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Significant Achievements in the Planetary Geology Program - 1977-1978

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Introduction

The 9th annual meeting of the Planetary Geology Program Principal Investigators was held May 31 - June 2, 1978 in Tucson, Arizona at the University of Arizona. The papers presented there represented the high points of research carried out in the Planetary Geology Program of NASA's Office of Space Science, Division of Planetary Programs. The purpose of this paper is to present a summary of the research and significant developments in Planetary Geology for this year, based on the oral presentations at this meeting. Additional information on the reported research, and reports of work in planetology during the past year, are contained in the abstract volume prepared for the annual meeting and are available as "Reports of Planetary Geology Program, 1977-1978" (NASA TM 79729; available from the National Technical Information Service, Springfield, VA 22161) and "A Bibliography of Planetary Geology Principal Investigators and their Associates, 1976-1978" (NASA TM 79732; available from the Planetary Geology Program Office, NASA Headquarters, Washington, D.C. 20546).

Reports of each session were written by the session chairmen of the Planetary Geology Program annual meeting. These contributing authors are listed below.

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Constraints on Solar System Formation

A. P. Boss and S. A. Peale (UCSB) have modeled the collapse of a rotating isothermal interstellar gas cloud with a nonuniform bar-shaped initial density distribution with a three spatial dimension numerical hydrodynamical code. Pressure forces smear out the initial density perturbation; by one free fall time the collapse is essentially axially symmetric about the rotation axis. This configuration will thus collapse down to form a transitory ring distribution, which can fragment into a multiple stellar system, providing a mechanism for changing spin angular momentum into orbital angular momentum, expelling single stars and their accompanying clouds which could be the source of the sun and the preplanetary nebula. It seems fair to say that the general result of this work is to make as regard the formation of planetary systems more as a natural consequence of ordinary stellar formation and less dependent on initial special configurations of pre-stellar nebulae. Hence our estimate of the frequency of planetary systems associated with stars would appear to be enhanced as a consequence.

A. G. W. Cameron (Harvard College Observatory) discussed the physics of the primitive solar nebula and the formation of giant gaseous protoplanets. Instigation of solar system formation was triggered by collapse of an interstellar cloud caused by the arrival of an expanding envelope of gas from a local supernova. Injection of some supernova material at the same time accounts for myriad isotopic anomalies. At the same time, cloud hydrodynamic collapse would cause breaking into smaller masses (one might be equivalent, say, to our solar system). The collapsing smaller mass would be extremely turbulent. The pile-up of mass on the way to the spin axes creates instabilities of a global nature and rings form -- at least in the outer portions. Then, as the cross-sectional area of the torus is reduced, there is another tendency for the ring to break up into cells that correspond to giant gaseous proto-planets. Merging by collision takes place. The initial proto-planet cells are still huge, perhaps 1 AU across. Planets will form only if aggregation from the cells takes place before the central mass (the sun) becomes so large as to disrupt the cells first. This raises the question of how the inner planets formed at all, but they may have formed very early when the central mass was small or have formed further out than their present radii. In any event, this idea explains nicely the division of the solar system into outer unstripped bodies and inner stripped "rocky" nuclei.

Simplified calculations regard the forming giant proto-planets as luminous self-gravitating bodies radiating into a vacuum. Energy is typically sufficient to cause convection to take over heat transport, so an adiabatic gradient is expected in these interiors, but not at the surfaces which radiate efficiently. More sophisticated models are being constructed allowing such objects to be embedded in the primitive nebula, an environment at perhaps several hundred degrees. As material is convected inside these objects, common phases like Fe, olivine, etc. can actually pass through the liquid phase enormously facilitating accretion of the condensed nucleus by solving the old "sticking" problem. Growth of "drops" of a few cm radii is rapid, and then they can fall to the surface of the nuclei. These nuclei can grow to be the present cores of gaseous objects or be stripped to form rocky metallic inner planets. A leftover crop of drops in a metastable size range may conceivably be represented in the chondrules.

C. P. Sonnett (University of Arizona) discussed natural magnetic remanence (NRM) in meteorites. A huge selection of meteorites (hundreds), including irons, several carbonaceous chondrites, H and L group chondrites and some achondrites, cluster around a line of unit slope on a log-log plot of magnetic moment gm^{-1} vs. susceptibility gm^{-1}. Four orders of magnitude in both parameters are covered on the plot. This is surprising considering the variability in the physical properties of different meteorite classes, modification of remnant magnetism by collisions in space, entry induction, remnant magnetism acquired on Earth, etc. A field of 1 oersteads is implied. There are several reasons why that field is unlikely to have arisen from a large meteorite parent body core. For one thing, the irons would probably have lost their field between the time the core froze and the time the curie point was reached. Also, it appears odd that the achondrites (presumably crustal flows) and irons seem to have been exposed to about the same field. There are several problems with a compressed interstellar field and fairly severe requirements for a localized solar field which would have to have been gigantic to induce the remnant magnetism observed. Carbonaceous chondrites seem to have had a history free of intense collisions, which argues against an origin by collision in the presence of an ambient solar wind field. At present, the candidate most free of objections seems to be field production by a hydromagnetic dynamo in the pre-planetary nebula. The generation of such a field in a very turbulent nebula seems reasonable and the pieces that make up the meteorite could all have been magnetized at the same time they were being irradiated by the early solar wind which seems to have saturated the outer rinds of meteorite grains.

Asteroids, Comets, and Satellites

The last year has seen developing maturity of the study of the many smaller bodies of the solar system in both heliocentric and planetocentric orbits. There has been sufficient time now to digest the remarkable Viking images of Phobos and Deimos and to realize how remarkably different these bodies are from each other and from our pre-mission expectations. Meanwhile, potential NASA interest in missions to comets and asteroids has spurred further research concerning these objects; both observational and theoretical studies were reported at this Planetary Geology meeting. Finally, with only a year to go before the Voyager spacecraft encounter the Jovian system, and with planning activities for the forthcoming Galileo mission now in full gear, there is motivation for further detailed studies of the remarkable Galilean satellites. More and more, scientists are beginning to understand the fundamental role the study of these worlds will have for understanding early planetary evolution as well as for revealing potentially exotic geologic phenomena.

E. M. Shoemaker and E. F. Helin (California Institute of Technology) reviewed current knowledge of the near-Earth asteroids. This population of small bodies has been sampled only very incompletely so far, raising the likelihood that searches with a larger dedicated telescope might reveal some extremely close neighbors of the Earth which would be economical targets for exploration, perhaps with manned missions. There is good reason to believe that the Apollo asteroid population contains both main-belt asteroidal fragments and extinct cometary cores. The near-Earth asteroid population provides a critical link between the meteorites and the more distant asteroidal and cometary populations. Since the near-Earth asteroids are so small, they likely possess thin regoliths and will present ideal environments for the study and acquisition of in situ primitive rocks.

A. Carusi, F. Pozzi, and G. Valsecchi, from Rome, Italy, reported on their computations of close encounters between several asteroidal and cometary populations and the planet Jupiter. They demonstrate the efficiency with which Jupiter modifies the population of inner-planet crossing objects, especially those objects which not only cross Jupiter's orbit but also enter the planet's sphere of influence.

C. R. Chapman, D. R. Davis, R. Greenberg, and J. Wacker reported further analyses of the collisional and fragmentational interactions of the main-belt asteroids being conducted at the Planetary Science Institute in Tucson, Arizona. Such collisions not only constitute the dominant geological process on these bodies, but serve to shape their size distribution and the production of fragments that ultimately become available for cratering the inner planets and providing meteorites to Earth. These investigators reported on comparisons of two separate computer programs designed to treat the problem of collisional evolution in somewhat different ways. One treats two separate populations of asteroids colliding with each other (e.g., representing the C and S classes) while the other considers only a single population but has the flexibility to model the collisional physics more exactly, including the evolution of the velocity distribution. An outstanding question concerning asteroid collisions is the efficiency with which the kinetic energy of a collision is transferred to the kinetic energy of escaping fragments. If the energy is partitioned efficiently (e.g., only a small portion is lost to heat and most fragments are ejected with nearly the same velocities) then the asteroids may be readily fragmented. On the other hand, if the partitioning is inefficient, asteroids will become highly fractured and crushed, but the fragments will not be readily dispersed, leading to relatively slow collisional evolution of a population of weakly cohesive objects composed of "mega-regolith."

Two papers reviewed recent cometary research at the Harvard Center for Astrophysics. Z. Sekanina reported calculations of the gravitational interaction of the fragments of a split comet in the sun's gravitational field. He finds a great variety of companion orbits (at the same separation velocity) depending most strongly on the position of the comet at the time of splitting, on the direction of separation, and on the location of the would-be companion on the surface of the parent nucleus. The separation velocity is not simply related to the mass of the comet. Sekanina believes that the existence of binary and multiple comets should not be discarded a priori. Meanwhile Fred Whipple has been reviewing the literature on comet observations in the hopes of determining the rotation periods of comet nuclei. He summarizes the probable rotation periods for eight comets, of which six are new determinations by himself, and a determination of the axis of rotation for one comet (P/Schwassmann-Wachmann I). The periods average near the mean asteroidal rotation period but there is a wider range (4.6 to 121 hours). The methods employed have led to further understanding of the surface physics of comets. In particular, it seems to be only the older comets that show the asymmetric activity required for determining rotation periods; perhaps comet surfaces become covered with meteoritic debris so that only small active areas remain.

A series of three papers addressed the recent Viking imagery of Phobos and Deimos. The speakers were T. C. Duxbury (Jet Propulsion Laboratory), P. Thomas (Cornell University) who has recently completed his doctoral dissertation on this topic, and J. Veverka (also of Cornell). Co-authors included J. Goguen and A. Bloom of Cornell. The presentations were dominated by the presentation of beautiful imagery, which the authors used to point out striking geomorphological traits of the craters, grooves, blocks, and albedo features on these bodies and to emphasize the substantial differences between the two satellites. While opinions were offered about the interpretation of these features in terms of geological processes, the clear advance in the past year has been the geomorphological classification of features, the description of spatial and stratigraphic relationships, and the comparisons between the two satellites.

Duxbury lists the dominant traits of Phobos and Deimos as follows: Phobos is dominated by fractures and craters, covered with a regolith perhaps a few hundred meters thick; it is uniformly grey with an albedo of 0.05 to 0.06; it has a mass of 9.6×10^{18} gm, volume of 5000 to 5600 km^3, and hence a density of 1.5 x 2.3 gm/cm^3. Deimos is smoother in appearance; a regolith of at least tens of meters depth has substantially filled in the 100 m diameter craters and no grooves are present; there are numerous boulders tens of meters in size strewn across the surface (unlike Phobos which has very few boulders); it is grey in color with albedo similar to Phobos but has brighter regions near the ridge-like intersections of several large flat areas; and it has a probable density in the range of 1.2 to 2.4 gm/cm^3 (its volume has not been well determined). The densities and reflectance spectra of both satellites suggest a carbonaceous chondrite (CC) composition which in turn suggests the satellites might be captured asteroids if CC material could not be condensed at the distance of Mars from the sun.

Thomas discussed many intriguing features in the Phobos and Deimos imagery. Most striking was his demonstration of the spatial relationships of the grooves on Phobos to the giant crater Stickney. Clearly Stickney either created, or enlarged, a system of fracture planes cutting through the entire body. Drainage of loose surficial material into the fractures best explains the morphology of the somewhat pitted grooves. Deimos, on the other hand, shows evidence of considerable surface blanketing (or other process of degradation) including the mysterious albedo streaks associated with craters, resembling Martian windstreaks. There was much discussion about why Deimos might be more subject to reaccumulating impact ejecta than Phobos, but no coherent explanation has yet been proposed. Veverka's presentation concerned primarily his analysis of dark patches on the floors of some craters on Phobos. He concludes that they are of similar albedo, but much coarser texture, than surrounding regions and hypothesizes that they may be pools of vesicular impact melts.

The results of a largely theoretical consideration of cratering processes on small bodies was presented by M. J. Cintala and J. W. Head (Brown University) and J. Veverka. They emphasize the low surface gravities and small radii of curvature of such bodies. Oblique intersection of shock waves with the curving surface may result in ejecta kinematics significantly different from those pertinent to cratering on larger planets. Much ejecta will escape small bodies and that retained may be primarily the latest-stage, blocky, most weakly shocked ejecta component. Cintala emphasizes the difference between the regolith evolution expected for Phobos and Deimos through Soter's mechanism (return of ejecta constrained in Mars orbit) and that expected for asteroids; asteroid regoliths should be blockier.

J. Pollack (NASA Ames) reviewed what is known about processes that have affected the surface compositions of the Galilean satellites. These include the physical conditions in the circum-Jovian nebula at the time of origin of the satellites, the subsequent internal differentiation of the bodies, any near-surface convective motions, and the exposure of satellite surfaces to the space environment, including meteoroids and magnetospheric particles. Spectral observations have shown that the surfaces of Europa and Ganymede are dominated by water ice. Callisto is expected to have much near-surface ice as well, but it is not readily observable. Either fresh coatings of water have not been introduced onto Callisto due to its relatively thicker and more stable crust or else the ice has been coated by extra-satellite dust swept up by Callisto. Pollack presented infrared spectra of Io, obtained with the NASA Airborne Observatory, that may be consistent with the hypothesis that Io is covered with an evaporite deposit. Pollack emphasizes the exceptionally anhydrous character of Io's surface indicated by his spectra.

C. B. Pilcher and N. G. Purves (University of Hawaii) discussed processes affecting the evolution of water on the Galilean satellites. They conclude that sputtering probably rapidly removes all free water from the surface of Io, forming a salt crust over any frozen salt solution present. No other process considered in their study (Jeans escape, photolysis, and atmospheric charged particle interactions) can account for substantial water loss from Io. Pilcher discussed the relative rates of sputtering and regolith gardening by meteoritic impact; the sputtering rate is quite substantial (5 to 500 meters per 10^9 years). Pilcher and Purves also investigated the distribution and migration of water on a satellite surface due to sublimation; such processes may contribute to the formation of a salt surface on Io only near its equator.

A. Metzger (Jet Propulsion Laboratory) presented a report by R. H. Parker _et al_. concerning the prospects for X-ray spectroscopy of the Galilean satellites. They have computed the X-ray emission from the surfaces of the satellites resulting from

Jovian magnetospheric charged particle impacts. Characteristic line emissions can be used to determine the abundance of such elements as Al, Si, K, Ca, Ti, Fe, and Ni. The dominant mechanisms producing emission are electron and proton ionization and bremsstrahlung-derived secondary excitation. Parker et al. find that (1) the intensity of line emission due to electron ionization always exceeds that from secondary ionization; (2) proton ionization is most significant for the lightest elements; (3) the ratio of proton-to-electron-produced-ionization is greatest for Io and Europa and essentially zero for Callisto; and (4) X-ray fluxes decrease with increasing orbital distance of the Galilean satellites.

Constraints on Planetary Interiors

R. Smoluchowski (Princeton) contrasted the magnetic fields and heat budgets of Jupiter and Saturn with those of Uranus and Neptune. For Jupiter and Saturn, both the metallic hydrogen and the molecular H_2 layers play roles in the magnetic field generation, and the internally generated heat can be attributed to He precipitation in the metallic H region. Uranus and Neptune differ in having large cores of rocky and icy materials, but while Uranus has a magnetic field and no appreciable internal heat source, Neptune has just the opposite characteristics. The difference in heat budgets between Uranus and Neptune may may be due to higher temperature as a function of pressure and a partially liquid core in the latter body, capable of sustaining an exothermic differentiation mechanism analogous to He precipitation in Saturn and Jupiter. Uranus may sustain a dynamo in the deep H_2 layer; the absence of a field in Neptune is more difficult to explain.

G. Schubert (UCLA), P. Cassen and R. E. Young (NASA Ames) presented the results of a quantitative study of subsolidus convective cooling of the terrestrial planets from hot initial states. Their technique uses an analytical simulation of convection, through a quasi-empirical relation between heat flux and the temperature of convection. The cooling models yield the convection temperature, lithospheric thickness, viscosity, and heat flux as functions of time. Important conclusions of their numerical experiments are that the temperature dependence of viscosity is the most important factor in determining planetary temperature, that the memory of the initial temperature is lost by the convection process, that primordial heat contributes 1/4 to 1/3 of the present heat flux in the planets, and that the surface heat flow lags behind the heat flux into the lithosphere for these bodies.

S. J. Peale (UCSB) and P. Cassen (NASA Ames) examined the conditions under which tidal dissipation may be an important heat source for a planetary interior. For the Moon, tidal dissipation is not an important contributor to heat for a "standard orbital evolution" and a homogeneous, isotropic, and incompressible interior. The importance of the tidal contribution to heat could be substantially enhanced by a previously molten core of sufficient size, by a Q for the Earth much larger at a time in the past when dissipation was high in the Moon (e.g., a Cassini state transition), or by an exotic orbital history with large eccentricities. Because all of these circumstances are special, Peale and Cassen found no compelling reason for their occurrence. Application of the theory to Mercury shows that tidal dissipation has been negligible. Dissipation in the Galilean satellites may have damped the libration of the Laplace relation among the orbital mean motions.

S. C. Solomon (MIT) and J. W. Head (Brown) described the thesis that the location and formation time of tectonic features near large basalt-filled basins on the terrestrial planets may be explained quantitatively by the superposition of local loading stress and global thermal stress in the planetary lithosphere. For the Moon, the preserved linear rilles at the edges of mare basins appear to have formed in the period 3.4 to 3.8 AE, while the mare ridges, interpreted as compressive features, continued to form within the mare deposits until times younger than the most recent basalt flows. Both features may be attributed to superisostatic loading and subsidence of the mare basins; the temporal dependence of rille and ridge formation is ascribed to a shift in the global thermal stress from extensional to compressive at about 3.6 AE, a conclusion that greatly restricts possible lunar thermal histories. Major basins on Mercury and Mars show different histories, because of both lesser basalt loads and different global stress histories.

R. J. Phillips (JPL) considered the implication of new Viking gravity data over Olympus Mons on subsurface structure. The gravity anomaly map consists of a pronounced high over the shield and flanking lows; the lows are too large in magnitude and too distant from the volcano to be ascribed to lithospheric flexure. The grooved terrain may also contribute to the gravity high, which would support the hypothesis of Blasius that this terrain represents an uncapped basic intrusive. The recent discovery of a positive gravity anomaly over the older Elysium volcanic province may provide a test of possible models for the excess mass of Tharsis. Calculation of the principal deviatoric stress at the surface of an elastic martian lithosphere from the 4th order and degree topography and gravity yields good agreement with the radial extensional and circumferential compressive features in the Tharsis region. Phillips attributes these features to the current lithospheric loading or relaxation phase of Tharsis, which followed an earlier uplift phase.

Volatiles and Regolith

Fraser Fanale (JPL) discussed the possible exchange of CO_2 between three reservoirs on Mars; the current atmosphere, seasonal and permanent polar caps, and adsorbed material in the regolith. He has measured the CO_2 adsorption on basalt, nontronite, and limonite as a function of temperature and CO_2 partial pressure. Despite uncertainties in the regolith distribution and mineralogy, he finds that adsorption in the regolith is a much larger storehouse for CO_2 than in the atmosphere plus polar caps system. This large potential reservoir helps explain the essential lack of an O^{18} enrichment despite large N^{15} enrichments found by Viking. The regolith will respond with a long time-constant to buffer the surface pressure against external changes, and could respond to long-term insolation changes to vary the atmospheric pressure enough to possibly effect the eolian transportation processes, and consequently to provide an explanation for the prominent layering seen in the polar deposits. The model is compatible with the large surface areas implied by the Viking gas exchange (biology investigation) results and by the mineralogy inferred from the Viking X-ray fluorescence experiment.

Henry Moore (USGS) presented the results of a study (with six other individuals at six institutions) of the information obtained on martian surface materials during the Viking extended mission. The surface materials at the Viking landing sites may be grouped into four categories based on their physical properties as determined by the combined use of spacecraft surface interactions during sampling and excavating and results from other experiments. In order of increasing strength, they are: (1) drift material at VL-1, (2) crusty to cloddy soil at VL-2, (3) blocky soil at VL-1, and (4) rocks at both sites. Mankind's deepest excavation on other planets is a 23-cm deep trench at VL-1 in reasonably uniform material at "Sandy Flats." Other trenches at VL-1 and VL-2 have reached lesser depth with considerable difficulty. Although the surface shows modification from the retro-engines, small conical piles of soil constructed by the surface sampler have not been altered by the martian winds. When the surface sampler was left buried in the soil, its temperature sensor indicated near constant temperature in the afternoon at a season when the Lander imaging indicated small frost patches on the surface. It is currently uncertain whether this constant temperature is the result of a phase change in the soil.

Hugh Kieffer discussed work done by Michael Booth at UCLA on a laboratory study of the formation of carbonate materials in soils under martian conditions. Using a pulverized tholeiitic basalt, and a two-fold acceleration of the martian day, carbonate growth occurs at a rate several orders of magnitude greater than required to account for the "missing" CO_2 inventory over the history of Mars. Experiments lacking diurnal cycling, receiving no UV irradiation into the chamber, or using fine-grained glass beads in place of the basalt, showed no detectable carbonate growth. Further work is in progress to identify the active chemical processes such as to allow quantitative extrapolation of the laboratory measurements to geologic time scales.

R. V. Morris, H. L. Lower and D. Prestel (JSC) have developed a weathering simulation chamber which can simultaneously chemically and physically weather samples under the gas composition, pressure and irradiation environment of Mars. The physical weathering is accomplished in a dynamic gas atmosphere which tumbles and knocks the sample particles together. The saturation magnetization of magnetite was measured as a function of UV irradiation time. It was found that about 30% of the magnetite was oxidized to hematite in 1000 minutes. The magnetite, as opposed to maghemite, oxidation product was determined by X-ray diffraction and thermal magnetic analysis.

D. McKay, U. Clayton, D. Morse and D. Prestel (JSC) have examined the physical products of Morris's experimentation with high resolution SEM and other techniques. They found that the oxidation of magnetite to hematite by both thermal and UV induced reactions creates morphological changes which can be readily characterized by high resolution SEM studies. Thermal oxidation of magnetite produces abundant crystals of hematite with an average size of 1000 Å and increases the surface area of the grains by orders of magnitude. Thermal oxidation may also produce hematite needles having a few hundred Å diameter and having length to width ratios which may exceed 100. In UV irradiation, individual magnitite grains are welded together by material converted to hematite. Such a coalescence mechanism may be responsible for the coherent clods of duricrust seen on the martian surface. UV irradiation of magnitite in air at room temperature produces euhedral crystals of hematite.

Ken Jones (JPL) reported on a thin layer of water ice condensate which was present at the VL-2 site for over 1/3 of a Mars year. The initial condensates appear as a discoloration of the surface and were seen about sol 221 (martian days after VL-2 landing). The frost appears to have increased monotonically in thickness until about sol 341, when it began to disintegrate into patches whose locations were controlled by rock shadows and topography. The extremely slow rate of return of the condensate to the atmosphere is consistent with H_2O and is inconsistent with either CO_2 or a CO_2 clathrate. A thin residual layer of dirt at the site suggests that condensate formation and dust deposition were related, and that the H_2O was probably transported to the site condensed on the surface of dust grains.

R. L. Huguenin of Brown University and University of Massachusetts at Amherst reported on laboratory studies which produce an O_2 release behavior similar to that observed by the Viking biology experiments. He found that oxygen was produced when fresh olivine was pulverized in a low temperature vacuum chamber with a supply of water vapor which condensed onto the sample at about $-15^{o}C$. He proposes that the frost is converted to hydrogen peroxide at the mineral surface; this hydrogen peroxide would then be a source of O_2 and it could oxidize the nutrients in the biology experiments to CO_2. Although photooxidation occurs on Mars, the net weathering process may result in an overall reduction of the surface by the penetration of frost associated H^+ into the crystals.

Instrument Development Techniques

B. Hapke (University of Pittsburgh) reported on photometric analyses of planetary spacecraft images and related topics. A quantitative theoretical planetary photometric function was completed. The function includes microscopic and macroscopic shadowing and multiple scattering and can be used to relate observed planetary properties such as spectral albedo, to microscopic properties of the planetary regolith, such as spectral absorption coefficients and particle size. A high-resolution, low-noise measurement of the spectral reflectance of Mercury was obtained between 0.65 and 1.25 µm. A new absorption band (at 1.03 µm, identified as probably due to Fe^{2+} in diopside) was discovered. However, the band may possibly also be caused by forsterite. A reflectance spectrum of Io was obtained over the range 0.32 - 0.85 µm. In addition to the previously-known blue edge at 0.5 µm and band at 0.6 µm, a new band at 0.33 µm was discovered. A possible band at 0.8 µm, which had been previously reported, was not confirmed. The strong resemblance between the spectral reflectance of Venus and Io increases the likelihood that the UV absorber on Io is elemental sulfur.

J. Stephens (JPL), D. Anderson (NSF), A. R. Tice (JPL), F. Fanale (JPL), and E. Gibson (JSC) reported on a Mars water instrument study. The functional architecture has been defined for the soil water analysis instruments. The functional architecture for the soil sample acquisition system has been defined to the extent that the soil water experiment requirements must be imposed.

Major critical elements of the soil water analysis instruments have been conceptually designed. A conceptual design for the soil sample acquisition system for three different rover concepts has been produced.

T. E. Economou, A. L. Turkevich (University of Chicago), and E. J. Franzgrote (JPL) described tests of a miniaturized chemical analysis system. The system, incorporates scattered alpha, alpha-proton and X-ray production modes, and has been tested at the Caltech accelerator using 6.1 Mev alpha particles. An important development during the last year has been the testing of ambient temperature HgI_2 detectors for the X-ray mode. Even at the present stage of development, these have resolutions for low energy X-rays that are appreciably better than proportional counters.

L. Lebofsky (JPL) reported on laboratory infrared reflectance studies. An extensive study of the infrared (1-5 μm) reflectance spectra of various materials is being carried out in an attempt to build up a database for the interpretation of telescopic and future spacecraft spectral observations of the surfaces of solar system objects for the determination of their surface compositions. The work to date has concentrated on the study of silicates and hydrated silicates both at room temperature and at temperatures similar to those encountered in the asteroid belt. In addition, a study of various salts (nitrates, sulfates, carbonates, etc.) was undertaken for comparison with the recent reflectance data on Io in the 1-5 μm spectral region, which shows the presence of several, as yet, unidentified absorption bands.

Planetary Cartography

Ray Batson (USGS) reported that twenty-two Mars 1:5,000,000 quadrangles were completed in FY77. Compilation of albedo overlays was discontinued so that more efforts could be expanded in including Viking data on maps remaining to be compiled. A shaded relief map of Mercury was completed at 1:15,000,000; initial plans called for the sheet to be published at 1:25,000,000, but this may be changed to publication at 1:15,000,000. Technology of preparing digital mosaics of raw spacecraft images was developed. These image databases can be treated as single frames thereby greatly reducing the cost of further processing. Processing of data for mapping Phobos and Deimos continues. A gazetteer of crater nomenclature on Mercury and Mars was completed and encoded for computer processing.

Geological and Geochemical Constraints on Planetary Evolution

R. G. Strom (University of Arizona) presented a review of mercurian geology, emphasizing the uniqueness of Mercury in terms of its lunar-like surface, but high density interior. The question of the origin of mercurian plains is still open; evidence has been put forward for both a volcanic and an impact-related origin. Major aspects of mercurian history include: accretion, intense bombardment and core formation, intercrater plains, global compression and scarp formation, Caloris basin, plains formation, continued cratering.

J. McCauley (USGS), J. Guest (University of London), N. Trask (USGS), G. Schaber (USGS), R. Greeley (Arizona State University), D. Gault (Murphys Center of Planetology), and H. Holt (USGS) reported on a formal stratigraphy of the Caloris basin and compared Caloris to the units and ring structure in the lunar Orientale basin. The main Caloris Montes scarp is thought to approximate the edge of the basin of excavation of Caloris and to be the structural and stratigraphic counterpart of the Montes Rook scarp around the Orientale basin on the Moon.

E. King (University of Houston) and G. McGill (Univeristy of Massachusetts) described the geologic history of the Victoria quadrangle (H-2) on Mercury. The authors found no evidence for a volcanic origin for any of the plains units in the region.

P. Masson presented an interpretation by Pierre Thomas (University of Paris-Sud) of the lineaments near the Caloris basin. The data were derived by fourier transforms using an optical data processing system, and it was concluded that many of the lineaments originated in the mercurian surface before the excavation of the Caloris basin.

M. C. Malin, R. J. Phillips, and R. S. Saunders (JPL) reviewed the problem of the interpretation of the martian highlands/lowlands dichotomy. No satisfactory explanation exists for the dichotomy.

L. Soderblom (USGS) showed that a number of surface color areas could be correlated with visual features on Mars. The correlations were striking, and work is progressing on the interpretations. The classical dark region found in the southern equatorial region and situated in the martian highlands is divided into two units on the color map. T. B. McCord and R. Singer (University of Hawaii) presented a progress report on their work to characterize martian surface units by ground-based spectra taken in 1971 and 1973. It is clear from their data that not more than 40% of the surface in the dark areas can be covered by bright material. R. L. Huguenin (University of Massachusetts and Brown University), J. W. Head (Brown University), and T. R. McGetchin (LPI) have used ground-based spectral measurements to map lithologic units in the Margaritifer Sinus and Coprates quadrangles. They interpret their spectra in terms of nine different petrologic units within these quadrangles. The chief differences in units are the relative amounts of clinopyroxene, orthopyroxene and olivine (or glass). The clinopyroxene-rich areas tend to be darker and contain most of the chaos and large channels. The most clinopyroxene-rich area is Solis Lacus, in which water vapor was observed during the 1971 and 1973 dust storms.

D. H. Scott (USGS) showed that a number of additional surface stratigraphic units could be mapped on Mars lowlands as a result of Viking orbiter imagery. He further suggests that "an ancient remnant surface may occur along the base of the boundary scarp separating the lowlands and highlands."

K. Hiller and G. Neukum (Ludwig-Maximilians-Universitat) reported on the Amenthes quadrangle of Mars and concluded that the erosion of the highland scarp on Mars occurred between 3.7 and 4.0×10^9 years ago, based on the cratering data and interpretations of Neukum and Wise.

P. Masson also presented a paper in which the structural evolution of the Claritas-Fossae area was outlined by lineament pattern analyses, and the relationship of the lineaments to the formation of Valles Marineris was shown to be compatible.

E. C. Morris (USGS) and J. R. Underwood (Kansas State University) described polygonal fractures on the martian plains. Large polygonal fractures on Earth are associated with dessication of thick playa sediments with polygon diameters up to 1 km. The authors propose that the Mars polygonal fractures could be the result of dessication of a thick layer of ice or water-saturated sediments.

G. McGill and M. Golembek (University of Massachusetts) treated the mechanics of graben formation and, in particular, the geometries of grabens. They argue that the bounding faults of grabens must intersect at some depth, and that below that depth the mechanical response of the rock is completely different.

Golembek applied these ideas to the Moon and found good agreement with the depth suggested to the base of the megaregolith. It appears that a small amount of extension caused by local basin movements can account for lunar graben formation.

J. H. Howard and B. B. Ellwood (University of Georgia) presented a discussion of magnetic susceptibility anisotropy in rocks and how it might be used in returned Mars or other planetary samples to investigate the mode of rock formation, direction or emplacement and mechanics of emplacement.

A model for the bulk composition of Mars was presented by K. Goettel (Washington University). An interesting property of this model is that it is rather insensitive to the models chosen for the condensation and accretion of martian matter. He concluded that Mars should contain substantially more volatiles than the Earth and that Mars should contain much more oxidized iron than the Earth, approximately 18% versus 8% in the Earth.

Fluvial Processes and Channel Formation

Major discussions in this session centered on the mode of origin of the channels. The issue divided between those who favor a water-flow origin, whether catastrophic or not, versus those who believe the channels were carved by winds, fluid lavas, or some other agent. The water-flow origin received strongest support in the presentations of V. R. Baker (University of Texas) and M. Carr (USGS), Baker pointing to the similarity to landforms in the Channeled Scablands and Carr documenting that the high porosities of volcanic rocks would be sufficient to allow high water discharges from the channel sources. On the other hand, K. R. Blasius and J. A. Cutts (Planetary Science Institute) argued against the water origin, favoring instead a formation by winds (at least in the case of the channels on Chryse Planitia); this suggestion met with strong objections from others.

Specifically, V. Baker reported on the hydrodynamics of erosion by catastrophic floods. The distinctive assemblage of landforms scoured in rock in the Channeled Scablands can be explained by a combination of three hydrodynamic processes: cavitation, macroturbulence, and streamlining. The presence in the martian outflow channels of the same total landform assemblage, unique to Scabland erosion on Earth, implies a catastrophic flood contribution to the evolution of the martian channels. Cavitation would have been facilitated in martian floods because of relatively low atmospheric pressure and gravity.

J. C. Boothroyd and T. Danlon (University of Rhode Island) reported on the landforms and morphology of selected terrestrial river systems. Fourier analyses were performed on the two-dimensional shapes of bars, channel islands, and erosional remnants in selected terrestrial river systems. Results show that the high discharge flows of the Channeled Scablands produce remnants morphologically similar to Chryse remnants. Large rivers produce similar forms but of reduced size. Still smaller rivers produce dissimilar forms, suggesting that there is a lower limit on the magnitude of the flow that will produce "Chryse-like" remnants.

Dag Nummedal (University of South Carolina) discussed the role of liquefaction in channel development on Mars. He proposed that modified endogenic channels with a source chaos are due to the sudden liquefaction of a subsurface, water-laden, metastable sediment unit. Liquefaction flows on Earth are known to be triggered by liquefaction shock-waves which may propagate at rates ranging from 10 to 100 km/hr. If the liquefaction waves on Mars would propagate at similar speeds, one could easily obtain discharges from some of the chaos of a magnitude commensurate with the scale of many of the flow-eroded features.

Mike Carr (USGS) proposed a model for the formation of martian flood features by release of water from confined aquifers. Many large martian channels arise full bore from discrete areas of chaotic terrain. It is proposed that the channels were eroded by water, released rapidly under pressures close to the lithostatic pressure, from deeply buried aquifers. Peak discharges depend on the hydraulic head, the radius of the orifice to the surface, the thickness of the aquifer and its hydraulic conductivity. Plausible values for these parameters give discharges in the range of 10^5 to 10^8 m^3/sec which are consistent with the values computed from the dimensions of the flood features.

D. T. Eppler, P. J. Brown, R. Ehrlich, and D. Nummedal (University of South Carolina) analyzed shape-frequency histograms of terrestrial and martian remnant landforms. Lack of modes on the shape frequency distribution descriptive of martian erosional remnants indicates that interaction between martian landforms and the process or processes by which they were formed does not produce a preferred shape. Comparison of the martian distribution with shape frequency distributions of terrestrial landforms implies that the martian remnants represent extremely immature landforms. Such a uniform distribution would be produced by an effective erosion agent acting over an extremely brief period of time, or by an ineffective, low density (?) agent acting over somewhat longer periods of time.

David Pieri (Cornell University) described small martian channels and their junction angles. Viking data show a rich heterogeneity of small channel morphology which may imply both a diversity of material response to the process which creates them and a diversity in the genetic processes themselves. Although the small channels are probably the result of a spatially and temporally diverse (though ancient) erosion process in cratered terrain, they exhibit systematic branching networks extremely suggestive of either downhill overland flow of water or, perhaps more likely, subsurface erosion by wet or dry sapping.

E. Theilig and R. Greeley (Arizona State University) proposed a channeling history of Maja Vallis. A channeling sequence can be established for the Vedra, Maumee, and Maja Vallis area of Lunae Planum. The earliest set of channels may be represented by small subdued channel segments which occur totally within the mountainous terrain at the eastern edge of Lunae Planum. Vedra Vallis was the earliest large-scale channel formed and was followed by Maumee Vallis. Maja Vallis was the third large channel formed. Erosional features associated with Maja can also be aligned with Maumee, suggesting that the two systems may be contemporaneous and related in origin.

A stability analysis for the origin of martian fluvial features was presented by D. E. Thompson (JPL). The detailed problem addressed is one in which a channeled fluid of variable viscosity, representing implicitly a volume of sediment concentration in the fluid, is perturbed analytically by oscillatory disturbances imposed on the three velocity components, the pressure distribution, and the viscosity profile itself. These perturbations are intended to give rise to longitudinal helicoidal secondary flow patterns in the fluid and relate to braiding and intense longitudinal grooving along the channel bed. Analysis was presented through development of the stability equations for this problem. The boundary conditions and schematic form of results were presented heuristically. Extensive comments were made concerning the applicability of this analysis to many types of fluids. An example was cited by which enhanced sediment entrainment by longitudinal vortices in martian fluids may create a variable viscosity fluid which is initially turbulent, then becomes a high discharge, laminar, but highly erosive flow. Behavior and evolution of a complex flow such as this is accessible through the type of stability analysis presented. Relation of results to answers for Mars and data constraints on theory were also discussed.

K. R. Blasius, J. A. Carr, and W. J. Roberts (Planetary Science Institute) discussed large scale erosive flows associated with Chryse Planitia, Mars and source and sink relationships. Chryse channels were compared in scale and morphology to terrestrial catastrophic flood eroded channels. The relatively small source areas of Chryse channels and the implied efficiency of the erosion process make the simple catastrophic flood hypothesis extremely improbable, according to the authors. A newly discovered similar channel system associated with Amazonis Planitia was described. No patches of chaotic terrain are associated with these channels but strong evidence of eolian deflation and scour is present locally.

Cutts, Blasium and Roberts outlined an alternative erosional model for the chaotic terrain and channels associated with Chryse Planitia. The erosional characteristics of martian outflow channels and source areas were compared in detail with those of terrestrial catastrophic floods and with a mathematical formulation of the alternative eolian hypothesis. The eolian model involves a type of avalanche effect in which saltating particles drawn from the chaotic terrain impact other particles, causing them to participate in a ground-hugging sand blast. According to the authors, the model accounts for the large size of the channels with respect to the source areas and for the increase in size with distance from the source.

C. E. Reimers and P. D. Komar (Oregon State University) described the flow mechanics and resulting erosional and depositional features of explosive volcanic density currents on Earth and Mars. Small channels on the flanks of certain volcanoes in the Tharsis region of Mars are attributed to the formation of explosive volcanic density currents (nuées ardentes and base surges). These channels were compared with similar channels on Earth volcanoes. A model was presented, based on the equations which govern debris flows (a similar species of gravity flows), which illustrates the mechanisms which create the erosional and depositional features associated with the flows. Komar also discussed the mechanics of transport of gravity-driven debris flows, flows characterized by high concentrations of sediments (mud plus rock fragments). The model involves the simultaneous solution of two equations: the first is a balance along the flow slope of the gravity component driving the flow versus the internal frictional resistance; the second equation employs Bagnold's grain dispersive pressure to support the grains above the bottom. The model explains the high mobility of debris flows and the observed inverse grading or sorting of the grains through the flow thickness.

Eric Christiansen and J. W. Head (Brown University) presented a classification of martian landslides and a discussion of their genesis. Landslide deposits on Mars can be classified according to the position of the deposit relative to the rupture surface. By comparison with terrestrial flows, the features of most of the Valles Marineris landslides (linear grooves and smooth non-digitate margins) indicate that they were emplaced without significant amounts of water, but as dry thixotropic flows.

B. K. Lucchitta (USGS) discussed landslides in the Valles Marineris, Mars, and concluded (1) that most landslides were coincident with young, vigorous eruptive activity of Tharsis volcanics, and approximately the same age as some channels; (2) the coefficients of friction of martian landslides are similar to very large terrestrial landslides; and (3) porewater may be present approximately 1 km below the plateau surface and 1 km behind trough walls (of approximately 7 km height). Quakes may lead to collapse, to liquefaction, and to tremendous mudflows.

Volcanic Processes

Jayne Aubele, L. S. Crumpler, and W. E. Elston (University of New Mexico) presented a summary of the multi-stage evolution of the Tharsis shield volcanoes on Mars. They suggested that Arsia Mons, Pavonis Mons and Ascraeus Mons show similar histories. Arsia Mons is the most complexly developed with its history being summarized: (1) main shield formation; (2) summit volcano-tectonic collapse and (3) parasite shield formation concurrent with and subsequent to volcano-tectonic subsidence.

R. S. Saunders, L. E. Roth, C. Elachi (JPL), and G. Schubert (UCLA) described the radar topography of the southern Arsia Mons region and suggested that significant modification of the presently available Mars topographic data can be justified using Earth-based radar profiles obtained from the Goldstone tracking station during 1971 and 1973. These improved slope data allow more precise rheological measurements of the lava flows emanating from the Arsia Mons region. J. B. Plescia and R. S. Saunders (JPL), using the radar derived slope information for the region south of Arsia Mons, presented rheological data using the method of Hulme that makes use of lava flow levee widths and heights. Yield stresses calculated were on the order of 1-4 x 10^4 N/m^2 suggesting SiO_2 contents in the low 50 percent and probable basalt composition. These are generally in agreement with values obtained by other workers.

R. Greeley and E. Theilig (Arizona State University) presented a discussion of the "pancake" shield-like structures of possible volcanic origin in the channelways at the southern

Chryse Planitia on Mars. They suggested that these features may be marshy ground; the martian features may be among the youngest volcanics on Mars. Don Wise, M. P. Golembek, and G. E. McGill presented an analysis of the structural trends in the Tharsis province of Mars. Detailed crater counts were obtained to date the major structural events in the region. The history of the Tharsis structural movements suggests an early development of province-wide semi-radial fault systems in the time span represented by crater numbers 10,000-30,000 (craters larger than 1 km diameter/10^6 km^2). During the span of crater numbers 5,000-10,000 many of the more local stress systems began to break the region into smaller blocks and sub-provinces, such as the Tempe Plateau and the Syria-Sinai-Solis region. Most of the faults of these regions are now covered with plains materials of crater numbers 2,000-4,000, showing only local, minor signs of fault reactivation. In the vicinity of the great volcanoes, small, local areas were intensely faulted in the crater time span 4,000-1,000. These areas now are largely covered with young volcanic edifices, their debris aprons or young volcanic plains. They suggested that the great young volcanoes may be the most impressive topographic features of the Tharsis province but that it is the older semi-radial fracture systems which provide the tectonic "glue" to hold the Tharsis province into a single entity.

R. S. Saunders presented a summary of crater count statistics on various volcanic surfaces within the Tharsis region of Mars as part of a study to document the relative ages of the surface types. Craters larger than 1 km/10^6 km^2 ranged from 16-80 on the

Olympus Mons scarp to 2512-3160 on the old plains south of Arsia Mons which were not covered by lavas from that shield. These crater data are in general agreement with those published by other workers.

Pete Schultz (Lunar and Planetary Institute) presented a discussion of floor-fractured craters on the northern edge of the Mars equatorial highlands at the contact with the northern martian plains. He emphasized the analogy of the lunar fractured floor craters on the margins of mare basins and inferred a volcanic origin for the floor modification. Schultz also suggested that hydrothermal ore deposits may be concentrated within these floor-fractured craters, being related to underlying plutonic bodies and the influence of trapped volatiles in the upper few kilometers of the martian surface.

Eolian Processes

Investigators of eolian processes on Mars have pursued three main paths of study: (1) terrestrial analogs; (2) direct observation via Viking imagery and data; and (3) laboratory and computational simulation.

R. S. Saunders and W. A. Hunter (JPL) presented a progress report on studies of eolian abrasion at Garnet Hill, California. They found that orientation of existing ventifacts seems consistent with the modern wind regime and they have in progress studies of evolution of the sand population, wind movement and sand transport rate, and abrasion of samples in a test plot. They hope to relate theoretical and laboratory work to wind abrasion under natural conditions. M. J. Grolier, J. F. McCauley and C. S. Breed (USGS) described two aspects of eolian erosion: (1) broad, flat-floored deflation hollows, yardangs and wind-fluted cliffs east of the Little Colorado River in northern Arizona; and (2) scour during the dust storm of 23-25 February 1977, which produced myriads of small yardangs in the Clovis-Portales region, New Mexico, and less than 12 hours of winds up to 100 km/hr suspended enough of the soil's clay fraction to produce an enormous dust plume which spread out into the mid-Atlantic Ocean. They suggested that (1) lithology largely determines intensity of wind erosion; (2) scarps locally intensify wind erosion; and (3) most wind erosion probably occurs during occasional short-lived but intense windstorms. A. W. Ward (University of Washington), J. F. McCauley and M. J. Grolier (USGS) reported measurements of morphologic change in, and wind flow over yardangs at Rogers Lake, California. Wind flow accelerates near the bow, falls off at the beam, and reaccelerates near the stern of the yardangs. Comparison of photographs taken in 1932, 1975, and 1977 suggests average erosion of two cm/yr at the bow and less than one cm/yr laterally.

D. Dzurisin (Hawaiian Volcano Observatory) described wind action in the Kau Desert, Hawaii, where generally-unidirectional winds have formed dunes of pyroclastic debris, wind streaks and lee drifts near boulders. Preliminary field mapping has delineated five transitional zones of progressive modification of a pyroclastic blanket produced partly by a phreato-magmatic eruption of Kileuea in 1790 A.D. He suggested that production and subsequent modification of basaltic pyroclastic blankets may be important processes for shaping local landscapes on Mars. A. D. Howard (University of Virginia) presented three topics in the mechanics of dunes: (1) saltation may increase the efficiency of heat transfer between the surface and lower atmosphere, which may account for the updrafts required over longitudinal dunes for helical vortices to form such dunes; (2) interdune transport is much more important than bulk transport in sparse barchan fields, but bulk transport rates in terranes completely covered by dunes may be 1.5 to five times greater than over flat sand surfaces; and (3) roughness contrast between dunes and adjacent terrain cannot account for differences between dune orientation and wind direction measured over nearby smooth terrain as envisioned by Warren, because wind veering due to roughness change occurs only after one to 50 km of flow over rougher dunes. C. S.

Breed (USGS) and W. J. Breed (Museum of Northern Arizona) described sand-ridge dunes which, unlike seif dunes, seem to form where the sand-transport resultant of bimodal winds is reinforced by an effective prevailing wind, as demonstrated by field studies in Australia and Arizona. The unidirectional roller-vortex model of wind for formation of these dune ridges (Folk, 1971) is not supported by these field studies.

C. S. Breed (USGS), A. W. Ward (University of Washington), and J. F. McCauley (USGS) suggested that sand-sea patterns on Earth and Mars imply similarities of physical processes including: (1) mechanisms of relative grain-size distribution in dunes and interdune areas; (2) time and distances from source materials required for sand-sea emplacement; and (3) persistence of regional wind regimes responsible for widespread, uniform sand-sea patterns. Sand seas in the north polar region of Mars seem to represent wind systems which redistributed materials by saltation over periods of 10^3 to 10^6 years. Some of these dunes are now obscured by blanketing layers of loess (?) and ice, which seem to have been deposited independently of the dunes. J. B. Pollack (NASA Ames) proposed another mechanism for the formation of circumpolar dune fields. He suggested that dust is now deposited preferentially in the north polar region because CO_2 ice condenses on dust-storm particles and the resultant large particles fall rapidly out of the atmosphere as snow to saltate and form dunes before the CO_2 sublimates in the spring. Wind calculations indicate strong west winds during winter, consistent with directions implied by dune morphology.

R. E. Arvidson (Washington University), K. L. Jones (JPL), and E. A. Guiness (Washington University) described the constraints on martian eolian dynamics imposed by Viking data: (1) The topography and most blocks at VL-1 appear to represent cratering, but VL-2 probably lies on a debris flow from the crater Mie; (2) Wind erosion of rocks at both lander sites is slight -- less than ten cm. If the age of the surface at VL-1 is 10^9 years, rock-erosion rates are less than 10^{-8} cm/yr. On the other hand, pedestal craters imply hundreds of meters of stripping of loose debris over a comparable interval, so rates of erosion in rock are 10^4 to 10^5 smaller than in loose debris, and wind seems unable to cut channels; (3) Only microns of removal are needed to make classic dark areas on Mars, based on wind stripping of bright dust at VL-1; (4) Dust has continued to accumulate on UV chips and magnets on both VL-1 and VL-2; and (5) Persistence of condensate formed near winter solstice at VL-2 indicates that it is water ice. Bright frost, microns thick, covered VL-2 after winter frost sublimated. This suggests that dust may nucleate H_2O and/or CO_2 snow and be deposited by the higher settling velocity of these enlarged grains. Unless wind removes it annually, this dust would bury rocks in tens of thousands of years. R. S. U. Smith (University of Houston) described eolian deposition of sand atop terrestrial boulders. If similar processes operate on Mars, debris caps on boulders at VL-1 need not be dust and need not represent a major episode of deflation.

J. Veverka, P. Thomas, J. Burt (Cornell) and T. Thorpe (JPL) described ultraviolet contrast reversal, under which local surfaces on Mars appear brighter than their surroundings under visible or red light but darker under ultraviolet light. Most of these surfaces are associated with eolian features, although most bright streaks do not exhibit contrast reversal. Laboratory measurements indicate that contrast reversal is a common property of relatively well-sorted, fine-grained samples of iron-oxide minerals.

R. Greeley (Arizona State University) and his colleagues described a series of experiments involving eolian abrasion and its effects under simulated martian conditions. D. H. Krinsley and R. Greeley (Arizona State University) reported that scanning electron microscopy of abraded, sand-sized quartz and glassy basalt revealed surface textures distinctive of eolian environments on Earth. With all other parameters held constant, the less-dense atmosphere of Mars allows more energetic erosion, and at high simulated martian wind velocities basalt particles seem to have been deformed plastically or melted. R. Greeley (Arizona State University) and R. Leach (NASA Ames) described the electrostatic behavior of 120-micron basalt particles that were abraded at 4 mb pressure and 60 m/s simulated wind speed. The particles fractured into small fragments (1-10 microns) which clumped into large agglomerates (~400 microns) due to electrostatic charges. Field and wind-tunnel measurements verified the magnitude of electrostatic charges of saltating particles. If this process is widespread on Mars, small particles (1-10 microns) may be picked up by the wind once agglomerated. Greeley further proposed that the agglomerated clods behave as sand to produce bedforms typical of sand. Once emplaced, the clods may lose part of their charge, but the bedform structure is preserved.

B. R. White and R. Greeley (Arizona State University) described wind-tunnel simulation of sand-transport rates on Mars. Under similar dynamic wind conditions (i.e., same percentage of wind speed above transport threshold on each planet), they found that martian winds move surface material more efficiently than do terrestrial winds. Although these high winds may occur less frequently on Mars, they seem able to move seven to ten times more material than on Earth. Wind-tunnel experiments conducted at one atmosphere pressure agree well with field data of Bagnold and others.

J. D. Iverson (Iowa State University) and R. Greeley (Arizona State University) described field and wind-tunnel studies of dark streaks associated with Amboy Crater, California. They reported good agreement between wind parameters measured in the field and in the wind-tunnel simulation.

Radar Studies of Planetary Surfaces

The study of planetary surfaces at microwave wavelengths has gained increased attention owing to the imminent start of radar-oriented spacecraft missions orbiting the Earth and Venus. In order to better understand the radar images, both scattering properties and surface topography must be examined. The three papers presented in this session highlighted terrestrial studies of backscattering (both in images and in "synthetic" spectra of surface roughness derived from visible photography) and studies of martian surface characteristics using spacecraft, bi-static techniques.

G. G. Schaber (USGS) presented a status report on an on-going evaluation of side-looking radar backscatter data in support of the proposed Venus Orbiting Imaging Radar (VOIR) mission in 1983. Results included completion of small scale relief analysis in Death Valley using a terrain analysis computer program developed for Apollo Lunar Rover Traficability studies. Correlation of radar film density with mean relief, relief standard deviation and mean slope (at various relief sampling intervals) showed a clear separation (at X-band wavelengths) between the salt pan and fan gravel surfaces. Calibrated airborne radar scatterometer data obtained over Death Valley are currently being analyzed. The ultimate objective is to derive empirical models for backscatter from various surface roughness categories that can be used to evaluate the more than 300,000 radar images to be obtained during the VOIR mission.

R. A. Simpson, G. L. Tyler, and H. T. Howard (Stanford University) reported a preliminary reduction of Viking bistatic radar data giving rms surface roughness in Hellas of about 4.5° on a horizontal scale averaged between 10 cm and 100 m. This roughness decreases slightly along the ground track (296°W, 47°S to 300°W, 40°S), south to north. The dielectric constant in this area appears to be about 3.1, slightly above Mars average. Simpson cautiously noted similarity of roughness values with those obtained from Earth-based radar near VL-1 in Chryse and similarity of both roughness and dielectric constant to lunar values in Oceanus Procellarum. Very preliminary results from the north polar region imply smoother surfaces there; laboratory measurements on dry ice suggest that solid CO_2 may be identified if crossed by one of the radar ground tracks.

C. Elachi (JPL) reported the development of a data base of radar, Landsat and surface images of a variety of geologic surfaces to support the interpretation of images which will be obtained with future orbiting imaging radars, particularly VOIR and SIR-A (Shuttle imaging radar). Preliminary results of analysis of radar images of volcanic fields in the southwest U.S. and the Grand Canyon wall stratigraphy were presented.

Cratering as a Process, Landform, and Dating Method

A. Woronow (University of Arizona) showed that accurate modeling of positional events amont craters (e.g., doublets, linear and arcuate arrays) requires accurate knowledge of the crater production function and allowance for crater overlap and obliteration. For the lunar craters such models can be constructed; but for Mars, where complex eolian and aqueous erosion of craters must be considered, accurate modeling techniques are not yet developed.

E. I. Smith and J. A. Hartnell (University of Wisconsin-Parkside) presented new size-shape data for Mercury and revised the crater data for the Moon. The data show important differences in the size-shape profiles for fresh craters between Mercury and the Moon, and significant differences in the size-shape data for different lunar terrains. The cause of the interplanetary differences in the size-shape data may be due to differences in gravity, substrate or impact velocity. Similar terrace and central peak curves for both the Moon and Mercury suggest that gravity is an important factor in controlling crater shape.

A reanalysis of Mariner 10 Mercury photography by R. A. DeHon (Northeast Louisiana University) showed that the earliest crater and basin counts included only the most obvious basins. The resulting counts pointed to an apparent gap between craters and large basins. Revised counts include 42 basins greater than 250 km diameter, which suggests that the basin population is not so unique as originally thought.

C. C. Allen (University of Arizona) searched all high-resolution Viking imagery for rampart craters. Craters were located in $5^{\circ} \times 5^{\circ}$ blocks. At this resolution every major geologic unit exhibits rampart craters, except for some parts of Olympus Mons, Arsia Mons, Olympus Mons aureole and fresh Tharsis lava plains. Rempart craters range through all longitudes, all latitudes (to the edges of the polar caps), and from -2 to +9 km in altitude. They predate and postdate the channel formation and occur on some shield volcanoes.

J. M. Boyce and D. J. Roddy (USGS) showed that if rampart craters result from impacts into water-saturated strata or into a permafrost layer, diameters of those craters could exceed twice those from identical impacts into dry substrates. They showed that a knee in the cumulative size-frequency curve at several kilometers diameter at the Viking I landing site could be removed by reduction of the diameter of only the rampart crater by a factor of 1/2. They also noted that because the lower diameter at which rampart craters form appears to vary regionally, crater size-frequency studies may have to consider the effects of such increases in diameters.

The interior morphometry of fresh martian craters was examinated by C. A. Wood, M. J. Cintala and J. W. Head (Brown University). They found that the occurrences of wall failure, central peaks and pits are modulated by the terrain types. In comparisons of martian craters to those of the Moon and Mercury, they found evidence that the development of crater interior morphology is not a simple function of either gravity or impact velocity, but that differences in upper crustal structure are also important.

The central pit craters on Mars, studied by C. A. Hodges (USGS), may be related to the hypothesis developed by Milton et al. (1972) at Gosses Bluff that peaks can be hollowed out during crater excavation; peaks, therefore, more likely form by dynamic rebound than by uplift due to collapse of the crater rim. The central pit craters may show the previously postulated continuity between peaks and peak rings, and, based on the Gosses Bluff analogy, suggest that crustal discontinuities vary both laterally and vertically on Mars.

The data collected during the 1971 and 1973 Goldstone radar ranging of Mars have been utilized by L. E. Roth, C. Elachi, R. S. Saunders (JPL) and G. Schubert (UCLA) to produce topographic profiles of large craters (in the diameter range of 20 to 500 km) located within the latitude band -14° to -22°. A linear log-log least squares fit to the depth vs. diameter plot suggests that the depths of the mixed crater population contained in the radar sample are only a weak function of diameter.

G. Neukum, U. Hiller, J. Henkel, and J. Bodechtel (Ludwig-Maximilians-Universitat) provided an updated version of the cratering curve by Neukum and Wise (1976) which shows slightly younger ages for features $<3.0 \times 10^9$ years. A comparison of the Soderblom and Neukum models shows substantial differences in the overall history of Mars due to individual shapes of the curves.

Workshop on the Tharsis Region of Mars
(R. J. Phillips, JPL)

INTRODUCTION: On September 5th through 9th, 1977 a workshop was convened in Vail, Colorado to discuss the origin, evolution, and present state of the Tharsis volcano/tectonic province of Mars. Workshop participants were Karl Blasius (PSI), Michael Carr (USGS), Gordon Eaton (USGS), Charles Gilbert (VPI), Michael Malin (JPL), Thomas McGetchin (LPI), Roger Phillips (JPL), Steve Saunders (JPL), Norman Sleep (Northwestern U.), Sean Solomon (MIT), and Donald Wise (U. Mass.). The goals of the workshop were: (1) to thoroughly review observational and theoretical constraints regarding Tharsis, (2) to outline multiple working hypotheses regarding the origin of Tharsis, (3) to test, in a preliminary fashion, the hypotheses against the constraints, and (4) to define areas of research to further constrain the hypotheses. To carry out the above-mentioned goals, the workshop was structured in the following manner: The first two days were used for individual tutorial presentations on the present state of knowledge of the geological, geophysical, and petrological constraints regarding Tharsis. From that point, a series of constraints were formulated that any hypothesis must satisfy. The third and fourth days of the workshop were devoted to formulating hypotheses and preliminary testing of these hypotheses against the specified constraints. The final day was devoted to defining crucial research necessary to help distinguish among the hypotheses.

THE HYPOTHESES FOR THARSIS: 1. Chemical Plume - Description: Mars formed by "classical" inhomogeneous accretion. In this model the primitive lower mantle is less dense (higher Mg/Fe ratio) and carries more radiogenics than the primitive upper mantle. The arrangement is unstable and becomes more unstable as the lower mantle is heated preferentially. The instability breaks out in a "chemical plume" that rises to the base of the lithosphere. The plume heats the local mantle relative to its surroundings and provides buoyant, thermoelastic, and possibly viscous stresses for the uplift of Tharsis. Difficulties: The hypothesis specifically requires inhomogeneous accretion with a nebular temperature at the start of accretion in excess of 1600°K. The temperature must drop some 1200° during the accretion interval. This seems implausible at the Mars distance. It is furthermore difficult to imagine this type of accretion in view of contemporary theories which require an intermediate stage of planetesimal formation. Testable Questions: Can the plume maintain volcanism for several billion years? There may be chemical differences among lavas at different places on the surface, testable by spectral differences or differences in flow morphology.

2. Homogeneous Accretion and Whole Mantle Convection - Description: The primitive mantle is homogeneous; after core formation whole mantle convection begins. Tharsis is the result of first harmonic convection. Lighter material separates at the top of the ascending limb and carries most of the radiogenic material. Difficulties: Where is the antipodal effect for the first harmonic? If the harmonic mode of convection is actually higher, where are the other contemporaneous volcanic centers? Testable Questions:

Can the convecting system produce the gravity anomalies and topography?

3. Compressional Arching - Description: This model suggests that the uplift of Tharsis and adjacent depressions of Chryse and Amazonis result from lateral compression and crustal warping. A possible mechanism could be global shrinking as a result of overall cooling. Difficulties: The model does not satisfy the volcanism requirement without an additional local source. The gravity data are not satisfied unless the crust can be thickened under Tharsis and thinned under the adjacent basins. The observed structural features are not consistent with such a model since no compressional features are observed in the basins.

4. Hellas Antipode - Description: Tharsis and Elysium are approximately antipodal to the large impact basins Hellas, Syrtis Major, and Isidis, and to Argyre, respectively, and may be connected in origin to them. On both the Moon and Mercury, tectonic effects antipodal to the largest basins may be present. Theoretical calculations indicate that for a large impact into a sphere much of the shock energy is focused in the antipodal region. Dissipation of shock energy in the antipodal regions will raise subsurface temperatures and could create a sizable thermal anomaly which in turn could cause updoming. Reflection of the shock waves from the surface will also create fracturing of the lithosphere. If mantle temperatures are close to the solidus previous to impact, then the effect of the impact may be to raise the temperatures above the solidus. Difficulties: The Tharsis and Elysium uplifts are not exactly antipodal to the largest impacts. As a mechanism in itself, it could not sustain long-term volcanism. This mechanism might be effective as a triggering device, such as pushing near-solidus temperatures just to solidus.

5. Primordial Inhomogeneity - Description: The model supposes that during either formation of the planet or during differentiation of its crust, compositional inhomogeneities developed in the martian mantle and that some parts of the mantle are relatively less depleted in radiogenic elements than others; then these predetermine the locations and areal extents of the martian volcanic provinces. Heating of these mantle regions gives rise to mass transfer of heat to the base of the lithosphere accompanied by injection, thermal doming, and fracturing. Difficulties: This model may not have an adequate life span to account for the longevity of the Tharsis activity. Testable Questions: Can the inhomogeneity sustain volcanism for several billion years? Are there chemical differences in surface lavas?

6. Core Formation - Description: Some years ago Elsasser proposed that the thermal gradient in an evolving planet would rise into the iron/iron sulfide melting curve at some intermediate depth in the mantle. The result would be a gravitationally unstable layer of liquid collecting at that intermediate depth, which would finally dimple and drain downward to form a core. Applied to Mars this process would provide an asymmetric deep heat source through the gravitational energy given up by the sinking fluid. Core formation on Mars is a slow process unlike the catastrophic runaway

envisaged for the Earth.) This heat pulse would then power localized convection and/or conduction in the overlying mantle to cause the Tharsis bulging and expansion. Other variations involving convective motion in an already formed molten core might be suggested for the heat asymmetry under Tharsis, but suffer from problems in maintaining an adequate temperature difference in one location to maintain convection in that spot. Difficulties: There seem to be no major difficulties with this model providing it is quantitatively reasonable. It has the potential to provide a localized heat source of long duration. Testable Questions: What is the heat budget and mass transfer as a function of time? What are the instability relationships and probable size of instabilities?

7. De-Sulfidization of the Lithosphere - Description: About 20% of the mass of Mars is in the core. If the lithosphere of Mars was cool during the time of main core formation, the Fe-FeS present in the lithosphere would remain there. During the time of core formation or thereafter, the sulfide layer (or disseminated sulfide) was lost from the Tharsis region and replaced by ordinary mantle of much lower density. This lower density causes permanent updoming and fracturing. A positive free-air gravity anomaly results from second order isostatic effects. Volcanism is concentrated by edifice effects on stress. Other possible chemistries include hydration and scapolitization. For these mechanisms the density difference between depleted and undepleted mantle is about 1%, insufficient to produce the Tharsis uplift. Difficulties: This process requires a mechanism to preferentially deplete Fe-FeS from one geographic region of the lithosphere or to initially concentrate Fe-FeS at some other region of the lithosphere. Testable Questions: Since this mechanism leads to a permanent density change and buoyancy, the same gravity anomaly, albeit scaled, ought to exist for Elysium. This can be tested with the low altitude Viking data now being collected. The Pratt isostatic mechansim implied here for Tharsis can be tested specifically against the gravimetric and topographic observables.

8. Mantle Lithosphere Overturn - Description: The mantle part of the lithosphere is colder and more dense than the underlying asthenosphere. If tensional deviatoric stresses occur, the lithospheric mantle may sink toward the center of the planet. The hotter material which replaces the sunken material is less dense and will produce uplift by isostasy and free-air gravity anomalies by second order isostatic effects. Slope reversals and recent faults are expected from this process and the uplift will decay in 300-400 M.Y. unless reactivated. Alternatively, desulfidization of the mantle may lead to a permanent density anomaly after the first overturn. Volcanism is concentrated in this mechanism by edifice effects on stress. Difficulties: This mechanism may require continual reactivation to explain the long duration of Tharsis volcanism. This would require periodic fracturing, which does not seem to be observed. Testable Questions: Are there, in fact, extremely young fractures?

Planetary Geology Field Conference on Eolian Processes

A comparative geology field conference chaired by Ronald Greeley (Arizona State University) was held in Palm Desert, California, January 10-14, 1978 in order to establish a dialogue between geoscientists interested in eolian processes on Earth and planetary geologists studying eolian processes on the planets. Approximately sixty-five participants attended the technical sessions and field trips. Invited participants included R. A. Bagnold, E. D. McKee, and R. P. Sharp; field trip leaders included R. P. Sharp, J. Shelton, R. Saunders, R. S. U. Smith, and T. Pewe. Field trips included Garnet Hill((a well-known ventifact locality), Salton Sea dune field, Algonones dune field, Amboy Crater, Kelso dunes, and general geology of the southern Mojave Desert and Imperial Valley.

A comparative geology field guide covering the area was published as a NASA publication and copies are available on request from R. Greeley.

Standard Techniques for Presentation and Analysis of Crater Size-Frequency Data - A Report of the Crater Analysis Techniques Working Group

A committee composed of twelve scientists deeply involved with the collection and analysis of crater statistics met in Flagstaff on September 8 and 9, 1977, to make recommendations for standards of crater measurements and statistical analysis methods. The committee, chaired by A. Woronow (University of Arizona) and J. Boyce (USGS/NASA HQ), recommended the following:

Graphs:

1. Display data on both a "cumulative Size-Frequency Plot" and a "Relative Size-Frequency Plot."
2. Make the abscissas and ordinates both base 10 logarithmic.
3. Use consistent units on both axes.
4. Use the same scale for both axes.
5. Plot the 1σ confidence intervals for the data points.

Tables:

1. Give all of the data in tabular form.
2. Bin the data in $\sqrt{2}$-factor or finer bins.
3. Give the number of craters in each bin.
4. Specify the amount of surface area on which the data were measured.
5. Deposit the data tables with LPI.

Supporting Information:

1. Specify the source and kind of materials on which the measurements were made.

2. Specify the measuring technique used and assess its accuracy.
3. Give the exact location of the area studied.
4. Give all other pertinent information such as the assumed scale of the photographs and the corrections, if any, made to the raw measurements.

Regression Analyses:

1. Give the 1σ confidence intervals on the regression coefficients.
2. Report the results of a goodness-of-fit test of the data to the regression.

Morphologic Analyses:

1. A quantitative measure is preferable to a qualitative measure.
2. Specify the exact criteria used for making qualitative assignments or measurements.

All of the recommendations were made unanimously by the committee and have been endorsed by the group 8 of the planetary basaltic consortium. A summary of the results and recommendations of this meeting are being drafted and will be published in the open literature as well as in NASA TM-79730. A second meeting, which will also include several new committee members, is planned to disucss standards for crater morphology statistical studies.

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16. Abstract

Recent developments in planetology research as reported at the 1978 NASA Planetology Geology Program Principal Investigators meeting are summarized. Important developments are summarized in topics ranging from solar system evolution, comparative planetology, and geologic processes, to techniques and instrument development for future exploration.

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