deformation zone, fractured plains, and embaying plain (C). Also, a wrinkle ridge system trending generally northeastern deforms much of the area, and all of the volcanic flows other than the young dark shield field. The dark shield field, Parra and the wrinkle ridge system all clearly postdate each of Kunhild’s flows.

**Conclusions:** Ereshkigal and Kunhild are not the youngest features in their region, but they do postdate the major deformation features. It is also significant that they have both undergone collapse processes. At least one period of tectonic movement related to a downward movement of Ereshkigal’s topography happened after the deposition of all large volcano flow units. The large volcanoes throughout Venus have been located, and currently are being analyzed for each one’s morphological category [7]. Kunhild is labeled a caldera volcano by some and Ereshkigal would likely be labeled a corona volcano [7]. It should be useful to check if other volcanic edifices with caldera and corona features have low free-air anomalies and isostatic anomalies that indicate they are isostatically compensated. The pairing of these characteristics may indicate a trend that isostatically compensated large volcanoes are extinct hot spots in a period of collapse.


**Fig. 1**

<table>
<thead>
<tr>
<th>Sequence of Events</th>
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<tbody>
<tr>
<td>Deformation Zone</td>
</tr>
<tr>
<td>Fractured Plains</td>
</tr>
<tr>
<td>Ereshkigal</td>
</tr>
<tr>
<td>1st flow</td>
</tr>
<tr>
<td>2nd flow</td>
</tr>
<tr>
<td>Kunhild 1st flow</td>
</tr>
<tr>
<td>2nd flow</td>
</tr>
<tr>
<td>3rd flow</td>
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<tr>
<td>Dark Shield Field</td>
</tr>
</tbody>
</table>

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Fig. 2

Key
FP = Fractured Plains
SF = Shield Field
DZ = Deformation Zone
EP = Embaying Plains
E# = Ereshkigal Flows
K# = Kunhild Flows
C = Impact Craters

Fig. 3
Introduction:
In 1979 Voyagers 1 and 2 discovered active volcanoes on Io. During the Voyager 1 encounter, nine separate volcanic plumes were detected. Four months later Voyager 2 revealed that all but one of these sites were still active [1]. Despite this volcanic activity, the disk-integrated rotational light curve for Io has remained constant within 4-5% for the past 50 years, implying that the overall surface composition has remained constant [6,7]. Since the Voyager missions, Io's volcanic activity has been monitored with infrared ground-based observations [1,2,3,4]. Ground-based and orbiting telescopes have measured Io's spectra in an effort to map the compositional variations on the surface. Early IUE observations (1979-1986) revealed a surface rich in sulfur and sulfur dioxide [5]. The early IUE observations correspond in time with the Voyager encounters. We also present here current IUE observations of Io's surface that correspond in time with the Galileo encounter. We have re-examined the longitudinal distribution of sulfur and sulfur dioxide at Io's surface. Our goals are to determine the current large scale compositional variations on Io's surface, to examine any temporal changes in surface composition between the Voyager epoch and the Galileo epoch, and finally, to correlate our findings with known volcanic eruptions in order to place possible constraints on magma compositions.

Methodology:
Part of the Voyager epoch IUE observations (1984-1986) were reprocessed using the NEWSIPS calibration software (developed by the IUE project). The Galileo epoch observations (1995-1996) were processed using the same software. All spectra were calibrated to a common distance scale and smoothed to the camera response function. Each epoch's dataset was co-added according to rotational phase angle in 30 degree longitude bins centered on the leading and trailing hemispheres. Our first task was to examine the large scale compositional variations within each epoch. This was accomplished by ratioing the spectra from each longitudinal bin to the bin centered on the trailing hemisphere. The results are shown in figures 2 (Voyager epoch) and 3 (Galileo epoch). Our second task was to look for temporal changes. This was accomplished by ratioing each longitudinal bin from the Voyager epoch dataset to the corresponding bin from the Galileo epoch dataset (figure 1). Finally, we correlated the IR observations of volcanic eruptions with the spectra of the spatial bins.

Results:
Longitudinal Variations: The reprocessed Voyager epoch spectra are consistent with the results presented by Nelson et al (1980) who found that SO$_2$ frost dominates the surface composition between longitudes of 72 and 137 degrees, with sulfur dominating everywhere else. The spectral ratios in figure 2 demonstrate that the surface composition of the leading hemisphere is different than that of the trailing hemisphere and that the inferred composition is similar between longitudes of 45 to 165 degrees compared to the trailing hemisphere. The negative slope longward of 3100 angstroms in the 15 to 45 degree bin argues for either a darkening agent in this area compared to the trailing side composition or a more reflective material on the trailing side compared to the material characteristic of this specific area. The Galileo epoch results shown in figure 3 also demonstrate a dichotomy in surface composition between the leading and trailing sides. However, the spectral nature of the dichotomy is different from that seen in the Voyager epoch dataset. In the 45 to 75 degree longitude bin, we see spectra that are indicative of SO$_2$ frost. In the longitude bins between 75 to 165 we see the characteristic sharp slope of SO$_2$ gradually degrading as a function of longitude to a spectral signature of sulfur. Thus, we find that SO$_2$ no longer dominates the surface composition between 75 and 135 degrees longitude.

Temporal Variations: Comparisons of the Voyager epoch ratio spectra for the longitude bins between 75 and 135 degrees to the corresponding ratio spectra from the Galileo epoch dataset display significant differences between the spectral slopes longward of 3000 angstroms. The Voyager epoch spectra show the sharp rise in slope indicative of sulfur dioxide [6]. The shallower slope seen in the Galileo epoch data are compensurate with sulfur, or sulfur overlying a previous sulfur dioxide deposit. The ratios of the two epoch datasets for these longitude bins show a trough centered at 3050 angstroms, (figure 1). The
adjacent longitude bins also show this feature, but to a lesser extent. Figure 1 shows that for the longitude bin centered on the trailing hemisphere, there have been no significant changes in composition between the two epochs. This verifies that the differences seen in the ratio spectra for the bins from 75 to 135 degrees longitude between the two epochs are not differences between leading and trailing hemisphere compositions but are temporal changes in the leading hemisphere’s surface composition. Nelson et al. (1980) found that the dominant surface constituent on the trailing hemisphere is sulfur. Loki is the largest volcanic feature influencing the surface composition and has been the largest contributor to the IR emission in this region [3,5]. From the lack of spectral changes on the trailing hemisphere between the two epochs we conclude that the material erupted from Loki has not drastically changed in composition over the past decade.

Conclusions:
In the past decade, the composition of Io’s surface has changed as a function of longitude. Whereas the composition of the trailing hemisphere has remained relatively constant, the dominant composition of the leading hemisphere has changed from a predominately sulfur dioxide frost to a sulfur composition. Io’s temporal variability can be explained by either a change in the composition of the magmas of the active volcanoes as seen by Voyager, or by new eruptions that have occurred which have a different magma composition (sulfur) compared to the Voyager epoch eruptions (sulfur dioxide).

Acknowledgments:
We would like to thank the LPI computer staff and the IUE data processing group for all their help.

Figure 1. Ratios of IUE spectra of the Voyager epoch (1984-86) versus the Galileo epoch (1995-96).
Spatial and Temporal Variations: P. Moth, D. Domingue, A. Lane

Figure 2. Ratios of Voyager epoch IUE spectra of the leading versus trailing hemispheres.

Figure 3. Ratios of Galileo epoch IUE spectra of the leading versus trailing hemispheres.

References

INTRODUCTION: Dark inclusions (DIs) are xenoliths composed mainly of fine fayalitic olivine grains occurring in CV3 carbonaceous chondrites. The origin of DIs has stirred much controversy as to whether they were 1) formed by condensation in the solar nebula with subsequent Fe metasomatism [1,2], 2) fragments of CV3 asteroids processed to various degrees by reaction with a low-T, oxidizing nebular gas preceding incorporation into host CV3 meteorites [3], or 3) CV3 regolith affected by different degrees of aqueous and thermal metamorphism on the parent bodies [4,5]. The CV3 chondrites have been generally interpreted to be primitive, and its asteroid has been thought to have escaped major secondary processes. From textual and mineralogical similarities to the CV3 host matrix, the previous interpretation of DI was that they represent primitive materials formed in the solar nebula [1-3,6]. Recent studies, however, have only supported the view that DIs experienced extensive aqueous alteration and subsequent thermal metamorphism in the asteroidal environment [7-13]. Fine fayalitic olivine grains composing DIs indicated that they were produced by dehydration and thermal transformation of phyllosilicates that had been formed by aqueous alteration [7], although this origin also has been a subject of controversy [1,12].

PREPARING SAMPLES AND ANALYTICAL PROCEDURE: Four polished thin sections of CV3 chondrites with dark inclusions, two from Vigarano (AMNH2226-7), the others from Allende (1961, octagonal) and one polished thin section of Ningqiang chondrite were studied using optical microscopy, backscattered electron (BSE) imaging by scanning electron-microscopy (SEM) and transmitted electron-microscopy (TEM).

After petrographic optical microscopic study, samples were carbon-coated to prevent any charging for BSE study. Several regions of DIs and Ningqiang chondrite were excavated from thin sections, sandwiched between copper grids and thinned by ion milling for detailed characterization by TEM. In this study, 304 spots in the milled sections were analyzed by an energy-dispersive spectroscopy (EDS) analysis system installed on the TEM. These spectra were collected for 350-400s. Many TEM images and selected area electron diffraction (SAED) patterns were used to identify phases in the DIs.

RESULTS AND THE DISCUSSIONS:
The range of olivine compositions: Fig. 1 contains histograms of fayalite concentrations in DI olivines (this study) and in CV3 matrix olivines (A-F are from Fig.8 in [14]). The range of matrix olivine compositions decreases, and the degree of chemical equilibration increases from Kaba to Allende. The most equilibrated matrix olivines are found in the Allende oxidized CV3 chondrite. Vigarano, which is a reduced CV3 chondrite, has more homogeneous olivines than oxidized CV3 chondrites. DIs' histograms showed such a tendency, which supports the interpretation that the precursors of DIs are CV type home asteroid(s). The greater compositional range of DIs as compared to matrix may be due to the presence of zoned olivines (see below). We note that the Allende Octagonal DI has an olivine histogram distinct from any other CV material.

Fe-Mg zoned olivines: Round, concentrically-zoned olivine grains are ubiquitously present in matrices of DIs, especially Allende Octagonal DI (Fig. 2,3). Some olivine grains showed Fe-Mg zoning of Fe22 to Fe66 from outer to inner as determined by at least 5 analyses aligned along a line. It should be noted that zoning is present even in 2-5 µm diameter very fine grains. Some grains showed unconcentrically
Dark Inclusions in CV3 Chondrites; Nakamura K.

reverse order (Mg-Fe) zoning, suggesting they are fragments of relatively large normal zoned olivine grains. These fayalitic olivines are commonly platy, and contain numerous voids and mineral inclusions. This is strong evidence that olivines in DIs and by extension the CV parent asteroid experienced aqueous alteration, forming phyllosilicates which were dehydrated to olivine during subsequent thermal metamorphism.

Unusual texture in Vigarano DI: The DI from Vigarano (AMNH2226-7) has an unusual texture best described as crosscutting arcuate bands, possibly from dust accumulation on an asteroidal surface and are similar to fluvial sedimentary deposits [3]. We succeeded in ion-milling the arcuate band. From study of TEM images, the olivine grains on the arcuate band are much finer (<800nm) than any other DI in this study, and interstices between the olivine grains are filled with tiny globules (>100nm), which appear to be Fe-Ni metal or Fe-Ni sulfides. The olivine grains on the arcuate band also have micro inclusions like other DI olivines. Interestingly, some of them are aligned along the edges of grains. Attempts to analyze Fe-Mg zoned olivines in the band failed. To resolve mysteries of the CV3 asteroidal events, further study of this unusual DI is necessary.

C phase: A few olivine grains in Allende Octagonal DI have carbon along edges, which could have formed by heating of carbonaceous material [14].

Ca-rich phase in Allende DI: 58 spots from Ca-rich phases in Allende 1961 DI were analyzed. From SAED study, some appear to be pyroxene, however the content of Si is lower than for pyroxene stoichiometry. Interestingly, some compositions of the Allende 1961 DI's Ca-rich phases are extremely similar to ones of Ca-rich glasses in matrix of Allende host shocked at 300 and 600°C [15] (Table 1).

Ningqiang DI: The Ningqiang chondrite was previously classified as anomalous but is now shown to be CV3-related composition. Its DI is very similar to other DIs, but fayalitic olivine grains in Ningqiang are finer than in DIs, and enclosed in amorphous silicate material. Fe-Ni metal and Fe-Ni sulfide are ubiquitous in interstices between olivine grains.

CONCLUSION: DIs are not exactly like CV3 chondrites, but similar enough to have been derived from the same asteroid(s). These record geological processes not revealed by CV3 host meteorite study, i.e., aqueous alteration, thermal metamorphism or sedimental processes.

I would like to acknowledge Tomoki Nakamura for his infinite help and wise counsel, Kentaro Kaneda for computer wisdom, and especially Michael Zolensky for all his unending patience, and continuing support throughout this work and this summer.

Dark Inclusions in CV3 Chondrites; Nakamura K.

Figure 1. Olivines in CV3 Materials

Fig. 2. TEM image of zoned olivine grain in Allende DI Octagonal

Fig. 3. BSE image of zoned olivine grains in Allende DI Octagonal

Table 1. Representative composition (wt%) of Ca-rich glassy grains in shocked Allende at 300°C and Ca-rich phase in Allende DI 1961
Sulfur Analysis of Tephra from Mauna Kea Volcano, Hawaii and Goldfield, Nevada: Implications for Acid Sulfate Weathering on Mars

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Samples of tephra and basalt from Mauna Kea Volcano, soils from the Goldfield mining district of Nevada and synthetic jarosite were analyzed for total sulfur abundances. Synthetic jarosite contained 14.4 wt% S, which is somewhat higher than the stoichiometric value of 12.8%. The sulfur content of tephra from Mauna Kea ranged from 250 µg/g to 2.5 wt%, and jarosite is known to be the dominant sulfur-bearing phase for Mauna Kea tephra. Samples from Kilauea fumaroles contain 0.3 to 1.3 wt% S, but the sulfur mineralogy of these samples is not known. Hawaiian basalts have ~200 µg/g S. The two jarosite-bearing samples from Goldfield have 2.7 and 4.3 wt% S. The high abundance of jarosite in the Goldfield samples results from acid sulfate weathering of sulfide minerals. Because of the absence of sulfide minerals, jarosite formation in the Mauna Kea samples likely proceeded by an acid sulfate weathering process in which the source of sulfur was volcanic SO_2 gas. By inference, it is possible that acid sulfate weathering induced by volcanic SO_2 gases may have contributed to the alteration of iron rich minerals on the surface of Mars and led to the formation of jarosite.

INTRODUCTION

Jarosite (KFe_3(SO_4)_2(OH)_6) is a well known iron alteration mineral derived from acid sulfate weathering processes. The usual mechanism of jarosite formation in terrestrial environments involves the oxidation of sulfide (e.g. pyrite, FeS_2) mineral deposits and the subsequent accumulation of sulfuric acid in the groundwater [1]. This highly acidic, iron and sulfate rich water will often dissolve underlying rocks and facilitate the precipitation of sulfur bearing alteration minerals such as jarosite. An occurrence of jarositic tephra in the summit region of Mauna Kea Volcano was recently reported [2]. Because sulfide mineralization is not indicated, acid sulfate weathering was apparently driven by acid sulfate solutions formed from interactions between SO_2 bearing volcanic gases and groundwater. In order to better understand the acid sulfate weathering process on the shield volcanoes of Hawaii, we collected a suite of both altered and unaltered tephra samples from the summit region of Mauna Kea and nearby Kilauea Volcano. Reported here are total sulfur analyses for those samples and, for comparison, synthetic jarosite and several samples where jarosite formed from weathering of sulfide minerals. The sulfur content of Martian surface materials and the possible spectral identification of jarosite imply that acid-sulfate weathering driven by SO_2 bearing volcanic gases may have been an important process for oxidative weathering on Mars.

SAMPLES AND METHODS

Samples

HWMK 11 - 13. Samples were collected from three distinctly colored layers (red, black and yellow) in basaltic tephra near the summit of Mauna Kea. The cinder cone, located at 4145 m elevation, consists of strombolian type ejecta [3].

HWMK 20, 22, 24, 26. Samples were collected from a road cut on the northwest flanks of the unnamed summit cone of Mauna Kea Volcano upon which the Japan National Subaru Telescope is situated [2]. The cone is part of the Laupahoehoe Volcanics and is composed of hawaiitic ejecta which form the magmatically evolved cap of Mauna Kea [4].

HWMK 501 - 517. Samples are red, yellow, white, green and black tephra collected from an ~8 m vertical section formed during excavation for the foundation of the Gemini telescope on the second highest cinder cone of Mauna Kea Volcano [9].
HWMK 530, 600. Samples are brown tephra collected from sites near the visitors center at Mauna Kea State Park and at an unnamed cinder cone on the southeast slope of Mauna Kea at 4040 m elevation.

PH-1 - PH-9, PH-13. Samples were collected at 30 cm intervals from a lava slab near the Puu Huluhulu cinder cone located approximately 15 km south of the summit of Mauna Kea. Sample color ranges from bright reddish-orange to brown [5].

PN 9. Sample was collected from the Puu Nene cinder cone between Mauna Kea and Mauna Loa Volcanoes at 2140 m elevation. The cone is part of the Laupahoehoe Volcanics and is composed of brown hawaiitic ejecta [6].

MK1980 4A - MK1980 6B. Samples are brown tephra collected from undocumented locations on Mauna Kea Volcano.

HAW 16, 17. Samples are gray basaltic tephra collected from the western slope of Mauna Kea Volcano as part of the Hawaiian Reference Suite [7].

HWSB 531 - 537, HWKV 501. Samples are red and brown tephra collected from Sulfur Bank fumaroles on Kilauea Volcano.

TT#12, TT#35. Samples are pale yellow jarositic soils collected from a site near the Goldfield, Nevada mining district [7].

LNVJAR 1. Sample is a yellow deposit of natural jarosite from Luning, Nevada obtained from the Wards Natural Science Establishment [2].

Synthetic Jarosite. Sample is bright yellow synthetic KFe3(SO4)3(OH)6 synthesized by D.C. Golden at NASA Johnson Space Center.

Methods

The tephra samples, which were collected in the field as <1 mm size fractions, were powdered with an alumina mortar and pestle to pass a 150 µm sieve and weighed into ceramic crucibles. Iron combustion accelerating powders and oxidizing reagents (V2O5 pellets) were added to the samples in order to ensure complete combustion during the sulfur analyses. Samples were burned in a Leco model 763-100 induction furnace, a procedure that involved heating the samples in a strongly oxidizing environment in order to covert any sulfur present in the samples into SO2. The relative amount of SO2 gas that was released by each sample was then measured using infrared spectrophotometry. Standard sulfur calibration curves were obtained using National Bureau of Standards sulfur calibration steel and used to estimate the total sulfur content of the tephra samples and synthetic jarosite. The relative amounts of sulfur bearing minerals contained in each of the samples was then estimated. To confirm that sulfur in palagonitic samples is present as jarosite, previously obtained Mössbauer and X-ray spectrophotometry data were consulted [2].

RESULTS AND DISCUSSION

Total sulfur analyses of synthetic jarosite and the natural jarosite sample LNVJAR 1 were performed to determine an upper limit of sulfur content for the samples. We found sulfur concentrations (in weight %) of 14.3% S for synthetic jarosite and 13.9% S for the natural sample. The theoretical maximum sulfur abundance in pure jarosite is 12.8% S. The Nevada samples TT#12 and TT#35 were rich in sulfur, with total concentrations of 4.3% and 2.7% respectively. The maximum jarosite content of samples TT#12 and TT#35 is therefore ~33%, assuming that all sulfur is present as jarosite.

Different amounts of sulfur exist in the Hawaiian tephra samples due to the differential weathering of basaltic glass. Unaltered basalts such as the HAW, MK1980 and PH samples had baseline sulfur concentrations of 0.02 to 0.04%, whereas several highly altered palagonite samples in the HWMK series had sulfur contents in excess of 1.0%. The sulfur in these rocks may be derived from hot, sulfur-bearing magmatic gases or fluids that are often present around active cinder cones [9]. The sulfur content of Hawaiian tephra samples is presented in Figure 1.

Experiments performed by the Viking X-ray fluorescence instruments determined that Martian fines have a sulfur content of approximately 3%, much higher than typical terrestrial soils [10]. The origin and exact composition of these soils is not known, but the presence of sulfur from acid sulfate weathering in Mauna Kea tephra raises the possibility that acid sulfate weathering may have led to the high sulfur contents in Martian soil. The high abundance of sulfur in samples collected from an environment that is devoid of sulfide deposits suggests that these processes may be commonplace in terrestrial volcanic environments, and that SO2 can supply the sulfur that is required for jarosite formation in
volcanic tephra. This process could also occur on Mars, where many large shield volcanoes may produce significant quantities of $\mathrm{SO}_2$ bearing gases. An acid sulfate weathering process similar to that found on Mauna Kea would provide a means of incorporating volcanic sulfur into the Martian tephra, and could be one possible explanation for the high abundance of sulfur in Martian fines.

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Chondrule Precursor Aggregates and Clastic Rims in Ordinary Chondrites

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Introduction

Ordinary chondritic meteorites are comprised of chondrules and matrix material believed to be products of the solar nebula. Chondrules are spherical particles that form when melted precursor materials composed of nebular condensate and previously crystallized chondrule materials cool and crystallize in the nebula. The crystallization textures include barred, radial, or porphyritic olivine and/or pyroxene. Matrix material is mostly fine grained olivine, pyroxene, and oxides and sulfides. During a detailed examination of highly unequilibrated ordinary chondrites, we found particles with seemingly incongruous textures juxtaposed. The particles contain chondrules, chondrule and mineral fragments, and nebular-like rim materials. We propose that these particles are best explained by the aggregation of the component material in the nebula. Using textural and compositional data, we recognize these particles as aggregates comprised of existing material from different sources that have clustered together prior to accumulation on a parent body. An accretionary origin is also proposed, in some instances, for rim material that differs from the particle it envelopes. These rims contrast with Rubin’s [1] coarse igneous rims which derive by partial melting from the particle to which they are attached. The aggregation of a group of particles can be identified as having occurred within the nebula by the presence of a fine-grained rim material, known as a nebular rim [2], surrounding the entire assemblage. Typically this rim appears black in transmitted light, flat gray in reflected light, and a grainy light gray in back-scattered electron images.

Techniques

We examined thin sections of 22 unequilibrated ordinary chondrites from the Antarctic meteorite collection at JSC. All were type 3.0–3.4, save a few simply designated type 3. We examined each section carefully, noting several interesting particles per section. A photographic catalogue was assembled of about 50 of these particles. Some of the most definitive are discussed in this abstract. Mineral analyses, back-scatter electron images, and chemical x-ray maps were collected with a Cameca SX-100 electron microprobe at JSC. Mineral standards were used for the quantitative analyses.

Petrography

ALHA 76004,9 P-1, shown in Figure 1, is a coarse, dendritic (barred) pyroxene chondrule along whose perimeter are intermittently spaced clusters of angular crystals of olivine and pyroxene. The pyroxenes in the rimming material have higher calcium content and Mg/Fe ratios than those in the dendrite. Clusters of olivines and pyroxenes are also found in a layer of encompassing sulfide which interfingers with an extremely fine-grained nebular rimming material [3].

ALHA 76004,9 P-2 consists of a largely metal-free central area of coarse, rounded olivines surrounded by an outer zone of finer, more angular olivines richly interspersed with concentrations of sulfide. The inner boundary of the outer zone is demarcated by a discontinuous band of thick metal and sulfide pockets. Fayallite levels in olivines range from 2.8% to 11%. Along the circumference of the particle is an uneven distribution of finer pyroxene grains. The boundary with the olivines is not clear cut and often the two minerals interpenetrate. Similar pyroxenes are enveloped in the unmistakable nebular rim that clearly encloses the whole particle.

The oval-shaped particle, ALHA 76004,9 P-4, is cored by large anhedral, twinned pyroxene grains with rounded boundaries and poikilitically enclosed olivine. A discontinuous rim of finer anhedral pyroxenes and olivines, both rounded and angular, surrounds the main particle. Large metal concentrations punctuate this finer material. The pyroxenes in the rim, while generally more iron-rich than those of the main particle, are not outside the range of iron levels found in the main particle pyroxenes. Olivines scattered in the rim contain slightly more iron than those enclosed in the pyroxenes of the main particle. A few particles included in this rim consist of fine-grained silicate and sulfide nebular rim material. One of these clumps of nebular rim material contains a small cluster of olivine and pyroxene grains at its center.

EET 83395,3 P-1 is completely surrounded by a thin, fine-grained nebular rim. At one point this rim is pinched by a clastic particle. The clastic particle itself, which is primarily fine grained, is enclosed within a nebular rim continuous with that of the main particle. One large BO segment, at least two other BO fragments (semi-circular in shape), and a jumble of skeletal tabular olivine crystals comprise the main particle. The bars in
the BO fragments are slightly rounded and have subhedral pyroxenes amongst them. The barred fragments don't appear to be optically continuous with the main BO fragment and in some cases are separated by granular crystals. The material surrounding these barred fragments is primarily subhedral, fine-grained, angular crystals. A few show signs of rounding and there are areas of larger grains.

LEW 86018,38 P-7 is comprised of three main portions: a quarter-circle BO fragment, a group of medium to coarse angular crystals, and a very large olivine crystal about 0.5 mm long. Pyroxene crystal overgrowths occur between the bars of the BO fragment. The coarse material consists of anhedral to subhedral olivine and pyroxene grains with some angular faces. The large subhedral olivine grain penetrates the region of coarse material. Unlike particles previously mentioned there is no unequivocal nebular rim isolating this group of particles. In some places it is possible to extend the limits of this aggregate to include neighboring particles where they are apparently connected by a continuous melt.

**Discussion**

All of the particles we studied are comprised, in whole or in part, of fragments of chondrules, isolated crystals of olivines and pyroxenes of various sizes, kamacite and troilite, and fine-grained "nebular" rimming material. As can be seen in Figure 1, the crystals irregularly distributed around the dendrite in ALHA 76004,9 P-1 are anhedral and coarser than the igneous rims described by Rubin [1]. The texture is most indicative of clastic fragments, not crystals that have been partially melted or melt-grown. The presence of olivine and the higher calcium content and Mg/Fe ratios of the pyroxenes in the rim point to a source other than the primary dendrite. Some clastic material is attached directly to the dendrite while some is completely surrounded within sulfide and fine-grained nebular rim material. Thus, the accretion of clastic fragments took place while the particle was still in the nebula.

![Photomicrographs of particle ALHA 76004,9 P-1](image)

**Fig 1.** Photomicrographs of particle ALHA 76004,9 P-1 showing core dendrite, clastic material, and nebular rim. A) In transmitted light, core dendrite and clastic material are apparent. B) In reflected light the metal and sulfide and fine-grained nebula components of the rim are evident. Scale bar is 0.25 mm.

The core of ALHA 76004,9 P-2 is divided into two concentric zones. The close-packed texture of rounded grains in the center show evidence of partial melting. The large, often spherical, metal/sulfide concentrations in the outer zone indicate some heating has occurred, but the more angular shape of the olivine crystals suggest the degree of partial melting was less than that experienced by the inner zone. These different heating histories suggest the inner portion existed before the outer material was added. The fringe of fine pyroxene grains on the perimeter of ALHA 76004,9 P-2 may have crystallized from the same melt as the main particle since the olivines are increasingly associated with pyroxene towards the edges of the particle. However, the pyroxenes that are actually enclosed in the distinct fine-grained nebular rim must have been accreted concurrently with the rim.

The degree of partial melting that has taken place in the rim of ALHA 76004,9 P-4 is uncertain as some rim grains are rounded, others angular. The compositions of the olivines and pyroxenes in the rim is close to those of
Aggregates in Chondrites: Russell, P.

the core particle crystals, suggesting origin from a single melt is possible. What calls in to question the igneous nature of the rim material are a few particles present that consist of the fine-grained silicate and sulfide nebular rim material. That the olivine-pyroxene grain enveloped in this nebular rim material had to have once been free in the nebula attests to the accretionary aspect of ALHA 76004,9 P-4's rim. All three particles discussed so far present evidence of rims that formed by accretion of material in the nebula. In addition, the rims of ALHA 76004,9 P-2 and P-4 show signs that igneous as well as accretionary processes played a role in their formation.

Particle EET 83395,3 P-1 is comprised of barred and skeletal fragments of olivine surrounded by a thick layer of clastic material. The smoothed bars and overgrowth crystals of the barred fragments indicate partial melting has affected this inner region. This contrasts with the primarily angular crystals and fragments making up most of the surrounding clastic material. The clastic material seems to be a later addition, similar to the clastic rims we have seen in other particles. The width of this rim and the range of particle size involved brings the idea of accreting rims to a larger scale. The multiple barred fragments enveloped in this rim demonstrate that the particles that came together to form aggregates included grains other than small clastic fragments. The barred fragments were originally part of a chondrule, that was broken and then the fragments incorporated into another particle while still in the nebula. The collision that resulted in the fine-grained clastic particle pinching out the well-defined nebular rim of EET 83395,3 P-1 and then being coated with more nebular rim material probably occurred in the nebula as well.

LEW 86018,38 P-7 shows clearly how different types of fragments may come together to form a new aggregated particle. The barred crystal is a fragment of a chondrule that shows signs of partial melting prior to fragmentation. The coarse material has a clastic texture. The inclusion of a grossly oversized grain suggests all the crystals did not form in place under identical cooling conditions, and rather have been aggregated together. The barred fragment is simply another component of the aggregate, just like the large olivine crystal.

The presence of whole or fragmented chondrules in aggregates means that chondrule material may be recycled; it can be fragmented and incorporated into another particle while still in the nebula. Experimental work by Lofgren and Le [4] has shown that such fragments may survive the process of chondrule formation under certain conditions, providing a method of obtaining relict chondrule textures within chondrules. The aggregates in this study may then be thought of as chondrule precursors.

The aggregates we studied range in size from roughly 0.5 mm to 2 mm, and contain only a few component grains, or become clusters the extent of which could not be determined confidently due to unclear boundaries. The presence of these aggregates formed in the nebula implies that a whole size range (larger than single grains or chondrules, but smaller than a parent body) of particles existed in the nebula. The formation of parent bodies by accretion of nebular particles could therefore have involved particles that already had a history of aggregation.

If the concept of aggregates collecting to form parent bodies is extended to parent bodies themselves, the aggregation of two or more parent bodies with different metamorphic histories could possibly help account for the petrologic variation observed in ordinary chondrites. For example, ALHA 76004,9 is classified as a LL3.2/3.4 and EET 83395,3 as a L3.2/3.6.

Conclusions

Aggregates and clastic-rimmed particles that formed by accretion in the nebula are present in low-grade type 3 chondrites. Depending on the degrees of partial melting and accretion, a combination of accretionary and igneous sources may account for a coarse rim. The presence of aggregates in the nebula implies that a whole size range (larger than single grains or chondrules, but smaller than a parent body) of particles existed in the nebula. The formation of parent bodies by accretion of nebular particles could therefore have involved particles that already had a history of aggregation.

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Moon Down Under
Clementine’s Multispectral Look on the Apollo Basin Characteristics.

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The Clementine probe offers a new insight into the large scale geological features and composition of the Lunar crust. Its multispectral data present excellent tools for variety of remote sensing efforts aimed at the Lunar Far Side.

Although the full details are still unconfirmed, it is believed that the lunar crust emerged from cooling of the global magma ocean. This event produced a stratified mass where the heavier, mafic minerals sank leaving behind an anorthositic cap in the upper layers of the crust. The lunar crust appears to have two major zones: a mixture of anorthositic rocks in the upper parts underlain by the more mafic ones deeper in the crust (Warren 1985).

Although we cannot actually drill through the lunar crust to prove this theory, the lunar crust can be studied using impact craters as natural drill holes. The crust has been subjected to a heavy bombardment, with some of the impacts excavating material from the lower crust while the others were restricted to the surface. Comparing and analyzing these materials helps reconstructing the composition and the structure of the lunar crust prior to the impact.

GEOLOGIC HISTORY:
Three distinct areas have been selected to test this approach. The “pre-Nectarian” age Apollo basin (480 km in diameter), located entirely within the large South Pole Aitken basin (which is already - 6 - 8 km below the mean crustal level), excavated an additional 20 km of crust thinned by the SP-Aitken event. The Nectarian age Korolev basin (440 km in diameter) is located approximately 900 km north of the Apollo basin, at the same longitude in the lunar highlands and excavated crust to depths of tens of kilometers. Furthermore, the lunar crust near the Korolev Basin is the area where the crust seems to be thickest. (Zuber et al. 1994). In addition, it appears that the crust in the vicinity of Korolev has not been thinned by a previous large scale impact (Figure 1). Both of these impact basins are located on the lunar far side. The Apollo 16 landing site, used for calibration, is located on the lunar near side.

Figure 1 - Cross section of the Apollo Basin stratigraphy and its relative location within the lunar crust.
CALIBRATION:

The Clementine image data used in this study range in wavelengths from 415 nm to 1000 nm. These data can be used to interpret spectral features of the lunar surface. For Clementine’s images to be used in this analysis is necessary to perform an array of calibrations, including flat-field calibration, dark-field subtraction, frame transfer, offset and gains, photometric and finally geometric calibrations. These calibrations are necessary because of the motion of the CCD camera and effects caused by the pixel saturation (excessive albedo), shadowing and changes in spectrometer angles, drift and noise during orbiting.

ANALYSIS:

The data were analyzed by band-ratioing. Three spectral bands were selected and ratioed to produce false color images of lunar surface where colors would depict spectrally different regions. The three bands used were A band (415 nm), B band (750 nm) and D band (950 nm) to produce red=B/A, green=B/D and blue=A/B. The ratioing thus produces a RGB image. The red color apparently represents the mature highland materials and lunar light plains, mare basalts are either purple (mature) or green-yellow (fresh, mare basalts). The light blue colored areas seem to be fresh, immature highlands, bright impact craters, ejecta blankets and secondary impact craters.

The red areas are predominant throughout the Apollo basin with the exception of the purple colored, older mare basalts in the center of the crater and the light blue rugged terrane on the eastern edge of the outer rim in the Apollo Basin, apparently partially blanketed with the ejecta rays from some another major impact (possibly the Orientale event).

RESULTS:

Detailed analysis of the values at differently colored locations within the Apollo Basin indicate noticeable differences. The analysis was performed by plotting reflectance values versus the filters which revealed significant spectral differences between the study areas. The mare basalts in the Apollo Basin had consistently lower albedo than the plains surrounding it. Furthermore, in comparison to the Korolev basin and the Apollo 16 landing site, the Apollo Basin’s overall reflectance values are significantly darker than the other study sites (Figure 2). The low-albedo characteristics of the Apollo Basin may indicate the possible presence of the mafic minerals. This suggests that the Apollo event excavated different materials than those present in the Korolev Basin and Apollo 16 site. The Apollo Basin is spectrally similar to the rest of the of the north-central SP-Aitken basin and therefore has excavated the same materials as the SP-Aitken Basin (Brown et al. 1993). This infers that the low-albedo material, predominant in the SP-Aitken basin is present to the depth excavated by the Apollo event. Furthermore, the Apollo basin is already stratigraphically different from the Korolev basin and Apollo 16 site (6 - 8km below the mean crustal level) and combined with its low-albedo properties and possible mafic composition it may represent the lower crust material.

Comparison of Apollo & Korolev Basins

![Graph](image-url)  
Figure 2 - Graph depicting spectral differences between the study areas.
According to the global iron map (Lucey et al. 1995), both Apollo 16 landing site and Korolev Basin are poor in iron. As discussed earlier, the lunar highlands are mainly anorthositic in their composition. Spudis and Davis (1986) describe the upper crust composition as “anorthositic gabbro.” On the other hand, the Apollo Basin is relatively iron rich (Figure 3) and is believed to be enriched in mafic minerals (Belton et al 1992). Detailed analysis of the reflectance values in the study areas based on the Clementine data produced comparable results to the global map.

CONCLUSION:

It is believed that the main reason for the iron distribution and spectral differences between the areas is caused by the Apollo Basin excavation of far deeper crustal material than its present in the other two study sites. Since the deeper material of the lunar crust appears to be materially (and spectrally) different from the upper materials, it’s thus plausible to speculate about the large scale layering present in the lunar surface. It also reinforces the hypothesis of the “magma ocean” as the main source of the lunar crustal origin.

CONSULTED WORKS:
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Scanning Electron Microscopy of Terrestrial and Extraterrestrial Samples: A Study of Bacteria and Nannobacteria
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The study of microorganisms in terrestrial rocks has exploded in the past two decades. Many details are known about biomineralization and microbial participation in the formation and destruction of sedimentary deposits. Recently the discovery of nannobacteria by Folk [1] has raised new interest in how different types of sediments are formed or altered. His findings along with the growing abundance of information on chemolithoautotrophic ecosystems has opened up new possibilities for the appearance of life elsewhere in the solar system, especially on Mars. In this project, several terrestrial samples from extreme environments on Earth and a sample from the Martian meteorite ALH84001 were studied under a scanning electron microscope for evidence of bacteria and nannobacteria.

Nannobacteria are smaller forms of regular bacteria that range from 0.02 to 0.2 µm in diameter. Normal bacteria may become stressed from starvation, changes in chemistry or temperature of their environment, or dehydration resulting in these dwarfed forms. However, Folk [2] observed nannobacteria in non-stressful, normal environments, concluding these bacteria have no "large" size equivalent.

Identifying nannobacteria in a sample is difficult because of the small size of the organism. X-ray analysis is almost impossible for such a restricted area. Thus a set of guidelines determined by Folk [2] is now accepted as a standard for recognizing nannobacteria in rock samples:

♦ **Clusters of bodies separated by large unpopulated areas.** This type of distribution is seen where living bacteria thrive.

♦ **Bodies same size as living bacteria, including nannobacteria.** Populations within a sample same as those of living bacteria. Populations can range from very well sorted to bimodal assemblages (normal and nannobacteria) to less well-sorted mixtures—different types of bacteria or varied stages of sporulation or nutrition.

♦ **Bodies similar shape to living bacteria: smooth to somewhat lumpy surfaces with shapes of cocci, ellipses, bacilli, or long filaments.** The bacteria can appear as chains of spheres or rods. Most small minerals form as minute euhedra or spheres made of tiny packed crystallites or radial fibers that give a rough microsurface.

♦ **Bodies do not contain Fe, but may have Ca or Si.** These are precipitates of bacteria. However, Folk does not include magnetotactic bacteria that contain iron in his discussion.

♦ **Bodies must not be confused with minerals or artifacts:** must be observed at very high magnifications (at least 35000X) to verify that the shapes are spheres, ellipsoids or rods rather than cubes.

**Methods**
Five terrestrial samples and one extraterrestrial sample were observed using the JOEL 35CF and the Philips 40XL Field Emission scanning electron microscopes (SEM) at 25kV. The five terrestrial samples consisted of Persian Gulf stromatolite, Antarctic marble, desert varnish, travertines from West Texas, and Columbia River basalts. The extraterrestrial sample was from the Martian meteorite ALH84001. All samples were freshly fractured before analysis. The travertines were lightly etched with a 1% HCl solution for one minute then rinsed with distilled water. Columbia River basalt (CRB) samples obtained from Todd Stevens and James McKinley were pretreated with high-sulfate groundwater, low-sulfate groundwater, and biomass solutions and studied along with unaltered CRBs. All samples were mounted on graphite discs or planchettes using double-stick tape and/or carbon paint. Each was sputter-coated with a gold-palladium alloy for 30 to 90 seconds in order to make it conductive for SEM study. Energy-dispersive X-ray analysis was performed using the PGT System IV associated with the JEOL 35 CF-SEM when possible.

**Results**
Microfossils, dormant bacteria and nannobacteria were found in all samples. The stromatolite provided microbial fossils ranging from 5 to 10 µm. These were identified as radiolarian and diatom remains. Most were calcium rich; however, several silica rich hollow rods were found and identified. Rods with a calcium precipitate were *Scytonema myochrous*. Those without the precipitate were *Microcoleus* [3].
Two or possibly three different types of dormant cyanobacteria were identified in the Antarctic marble. The cyanobacteria had varying sizes: 5 to 10µm chains of 1µm cylindrical segments, 1µm spheres, and 1µm rods that appeared to be dividing. The chains are possibly *Anabaena cylindrica*. The spheres could be *Chrococcus turgidus*, with the rods being the dividing phase [4]. The cyanobacteria showed a strong X-ray peak for calcium and traces of chlorine, argon, silicon, and magnesium.

Desert varnish from South Mountain Park, Phoenix, AZ, and Newspaper Rock, Petrified Forest, NM was analyzed. A bimodal colonial distribution of spherical bodies was discovered both on the surface of the rock and at the meridian where the varnish was first precipitated. The South Mountain Park spheres were 150 nm. The spheres in the Newspaper rock were 30-75 nm in diameter. Also found in Newspaper Rock desert varnish were tubular bodies 75 to 100 nm in length and approximately 20 nm in width.

Fossils of dividing and rimmed bacteria were found in the travertine from bedding plane fault in Guadeloupe Pass, West Texas. The spherical bacteria had an approximate diameter of 250 nm. Identified between two pairs of dividing bacteria was what appeared to be a biofilm. The composition of the rims is uncertain. Chemical analysis of this area was not possible because the count rate was not sufficient.

Several different types of bacteria and morphological features were found in the four samples of the Columbia River basalts. These basalts were collected from approximately 5 km below Earth's surface. No bacteria were imaged in the untreated sample; however, bacteria may exist. There was no opportunity to view this sample at a magnification higher than 30000X. Phyllosilicates were present on almost the entire surface.

The surface of the biomass sample was also coated with phyllosilicates. Segmented bodies of 250nm to ~2µm length and a diameter of 20 to 50 nm were found and appeared to be formed by extremely small spheres. The bacteria were arranged in circles, chains, and knots. It is interesting to note that at every bacterial location was a dome shaped object of similar spheres either close to or along the bacterial body.

Four types of bacteria, abundant phyllosilicates, and a possible microbial mat were found in the low-sulfate groundwater samples. The bacteria in this sample were in about the same abundance as those in the biomass solution. Bacteria identical to those in the biomass were present (fig. 1), along with a larger form of ~150 nm diameter and 2µm length. The third type of bacteria was 1 to 2 µm in length and very clearly made of chains of ~150 nm diameter spheres. The fourth type of bacteria found were 250 nm spheres. Budding bacteria was imaged.

In the high-sulfate solution samples, two possible types of bacteria were imaged: 1µm spheres and an ~6µm segmented body. The spheres could be bacteria; however, they are also similar to sulfur particles or yeast. X-ray analysis was not performed. The segmented body was considerably longer than the previously observed bacteria and consisted of irregular segments. Again, phyllosilicates were present.

Several colonies of tubular bodies and a larger singular tubular body were imaged in ALH84001. The colonial bodies were approximately 150-200 nm in length and 10-30 nm in diameter. The singular body was approximately 400nm long and 50 nm in diameter (fig. 2). Ovoids of approximately 250 nm were also found in ALH84001, some of which appeared to be dividing.

**Discussion**

Each of these samples was evidence that bacteria can survive in extreme environments on Earth, from the freezing temperatures of Antarctica to 5 km beneath the Earth's surface. What does this say about the possibility of life on Mars? The best examples in this study would be the analogies of the environments of the travertines and the Columbia River basalts to environments on Mars.

Travertines formed from thermal springs are an excellent environment for preservable microbial communities on Earth. The springs can range from 5 to 95°C and are most commonly found near volcanically active sites [5]. Hydrothermally active sites similar to these terrestrial hot springs are said to have existed on Mars from the early history of the planet. Mouginis-Mark [6] has studied the northwestern area of Tharsis and has suggested that water release has occurred as recently as 1by ago. In his models explaining this hydrothermal activity, volcanic heat sources interact with a supply of water...
that may be either a liquid water source associated with basal melting of an ice sheet or a ancient subsurface ice layer on Mars.

In terrestrial hydrothermally active sites, many different kinds of microbes are found, including methanogens, acetogens, sulfur- and sulfate-reducing bacteria, and thionic denitrifying bacteria. [6] Methanogens and acetogens are anaerobic microbes that metabolize carbon from CO₂ as their only carbon source for biosynthesis. Sulfur-reducing bacteria receive their energy from reducing sulfate with hydrogen producing H₂S. A thermophilic archaebacteria using CO₂ as its only carbon source oxidizes hydrogen with sulfur, also producing H₂S. Fermentation by sulfate-reducing bacteria distorts amounts of inorganic sulfur compounds in soils. Thionic species of bacteria oxidize reduced forms of sulfur with nitrate. In the presence of hydrogen gas, iron-reducing bacteria use ferric iron as a source of energy. Since Martian soil is very rich in sulfur and ferric iron, these types of chemolithoautotrophs are all possibilities for life on Mars.

The very recent discovery by Stevens and McKinley [7] of bacterial activity in the basalts of the Columbia River adds even more promise to the idea that life could have existed on Mars. These methanogenic bacteria get their source of hydrogen not from other microbes, which is normally the case, but from the basalt itself when its ferrous silicates react with water. Several laboratory experiments involving the saturation of basalts with high-sulfate groundwater, low-sulfate groundwater, and biomass were performed, and microbial metamorphism was found to be present in all samples. Our SEM studies imaged the actual bacteria in the samples. Thus since basalt, liquid water and bicarbonate are believed to have been present on the Martian surface, this type of bacteria could have survived.

**Conclusions**

It is quite evident that microbes play a significant role in the formation and destruction of terrestrial sediments. Bacteria can survive in extremely harsh environments, including those with no organic carbon or sunlight. The presence of these bacteria on Earth and the similarities between their terrestrial environments and past Martian environments leads to the conclusion that bacteria could have existed on Mars. And, since the geothermal subsurface conditions of Mars are still uncertain today [8], these types of bacteria could be presently living on Mars. Regardless, some of the bodies in the terrestrial samples were similar to those imaged in ALH84001 by McKay et al. [9] that were interpreted to be fossilized bacteria.

**References:**
