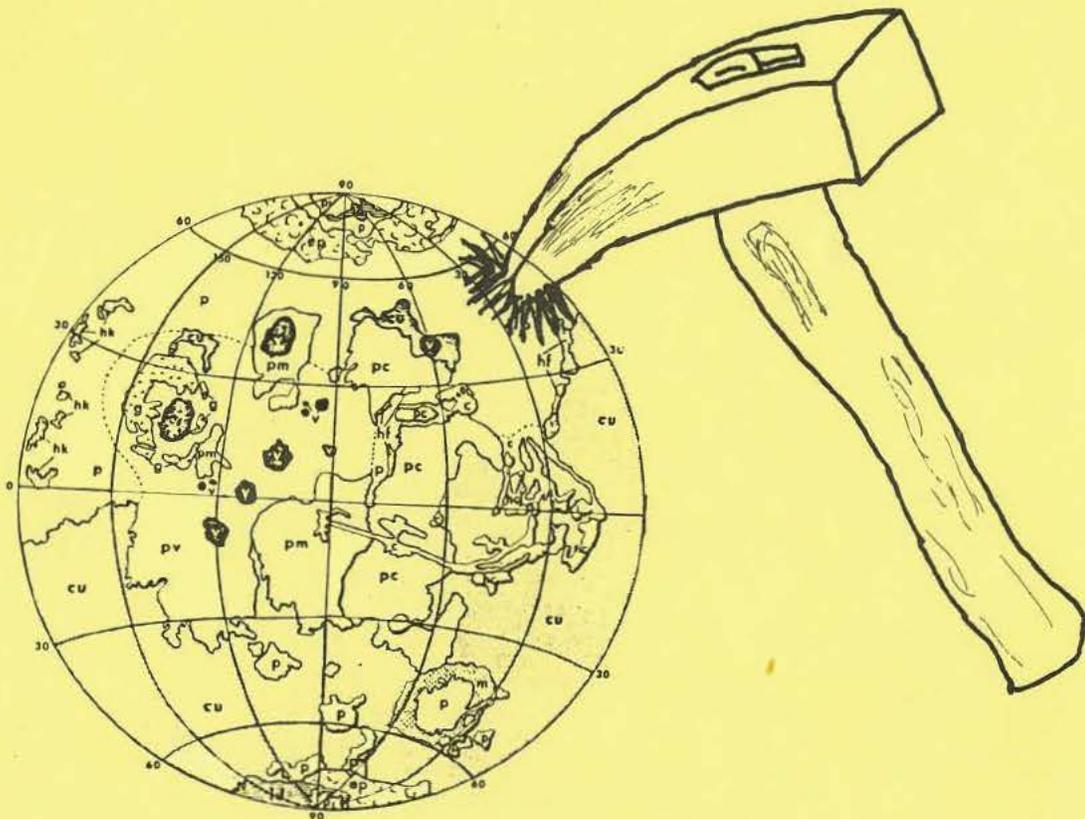


3/4

WORKSHOP
ON
MARS PETROLOGY

6-8 FEBRUARY 1978

LUNAR AND PLANETARY INSTITUTE



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MINUTES OF WORKSHOP

ON

MARS PETROLOGY

Lunar and Planetary Institute

6, 7 and 8 February 1978

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Igneous Petrogenesis
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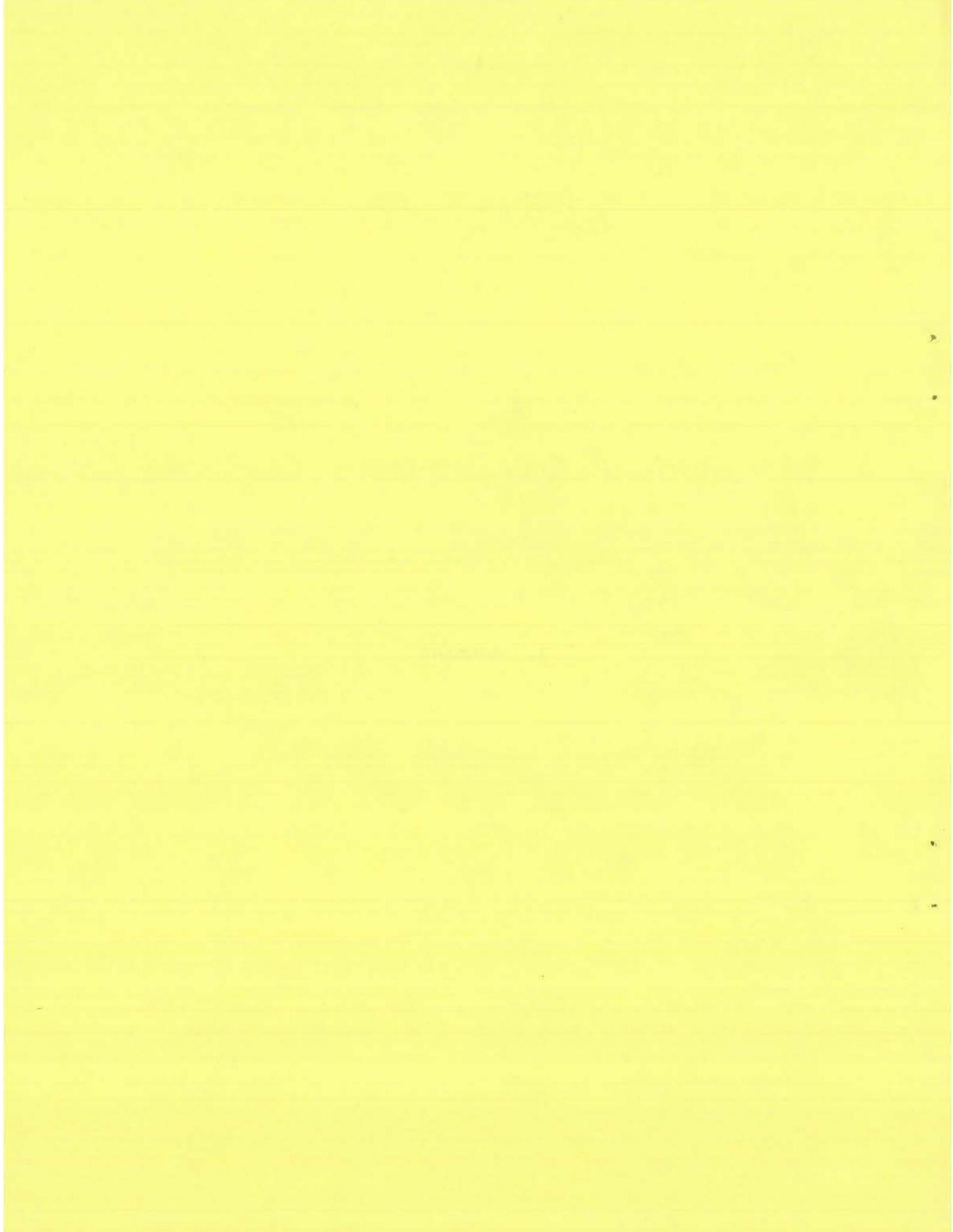
Compiled by

Thomas R. McGetchin and Robert L. Huguenin

Assisted by
Carolyn Kohring



1. SUMMARY



WORKSHOP ON

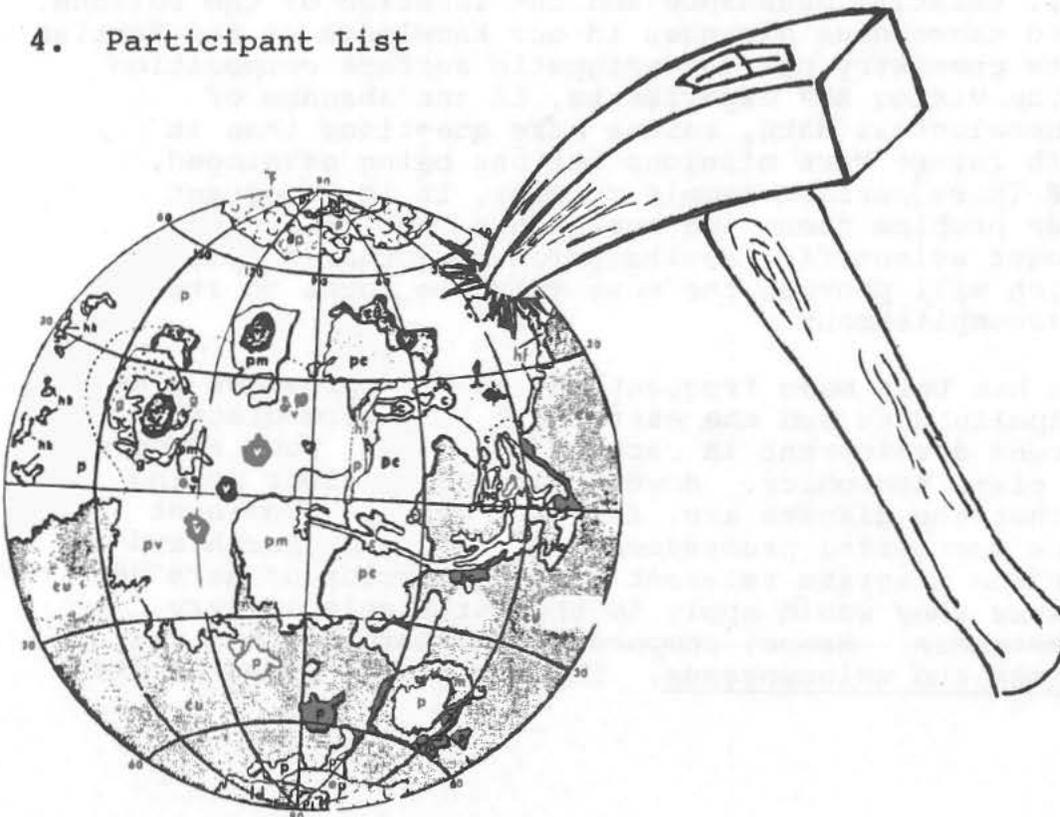
MARS PETROLOGY

6-8 February 1978

Lunar and Planetary Institute

Summary

1. Background
 - 1.1 Description of Workshop
 - 1.2 Mars-Data Base, Uniqueness, Relationship to other Science
 - 1.3 Significance of Igneous Petrogenesis
 - 1.4 Surface Weathering Processes
2. Conclusions and Recommendations
3. Workshop Program
4. Participant List



1. Background

1.1 Workshop

This workshop brought together, for two and a half days, a divergent group of scientists (representing planetary geophysics, surface chemistry, remote sensing, field petrology and geochemistry, terrestrial igneous petrology - both experimental and observational, mineralogy, Viking team investigators and lunar petrologists and geochemists) to discuss the petrology of Mars in two categories:

- igneous petrogenesis
- surface weathering

We reviewed observations, discussed the status of current models, and conducted a tutorial in igneous petrology and weathering processes. The most important and tractable problems were identified and approaches to their solutions suggested or defined.

1.2 Mars

The data base for Mars is very rich and yet it is incomplete in critical items. In particular we lack knowledge of the physical properties of the upper mantle — density and the seismic velocities are key parameters in constraining compositional models in terms of bulk chemistry, volatile abundance and the location of the solidus. Viking provided tremendous advances in our knowledge of the Martian surface and its chemistry but the enigmatic surface composition indicated by the Viking XRF experiments, in the absence of supporting mineralogical data, raises more questions than it resolved. With future Mars missions options being developed, including MSSR (Mars surface sample return), it is important to define those problem areas and approaches most likely to yield significant scientific results prior to actual sample return and which will provide the most valuable input to its planning and accomplishment.

The case has been made frequently that Mars provides a key link between Apollo data and the earth - it is intermediate in size and apparent development in certain processes, such as core formation and plate tectonics. However it became clear during the workshop that the planets are, in fact, unique. Dominant Martian surface weathering processes do not occur on Earth and vice versa. Phase diagrams relevant to the interior of Mars do not exist because they would apply to the Earth only in very unusual circumstances. Hence, comparative planetology has two aspects - analogs and uniquenesses. The workshop focused on these uniquenesses.

During the discussions it became clear that as specialized as Martian research is, it bears on some very general and important scientific problems and on some timely practical ones as well. Among them are:

- insights into incipient stages of plate tectonics and their relationship to core formation
- clues about climate change and its causes
- surface environmental effects of the absence of an ozone layer
- clues regarding surface processes relevant to the origin of life on Earth
- clues to the evolution of the earth's early atmosphere
- iron and volatile-rich systems and the genesis of sulfide ore deposits
- solar system cosmological modeling, particularly the volatile inventory of the planets
- planetary thermal evolution modeling, including the Earth

1.3 Igneous Petrogenesis - Significance

The composition of the surface igneous rocks and in particular changes with time will be a direct reflection of the thermal and chemical evolution of the interior of Mars. This is particularly important because (1) the martian mantle may have a substantially different bulk chemical composition than the Earth's indicated by its high density, (2) the volatile inventory of the interior also may be quite different than the Earth because of different (cooler) conditions during its accretion, and (3) the process of core formation may have occurred late in martian history and quite passively relative to the Earth; if so, the gradual subtraction of core-forming elements from the mantle would have occurred through time. These gradual changes in time and marked difference from the Earth (and Moon) should be reflected in the igneous rocks.

Volcanism spans time from old, cratered, low-albedo plains units inferred to be volcanic floods, to the shields which may be active now or, in any case, are very young. The reflection spectra of the martian surface (derived from both earth-based photometry and Viking orbital color imagery) indicate substantial regional differences particularly in the dark areas which are believed to represent differences in primary (igneous) mineralogy. The Viking XRF analyses, while probably not representative of a

primary lava composition, suggest a derivation from rocks with low Al content, high sulfur abundance and high iron content, consistent with iron-rich basaltic or ultramafic lavas, possibly in a sulfur-rich system. The question of the oxygen abundance and fugacity in the interior is wide open, even for the earth, although there is a growing consensus that oxygen fugacity may be buffered by elemental carbon.

Available data suggest that the composition and evolution of the martian interior was quite unlike either the Earth or Moon. The composition of igneous rocks erupted to the surface will reflect these differences in composition and evolution in a very direct way.

1.4 Mars Surface Weathering

One of the most exciting discoveries of the Viking mission was the unusual surface chemistry discovered by the lander biology experiments. The discovery of the highly magnetic nature and remarkably high sulfur and low alumina contents of the soil were equally unexpected. The Viking mission in fact raised a myriad of new questions about surface weathering and regolith processes on Mars, and stressed the need to expand research efforts in several important problem areas.

It is now apparent that the differences in surface environments on Earth and Mars have resulted in two quite different sets of weathering processes on the two planets. These two sets of processes produce distinctly different weathering products, and they have probably had very different effects on regolith composition, physical properties, and surface morphology over geologic time.

Research efforts should focus on determining the mechanisms, rates, and products of weathering processes that occur in the unique martian environment (UV radiation, absence of liquid H₂O, low temperatures, etc.). Laboratory studies clearly need to be expanded, and remote observations of surface composition continued. Terrestrial and planetary analogs have proven useful in the past, but more attention needs to be focused on the uniqueness of the martian environment.

2. Conclusions and Recommendations

The principal conclusions of the workshop were:

- More Remote Sensing Observations are Needed

It appears likely that spectral signatures of primary igneous minerals can be distinguished from weathering products. Furthermore, spectra of the dark areas on Mars appear to be quite variable from place to place, perhaps indicating differences of igneous mineralogy. More observations with high spectral and spatial resolution are necessary. Laboratory simulations, laboratory studies of spectral signatures of mixtures and complex systems and field studies, all will contribute important data.

- Martian Weathering is Unique - Simulation and Theory Needed

Surface weathering processes dominant on Mars do not have terrestrial counterparts and conversely the dominant terrestrial weathering processes do not occur on Mars. This is because (1) liquid water does not exist on Mars and (2) UV radiation penetrates to the surface. These problems can be profitably pursued by experimental simulation.

- Experimental Petrology of Systems Relevant to Mars Needed

It is possible that the martian mantle is iron-rich relative to the Earth and that it may be quite rich in volatiles, particularly sulfur. Experimental studies of such systems at mantle conditions are in their infancy. While much of the desired work (subsolidus high pressure phase relations and liquidus compositions in iron-rich and volatile-bearing peridotite systems; effects of f_{O_2} and f_{S_2} on mineral stability and melting relations) is proceeding for their application to terrestrial petrology and ore deposits, this work is going slowly; it could be accelerated and brought to bear on Martian problems years in advance of the unstimulated time. Also determination of the near-liquidus phases from such liquids at low pressure is important for comparison with reflection spectroscopy and weathering studies. They will contribute materially to our knowledge.

- Volatiles - They are Crucial and Very Poorly Known

Volatiles in the interior of Mars will play a crucial role in understanding igneous processes. Investigations (including experimental studies at high temperature of liquid-vapor equilibrium and kinetics related to accretion in the early solar system) should be pursued with vigor.

- Theoretical Modeling Studies and Synthesis are Important and Timely

Modeling studies of several sorts will be very valuable as guides to observational and experimental work.— This is a consequence of a rich data base but one which is missing crucial items. It seems appropriate to vigorously encourage theoretical studies and to proceed with analog and simulation experiments. Many important problems are likely to develop rapidly if pursued properly. A number of specific data synthesis and analysis tasks were discussed, which would be very worthwhile. Among them are: refinement of Viking XRF data, analysis of the Soviet orbital x-ray data, analysis of Viking orbit properties, analysis of high resolution Viking gravity data, correlation of regional geology of Mars with spectral data, synthesis of geophysics, petrology, regional geology, thermal modeling, and experimental weathering studies.

- Geophysical Constraints on the Interior of Mars are Weak and Crucial

Our ability to model many aspects of Martian evolution and processes is badly hampered by ignorance of the most basic facts about the properties of the Martian interior. It is crucial to improve this situation in all ways available, such as better determination of C/Mr^2 from Viking orbiter (keep on tracking), maintenance of the Viking seismometer. Every effort should be made to improve these crucial geophysical constraints.

The following items were discussed as issues during the final plenary session:

- Orbiter Data and MSSR - Necessary in Site Selection or Not?
- Funding Rationale - Space Spectaculars or a Planetary DSDP?
- Possible Role of Manned Flight - Its Impact on MSSR
- SRT and DA Funds - Mars/Theoretical and Follow-on Funding

No attempt was made to reach a formal consensus. All participants agreed that orbital geochemistry and SR mapping definitely was required as part of the sample return data base. Some felt it was not essential as a precursor to site selection prior to landing of MSSR, but the dissenting opinion was that without high-resolution geochemical mapping, important local differences and distinct regional units are unlikely to be identified especially through the veil of pervasive weathering. There was

uniform concern expressed that mission planning was torqued by an emphasis on public appeal toward the spectacular rather than a conservative but scientifically better sequence. The difficulty experienced by LPO, when viewed as the proto-type TBO (terrestrial body orbiter) with Mars as an application, was cited. Also the current effectiveness of the DSDP (JOIDES) program was contrasted with the ill-fated but spectacular Mohole project. The opinion was expressed that public and congressional support is strong for the planetary exploration program and a more aggressive program would not only be tolerated but welcomed. (There was a brief but vigorous discussion of this point — namely regarding the meaning of public interest and support of space exploration reflected in such widely diverse items as the Star-Wars phenomena, O'Neill's ideas, Governor Brown's popularity, criticism in Congress of NASA testimony. No agreement was evident regarding the meaning of these for planetary exploration funding.)

The impact of manned flight on the planetary exploration program was discussed briefly; changes in current commitments would clearly reflect large shifts in national policy and are beyond prediction. Many felt that it is not unreasonable to consider MSSR in terms of these more ambitious options, unlikely as they seem at present.

It was clear that there is a wealth of SRT and DA tasks to be done. Mars is ripe for theoretical modeling, laboratory simulation, more observation, new experimental work, and fine-tuning the available data for some basic data and constraints.

There was a general consensus that the interaction was profitable from the viewpoint of people's research. A number of specialized workshop topics for the future were suggested and will be pursued.

WORKSHOP ON MARS PETROLOGY

6, 7, 8 February 1978

Program

MONDAY A.M.1. Review of Observations of Mars

Benton Clark - Viking Geochemical Analyses - Status Report

Priestley Toulmin III - Viking XRFs Results

Robert Huguenin - Huguenin-Adams-McCord - Earth Based Observations
of Mars and Laboratory SpectraLaurence Soderblom - Global Color Variations on the Martian Surface
(read by Thomas McGetchin)MONDAY P.M.John Minear - Status and Possible Input to Future Mars Mission
Planning2. ModelsRoger Phillips - Thermal History, Structure, and Tectonics of Mars
- Tharsis and Tectonics

Robin Brett - Volatiles in Planetary Interiors

Everett Gibson - Mars - Wet or Dry

Joe Smyth - Smyth-McGetchin - Models for Surface Petrology

Ernest Schonfeld - Inferred Composition of Lavas from Lava Flow
MorphologyTUESDAY A.M.3. Tutorial in Igneous Petrology of Mars

David Walker - Overview on Basalt Genesis on the Moon and Earth

Dean Presnall - Iron-bearing Silicate Systems and Their Bearing on
Basalt Petrogenesis on Earth and Mars

Charles Gilbert - Sulfide - Silicate Relations

Russell Merrill - Role of Volatiles in Basalt Petrogenesis

Tony Irving - Partial Melting of the Earth's Mantle and Basalt
Petrogenesis - Observations

TUESDAY P.M.

4. Low Temperature Geochemistry

David Wenner - Palagonites

Randy Stewart-Perry - Desert Soils - Composition and Surface Properties

Mike Booth - Simulation of Martian Surface Conditions

Robert Huguenin - Weathering in the Absence of Liquid Water

WEDNESDAY A.M.

5. Discussion in Working Groups

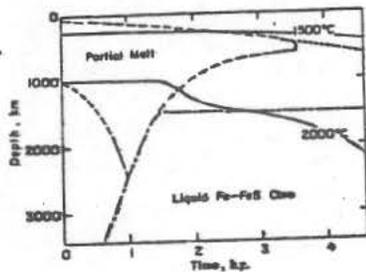
Definition of Major Problems/Questions

Experimental and Observational Approaches

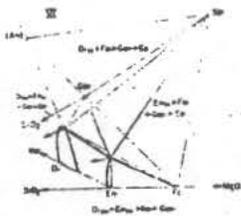
6. Plenary Session/Readout

WEDNESDAY P.M.

7. Tour of Johnson Space Center



Thermal History Modeling



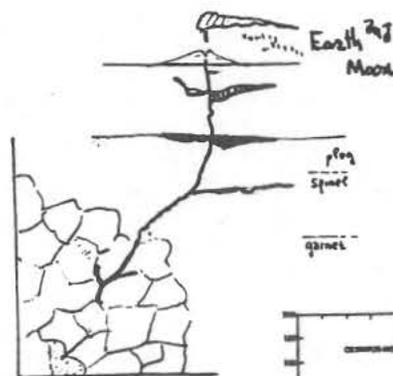
Experimental Petrology

WE NEED:

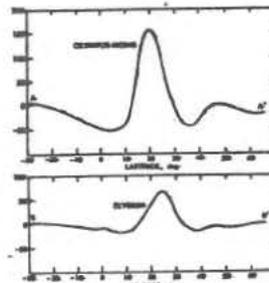
- better geophysical constraints - keep on trackin*
- support to THINK - modeling is important now; so is synthesis of data
- experimental petrology on new (Fe-rich and volatile bearing) systems
- more high, spectral and spatial, resolution observations of Mars - SR is going to work; lab support
- laboratory simulations of weathering processes
- experiments and ideas on volatiles in planets - accretion to ore deposits
- to do a lot of SRT and DA tasks



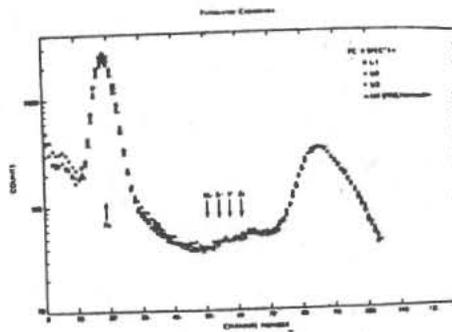
Regional Geology of Mars



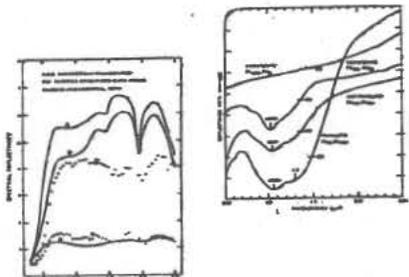
Xenolith-Basalt Petrology



Planetary Geophysics



Viking XRF

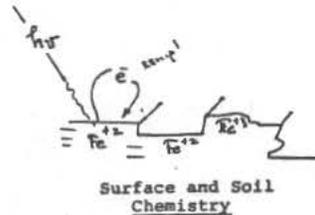


Reflection Spectroscopy

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PETROLOGY OF MARS

...it's just beginning to crack...



Surface and Soil Chemistry

WORKSHOP ON MARS PETROLOGY

6, 7, 8 February 1978

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2. ABSTRACTS OF WORKSHOP TALKS

VIKING GEOCHEMICAL ANALYSES - STATUS REPORT

B. Clark

Although the Martian landscape appears to be littered with rocks of all sizes, forming a population greater than seen at most Apollo sites, no rocks of pebble-size have been successfully delivered to the Viking x-ray experiment. At lander-2, over a dozen attempts to obtain 2 to 12 mm material has produced no detectable sample. Ground-based tests with a simulated lunar soil yields detectable quantities of 2 to 12 mm fragments in at least 90% of sampling attempts. At lander-1, material obtained is thought to be duricrust clods on the basis of soil-like composition and low density.

All samples obtained to date on Mars are fundamentally similar from a geochemical standpoint, but numerous subtle variations in chemical composition have been detected. Increased S content invariably correlates with either a decrease or no change in Ca and Fe, Figures A and B. Si remains relatively constant.

Evaluation of the early data-return identified three "anomalous" results:

- 1) Lack of a well-defined valley between Si and the K-Ca composite peak.
- 2) Unexpectedly broad peak in the Fe-55 backscatter region.
- 3) Smooth trace-element valley (TEV), but elevated above expected level, Fig. D.

Laboratory studies using residual flight instrumentation and analyses of pre-flight calibration data have aided the resolution of these "anomalies". Item (1) is explained by the deduced high S and Cl content of Martian fines. Item (2) was due to a temporary loss in resolution by the detector involved, presumably due to landing shock. As the mission progressed, this detector has recovered fully.

Item (3) was thought at first to be due to some extraneous, unaccounted-for background. Calibrations between samples have allowed correction of spectra for increases in RTG background, but residual excess counts in the TEV remain. Detection of Br in some samples, Fig. D, explains part of this excess. The presence of appreciable Zn (100's of ppm) is also indicated.

Metalliferous sediments obtained as potential Mars analogs because of their major element chemistry (high Fe/Al ratio, moderate Si) often contain several trace elements detectable by this instrument in the TEV region of the spectra. Figure E shows some samples of such nontronite-rich sediments.

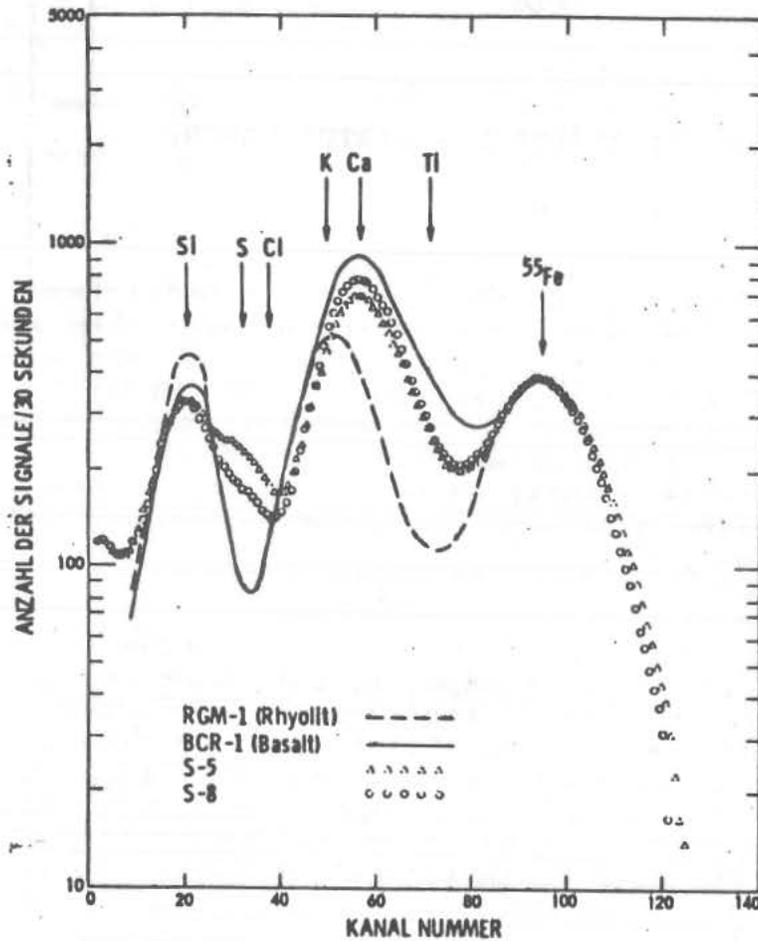


Figure A

(b)

LANDER No.	SAMPLE No	SAMPLE Site		Al	Si	S	Ca	Tl	Fe	Br	Sr
1	S1	Fines	(Sandy Flats)		(+)			(+)	0%	+	+
	S2, S3	Crust	(Rocky Flats)			++	--			+	(-)
	S5	Crust	(Atl. City)		(-)	+++	--		- 1%	++	
	S6 *	Fines (23 cm)	(Deep Hole #1)						0%		
	S7	Fines	(Jonesville)	+	(-)	-	(+?)		+ 9%		
	S8	Fines	(Rocky Flats)	(-)		--		++	+ 6%	(+)	
	S9	Fines	(next to Bashful)					+	+ 5%	(Pb+?)	+
	S11	Bulk	(Intermed. Deep Hole #2)			++	--	+			
2	U1 *	Fines	(Bonneville)						0%		
	U2	Fines	(Under Notch)		(+)	+			- 8%		
	U3	Fines (5 cm)	(Spall. Vly)			-	(+)	(-)	- 3%		
	U4	Fines	(Under Badger)	+		+		-	-13%		
	U5	Bulk	(Phys. Plan.)		(-)	+	-	-			
	U6	Fines	(Intermed. Deep Hole)			(Cl-)	(-)	-			
	U7	Fines	(Deep Hole)		(-)	(Cl-)		-			

Figure B

*REFERENCE SAMPLE

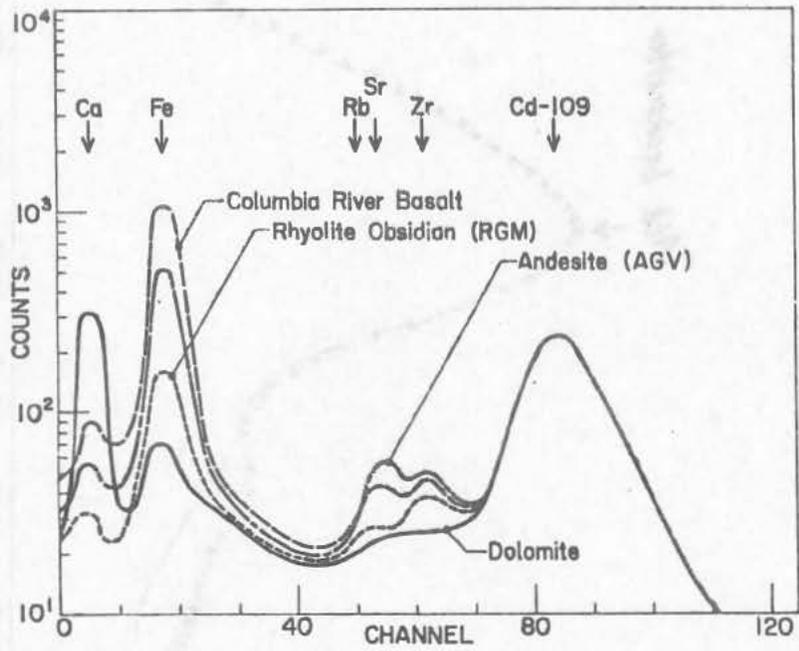


Figure C

KEY=1:PC-4.RTG CORRECTED,5-6.VL1.NSP-32,FACT=0.18052 PEBROWN
49999V.011978 183

— 6047 Analog. PC-3. PTC. NSP 1622
● PC-4, RTG Corr. 5-6, NSP-31 182

Figure D

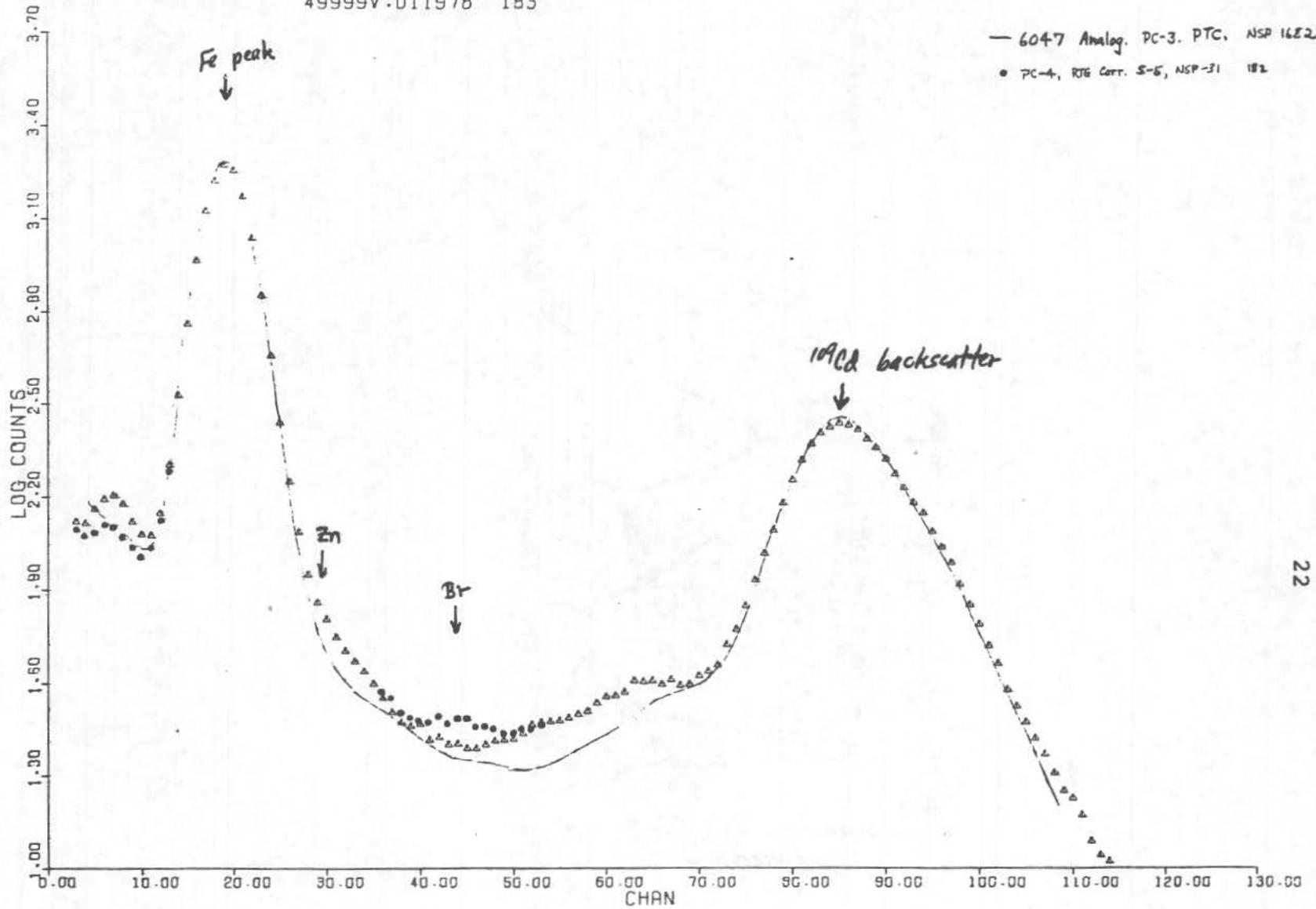
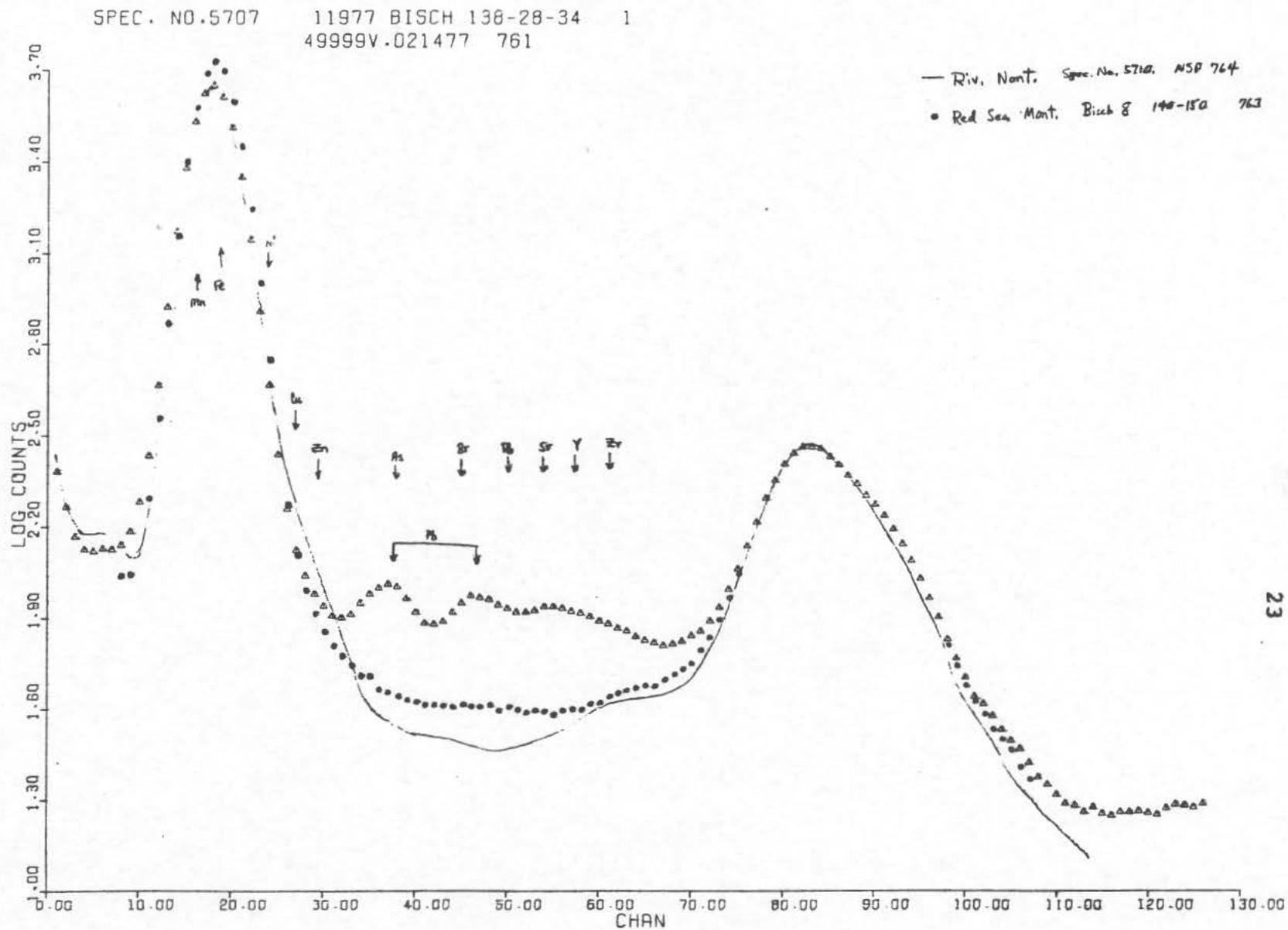
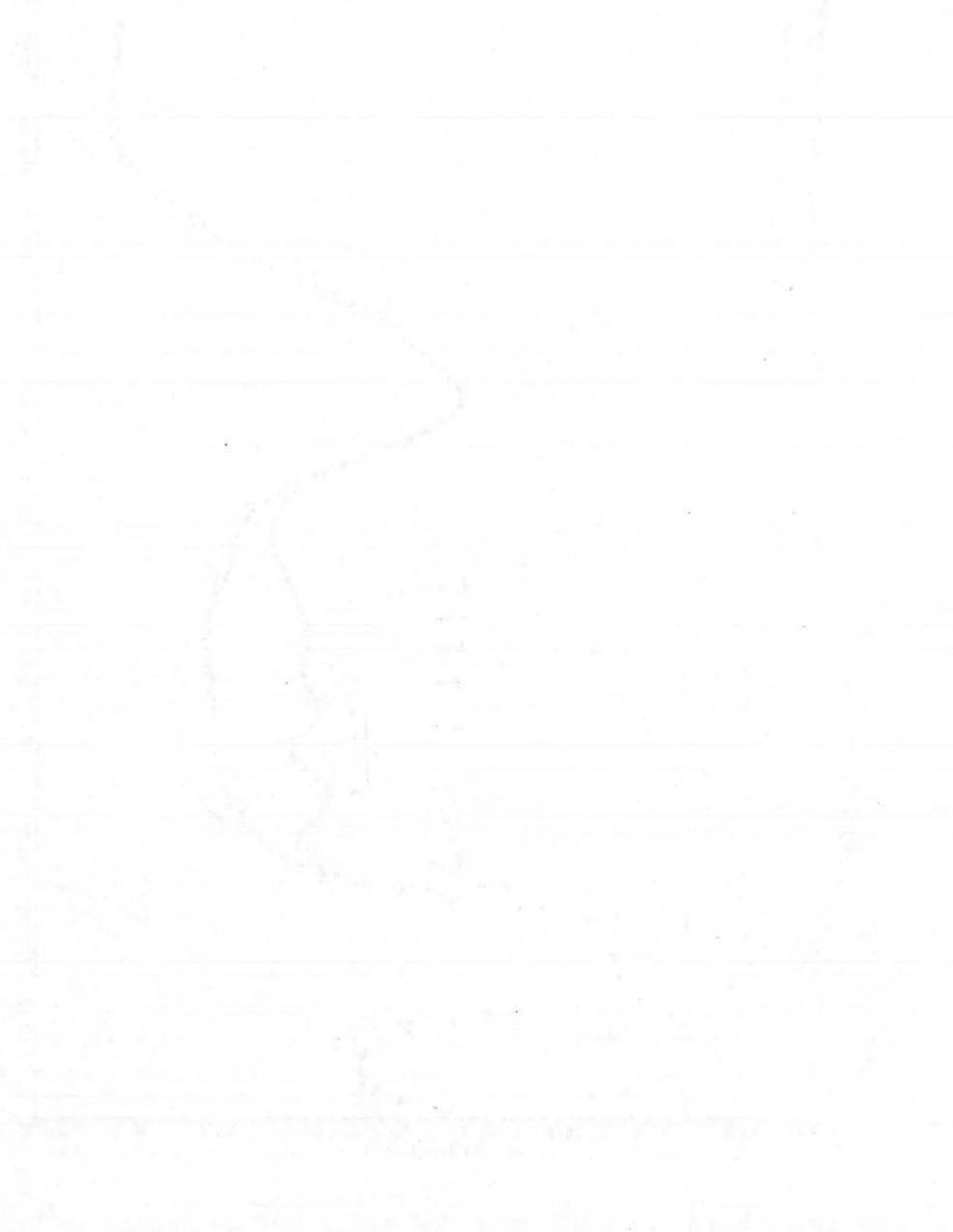


Figure E





VIKING XRF RESULTS

P. Toulmin, III

From a petrologic point of view, the following aspects of the Viking XRF results are especially significant:

- (1) other than relatively minor variations related to micro-environments, the samples of presumably wind-blown dust from two widely separated locations are very similar in composition, implying a similarly extensive source area;
- (2) certain aspects of the composition, especially the low Al, low Si, and high Fe, show that the fines do not represent a primary magma;
- (3) the composition is more reminiscent of weathering/alteration products of mafic rocks, especially those containing abundant Fe-rich, Al-poor clays such as nontronite;
- (4) the concentration of sulfur, chlorine, and bromine in fragments of indurated fines suggests cementation by water soluble salts, suggesting that at least some of the high sulfur content of the fines is a secondary concentration. The last consideration, the apparent lack of evolution of H₂S in the GCMS experiment, and the highly oxidized nature of the Martian surface all suggest that the sulfur is oxidized to the sulfate form. A working hypothesis is offered that the fines may represent in part a palagonite-like material derived from the interaction of iron-rich mafic magma and subsurface ice.

REFLECTION SPECTROSCOPY

R. Huguenin

Earth-based reflectance spectra of small areas (200-400 km dia.) reveal that bright areas and dust clouds are composed principally of the same dust with a composition of 6-10% Fe_2O_3 - FeOOH , 3-5% opaques (probably magnetite), and highly dessicated mineral hydrate. Distinct absorption bands of other mineral phases are not present.

Reflectance spectra of dark areas indicate them to be windows through the dust mantle, with soils (and/or rocks) containing distinct Fe^{2+} -silicate absorption bands. The mineralogy varies from region-to-region, although olivine or basaltic glass is the dominant silicate. Other observed silicates include pigeonite (or orthopyroxene), augite, and diopside. In Erythraeum M. there is a titanaugite, and in M. Acidaleum there is apparently an Fe^{3+} -bearing augite or diopside (minimum few tenths of a percent Fe_2O_3).

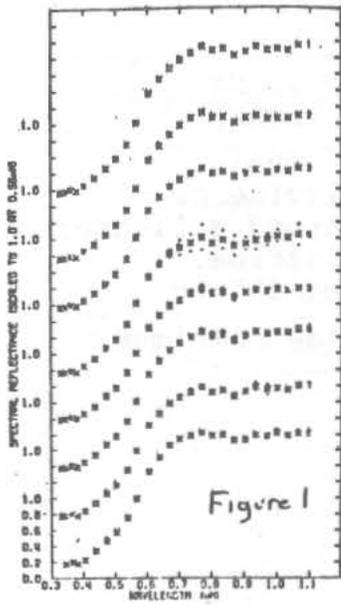


Figure 1

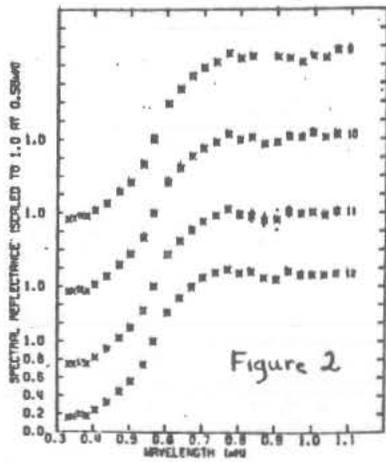


Figure 2

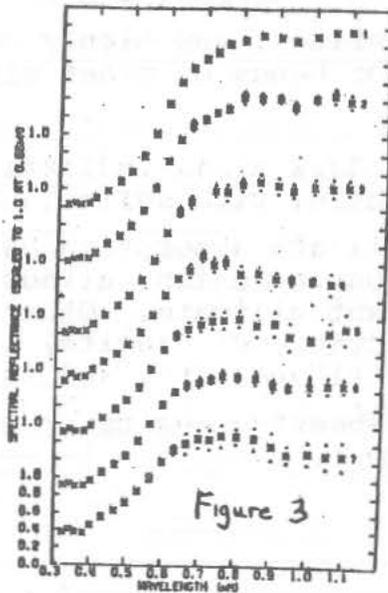


Figure 3

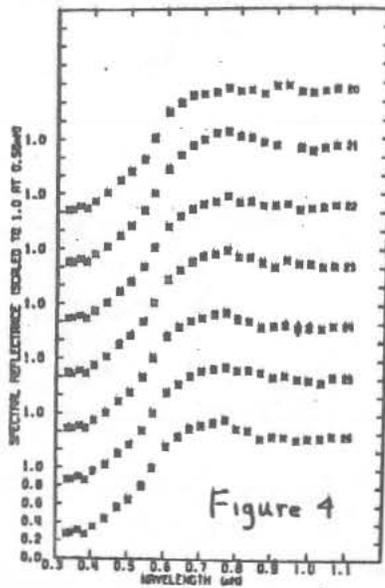


Figure 4

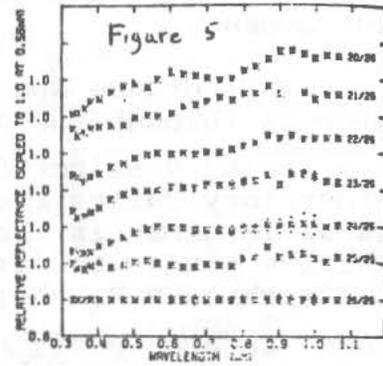


Figure 5

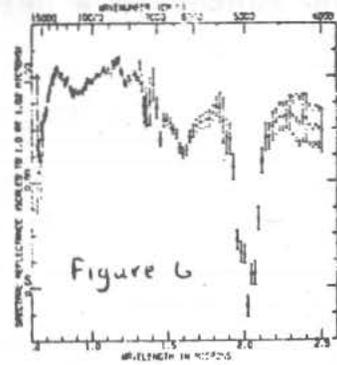


Figure 6

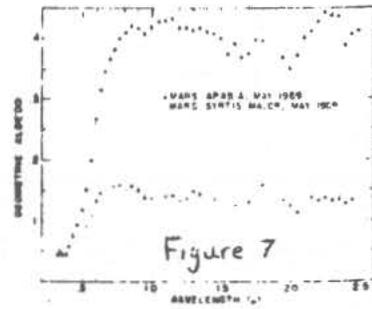


Figure 7

GLOBAL COLOR VARIATIONS ON THE MARTIAN SURFACE

L. Soderblom

Surface materials exposed throughout the equatorial region of Mars have been classified and mapped on the basis of spectral reflectance properties determined by the Viking II Orbiter vidicon cameras. Frames acquired at each of three wavelengths ($0.45 \pm .03\mu\text{m}$, $0.53 \pm 0.05\mu\text{m}$ and $0.59 \pm 0.05\mu\text{m}$) during the approach of Viking Orbiter II in Martian summer ($L_S = 105^\circ$) were mosaicked by computer. The mosaics cover latitudes 30°N to 63°S for 360° of longitude and have resolutions between 10 and 20 km per line pair. Image processing included Mercator transformation and removal of an average Martian photometric function to produce albedo maps at three wavelengths.

The classical dark region between the equator and $\sim 30^\circ\text{S}$ in the Martian highlands is composed of two units: (1) an ancient unit consisting of topographic highs (ridges, crater rims, and rugged plateaus riddled with small dendritic channels) which is among the reddest on the planet ($.59\mu\text{m}/.45\mu\text{m} \approx 3$); and (2) intermediate age, smooth, intercrater volcanic plains displaying numerous mare ridges which are among the least red on Mars ($.59\mu\text{m}/.45\mu\text{m} \approx 2$). The relatively young shield volcanoes are, like the oldest unit, dark and very red. Two probable eolian deposits are recognized in the intermediate and high albedo regions. The stratigraphically lower unit is intermediate in both color ($.59\mu\text{m}/0.45\mu\text{m} \approx 2.5$) and albedo. The upper unit has the highest albedo, is very red ($0.59\mu\text{m}/0.45\mu\text{m} \approx 3$), and is apparently the major constituent of the annual dust storms as its areal extent changes from year to year. The south polar ice cap and condensate clouds dominate the southernmost part of the mosaics.

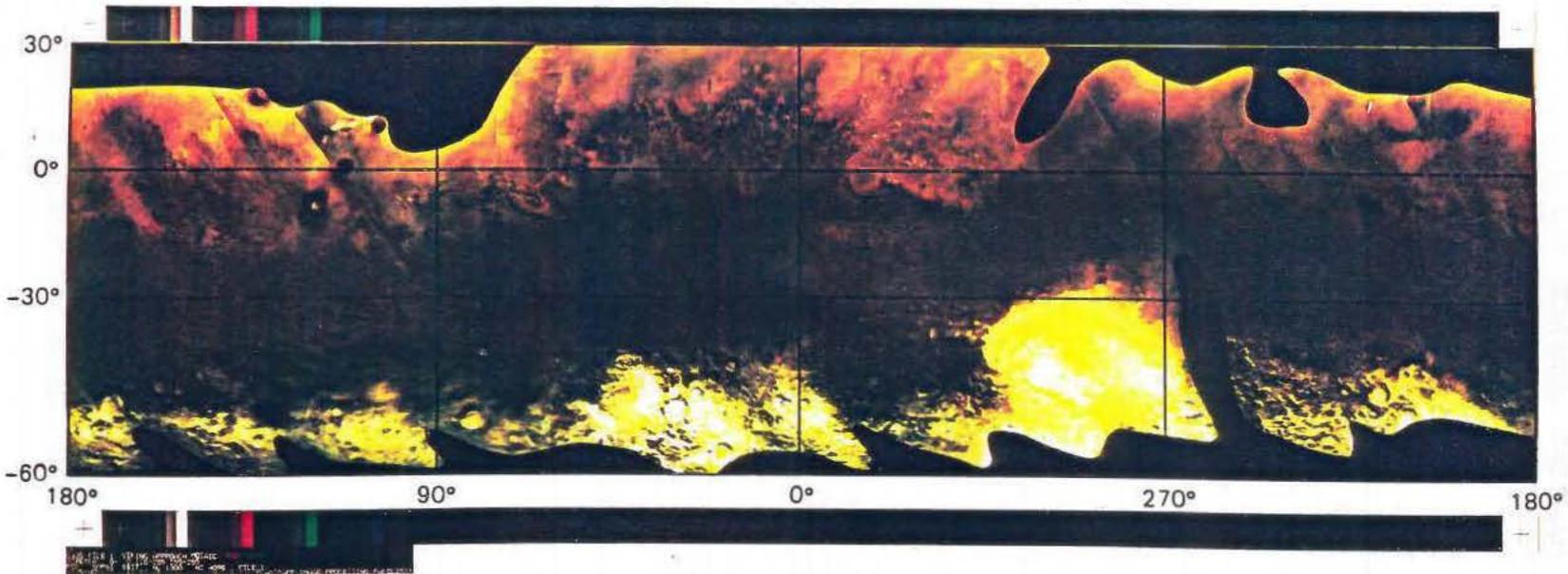


Figure 1.

Natural color composite. Each spectral component was stretched so an albedo of zero is black, an albedo of 25% is white.



Hybrid color composite to enhance color and albedo variations. Blue component - $0.45\mu\text{m}/0.53\mu\text{m}$ ratio, green component - albedo at $0.59\mu\text{m}$, red component - $0.59\mu\text{m}/0.53\mu\text{m}$.

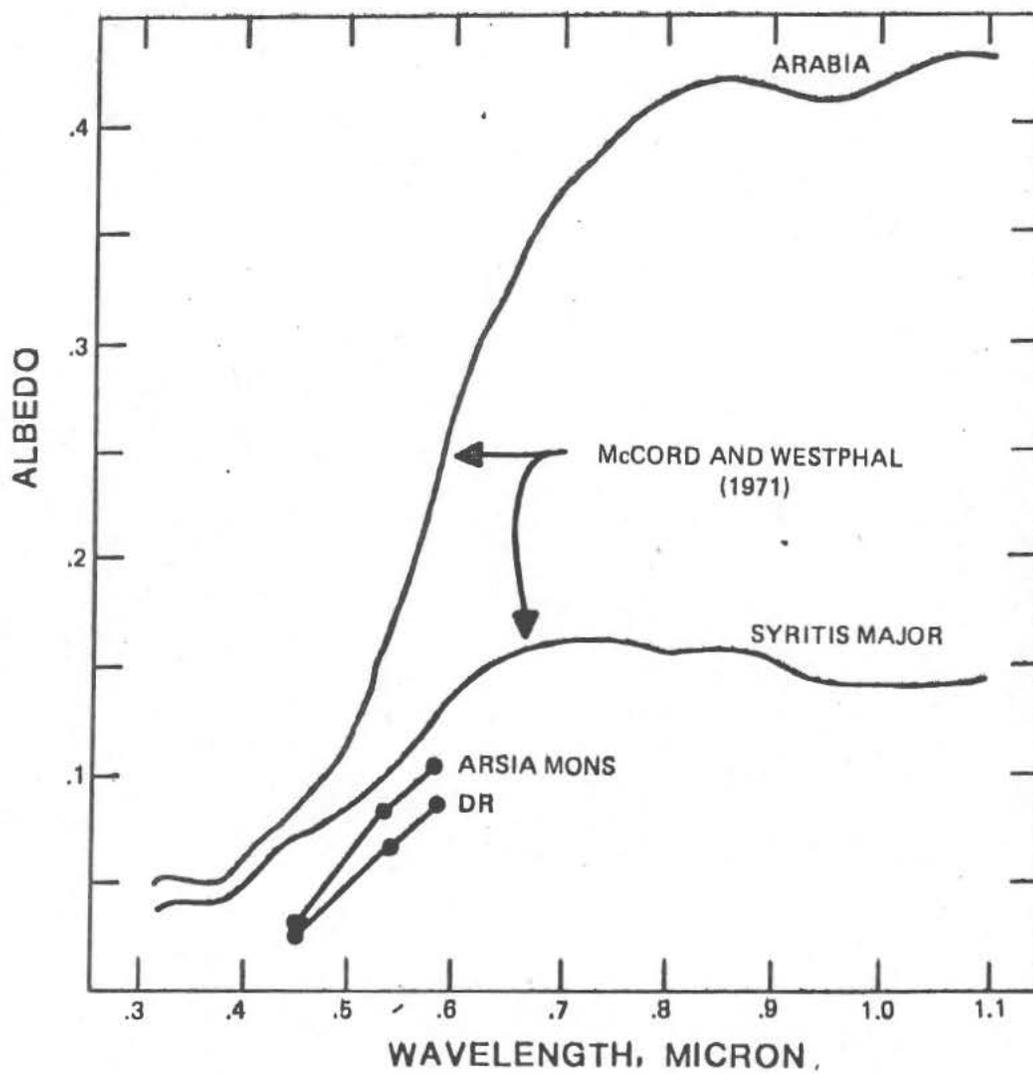
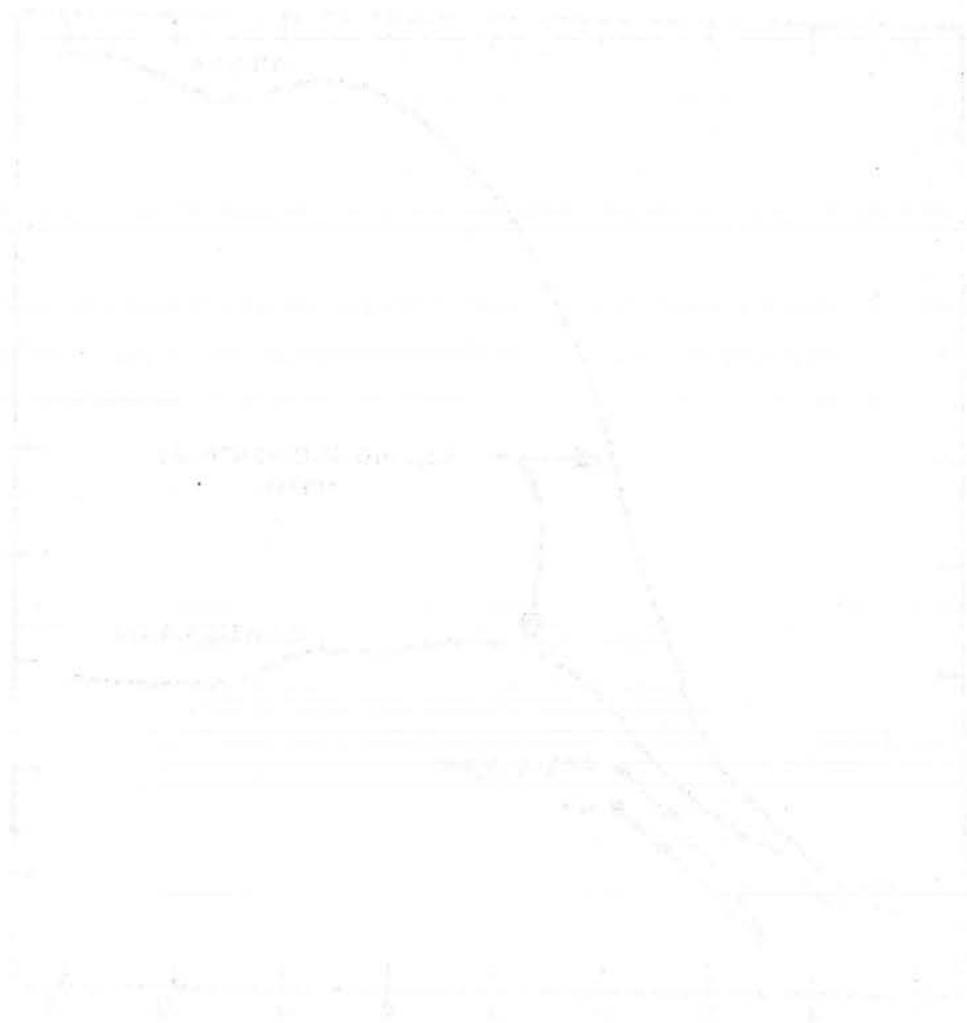


Figure 2. Comparison of reflection spectra of McCord and Westphal (1971) with anomolous dark red areas in multispectral mosaic . Dr - dark red highland unit A



10.00000000

The graph shows a curve that starts at the top left, rises to a peak, and then descends towards the bottom right. The curve is labeled "A-1077" at its top left end. There are several other faint lines and annotations on the graph, including a horizontal line labeled "10.00000000" and a vertical line labeled "10.00000000". The x-axis is labeled "10.00000000" at the bottom center.

MARS PETROLOGY AND A MARS SAMPLE RETURN MISSION

J. Minear

Mars is perceived by many to be the next planet at which to focus our planetary exploration effort. Among the arguments that can be mustered to support this focus are the similarity of Mars to Earth, the presence of an atmosphere that may have been much denser in the past, the need for a good determination of the bulk chemistry of a planet at a different solar distance than the earth and its moon, the possibility of life on Mars, and the accessibility of Mars' surface.

Of the exploration modes - orbital remote sensing, network science, in situ analysis and sample return - needed to address the first order planetological questions about Mars, sample return is the best way to attack a large number of the questions. Reality seems to dictate that samples from only a very few - perhaps only one or two - different sites can be expected in the foreseeable future. The type of sample to be expected may strongly affect the engineering design of either a sample return or in situ analysis mission.

The broad question is how to get a sample that allows age dating and detailed petrologic and geochemical studies. Specific questions that this workshop could address are:

1. Can rock chips be expected in the soil?
2. Are basaltic rocks present on the surface? As exposed bedrock?
3. What is the extent of weathering? Is some minimum sized rock required to obtain an unweathered sample? What can be done even if the rock is weathered?
4. What type of analysis must be done in sampling to ensure that an igneous rock is collected?

A second broad question is, given that a sample is useful and that we should get one, what can be done with experimental and theoretical studies to support sample return?

THERMAL HISTORY, STRUCTURE, AND TECTONICS OF MARS

R. J. Phillips

Thermal History

State-of-the-art history models for Mars involve two-dimensional flow with temperature strongly coupled to Newtonian viscosity. Improvements in thermal modeling calculations will include three-dimensional non-Newtonian flow.

For any given numerical model, there are two general classes of non-uniqueness. One is associated with the uncertainty in initial conditions, such as initial temperature profile, Fe/FeS ratio, and distribution of heat sources. Another uncertainty is associated with the initial perturbations in the temperature and/or velocity fields. There is presently intense debate in the geophysical fluid dynamics community as to whether or not there are global properties, such as Nusselt number, that characterize planetary heat flow independent of the initial perturbations to the system.

Thermal models are at the present time useful in understanding possible scenarios of planetary evolution and the interrelationship of major planetary events such as core formation and mantle partial melting. Depending on initial conditions present martian thermal models offer a wide range of core formation times and distribution in time-depth space of mantle partial melting.

The tensile tectonic features on the surface of Mars suggest that the planetary history is dominated by expansion, although the consequences of this expansion are asymmetrically distributed. Thermal history models that satisfy the expansion constraint have continual warming of the deep interior over much of martian history. Models in which a large part starts initially hot or which have early planet-wide differentiation are excluded. Such models do not start core-formation until late in Mars' history and have important implications for mantle petrology in terms of the timing of Fe-FeS loss from the mantle.

Interior Structure

The gross radial division of Mars is constrained by the mass and moment-of-inertia while crustal thickness variations are estimated from the set of gravity and topographic harmonic coefficients.

An upper limit to the moment of inertia factor is probably the hydrostatic value of 0.377. The non-hydrostatic effect of Tharsis has been estimated to yield a value of 0.3654. Consideration of the isostatically compensated crust of the remainder of the planet will lower the value still further. On the other hand, it has been recently argued, by analogy to the Earth and Moon, that the hydrostatic value is correct. Within a plausible range of moment of inertia factors and core densities, the martian mantle STP density lies between 3.4 and 3.7 gm/cm³, under the assumption of chemical homogeneity.

The higher order harmonics of the gravity and topography suggest a wide range of crustal thicknesses on the planet, with an average thickness between 50 and 150 km.

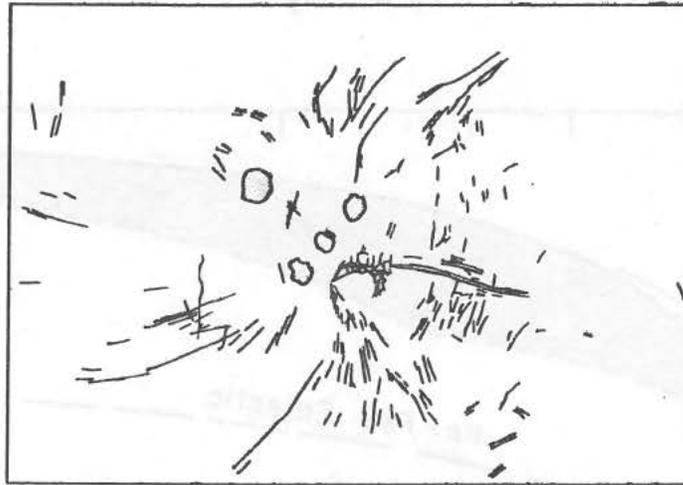
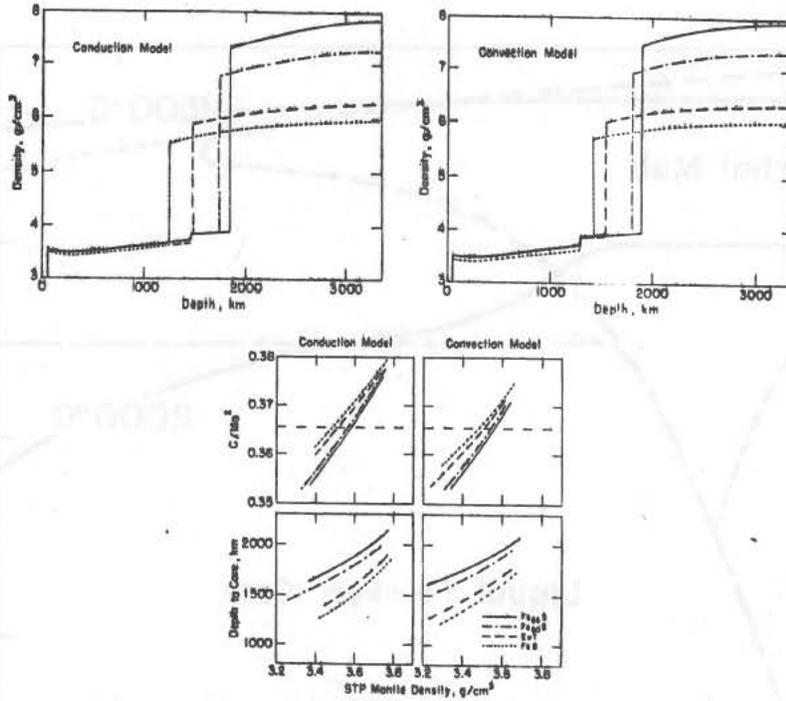
Both thermal model and lithospheric loading studies suggest the elastic lithospheric thickness is about 100 km. Better confidence in this estimate will come from low altitude Viking gravity data. The thermal lithosphere thickness may be two to three times the elastic lithosphere thickness.

Tharsis and Tectonics

The Tharsis prairie of Mars is a region roughly 4000 km square centered at about 110°W longitude on the equator, characterized by well defined and closed topographic and gravity highs, a pronounced concentric and radial fracture system, and a concentration of shield and plains volcanism. The regional doming, shield volcano construction, free air gravity anomaly, and fracture system of the Tharsis prairie are unparalleled in the explored solar system. Much of the surface tectonics of the planet appear to be associated with the uplift. For example, Valles Marineris is in a region of north-south deviative tensile stress created by the uplift and is undoubtedly genetically related. The tectonic picture strongly suggests that Tharsis was a region of incipient lithospheric breakup that was never fully achieved.

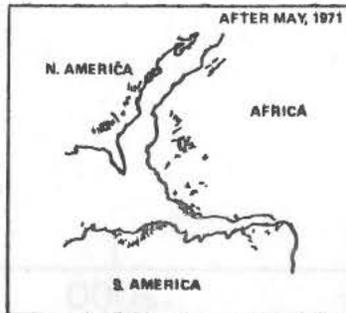
Hypotheses for the origin of Tharsis include: (1) A chemical plume from the lower mantle; (2) Homogeneous accretion and whole mantle convection; (3) Compressional arching; (4) Energy focusing at the antipode of the Hellas impact; (5) A primordial inhomogeneity; (6) A consequence of asymmetric heat release from core formation; (7) Desulfidization of the lithosphere followed by isostatic adjustment; and (8) Overturn of the mantle lithosphere and replacement by less dense asthenosphere.

A key constraint on Tharsis is whether or not the Tharsis gravity anomaly is statically or dynamically supported. Viscoelastic calculations show that Tharsis must be supported in the elastic lithosphere. Stress levels depend upon lithospheric thickness and the particular isostatic mechanism adopted; the consideration of the stress state leads to testing of the finite strength hypothesis.

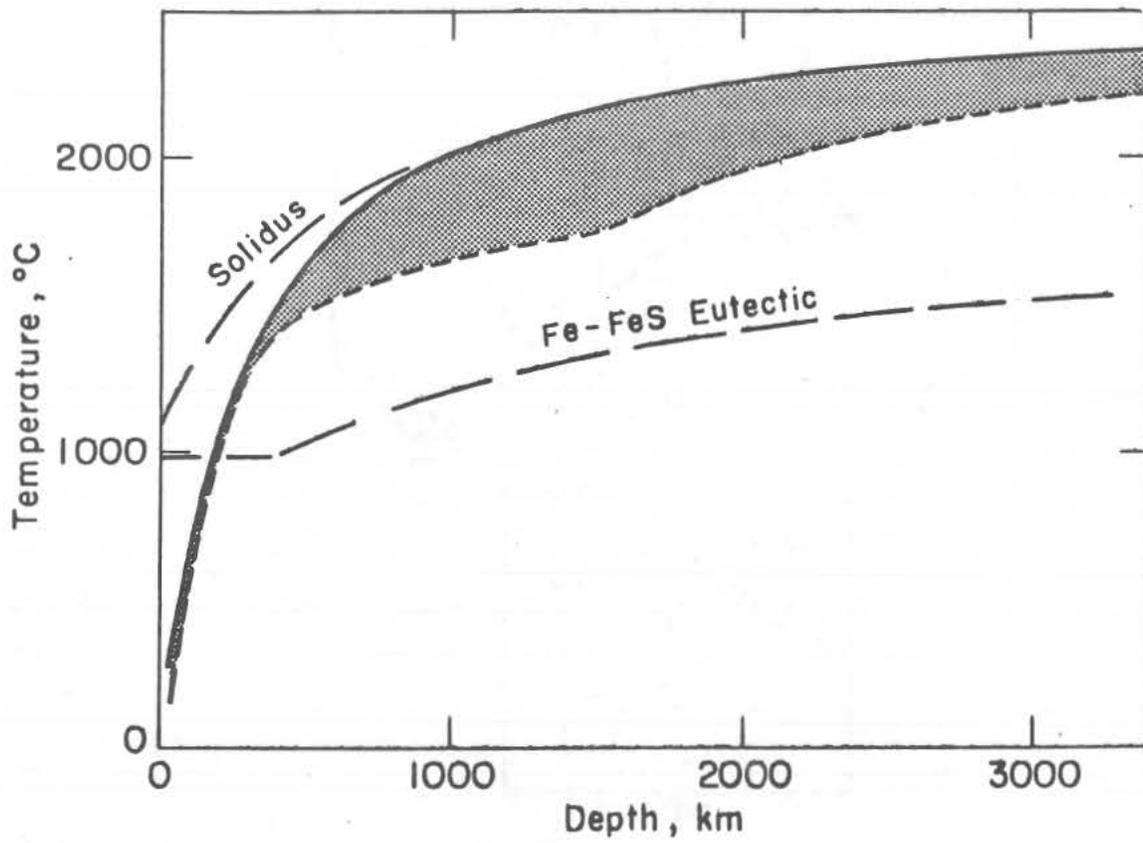
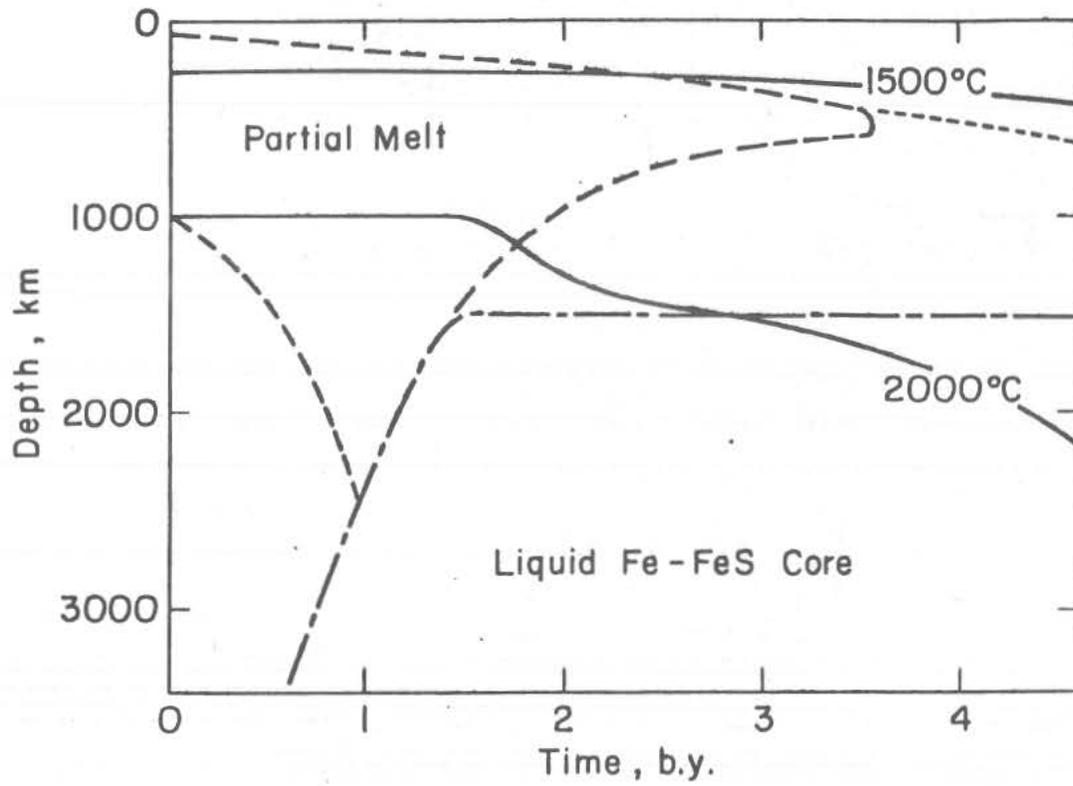


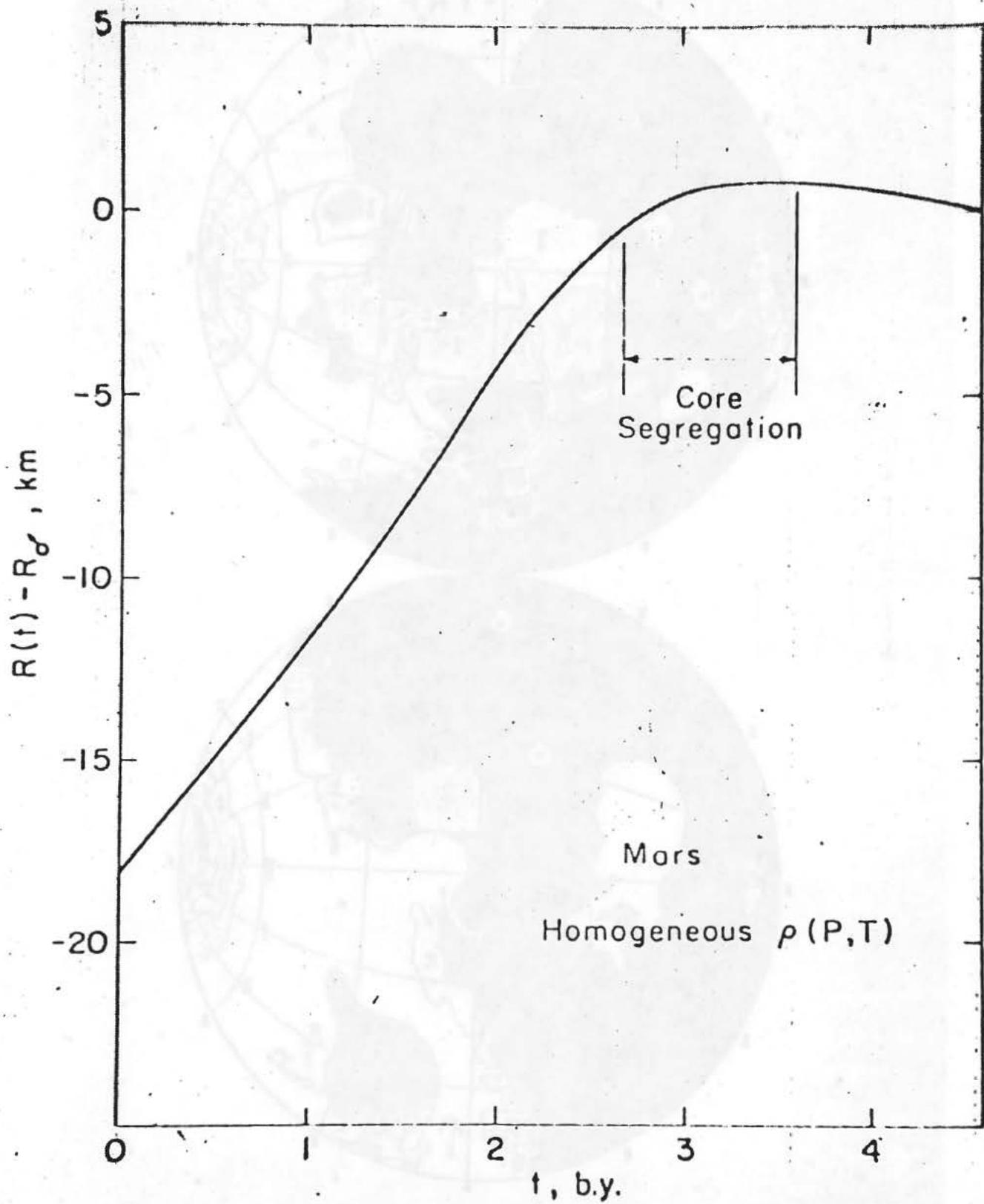
MARS

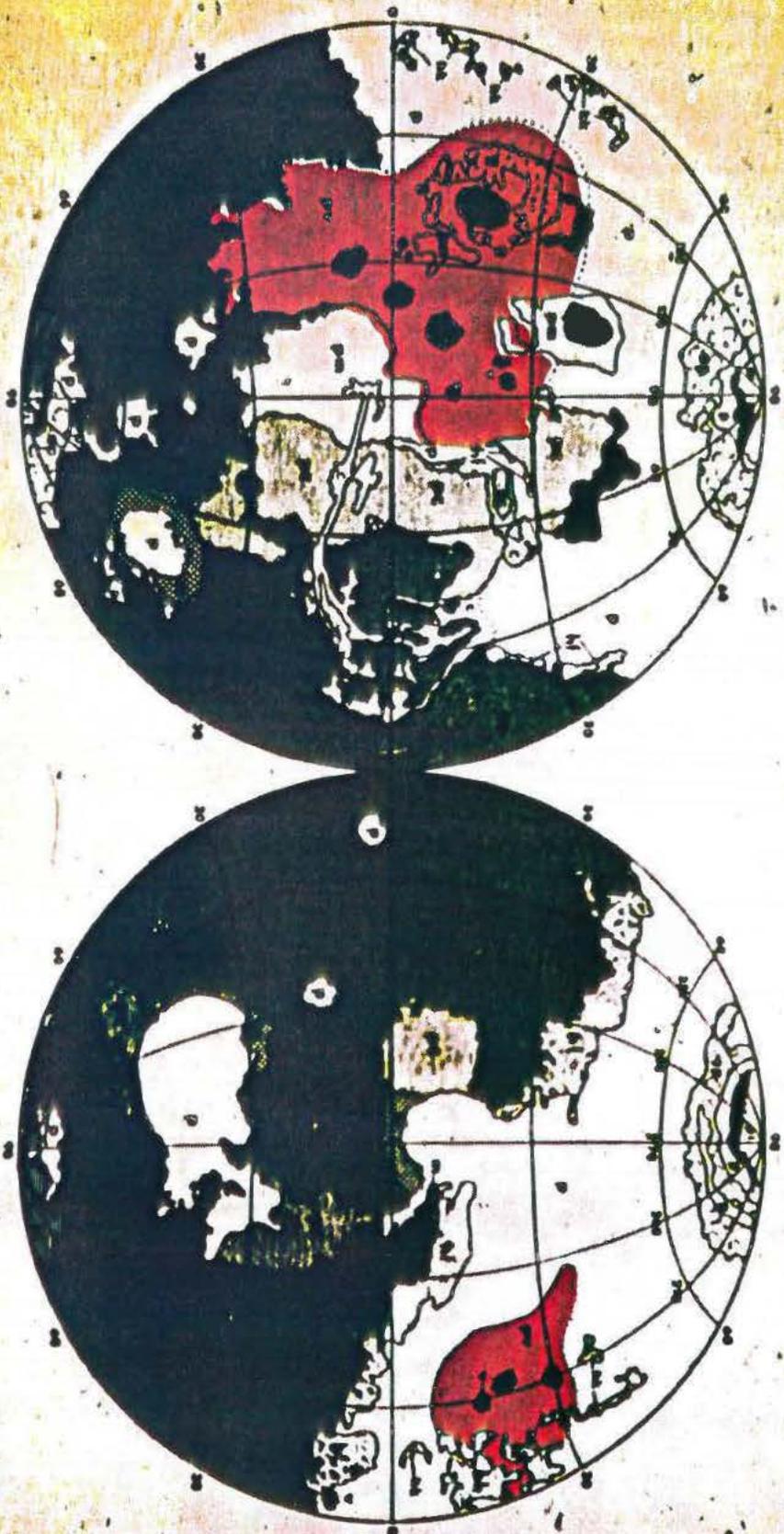
0 500 1000
km

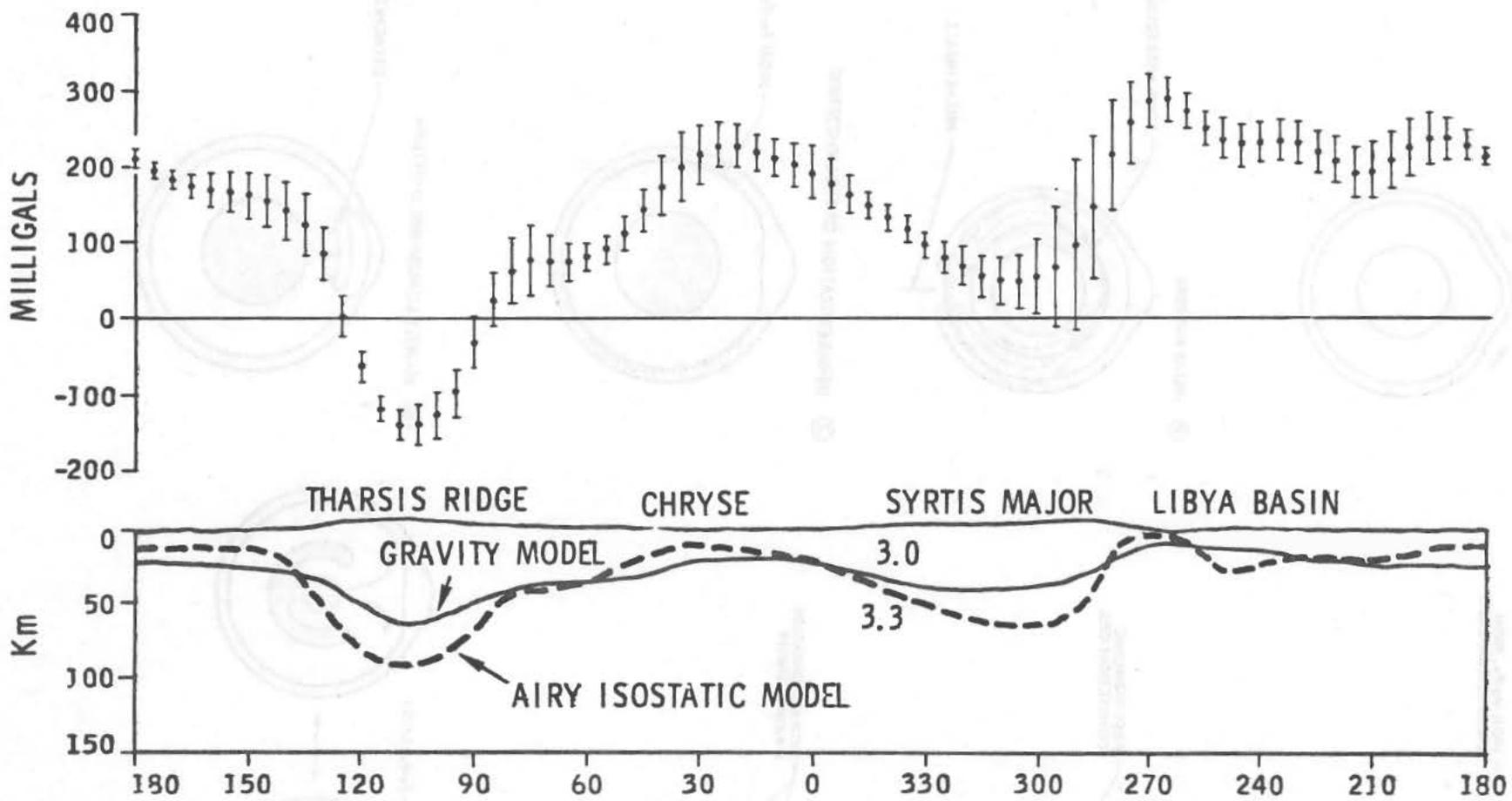


EARTH

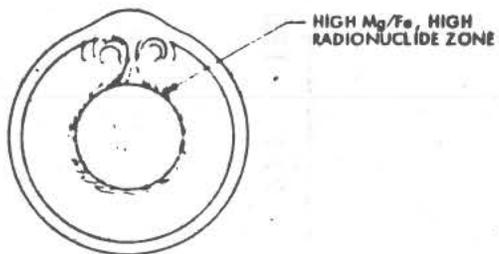




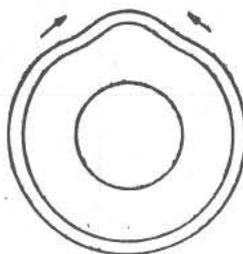




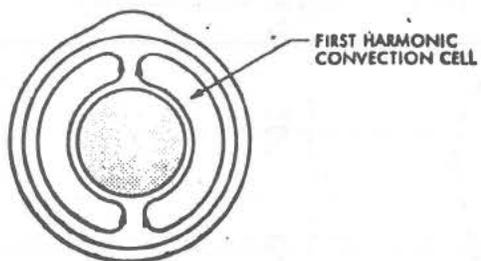
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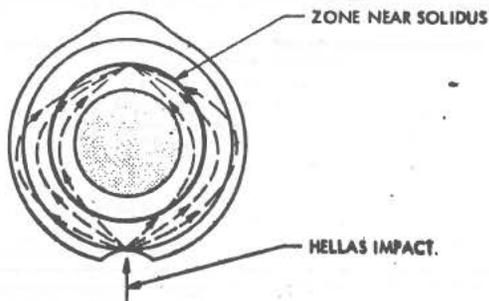
③ COMPRESSIONAL ARCHING



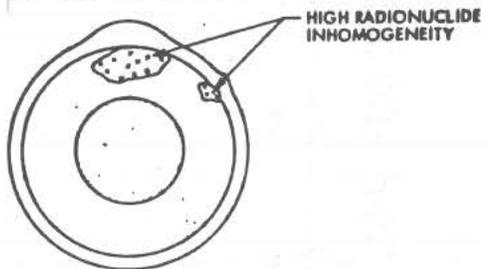
② WHOLE MANTLE CONVECTION



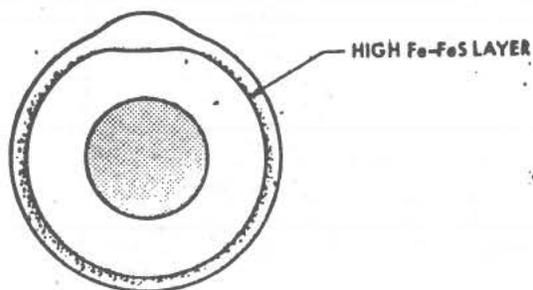
④ HELLAS ANTIPODE



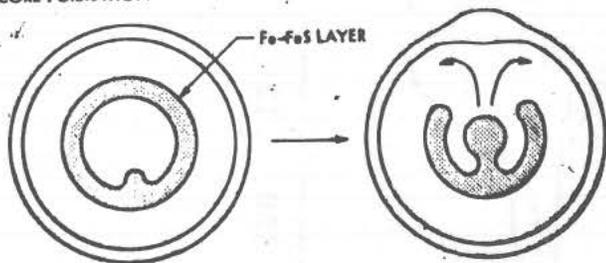
⑤ PRIMORDIAL INHOMOGENEITY



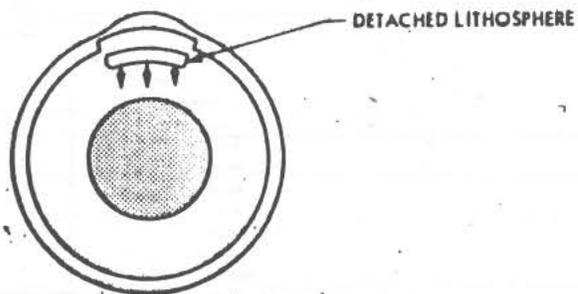
⑦ DE-SULFIDIZATION OF THE LITHOSPHERE

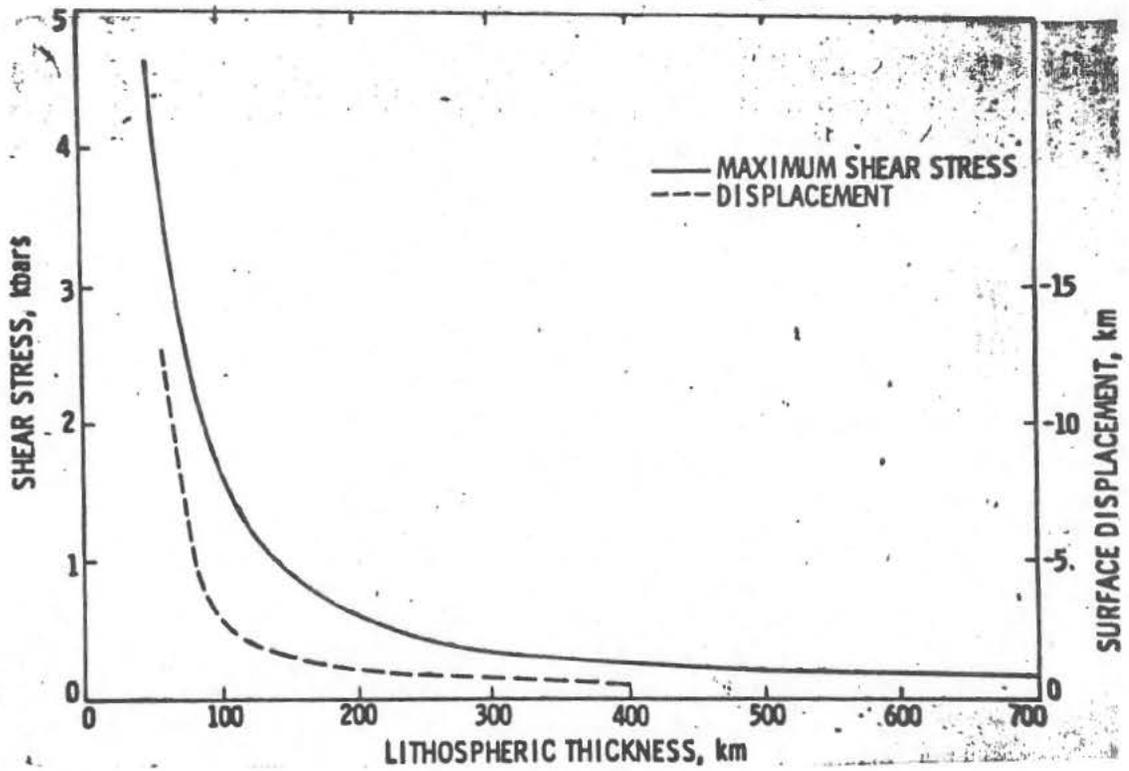
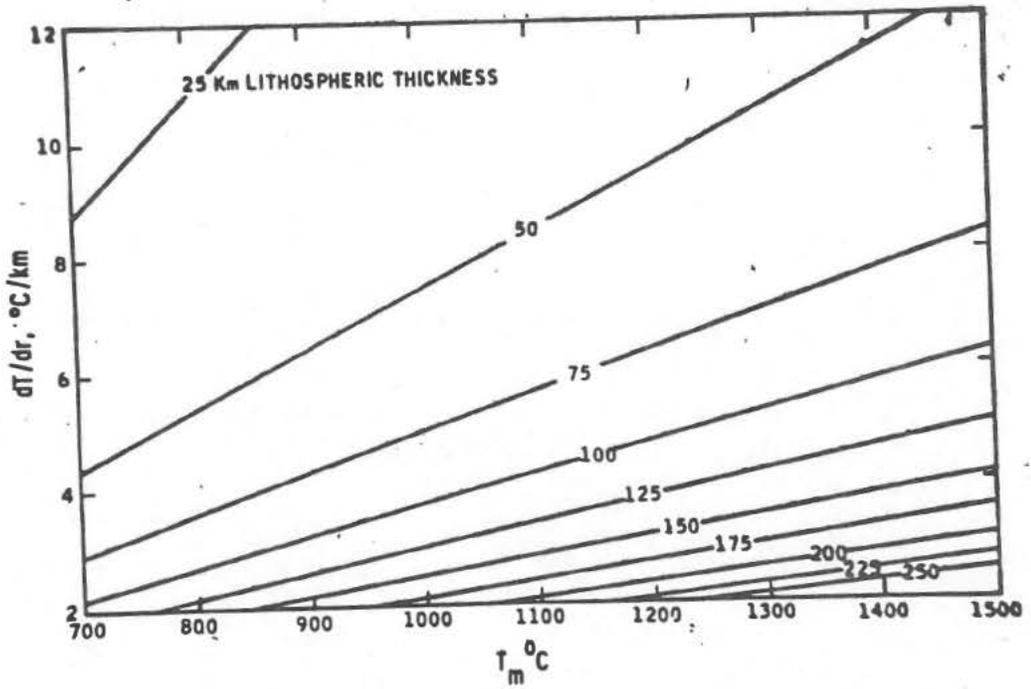


⑥ CORE FORMATION



⑧ MANTLE LITHOSPHERE OVERTURN





VOLATILES IN PLANETARY INTERIORS

R. Brett

Factors that determine the amounts of volatile elements in planets are the accretional mixture, rate of accretion, thermal history and convection rate, and the size of the body. Volatile elements are important for determining bulk composition, redox reactions, melt behavior including temperature and viscosity, nature of mineral deposits, and the nature of a core, if any.

The presence of H₂O is most important not only for its effect on melts, but also because dissociation occurs near the surface with the release of hydrogen. Hydrogen loss causes oxidation; this may be the major cause of oxidation of planetary crusts as in the Earth and Mars (?); the moon, lacking H₂O does not show crustal oxidation.

Sulfur is significant when considering core formation, mineral deposits, and the Mars regolith. Haughton et al. (Econ. Geol., 1974) have experimentally determined the S abundance in a basaltic melt (as sulfide) S_m , is related to other variables:

$$\log S_m = \frac{1}{2} \log f_{S_2} - \frac{1}{2} \log f_{O_2} + \sum a_i N_i$$

where f_{O_2} = oxygen fugacity, f_{S_2} = sulfur fugacity, a_i = constant

for oxygen species i , N_i = mole fraction of oxide component i in the melt. Increase in f_{S_2} , TiO₂ and FeO increases solubility;

increase in f_{O_2} , CaO, Al₂O₃ decreases solubility. Preliminary

experimental work (Helz, 1977) indicates that pressure does not markedly affect S solubility. The terrestrial and lunar mantles appear to produce melts saturated or near-saturated in S (e.g. Moore and Fabbi, 1970?, Brett, 1975). The Haughton et al. data preclude Martian melts of any reasonable composition that would be saturated with as much as 3 percent S — the high S content at the surface must therefore be due to surface processes. Sulfate in the Martian mantle appears unlikely as no other primary solar system material contains sulfate as the primary form of S.

Sato (1978) suggests that planetary mantles are buffered by the graphite surface (C-CO-CO₂) buffer. In the upper mantle this gives oxygen fugacities just above the iron-wüstite buffer. This seems to apply to the Earth and Moon — if it can be applied to Mars we have f_{O_2} estimates for experimental modelling. If

magnetite-hematite occur at the surface, we can perhaps use this

as an upper limit. Such f_{O_2} conditions would produce a core of Fe-S-O (metal-sulfide-iron oxide).

In summary, I suggest that the oxidized crust is a surface effect possibly due to H_2 outgassing, the Martian upper mantle is bounded by the iron-wüstite and magnetite-hematite buffers, the Martian core consists of Fe-S-O, and the high surface S abundance is not necessarily a reflection of high interior S abundance.

MARS - WET OR DRY

E. Gibson

The topic was reviewed by examining the evidence for having a "wet-or-dry" Mars. The evidence for having a dry Mars include the following: no present oceans or standing water, the present pressure and temperature conditions on Mars rule out pure water, no apparent biological activity and the periodic dust storms. Conversely, models of planetary formation suggest that Mars formed from material at 300°K during accretion of the planet resulting in Mars having a larger H₂O, C, N etc. component than the earth. The models suggest that Mars may have contained and outgassed at least five times more water per unit mass than the Earth.

Evidence for Mars water or "being wet" was reviewed by examining telescopic data, Mariner 9, and Viking results. From the Viking atmospheric data, models were developed, based on the ³⁶Ar results, to show that the present Martian atmosphere is depleted in ³⁶Ar relative to what would be expected from outgassing of Mars over geologic time. It was proposed that Mars is presently depleted in water and that major amounts of volatiles (including H₂O) may still be retained within Mars. Methods for storing and cycling water within the Martian regolith were reviewed. Evidence exists for retention of large amounts of water in the regolith by adsorption and/or chemical weathering processes.

EVIDENCE FOR A "DRY" MARS

- * NO PRESENT OCEANS.
- * NO STANDING WATER.
- * P,T CONDITIONS RULE OUT PURE LIQUID H₂O.
- * NO APPARENT BIOLOGICAL ACTIVITY.
- * DUST STORMS

MODELS FOR ORIGIN OF MARTIAN VOLATILES DURING PLANETARY FORMATION

- * Mars formed from material of 300°K during accretion of planet. This resulted in Mars having a larger H₂O, C, N etc component than the Earth.
- * Retention of tremolite during formation of Mars suggests that Mars may have contained and outgassed at least five times more water per unit mass than the earth

EVIDENCE FOR MARTIAN WATER

- * TELESCOPIC OBSERVATIONS -- ATMOSPHERIC H₂O VAPOR.
- * REFLECTANCE MEASUREMENTS/POLARIZATION STUDIES SUGGESTED "WEATHERED" MAFIC SILICATES
e.g., LIMONITES/GOETHITE-HEMATITE
- * MARINER 9 DATA
 - * CLOUDS
 - * STREAM BEDS/CHANNELS, ETC.
 - * SPECTRAL STUDIES SUGGESTED CLAYS (MONTMORILLONITE)
- * VIKING STUDIES
 - * M.A.W.D./IRTM H₂O VAPOR ABUNDANCES MAPPED
POLES CONTAIN H₂O CAPS
 - * CLOUDS/GROUND FOG/FROST AT V2 LANDER
 - * GCMS 0.1-1.0% H₂O IN SOILS
 - * M.S. ATMOSPHERE 0.03% H₂O VARIABLE
 - * BIOLOGY EXPERIMENTS

WATER "TIED" UP ON MARS

- * POLAR CAPS
 - * H₂O ICE
 - * H₂O/CO₂ CLATHRATES
- * REGOLITH
 - * SUBSURFACE ICE
 - * ADSORBED H₂O
 - * MINERALS/ROCKS *Lepidocrocite, Akaganeite*
 - * HYDRATES-GOETHITE, DEPIDOCROCITE, AKAGANEITE (BRUCITE, GIBBSITE, BOEHMITE, DIASPORES)
 - * CLAYS -- MONTMORILLONITES
 - NONTRONITES
 - SAPONITES
- * CHEMICAL WEATHERING PRODUCTS - Carbonates, sulfates
- * SOLAR U.V. PRODUCED H₂O
- * BASALTS
- * ATMOSPHERE

SPECULATIONS ON MARS VOLATILES

Basic Assumptions:

1. ³⁶Ar has not been lost from Mars, nor trapped in an atmosphere "sink"
2. Original ³⁶Ar concentration of Mars and Earth were the same; ³⁶Ar thus monitors degassing extent of Mars relative to Earth.
3. Original ³⁶Ar/H₂O, CO₂/N₂ abundance ratios and C, O, N, isotopic ratios were similar between Mars and Earth.
4. Isotopic fractionation (or lack of it) in O, N, and C reflects thermal escape from a gas inventory.

Volatile	Abundance on Earth	Abundance Mars Atmos.	Depletion factor of Mars Atmos. relative to Earth	Depletion factor in Mars Atmos. relative to Mars ³⁶ Ar
³⁶ Ar	31 ppm (air)	3.6-7 ppm	$\approx 10^{-2}$	-
Relative to ³⁶ Ar = 1		If ³⁶ Ar = 1		
⁴⁰ Ar	296 (air)	2750±500	$\approx 10^{-1}$	$\times 10$ excess
H ₂ O	9.6×10^6 (surface)	$\approx 0.07\%$ variable	-	$\times 10^6$ depleted (few meter liquid layer)

WATER CYCLING

- * EARLY GROUND TEMPERATURES WERE SUFFICIENTLY HIGH TO PERMIT DOWNWARD SEEPAGE OF LIQUID WATER.
- * SUBSEQUENTLY THE GROUND TEMPERATURE FELL BELOW FREEZING, SO THAT GROUND ICE FORMED TO DEPTHS OF SEVERAL KILOMETERS.
- * "RECENTLY" SOME FRACTION OF THIS GROUND ICE HAS BEEN MELTED TO ASSIST THE FORMATION OF COLLAPSE AND SURFACE RUN-OFF FEATURES.

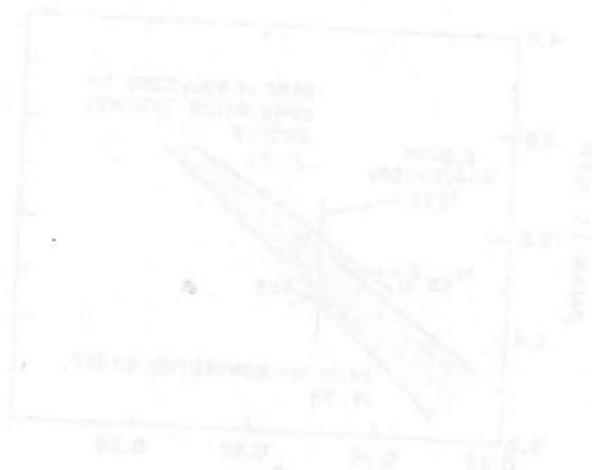
SUMMARY OF CONCLUSIONS FROM ATMOSPHERIC EVOLUTION MODELS

- * MARS HAD AN EARLY DENSE ATMOSPHERE.
- * WATER CONDENSED FROM ATMOSPHERE -- PERCOLATED BENEATH SURFACE -- RESULTING IN GROUND ICE.
- * ADDITIONAL VOLATILES (e.g. H₂O) ADDED BY EPISODIC VOLCANIC ACTIVITY (LESSER CONTRIBUTOR)
- * EXOSPHERIC ESCAPE LOWERED N₂ VALUES -- BUT DID NOT REDUCE CO₂ -- UNLESS A MECHANISM EXISTED IN EARLY ATMOSPHERIC HISTORY FOR REMOVAL OF CARBON AS CH₄.
- * VOLATILES IN POLAR CAPS ARE ONLY A SMALL FRACTION OF VOLATILES EXPECTED FROM TERRESTRIAL-LIKE OUTGASSING.
- * REGOLITH ENTRAPMENT (e.g., ADSORPTION OR CHEMICAL WEATHERING) MAY PROVIDE MEANS FOR VOLATILE STORAGE.
- * ADSORPTION AND CYCLING MAY PROVIDE MECHANISM FOR OBSERVED DIURNAL AND SEASONAL CHANGES IN WATER CONCENTRATIONS IN ATMOSPHERE.

MODELS FOR SURFACE PETROLOGY

J. Smyth

This work is based on models for the chemistry and mineralogy of the mantle of Mars. Current estimates of the density of the martian mantle (3.55 g/cc, Reasenberg, 1977) (see figure 1), while somewhat lower than previous estimates, are substantially greater than the earth's mantle (3.35 g/cc). Model mineral assemblages (at 30 kb) can be calculated using a modified (high pressure) CIPW norm scheme by adding FeO to model terrestrial mantle compositions (see figure 2). The density of the resulting mineral assemblages varies with increasing FeO content, due to increasing Fe/Mg ratio in individual minerals and also the abundance of garnet. An important transition in the assemblage occurs at a density of about 3.5 g/cc, namely at lower densities the phases present are olivine, garnet, cpx and opx (minor ilmenite), whereas above 3.5 g/cc orthopyroxene is replaced by oxide (see figure 2). This is due to the decreasing cation/Si ratio in the bulk composition, as FeO increases. Hence by this model the martian mantle is not garnet-lherzolite, but rather is an oxide-garnet wehrlite (wüstite 2%, garnet 11%, olivine 73% and clinopyroxene 12%, with no orthopyroxene). Partial melting of such an assemblage would yield unusual iron-rich, very low viscosity melts. Model partial melts, assuming production from a quaternary eutectic near $ol_{74}cpx_{43}ox_8$, yields a picritic alkali-olivine basalt (see table I) with a computed viscosity of 12 poise at $1200^{\circ}C$.



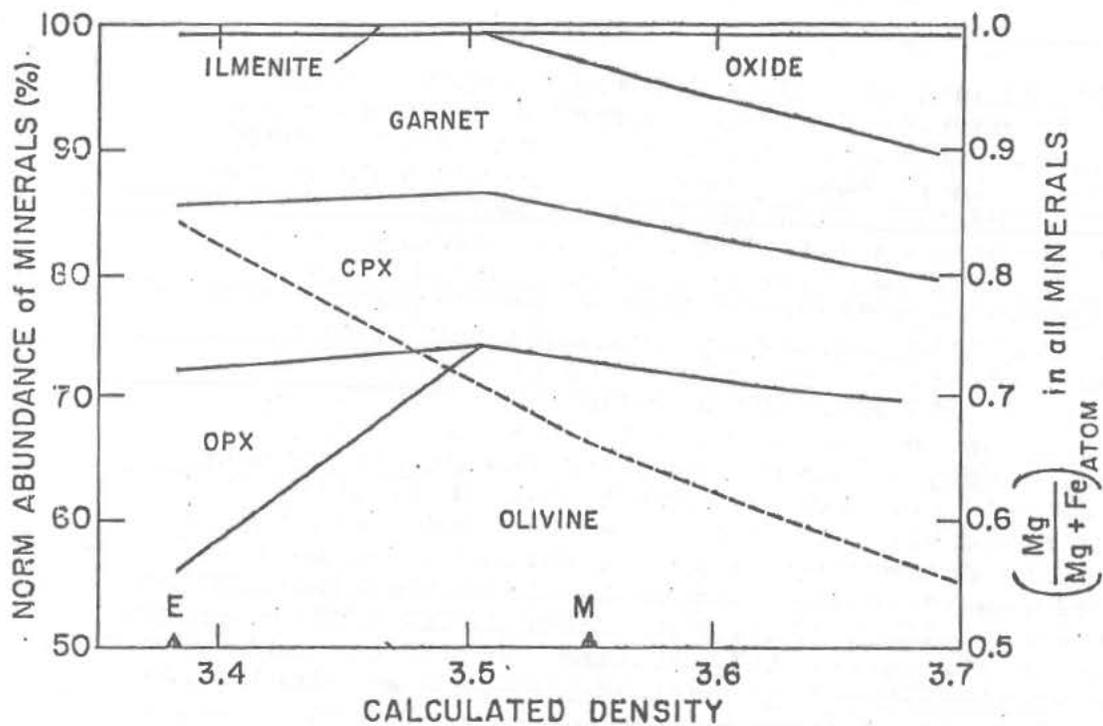


Figure 1

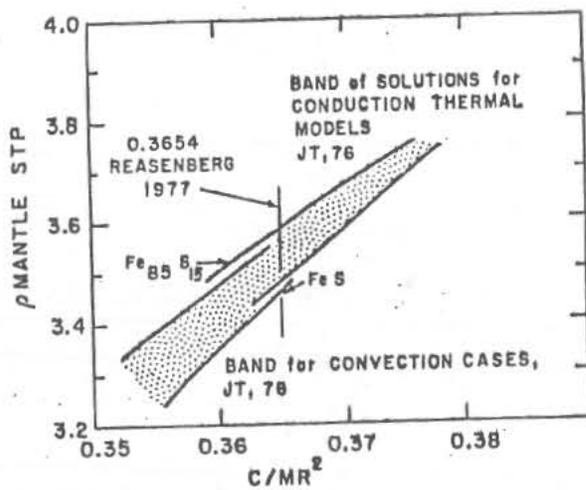


Figure 2

Table 1. Summary of lava compositions (Model and Real).

		Calculated Model Lavas				Terrestrial Lavas			Lunar Basalts		Martian Soil		
		MARS		EARTH		Mid-ocean ridge basalts		Komatite	Apollo 11	Apollo 12	Viking XRF		
		K_D^{Fe}	K_D^{Mg}	K_D^{Fe}	K_D^{Mg}	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Chemistry (oxide wt %)	SiO ₂	44.48	41.5	51.38	48.0	47.01	50.83	45.4	40.5	45.0	44.7		
	Al ₂ O ₃	11.25	10.5	8.77	8.2	15.57	12.67	7.5	8.7	8.59	5.7		
	Fe ₂ O ₃	3.00	2.8	2.36	2.2	2.32	3.10	-	-	-	18.2		
	FeO(+MnO)	11.38	23.9	4.86	19.6	11.57	11.39	12.9	19.0 + 0.25	21.0 + 0.28	-		
	MgO	17.32	7.5	23.58	13.5	5.25	4.19	25.1	7.6	11.6	8.3		
	CaO	9.54	8.9	7.47	7.0	9.77	8.18	7.4	10.2	9.42	5.6		
	Na ₂ O	1.77	1.7	1.37	1.3	3.00	3.24	0.73	0.50	0.23	n.d.		
	K ₂ O	0.40	0.4	0.31	0.3	0.31	0.87	-	0.29	0.064	0.1		
	TiO ₂					3.20	3.44	0.39	11.8	2.90	0.8		
	Cr ₂ O ₃					-	-	0.40	0.37	0.55	-		
	P ₂ O ₅					0.32	0.75	-	0.18	0.07	-		
	SO ₃ (or S)					-	-	-	-	0.06 (S)	7.7 (SO ₃)		
Mineralogy (calculated low pressure norms)	plag	or	2.36	2.36	1.83	1.77	1.83	5.14	-	1.71	0.38	1	1
		ab	10.37	9.46	11.59	11.00	25.39	27.42	6.18	4.23	1.95	0	0
		an	21.57	19.84	16.86	15.65	28.10	17.46	17.19	20.64	22.22	18	19
	nepheline	ne	2.50	2.67	-	-	-	-	-	-	-	-	-
		en	-	-	28.30	16.03	5.89	7.02	9.23	12.54	19.47	-	-
	hyp	fs	-	-	3.36	16.29	6.33	7.52	3.35	10.29	22.78	20	31
		wo	10.25	10.15	8.43	7.96	7.63	7.61	8.15	12.02	8.33	-	-
	diop	en	7.02	3.09	6.68	3.88	3.63	3.42	5.52	6.39	3.81	10	14
		fs	2.99	7.49	0.79	3.94	3.90	4.15	2.00	5.25	4.45	-	-
	oliv	fa	25.32	10.93	16.65	9.62	2.49	-	33.48	-	3.94	-	-
		fa	11.91	29.17	2.18	10.77	2.95	-	13.39	-	5.08	-	-
	oxides	mt	4.35	4.06	3.42	3.19	3.36	4.49	-	-	-	-	-
hm		-	-	-	-	-	-	-	-	-	22	-	
ilm		-	-	-	-	-	6.53	0.74	22.61	5.51	-	2	
qtz	qtz	-	-	-	-	-	5.16	-	2.94	-	27	21	
	cr(F/S)	-	-	-	-	(sp=0.76)	(sp=1.78)	-	(cm=0.54, sp=0.43)	(cm=0.81, sp=1.66)	8	8	
Rock name		picritic olivine		olivine tholeiite		olivine tholeiite	qtz tholeiite	komatite	high K basalt	olivine basalt			

Footnotes and References for Table VII.

- Lava compositions recalculated for a Fe and Mg distribution coefficient (K_D) of .28 between olivine and coexisting liquids.
- Olivine tholeiite, Albemarle Island, Galapagos (McBirney and Williams, 1969, p. 121, analysis 63).
- Quartz tholeiite, Thingmali, Iceland (Carmichael, 1964, p. 439, no. 10).
- Peridotitic komatite, spineflex-textured lava from Manro Township, South Africa (Arndt, 1977, p. 557, Table 17).
- Apollo 11, high K basalt (average) } (Taylor, 1975,
- Apollo 12, olivine basalt (12009) } p. 136, table 4.3).
- Drift deposit of aeolian sediment from Viking site 1, less than 2 mm sized material sampled from 4 to 6 cm depth (Beird et al., 1976).

INFERRED COMPOSITION OF LAVAS FROM LAVA FLOW MORPHOLOGY

E. Schonfeld

The purpose of this work is to present a preliminary evaluation of certain topics related with Martian volcanism. The topics include: rocks, chemistry of samples, volcanoes, and channels. The data used are from the Mariner and Viking missions to Mars.

Martian rocks. Remarkably good pictures were obtained by the Viking missions of Martian rocks (1,2). Some of the rocks appear to be igneous and especially in the Utopia region (Viking 2 site) many appear very vesicular. Both features are consistent with a volcanic origin for these rocks.

Chemistry of Martian samples. The results of the Viking mission show that the chemistry of soils, fragments, and soil under the rock (Vk-2) have remarkably similar compositions even though the landing sites are about 6500 km apart (3,4). The chemistry of the samples has been interpreted as weathered products (such as clays) from igneous rocks (5). One explanation for the similarity in chemistry of materials at both landing sites could be wind transport. Differences in ultraviolet spectra (6) and in albedo on Mars (7) argue against this hypothesis.

An alternative explanation of the chemistry is that it is consistent with a basaltic composition rich in oxidized iron, volatiles and sublimates, with little or no weathering products. Both landing sites would represent products of basaltic volcanism with similar composition; this composition would be, relative to terrestrial basalts, rich in oxidized iron. The occurrence of such basalts would be consistent with estimates of the bulk composition of Mars (8,9).

Volcanoes. Mars has several volcanoes that apparently formed over a long period of time (10,11). The height of these volcanoes varies inversely with relative age based on the data by Carr (11); this is shown in figure 1. The source depth of a volcano can be estimated by calculating the hydrostatic head needed to pump magma to the top of the volcano (12). This calculation requires certain assumptions on the density of the magma, volcano, crust and mantle (see figure 2), so it is model dependent. The depth of the source is estimated at about 200 km for the tallest Martian volcano (9,11). Assuming the same density profile at all the volcano locations, the relationship shown in figure 1 suggests a variation of source depth with time. The older the volcano the closer to the surface is the source magma. A similar relationship (source depth with time) happens on the Moon based on many studies on lunar basalts (13,14,15) and is consistent with thermal models for the Moon (16,17). A thermal model for Mars (9) also indicates an increase in source depth of available liquids with time.

Martian channels. Some of the small channels that resemble lunar rilles and others closely related to volcanic constructs are almost certainly volcanic in origin (18,19). The large channels on the surface of Mars are one of the most puzzling features. These large channels show "fluvial" (tear-drop shaped) features apparently produced by a low viscosity fluid. Present consensus is that this fluid was water (19-23). Several difficulties exist with water as the fluid: 1) Under present pressure and temperature conditions on the surface of Mars, liquid water is not stable. 2) The source of the liquid appears to be highly localized in a chaotic terrain (22) and the location of the large channels along the cratered terrain-plains boundary (21) suggest an internal origin

process instead of an external process. The highly localized nature of the source of fluid argues against water by precipitation. Another possible source would be melted permafrost. Lava cannot melt large quantities of ice (25) probably because the heat capacity and heat of fusion of ice, are rather large. One possible way would be to have a source of geothermal energy near the surface that could melt the very large volume of water required to make the channels, but even then it might be necessary to increase the atmospheric pressure to keep water liquid. 3) The landing site of the Viking 1 mission was in the Chryse Planitia region (a low-lying basin) near the terminus of a large channel system. However, no evidence for a thick accumulation of sediments was found in the middle of the Chryse basin (26). 4) There is no evidence of deltas at the mouth of the large channels. 5) The Viking 2 landing site does not show large channels nearby and the region appears to be of volcanic origin (21); however, the chemistry of both landing sites appears to be almost identical (4). 6) Some of the large channel systems (i.e., Elysium, Hellas) are associated with volcanic constructs (21).

An alternative fluid, a low viscosity turbulent flow lava, is proposed for the origin of the large Martian channels. Most of the terrestrial lava flows are laminar flow and the main erosion mechanism is by melting (19) whereas on Earth water will, in most cases, have turbulent flow motion. Therefore, it appears that the "fluvial" features could be produced by the turbulent flow motion. If the viscosity is low enough (iron oxides and water will decrease the viscosity, see ref. 27), the lava flow could be turbulent on Mars and might produce "fluvial" features. None of the difficulties for water as a fluid are absolute, but it appears that lava could better explain the origin of the large channels. One of the problems with lava could be cooling, but if the volume rate is large enough, the viscosity is low, and some low heat conductivity crust is formed, lava could then travel very long distances without accumulating near the source (28-30). Another potential problem with lava is that it might require a near-surface origin (19). The large channels are very old (24) and as shown before (see previous section on volcanoes), the data on volcanoes suggests that there could have been near-surface sources of lava at the time of channel formation. The Chryse basin volcanism and "fluvial" modification of the region were not separated greatly in time (26). This supports the hypothesis of lava as the fluid that produced the large Martian channels.

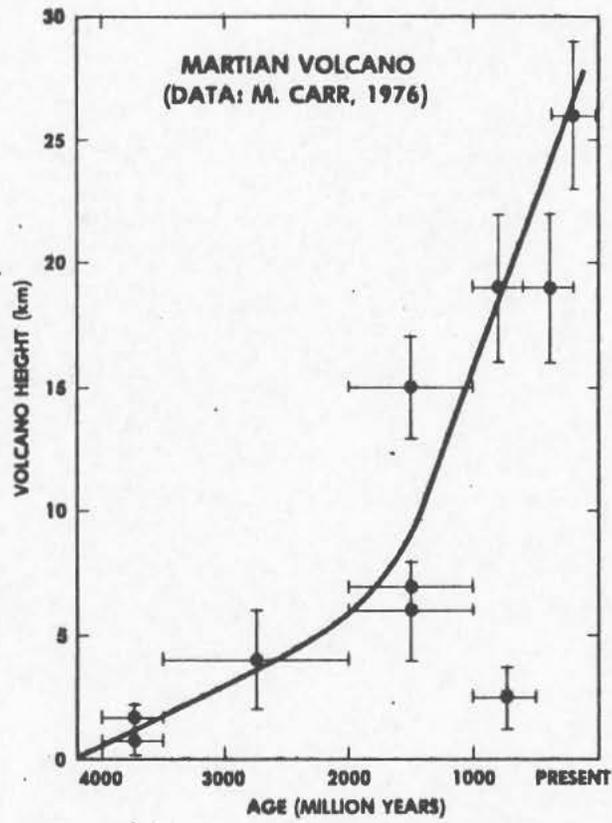
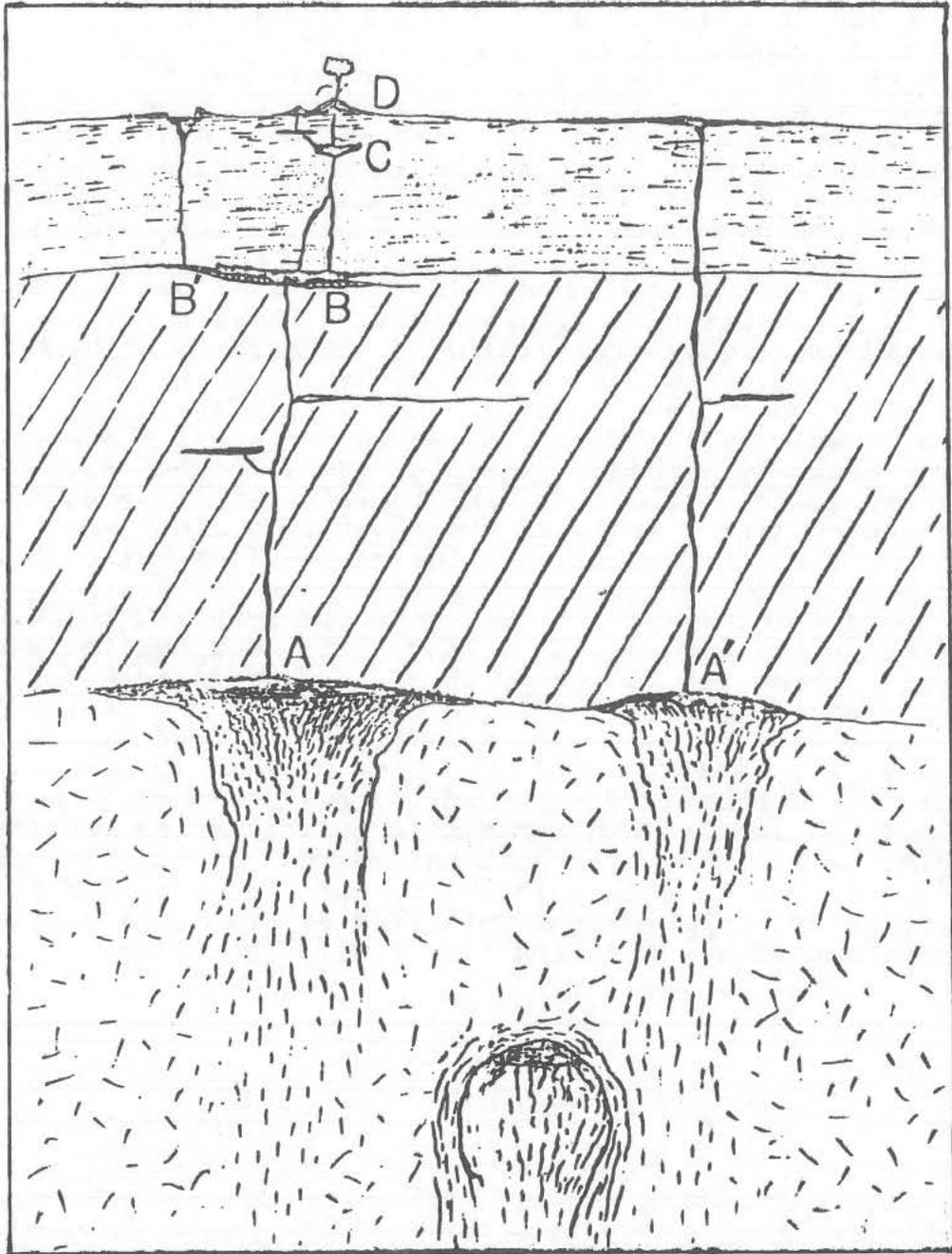


Figure 1. Martian volcanoes. Height is approx. inversely proportional to relative age.

OVERVIEW ON BASALT GENESIS ON THE MOON AND EARTH

D. Walker

Experimental petrology is important to studies of the generation of basaltic magmas because the composition of magmas is largely controlled by crystal-liquid phase equilibria. These equilibria may be determined in laboratory experiments and used to discover the controls on basalt composition. These equilibria vary as a function of pressure and so basalt compositions controlled by equilibria at the (high) pressure appropriate to their source regions may be informative about the mineralogy of the residual source region crystals. However, the basalts erupted in the largest volumes on the earth and moon (and the eucrite parent planet) have compositions which are controlled by crystal-liquid interaction at low pressures. Basalts which have compositions controlled by crystal-liquid interaction at high pressures (and therefore might be informative about the petrology of the mantle) are much less abundant. We should anticipate that similar relationships will be discovered on the other terrestrial planets. Consequently a randomly sampled basaltic rock from Mars or Mercury is more likely to contain information about its emplacement and cooling history in the crust than about the constitution of the source region in the mantle from which it was derived. This mode of basalt genesis is seen in A + D in the figure. Magma ponding and fractionation occur in A + D to obscure the direct connection between the primary magma segregation and direct eruption shown schematically at A'. In cases such as A' where direct eruption of primary magma does occur, the chemistry of primary magma cooling units may be affected by crystal settling right at the site of emplacement. Examples of this are evident in each suite of mare basalts returned in the Apollo program and is very common in picritic and komatiitic primary magma cooling units on earth. This mode of fractionation must be expected on Mars as well and considerable selectivity must be exercised in choosing samples for experimental work if they are to be relevant to a determination of the constitution of Mars' interior.



IRON-BEARING SILICATE SYSTEMS AND THEIR BEARING
ON BASALT PETROGENESIS ON EARTH AND MARS

D. C. Presnall

Basaltic lavas are the result of some combination of chemical control by partial fusion at the source, fractional crystallization on the way to the surface, and possibly contamination and mixing processes. Existing liquidus phase diagrams for iron-bearing systems are almost totally limited to one atmosphere pressure and thus are useful for Mars studies only to the extent that the lavas are fractionally crystallized under near-surface conditions. All the existing data show that fractional crystallization at constant bulk composition leads to an iron-rich residual liquid, whereas iron-enrichment can be suppressed if the oxygen fugacity is buffered at a high enough value to produce a large magnesioferrite field (Figures 1 and 2). High pressure liquidus studies are most complete for the system $\text{CaO-MgO-Al}_2\text{O}_3\text{-SiO}_2$ up to about 20 kb. The next obvious steps are (1) to extend these data to higher pressures where garnet is involved in the equilibria and (2) to add iron oxide and possibly Na_2O to the system. When this is done it will be possible to model the melting behavior of all the terrestrial planets to a very close approximation, if volatiles can be ignored. Experimental methods for studying iron-bearing systems at one atmosphere pressure are now solved and are probably not formidable at high pressures, at least under anhydrous conditions.

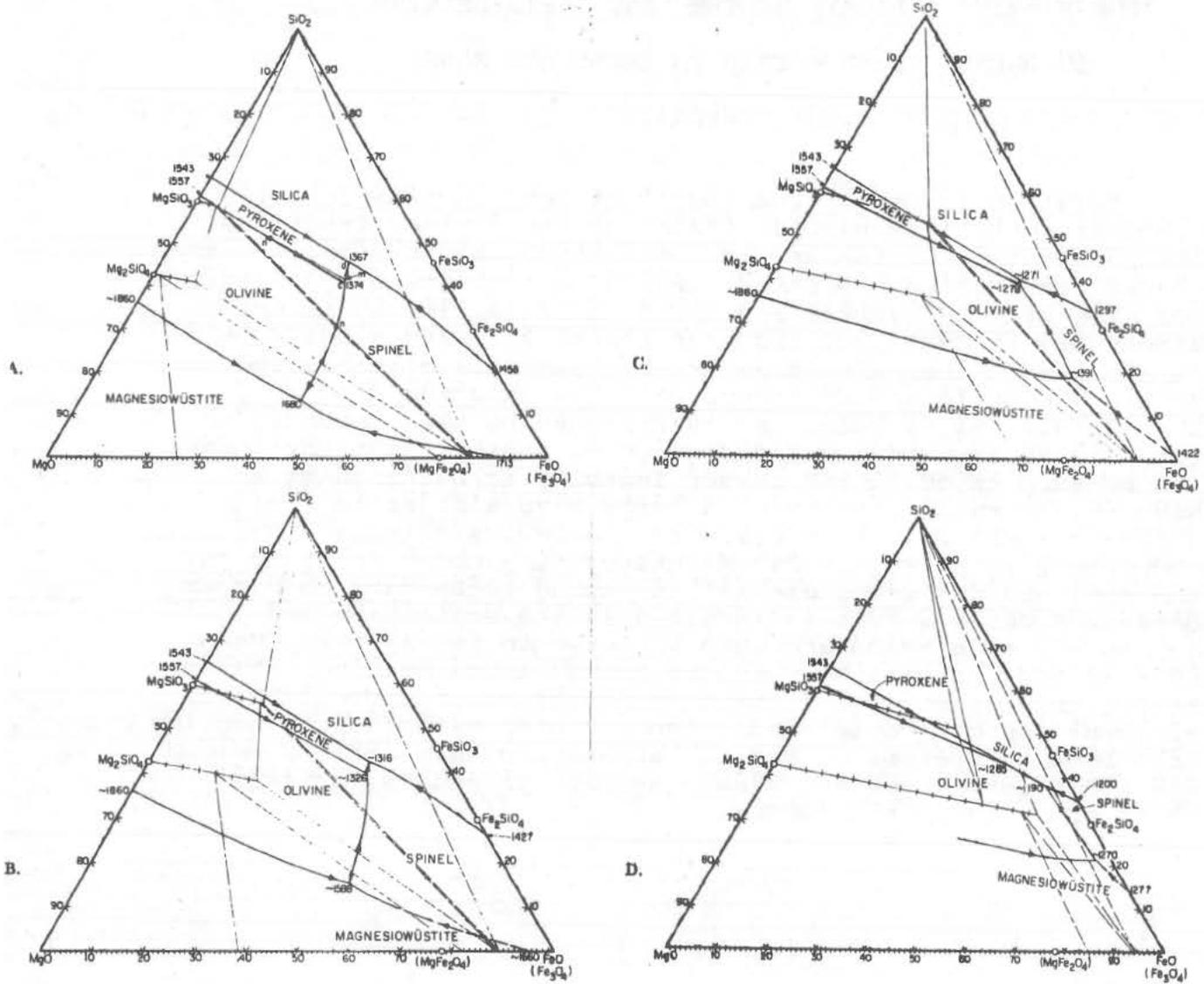


Figure 1

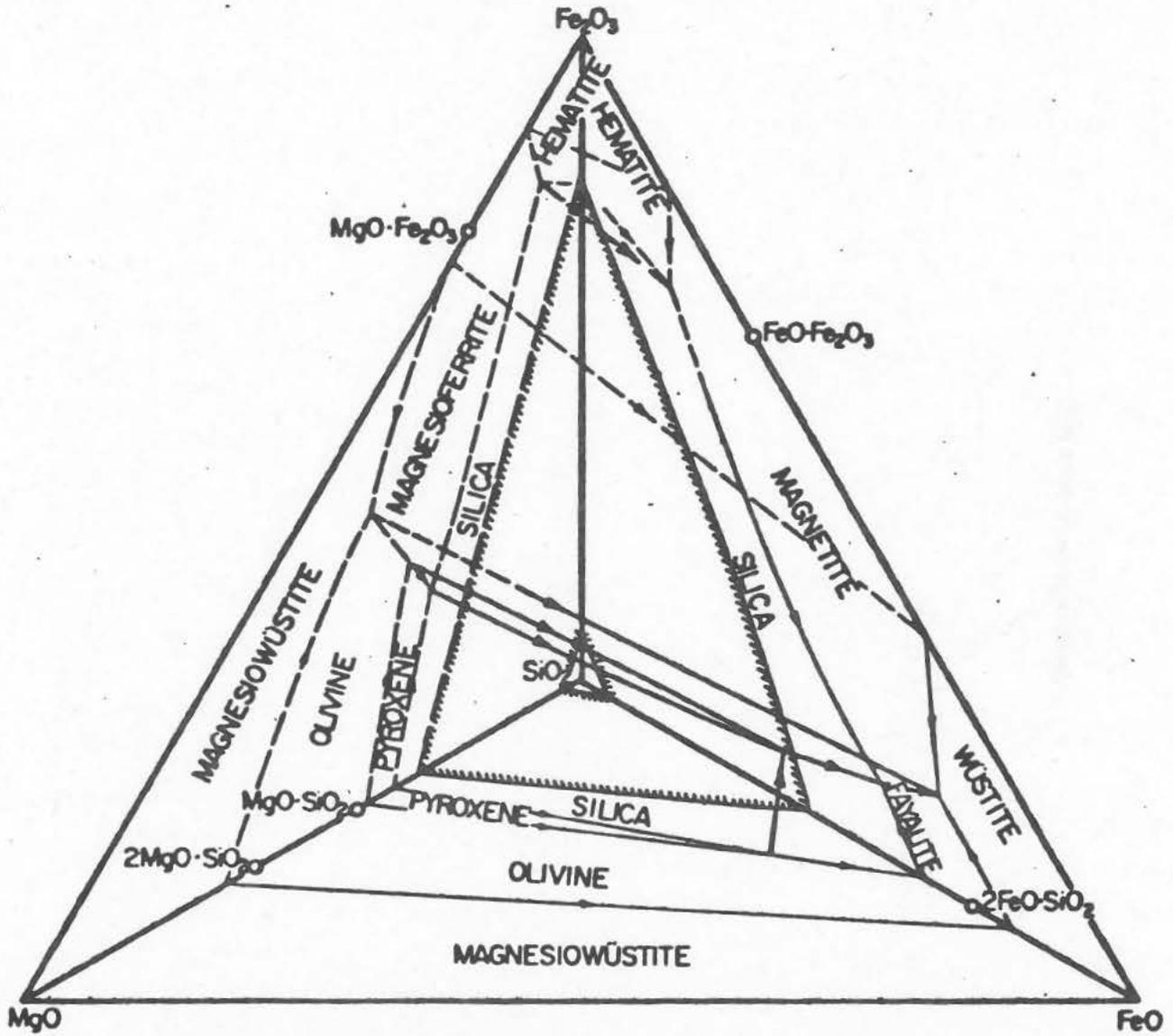


Fig. 2 Diagram showing phase relations in the liquidus temperature region of the system $\text{MgO-FeO-Fe}_2\text{O}_3\text{-SiO}_2$, after Muan and Osborn.^(27,28) Boundary curves on the four faces of the tetrahedron are drawn as light lines, and those within the tetrahedron as heavy lines.

SULFIDE-SILICATE RELATIONS

M. C. Gilbert

1) Igneous (solid-liquid equilibria)
System FeO-FeS-SiO₂

Principles Illustrated by the System

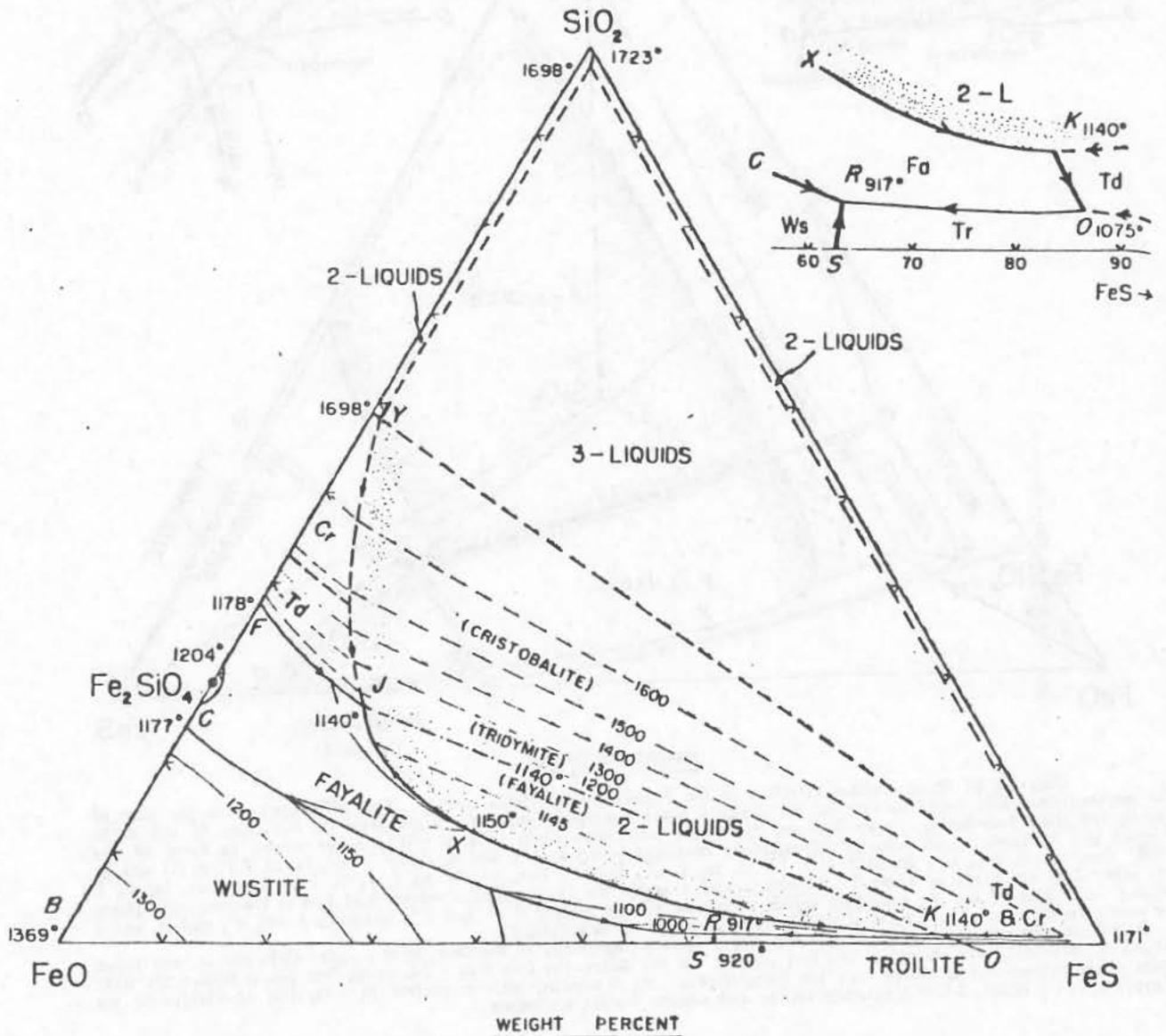
- a) For simplified bulk composition: 2 crystalline assemblages:
Po + Fa + Qtz
Po + Wu + Fa
- b) Addition of S does not lower solidus temperature all that much - interestingly less for Qtz-bearing assemblages than for oxide-bearing ones (Qtz-bearing ones melt at higher temperature!)
- c) Very iron-rich L (lava) formed on melting either of these assemblages.
- d) For most of compositional space (~65%) get a more S-rich liquid.
- e) Qtz (silica polymorph) bears reaction-relation with L when coexisting over good part of the Fa + Qtz + L range.
- f) Boundary curves have extremely shallow slopes - so small changes in temperature make big differences in L loop.
- g) High f_{O_2} - put more SiO₂ in L (shift boundary curves).
- h) High P - generate FeSiO₃ (ferrosilite) and new join.

2) Metamorphic (solid-vapor equilibria)
System Biot + Sulfur from Tso, Gilbert, Craig submitted to
Amer. Min. 1978

- a) Balance between f_{O_2} - f_{S_2} to get coexisting sulfides and oxides (po + mt)
- b) At higher f_{O_2} - silicates become more Mg-rich
at higher f_{S_2} - silicates become more Mg-rich (small variations in f_{S_2} make bigger difference than small variations in f_{O_2})
- c) Need biot coexisting with mt + po to be able to apply these data - choose natural samples carefully.

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- Haughton, D. R., Roeder, P. L., and Skinner, B. J., 1974, Solubility of sulfur in mafic magmas. Econ. Geol. 69, 451-467.
- MacLean, W. H., and Shimazaki, H., 1976, The partition of Co, Ni, Cu, and Zn between sulfide and silicate liquids. Econ. Geol. 71, 1049-1057.



The FeS-FeO-SiO₂ system as revised by MacLean (1968, 1969) after Ol'shanskii (1951) and Yazawa and Kamada (1953). All phases are in equilibrium with iron (below its melting point) except troilite; thus phase boundaries are projected onto this plane from within the FeS-Fe-Fe₂O-SiO₂ system. The edge of the two-liquid field (silicate and sulfide liquids) is stippled. Contours within the two-liquid field are on the surfaces between this field and the fields of the crystalline phases (in parenthesis). JK is an isothermal trough. Detail of the area around R, K, and O is shown (distorted) in the inset.

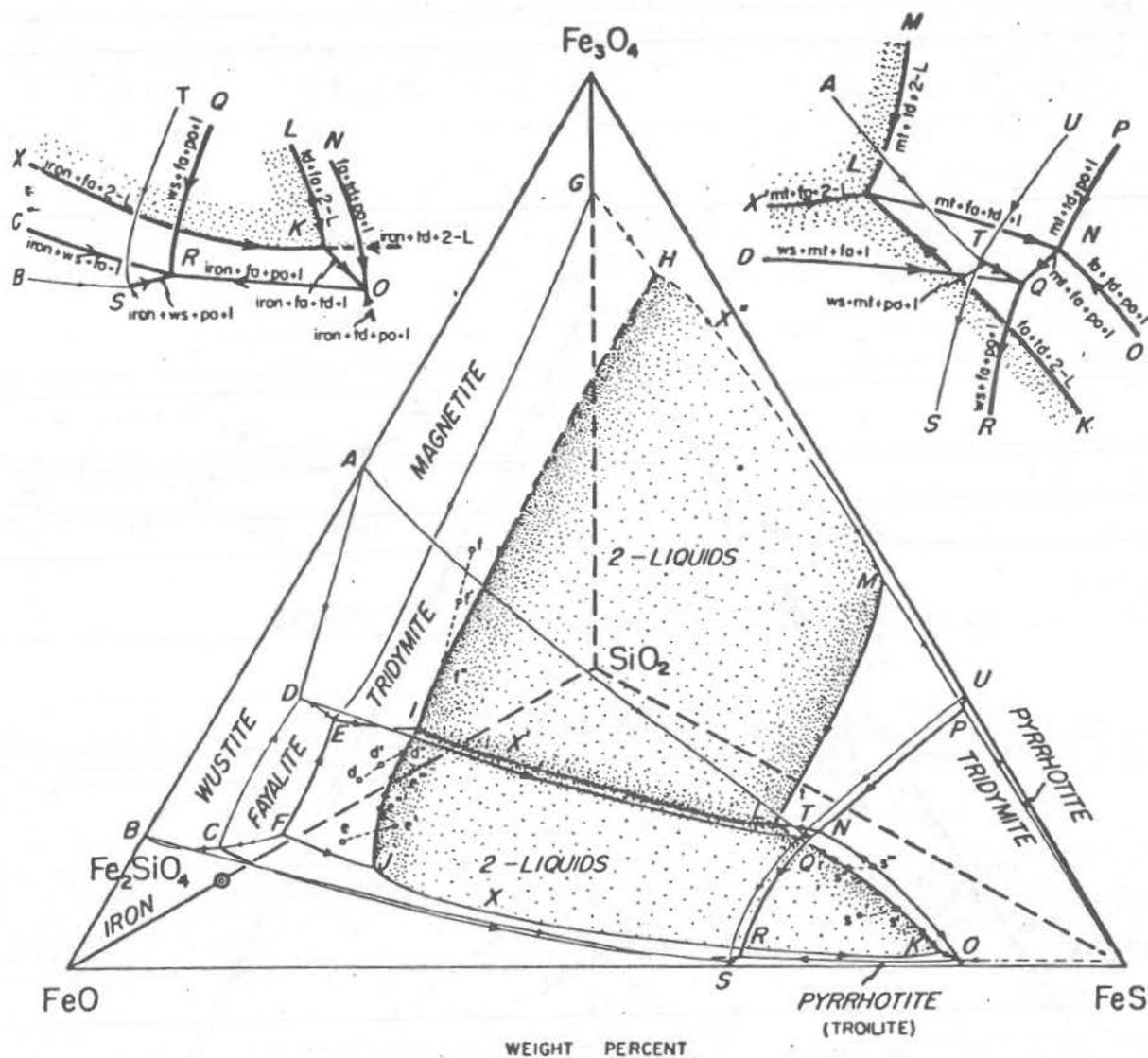
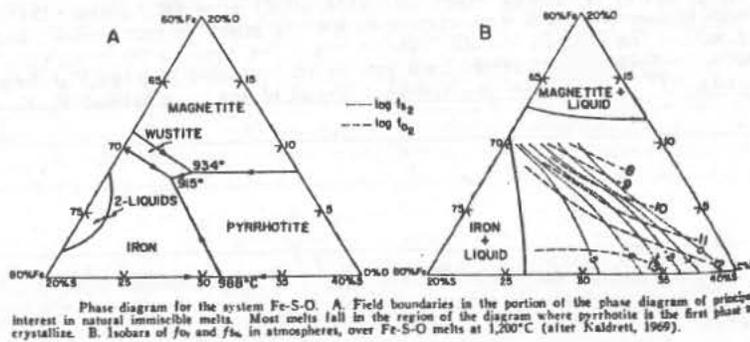
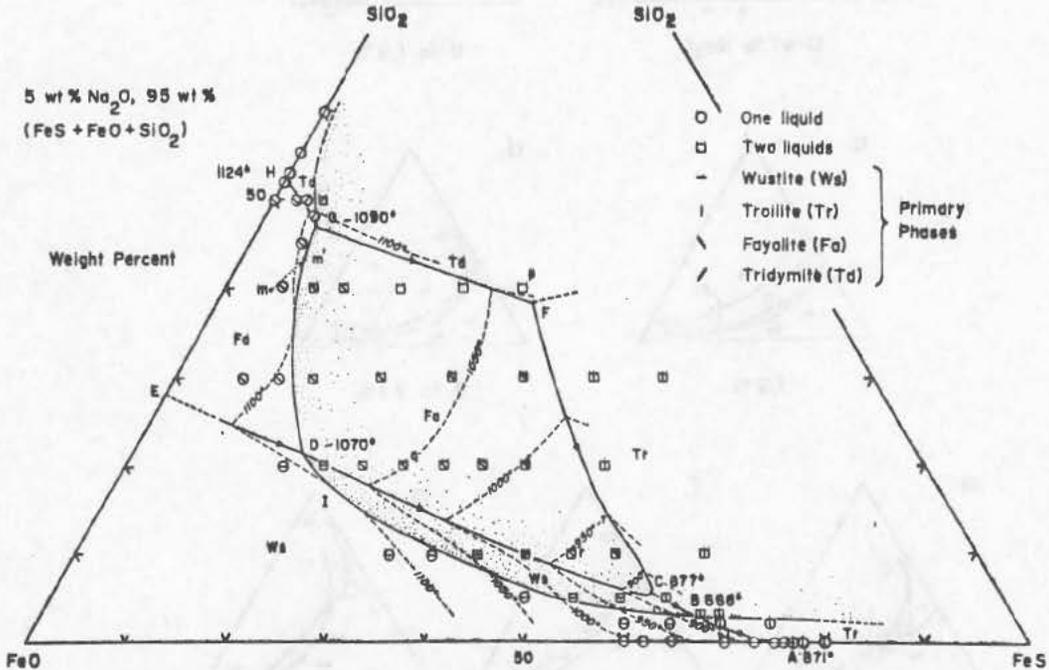


Diagram of liquidus phase relations in the $\text{FeS-FeO-Fe}_3\text{O}_4\text{-SiO}_2$ system. The SiO_2 apex is to the rear of the tetrahedron. The front surface of the 2-liquid phase volume is stippled. Light lines on the faces of the tetrahedron are phase boundaries; heavy lines are quaternary univariant lines. Phase relations are shown in front of the 2-liquid and tridymite phase volumes. Quaternary invariant points are: J and K, $1,140^\circ$ (iron, fa, td, 2-L, v); I and L, $1,095^\circ$ (mt, fa, td, 2-L, v); N, 955° (mt, fa, td, po, l, v); Q, 945° (ws, mt, fa, po, l, v); R, 917° (iron, ws, fa, po, l, v); other data are given in Table I. Liquids *d* and *e* are in the fayalite phase volume and *f* is in the magnetite phase volume. *s*, *s'* and *s''* are the conjugate sulfide liquids of silicate liquids *e'*, *e''* and *e'''*; similarly *r* and *d''*, and *f''* and *t* are conjugate liquids. The $\text{FeO-Fe}_3\text{O}_4\text{-SiO}_2$ ternary is after Muan (1955).

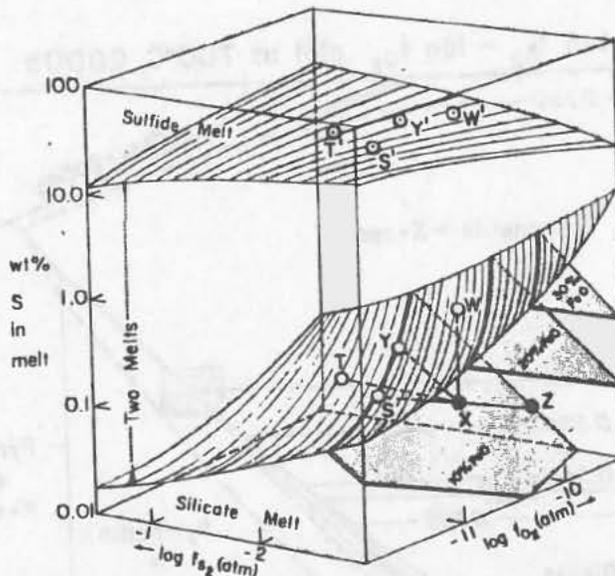
Details around invariant points L, N and Q are shown (distorted) in the inset in the upper right corner, and those around R, K and O are shown in the left corner. In the latter, the iron + td + 2-L univariant line is behind the tridymite phase volume but is shown here for completeness. ws = wustite, mt = magnetite, fa = fayalite, td = tridymite, po = pyrrhotite, l = liquid, 2-L = coexisting sulfide and silicate liquids, v = vapor.



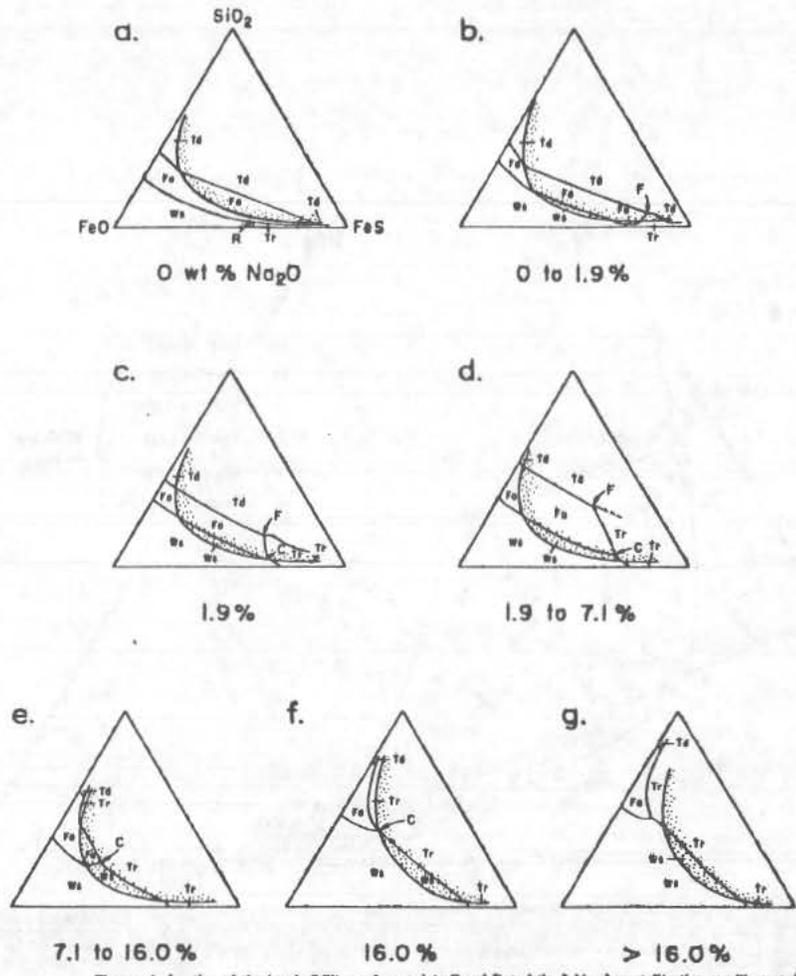
Phase diagram for the system Fe-S-O . A. Field boundaries in the portion of the phase diagram of practical interest in natural immiscible melts. Most melts fall in the region of the diagram where pyrrhotite is the first phase to crystallize. B. Isobars of f_0 and f_1 in atmospheres, over Fe-S-O melts at $1,200^\circ\text{C}$ (after Kaldrett, 1969).



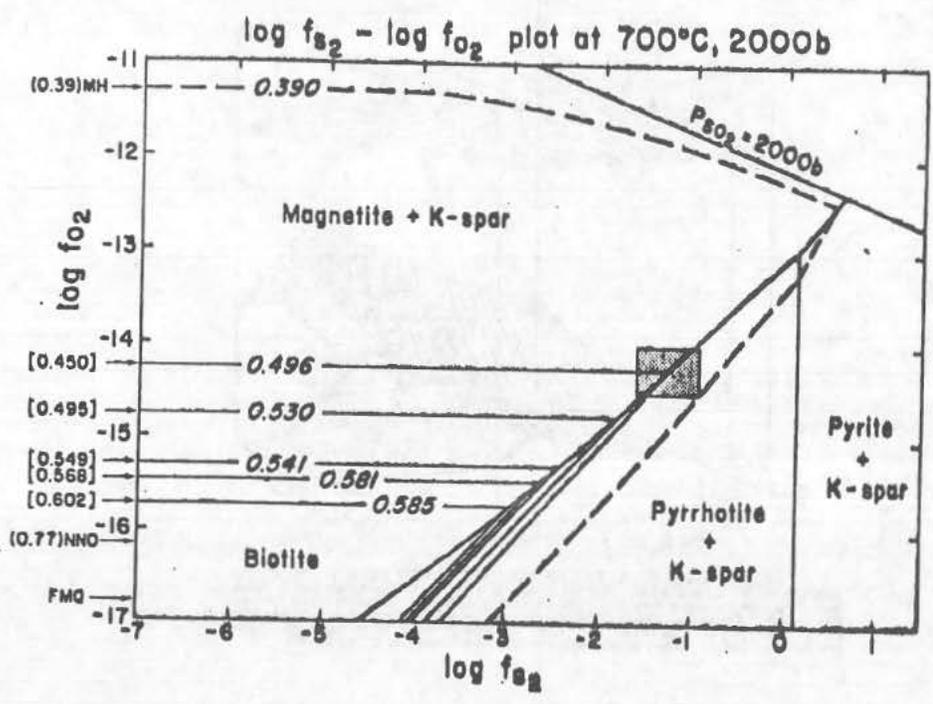
Liquidus phase relations on the 5 wt % Na₂O section in the FeS-FeO-SiO₂-Na₂O system. The two-liquid region is stippled. Temperatures are shown in degrees centigrade on the liquidus surface. The curves separating the fields of primary crystallization are also shown extended under the field of liquid immiscibility. Contours and slope arrows show temperature variations across the diagram. However, it must be emphasized that this is an isocompositional section and not a liquidus surface. Crystallization paths, such as m m', do not lie in this plane but project through it, i.e., melts initially having less than 5% soda may be enriched to in excess of 5% soda by crystallization of nonsoda-bearing phases.



Relation between f_{O_2} , f_{S_2} , FeO, and S contents of basaltic magmas at 1200°C. The sulfide saturation surface defines the sulfur content of a magma in equilibrium with a sulfide melt. The lines connecting coexisting melts are parallel to the axis on which the sulfur content is plotted (vertical). Planes in the silicate melt volume are contours of constant FeO content of the magma. The circles, T, S, Y, W, represent silicate melts on the sulfide saturation surface (shaded). These silicate melts coexist with sulfide melts T', S', Y', W'.



Changes in location of the immiscibility surface, points C and F and the fields of crystallization are illustrated by a series of simplified schematic sections at increasing soda contents. (a) The soda-free system of MacLennan (1968) was discussed and presented as Figure 3. (b) For soda additions up to 1.9 wt % (from run B138, Table 1) the assemblage Tr + Ws + Fa (+ lcs) corresponding to invariant point R from Figure 3 moves along a univariant curve but remains in the one-liquid region. However, the wustite field has expanded and partly underlies the immiscibility field. (c) The



ROLE OF VOLATILES IN BASALT PETROGENESIS

R. Merrill

Volatiles, probably H_2O and CO_2 for the most part, "lubricate" igneous processes on the Earth by lowering the temperatures required to produce magmas. While lunar magmas appear to have contained only small amounts of CO_2 , Mars appears to possess abundant supplies of both H_2O and CO_2 ; therefore much of what we have learned about igneous activity on Earth may be applicable to Mars as well. Mars also appears to possess significant amounts of sulfur, the behavior of which is less well-understood.

Volatiles are stored within planetary mantles as components of magmas, of free fluid phases, or of minerals. Minerals thought to be important reservoirs of volatiles within Earth's mantle include calcic dolomite, calcic amphiboles, phlogopite, humites, and an (as yet poorly-understood) high-pressure sheet silicate.

Figure 1 is a schematic representation of the melting of peridotite ("parental" material) and of a silica-undersaturated basalt ("magma") in the presence of water. These solidus and liquidus curves are the loci of pressure-temperature conditions required to produce basaltic magmas within planetary mantles composed of peridotite. Note that the addition of even a small amount of water to peridotite at 200 km depth would reduce the temperature of first melting by $600^\circ C$. Additional water or a rise in temperature would cause a larger percentage of the rock to melt. Similarly, the derived basaltic liquid remains stable over a wide range of temperatures, only beginning to crystallize once the temperature drops below the liquidus as constrained by the amount of water available.

Figure 2 shows the dehydration reactions of amphibole, titanoclinohumite and phlogopite in the presence of excess water. The high-pressure reversal to a negative slope is typical, and implies mineral instability with increasing pressure as well as increasing temperature. If the only water present in the system is bound in mineral lattices, then initial melting is delayed until dehydration of the mineral begins (Figure 3); hence such minerals can exert very important controls on melting reactions.

Addition of CO_2 to rock systems has less effect on melting temperatures than the addition of water (Figure 4), reducing the peridotite melting temperature only by about $400^\circ C$ at 200km,

but may alter the compositions of resulting melts markedly towards silica-undersaturation. Similarly, the high-pressure basalt liquidus temperature is depressed only 100°C by the solution of 9 percent CO₂, but drops 350°C on the addition of 9 percent H₂O (Figure 5).

Knowledge of the presence or absence and relative abundances of these volatiles within the martian mantle is crucial to our understanding of igneous processes active on Mars.

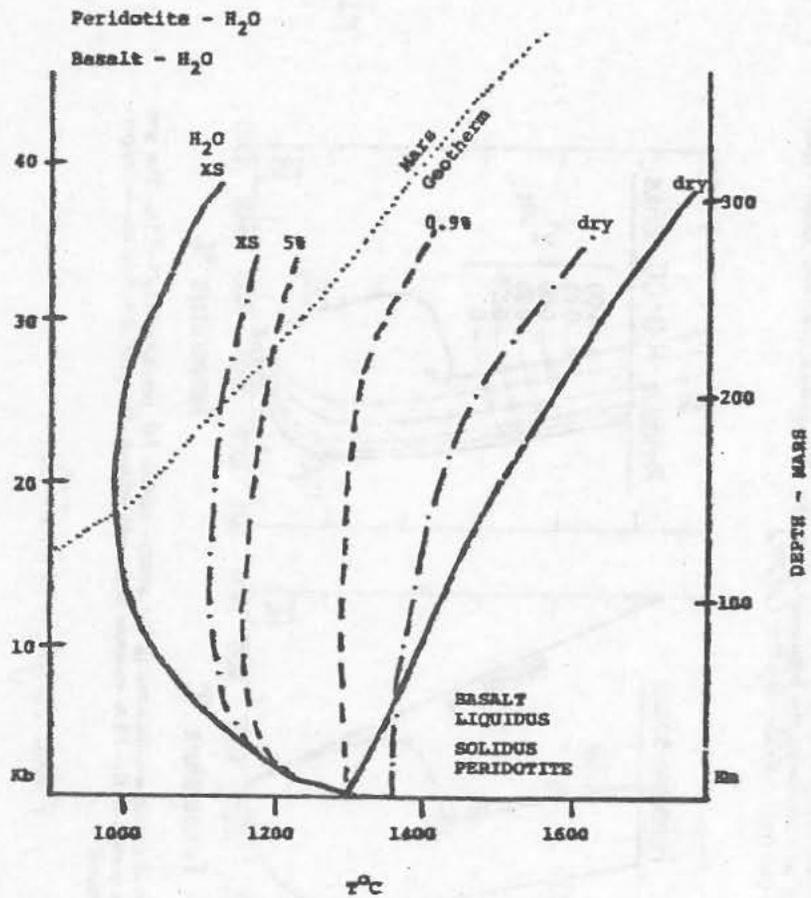


Figure 1

HYDROUS MINERAL BREAKDOWN

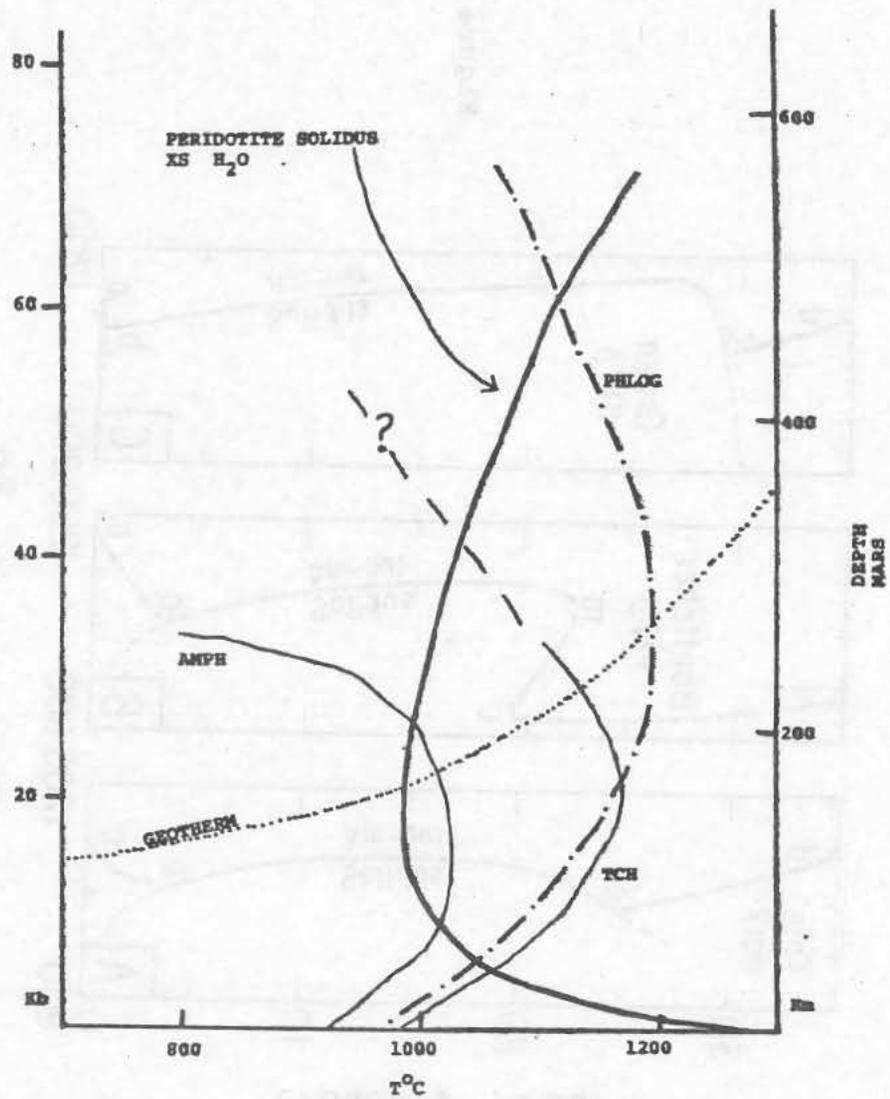


Figure 2

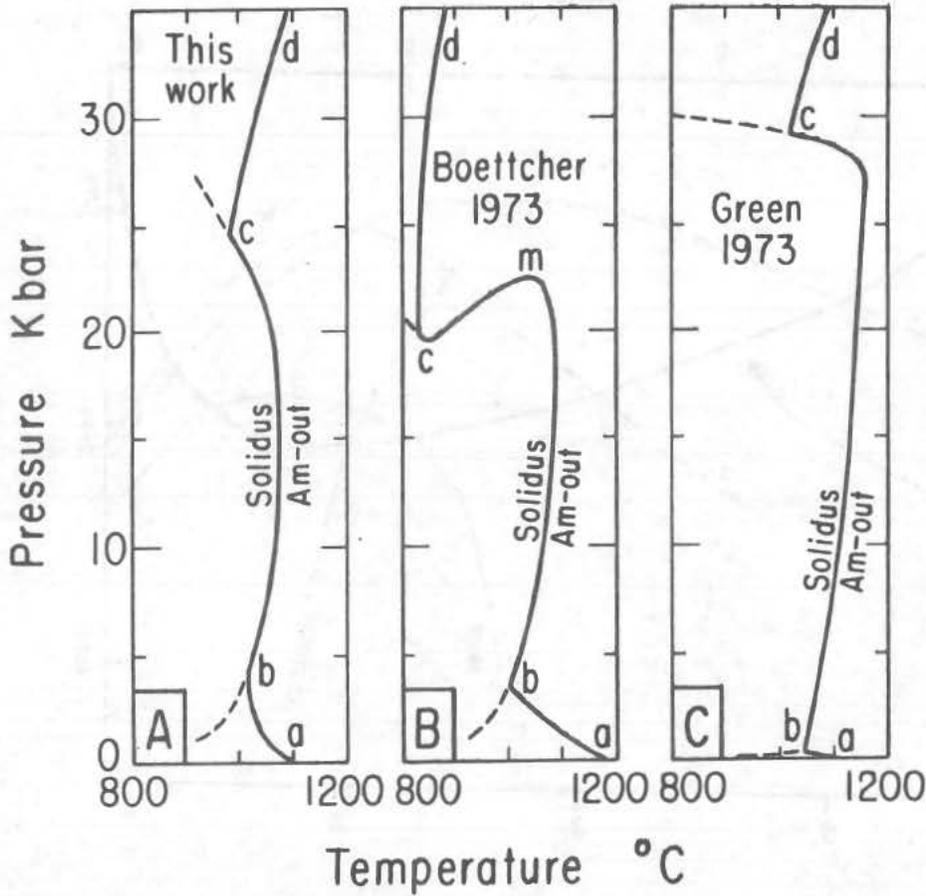


Figure 3

—Comparison of results of three studies on the solidus of peridotite in the presence of 0.2 wt% water. In each case, portions a to b and c to d are coincident with the water-saturated solidus; the solidus from b to c represents the beginning of melting of amphibole peridotite under vapor-absent conditions (see text). *After Wyllie (1977).*

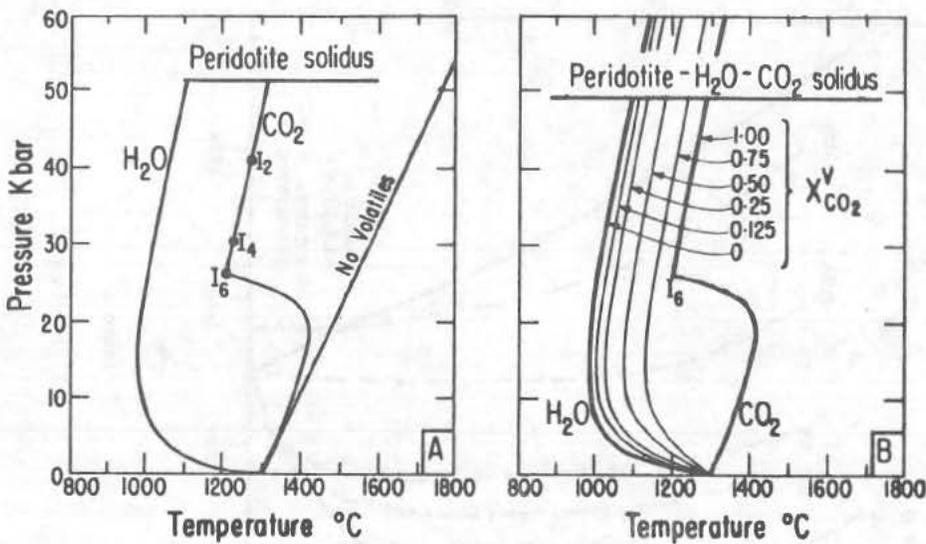


Figure 4

—Schematic diagram illustrating the solidus surface for peridotite-H₂O-CO₂. The geometrical shape is correct in the PTX volumes of present interest, but precise values require experimental determination.

From Wyllie (1977).

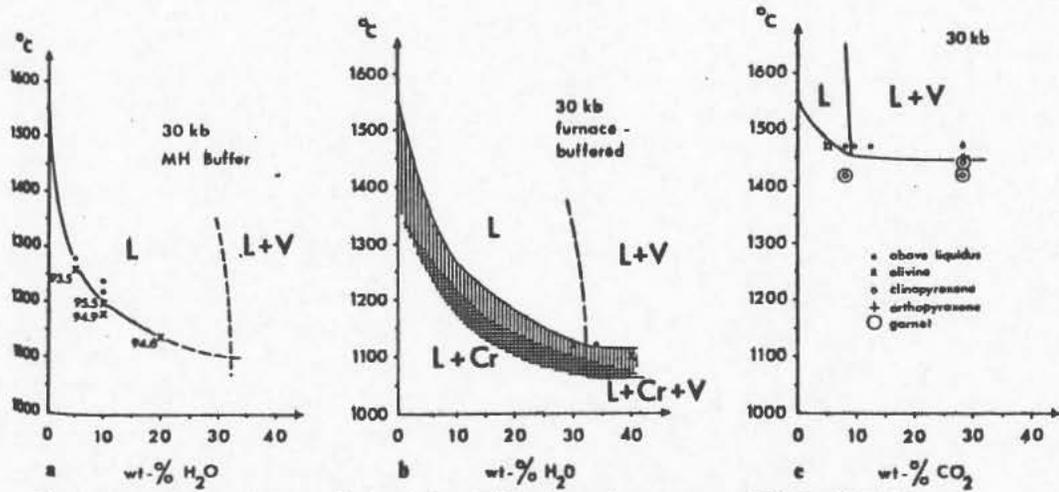


Fig. 3a. Liquidus of olivine melilitite 2927 at 30 kb with various amounts of H₂O added. Numbers are forsterite content in olivine. b Determination of maximum solubility of H₂O in olivine melilitite 2927 at 30 kb. Liquidus temperatures interpolated from experiments at 25 and 35 kb (Brey and Green, 1975). Vertical lines represent a field with olivine alone as liquidus phase, the hatched area with olivine and clinopyroxene. c Liquidus and liquidus phases of olivine melilitite 2927 at 30 kb with various amounts of CO₂ added. *From Brey and Green (1977).*

Figure 5

PARTIAL MELTING OF THE EARTH'S MANTLE
AND BASALT PETROGENESIS

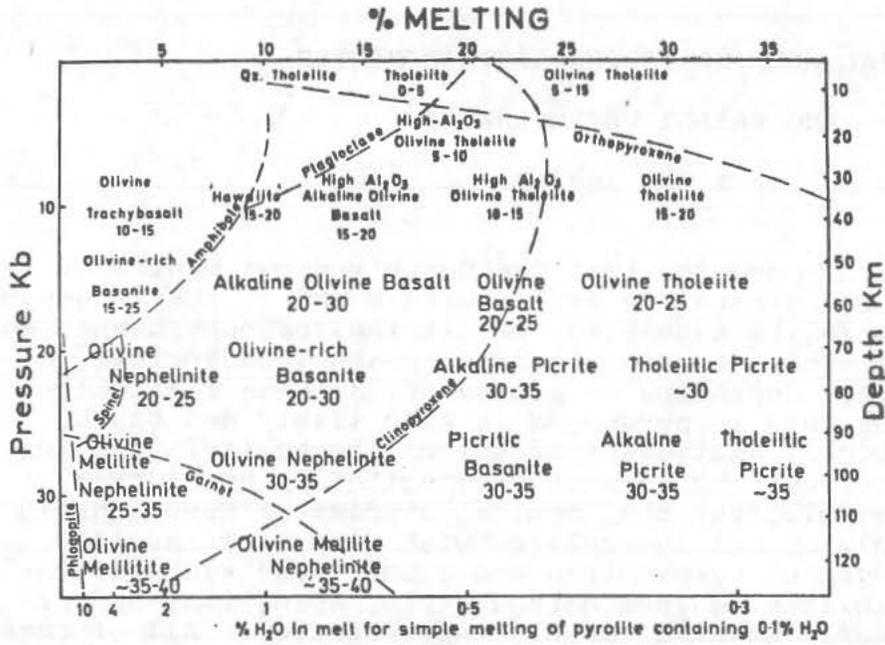
A. J. Irving

There is a consensus that the Earth's upper mantle is peridotite. The mineralogy varies with P and T, but is generally a 4-phase lherzolite assemblage of olivine, orthopyroxene, and clinopyroxene with a fourth aluminous phase (plagioclase, spinel or garnet depending on pressure); 3-phase lherzolite with all Al_2O_3 held in pyroxenes is also likely and can be viewed as a high T equivalent of spinel lherzolite. The most direct evidence bearing on mantle constitution comes from continuing petrological and chemical studies of xenoliths in basalts (mainly spinel lherzolites with some Al-Ti-augite pyroxenites, garnet pyroxenites and gabbro) and kimberlites (garnet lherzolites, garnet harzburgites, eclogites) and of Alpine ultramafic massifs (mainly harzburgites). All of these are probably modified mantle samples, broadly of 2 classes (residues after partial melting and high P cumulates or related liquids). Recent complexities are the reality of mantle heterogeneity and mantle metasomatism.

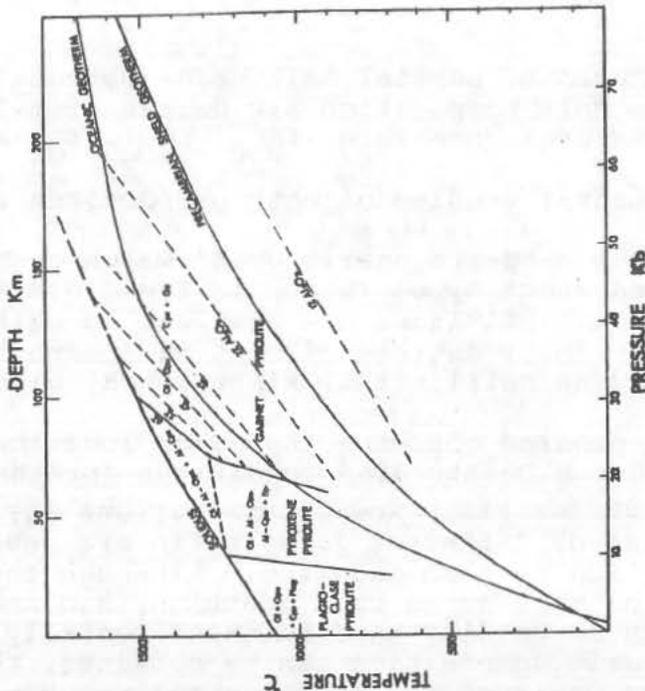
The major and trace element chemistry of basalts also places important constraints on mantle constitution. Simple consideration of Fe-Mg exchange equilibrium between olivine and basaltic liquid yields the constraint that for mantle olivine $Fo_{86} - Fo_{90}$ primary magmas must have $100Mg/Mg+Fe^{2+}$ of 66-75. Magmas with lower "Mg-values" must have fractionated (at high or low P). Trace elements (especially REE) can, for example, distinguish among residual mineralogies containing plagioclase, spinel or garnet.

Basalts are produced by partial melting of peridotite. The major controls on melt composition are degree of melting (equivalent to temperature), pressure, f_{H_2O} , f_{CO_2} , f_{O_2} and perhaps f_{S_2} . Experimental studies of both peridotites and basalts are building up a "petrogenetic grid" which currently explains most observed magma types (which in fact form a continuum). H_2O and CO_2 activities are critical to melt compositions formed by small degrees of melting (basanites, potassic basalts, olivine melilitites, kimberlites, carbonatites).

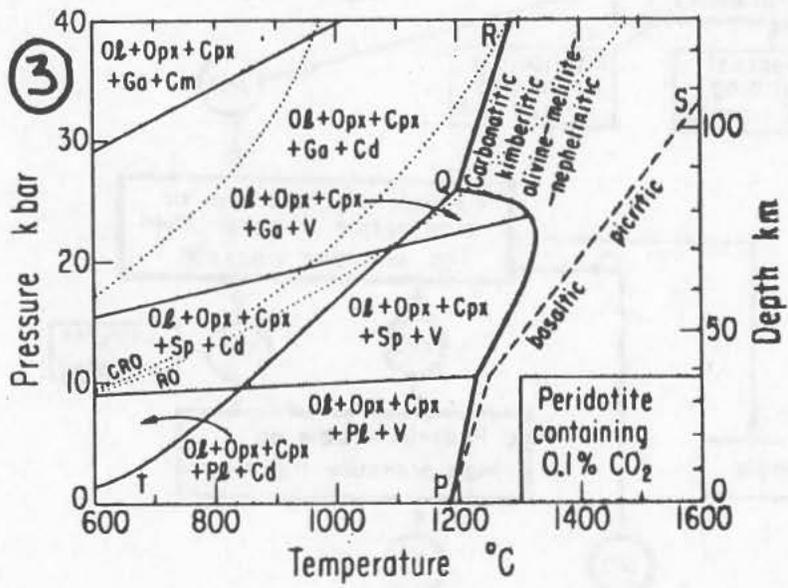
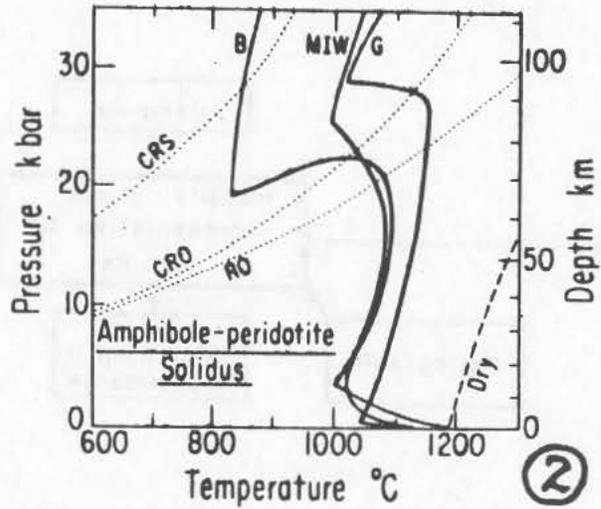
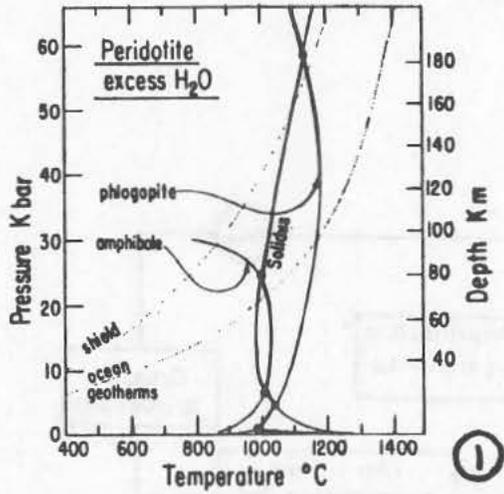
One outstanding problem concerns the exact location of peridotite solidi under H_2O -saturated conditions (present results range over $200^{\circ}C$ at 20 kbar!!). New determinations for a variety of peridotites of different Fe/Mg ratio are needed for both terrestrial and martian modeling. Although the nature of volatiles on Mars is an open question, H_2O and CO_2 appear likely and can be readily handled experimentally. If a martian surface basalt composition can be obtained, the attached flow diagram outlines the experimental procedures used in attempting to deduce the internal constitution of the planet.



(Green 1970). A petrogenetic grid for mantle-derived basaltic magmas. Various basalt magma types are assigned to a % Melt, Pressure grid (implying also specific % H₂O and temperature of melting, see figs. 2 and 3) in which they are regarded as partial melting products of a pyrolite composition containing 0.1% H₂O. The numbers placed with each basalt type refer to the normative olivine content of this liquid at its depth of origin—because of the expansion of the olivine crystallization field at low pressure most basalts will precipitate olivine before other phases if fractionation occurs at lower pressures. The dashed boundaries marked with a mineral name show that this mineral will occur among the residual phases remaining after extraction of magma types to the left of the boundary. Olivine is present in equilibrium, i.e. is a residual phase in the pyrolite composition for all the magma types, cf. fig. 3.

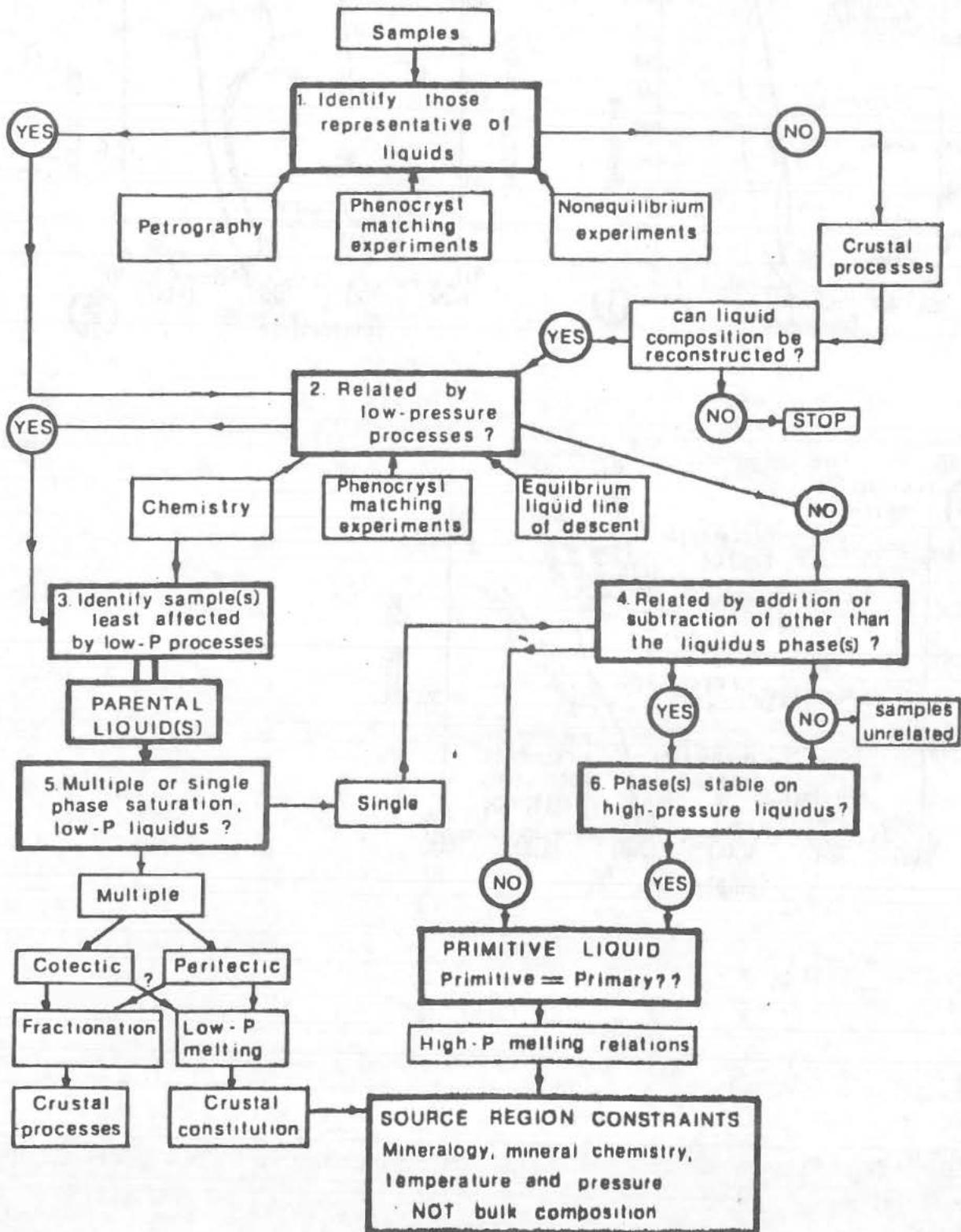


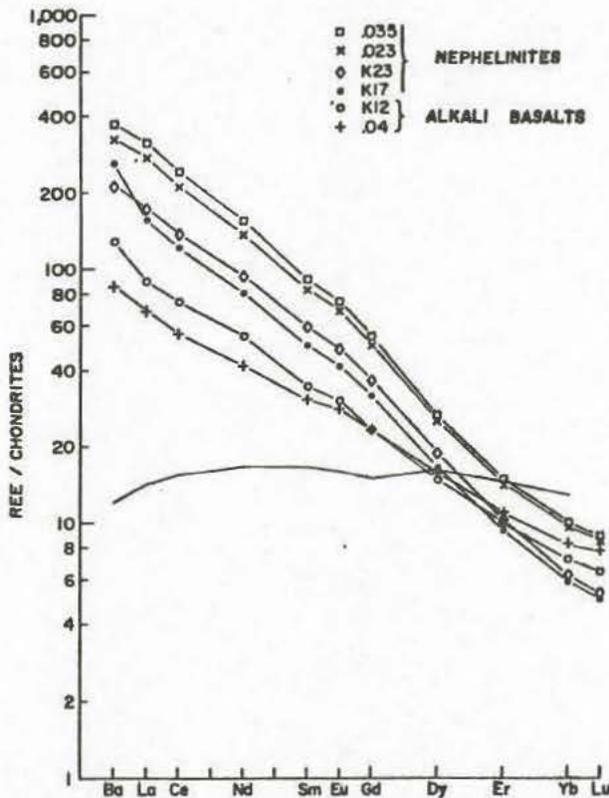
(Green and Ringwood 1967a). Diagram illustrating the P, T, fields of different mineral assemblages in pyrolite composition under anhydrous conditions. The figures 1% Al₂O₃, 2% Al₂O₃, 3%, 4% etc. refer to the Al₂O₃ content of orthopyroxene in equilibrium with garnet, clinopyroxene and olivine in the garnet pyrolite field. Positions of two estimated geothermal gradients are also shown.



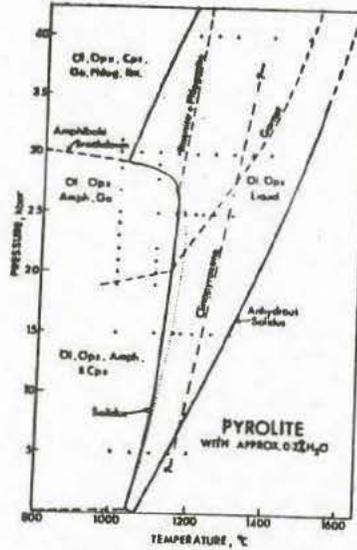
EXPERIMENTAL PETROLOGY FLOW DIAGRAM

UsseIman, T.M. and BVSP Team 3

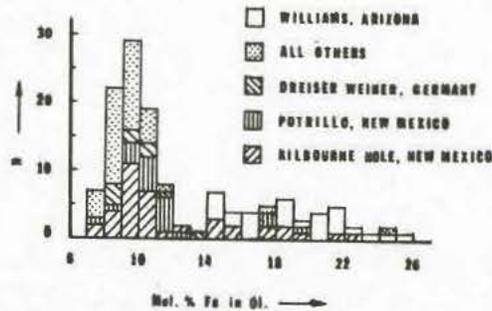




—The rare earth content of nephelinites (O23, O35, K23, K17) and alkali basalts (O4, K12) from Oahu and Kauai, plotted as multiples of chondritic meteorites (table 2). The line without points is a tholeiitic midocean ridge basalt (see fig. 1). Note the high concentrations of light rare earths in the nephelinites and lower concentrations in the alkali basalts. The nephelinite patterns are roughly parallel. The alkali basalts have higher heavy rare earths than two of the nephelinites. None of the samples has a europium anomaly.



Solidus temperature, and both sub-solidus and above-solidus mineralogy for pyrolite + 0.2% water. Specific minerals are present as residual phases in the melting interval at temperatures below the dashed curves marked garnet, clinopyroxene etc. Olivine and orthopyroxene are residual phases at all experimental points shown. Note that the geotherms of Fig. 13 would intersect the solidus for pyrolite + 0.2% H₂O at ~29 kbar (D.H. Green, 1978a).

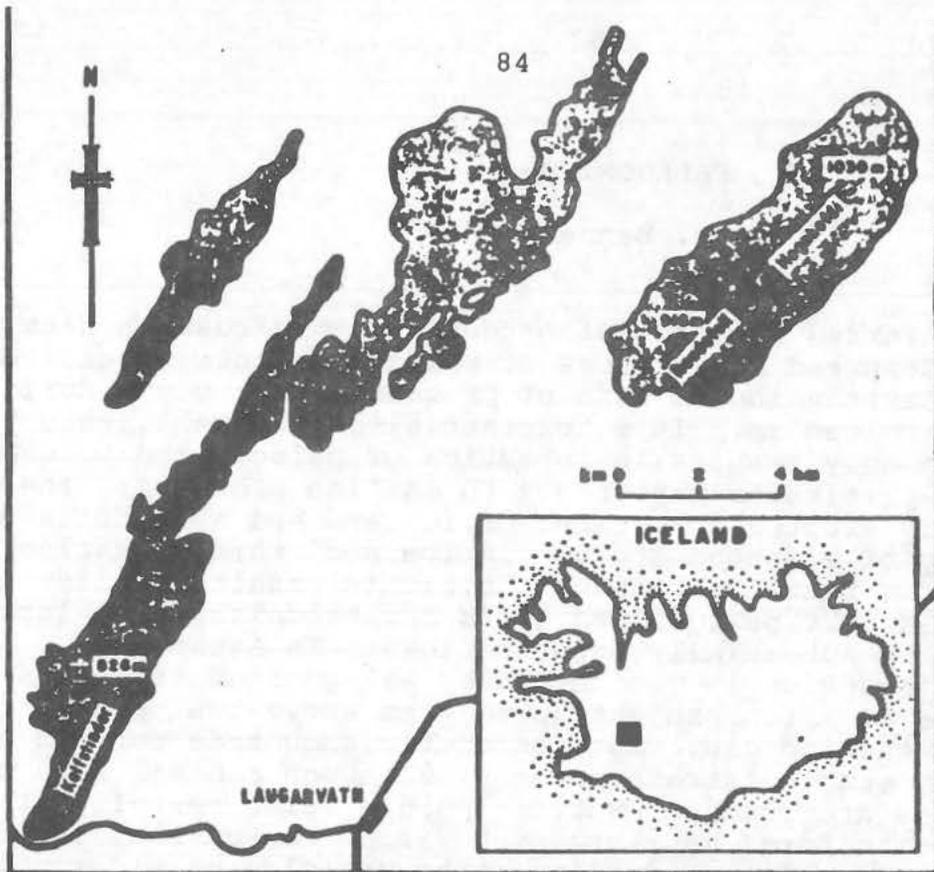


NWILber of samples (N) versus mol percent fayalite content of olivine for 4-phase lherzolite xenoliths from continental localities.

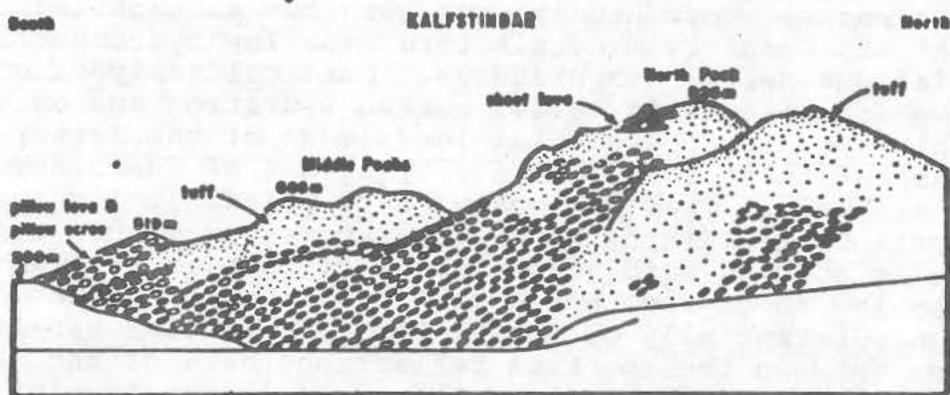
PALAGONITES

D. Wenner

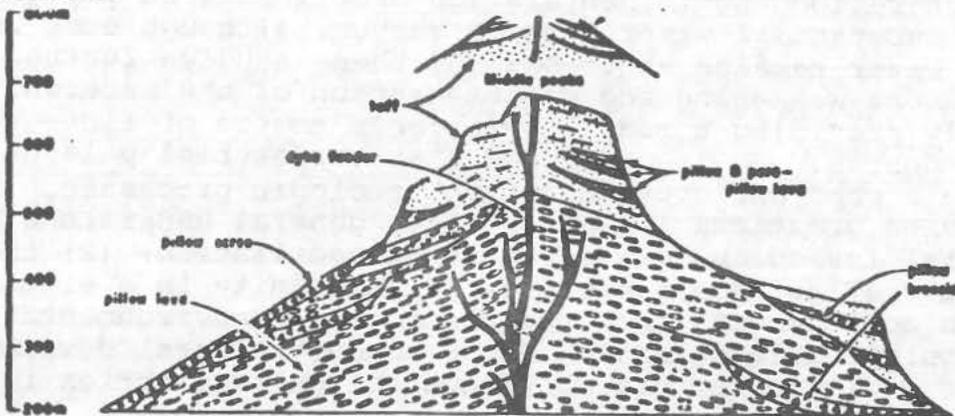
The inferred presence of extensive permafrost on Mars and the widespread occurrences of volcanic events necessitate that an understanding be made of processes that occur during subaqueous volcanism. In a terrestrial environment, this process commonly results in formation of palagonized volcanic rocks. Of particular importance to martian processes, the subglacially erupted formations of Iceland and Antarctica seem most worthy of expanded study. In Iceland, this formation consists of a basal section of tholeiitic basaltic pillow lavas overlain by palagonized tuffs and breccias; some localities are capped by subaerially erupted flows. In Antarctica, subglacial eruption is manifested by palagonized trachybasaltic units, some of which project up to 2 km above the present surface of the ice cap. Some Antarctic sequences contain subaerially erupted stratovolcanos, although a basal zone of pillow lavas are absent. Petrographic studies reveal that palagonization forms as a brownish yellow non-crystalline rim along the outer edges and adjacent to vesicles of sideromelane (basaltic glass) fragments; crystalline phases remain unaffected by alteration. Secondary minerals such as zeolites (Phillipsite and chabazite dominant), saponite, calcite and opal occur in palagonized rocks. Most studies suggest that palagonization and development of secondary minerals form from low hydrothermal to surficial weathering temperatures. Chemical analyses of sideromelane and palagonite reveal marked hydration and oxidation and variable amounts of elemental loss; most of the latter, however, appear to be accounted for by uptake of associated secondary minerals. Chemical analyses of palagonite indicate poor comparison with Viking XRF data, suggesting either that palagonite is not the major constituent of martian 'soils' or that the source rocks from which palagonite forms have a composition substantially different from terrestrial basalts. Comparisons between the spectral reflectance data of the martian bright areas and Antarctic palagonites reveal certain similarities in major absorption bands at 1.9μ and 1.4μ , deep Fe^{+3} absorption, and high reflectance. Dehydration experiments on palagonite reveal substantial water loss in vacuum, although some 20% of the water remains above $\sim 125^{\circ}C$; these studies further reveal an apparent weakening and disintegration of the material, possibly providing a readily available source of fine-grained eolian debris. It is concluded that terrestrial palagonites provide a good analogue to martian geologic processes. Major unanswered questions include: (1) a general understanding of elemental losses and gains during palagonization; (2) the spectral reflectance properties of palagonite in a simulated martian environment; (3) the chemical and environmental variables that control palagonization and secondary mineral development; (4) the geologic factors which control palagonization in a vitric tuff pile.



—Location and plan outline of the Kalfstindar and Raudfjell-Hognhöfði volcanoes



—Kalfstindar viewed from the northeast, showing distribution of rock types. Width of field of view about 6 km.



—Diagrammatic composite cross section of Kalfstindar. No vertical exaggeration.

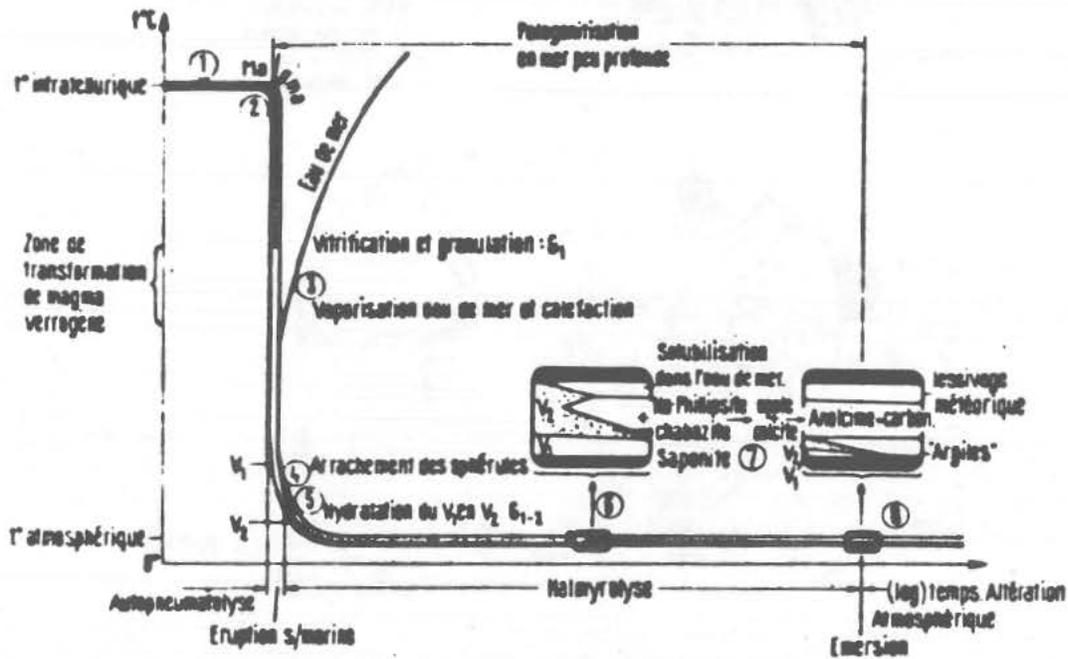
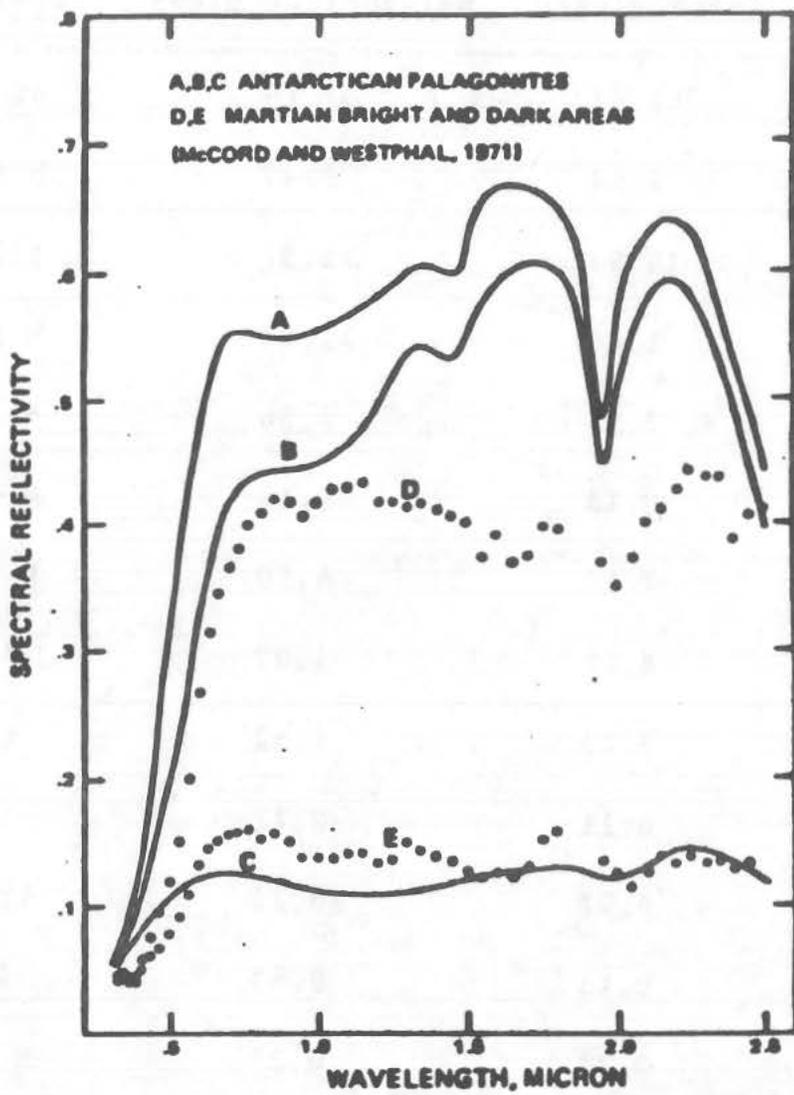


Schéma température-temps résumant les différents stades de la palagonitisation depuis le moment où le magma basique fait éruption en mer peu profonde, jusqu'à ce que l'hyalo émerge; les numéros encadrés renvoient aux explications données dans le dernier paragraphe («conclusions générales»).

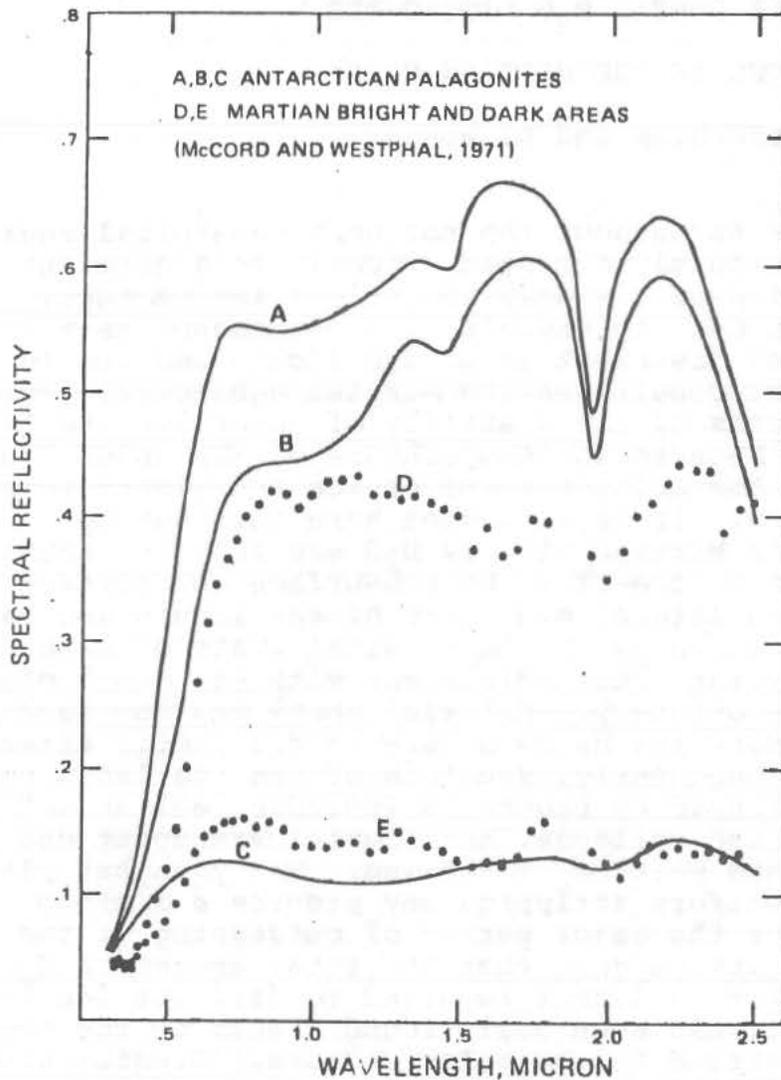
	V ₁ fresh glass	V ₂ palagonized glass	zeolite
SiO ₂	51.62	37.19	46.82
TiO ₂	1.57	2.47	N D
Al ₂ O ₃	15.92	10.32	19.17
Fe ₂ O ₃	1.80	11.74	N E
FeO	7.90	2.56	N D
MnO	0.13	0.15	N D
MgO	7.10	6.50	N D
CaO	8.61	7.07	3.78
Na ₂ O	3.29	1.52	6.38
K ₂ O	0.28	0.22	2.56
H ₂ O ⁺	0.97	10.22	12.93
H ₂ O ⁻	0.16	9.93	4.77
P ₂ O ₅	0.22	0.24	N D
total	99.57	100.13	96.41



POSSIBLE FOSSIL H₂O LIQUID-ICE
INTERFACES IN THE MARTIAN CRUST

L. Soderblom and D. Wenner

Extensive areas throughout the northern equatorial region of Mars have been uniformly stripped, roughly to a constant depth. These terrains vary widely in their relative ages. A model is described here to explain this phenomenon as reflecting the vertical distribution of H₂O liquid and ice in the crust. Under present conditions the Martian equatorial regions are stratified in terms of the stability of water ice and liquid water. This arises because the temperature of the upper 1 or 2 kilometers is below the melting point of ice and liquid is stable only at greater depth. It is suggested here that during planetary outgassing earlier in Martian history H₂O was injected into the upper few kilometers of the crust by subsurface and surface volcanic eruption and lateral migration of the liquid and vapor. As a result, a discontinuity in the physical state of materials developed in the Martian crust coincident with the depth of H₂O liquid-ice phase boundary. Material above the boundary remained pristine; material below underwent diagenetic alteration and cementation. Subsequently, sections of the ice-laden zone were erosionally stripped by processes including eolian deflation, gravitational slump and collapse, and fluvial transport due to geothermal heating and melting of the ice. The youngest plains which display this uniform stripping may provide a minimum stratigraphic age for the major period of outgassing of the planet. Viking results suggest that the total amount of H₂O outgassed is less than half that required to fill the ice layer, hence any residual liquid eventually found itself in the upper permafrost zone or stored in the polar regions. Erosion stopped at the old liquid-ice interface due to increased resistance of subjacent material and/or because melting of ice was required to mobilize the debris. Water-ice may remain in uneroded regions, the overburden of debris preventing its escape to the atmosphere. Numerous morphological examples shown in Viking and Mariner 9 images suggest interaction of impact, volcanic, and gravitational processes with the ice-laden layer. Finally, volcanic eruptions into ice produces a highly oxidized friable amorphous form, palagonite. Based on spectral reflectance properties, these materials may provide the best analogue to Martian surface materials. They are easily eroded, providing vast amounts of eolian debris, and have been suggested (Toulmin et al., 1977) as possible source rocks for the materials observed at the Viking landing sites.



Comparison of spectral reflectivities for Antarctic palagonites and for Martian bright and dark regions (from McCord and Westphal 1971). The palagonite spectra were supplied by T. V. Johnson and F. P. Fanale of the Jet Propulsion Laboratory. The Antarctic samples show deep absorptions near 1.4μ and 1.9μ due to absorbed water. The samples are trachy-basalts which vary strongly (A,B) to weakly (C) palagonitic. The comparison is not intended as an identification but as a demonstration that deep ferric absorptions and high infrared reflectivities as observed for Mars are produced by simple interaction of basaltic lavas and ice.

DESERT SOILS - COMPOSITION AND SURFACE PROPERTIES

R. Stewart-Perry

Multi spectral mapping has proven useful in mapping the surface mineralogy of Mars. Interpretation of this spectral data, obtained from the outer few microns of rocks and soils, and the subsequent inferring parent rock types requires a careful study of earth alteration processes where samples can be collected and compared to remotely obtained data. With our current knowledge of weathering systems it is difficult to infer the composition of the martian mega-regolith from surface alteration materials.

The remote identification of rocks on the earth's surface is compounded by biological weathering products and vegetation. In desert regions it is possible to use diffuse reflectance spectra (0.35-2.5 μ m) to identify alteration products and unweathered rocks. In some cases the parent rock types have been inferred from their surface weathering products, however, rocks that are covered with a black coating, commonly called desert varnish may not be distinguished. Desert varnish forms on nearly any substrate that is reasonably stable. The geographical extent of desert varnish is not known, however its unique spectral signature (Figure 1) would permit its mapping. The components of varnish are derived from eolian deposition that diagenetically forms a layered coating. It is not normal weathering of the substrate (Figure 2). Whether the diagenesis is inorganic or biologically induced similar coatings might form on Mars.

The origin of desert varnish and many other weathering products is not known. Most studies have concentrated on unweathered rocks and their "final" alteration products with less concentration on intermediate phases.

Surface weathering on the earth occurs in close association with complex biological systems. The presence of bacteria, algae, fungi and lichens significantly changes the chemical characteristics of alteration products Figure 3. Before earth soils, alteration products and coatings can be used as martian analogues, the effects of microorganisms and their associated chemical compounds must be isolated.

On Mars the most likely place to find "life" is on the reasonably stable surfaces of rocks - probably as endolithic cyanobacteria (blue green "algae"). In the "sterile" valleys of Antarctica the suggested martian analogue soils presently contain non-detectable or limited biology. However, the rocks do support endolithic cyanobacteria (Figure 4).

Most aridosols and entisols on earth represent dynamic systems that were historically non-arid. The profusion of biological activity and the effects of biogeochemistry on soils and their formation, both past and present, require better understanding before being used as martian analogues.

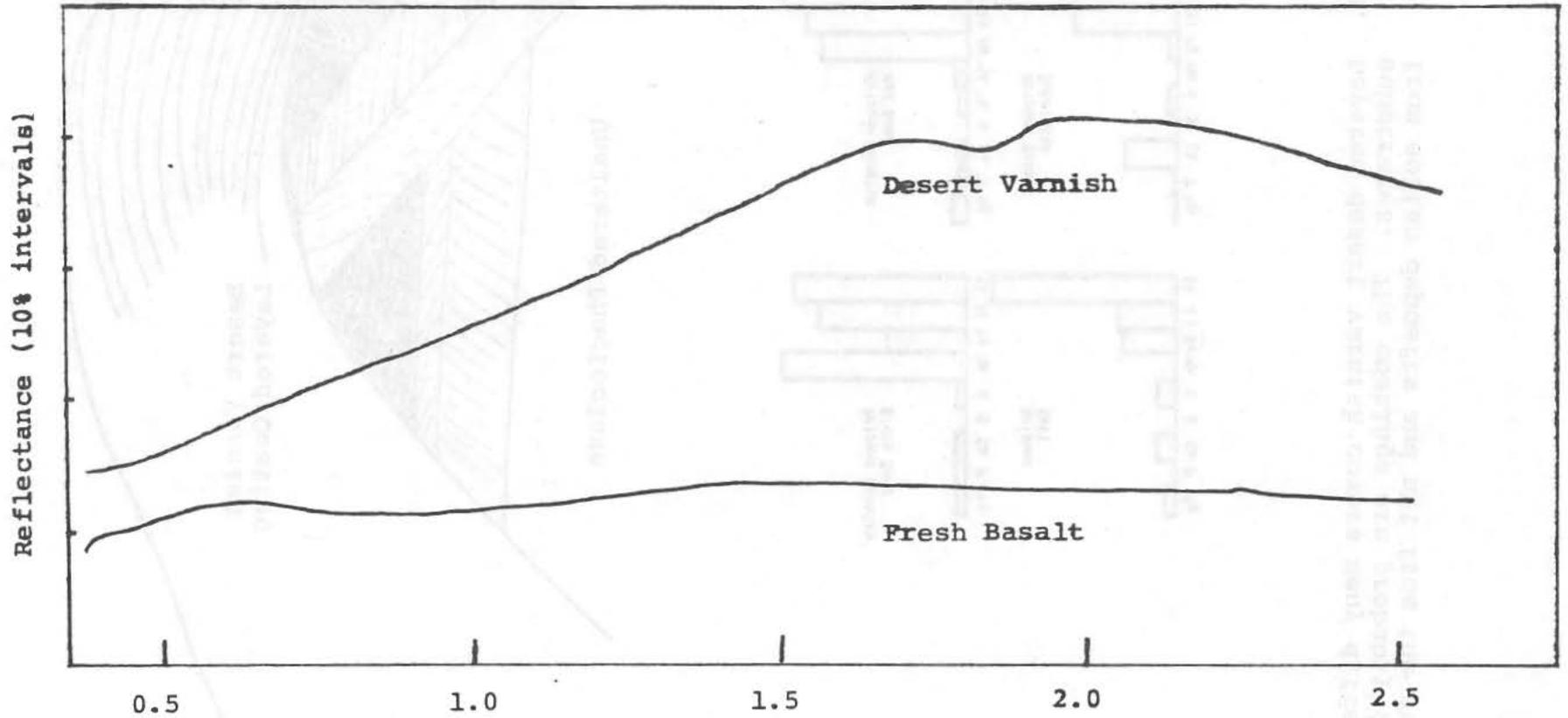


Figure 1

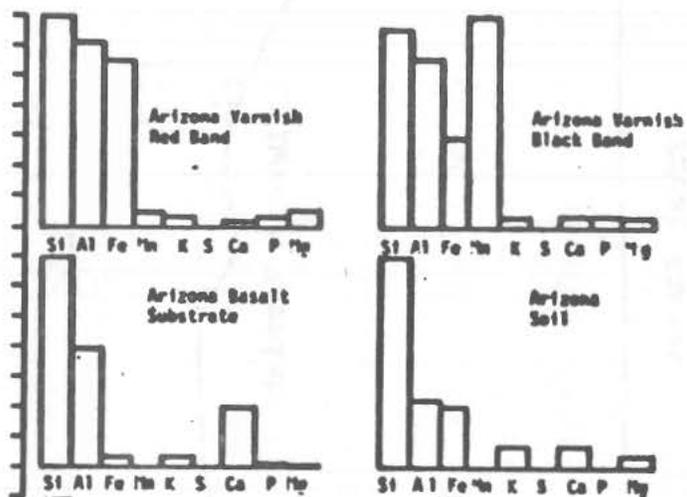
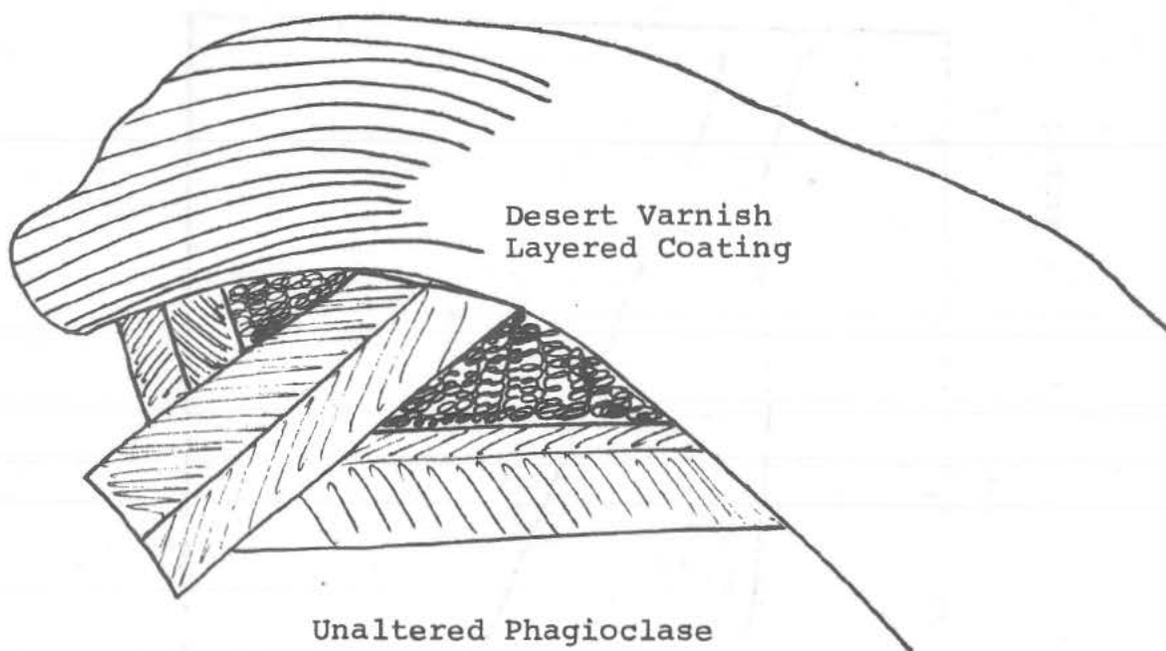


Figure 2. Layered desert varnish covers many different substrates. The coatings are probably derived from eolian deposits and not from the substrate.

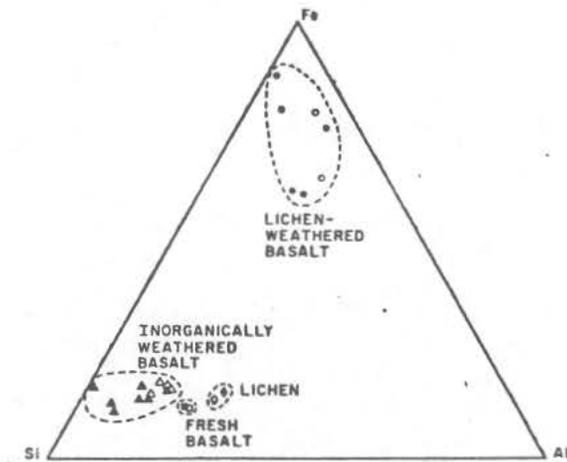


Figure 3



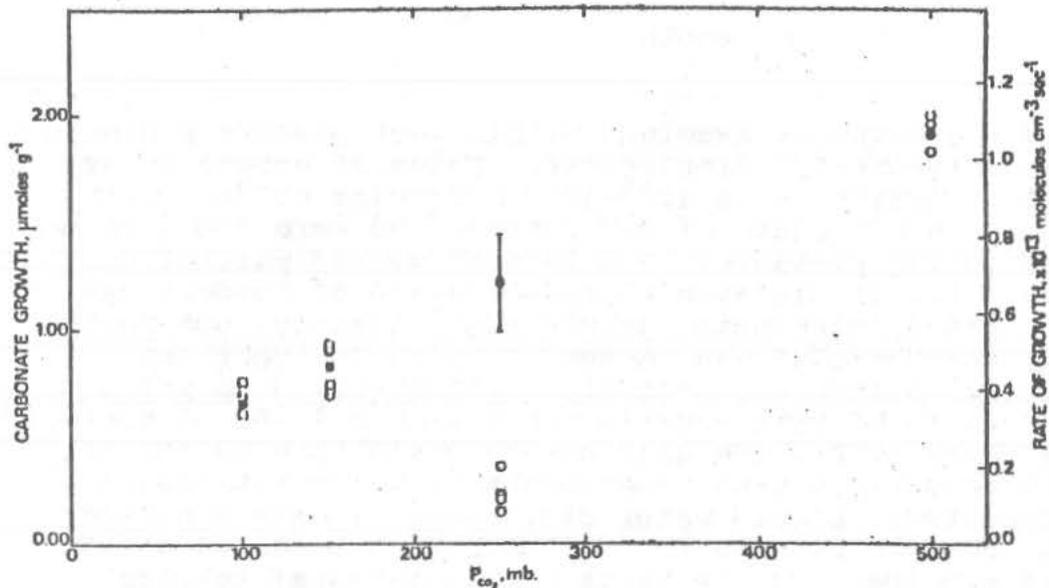
Figure 4. SEM of endolithic algae from the Negav Desert x 3500.

SIMULATION OF MARTIAN SURFACE CONDITIONS

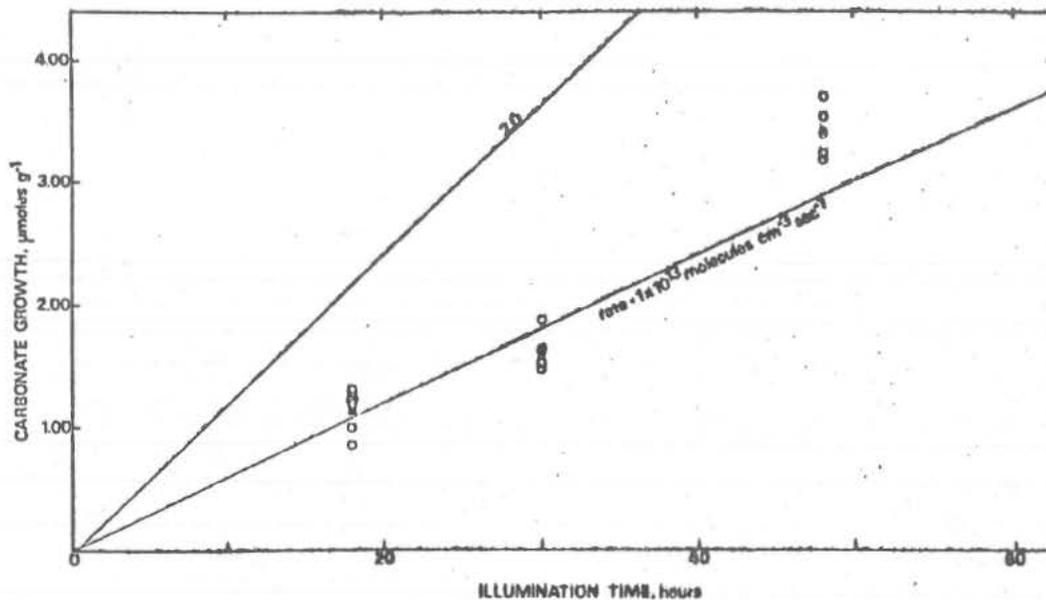
M. Booth

Carbonate growth was examined within rock powders subjected to Marslike environmental simulations. Rates of growth under experimental conditions were 10^{12} - 10^{13} molecules $\text{cm}^{-3}\text{s}^{-1}$ with or without an aqueous phase of H_2O present and were found to be proportional to CO_2 pressure, H_2O abundance, and particle surface area. Direct ultraviolet illumination of powders was found not to affect carbonate growth significantly, but photochemistry of absorbed H_2O was thought to play an important role in chemical alteration activity. Transitory damp periods induced in powders of some experiments by the melting of surface frosts were found to provide only slight assistance to the rate of growth in comparison with experiments in which sublimation of frosts occurred. Liquid water did, however, have a noticeable effect upon the distribution of carbonate material within experimental samples. On the basis of experimental results, carbonate formation is shown to be fully compatible with the low-pressure arid conditions characteristic of the present Mars surface environment. It is further concluded that carbonate material is likely to represent a major chemical reservoir for the outgassed CO_2 inventory of Mars, and that in the absence of an aqueous phase of H_2O in the environment this carbonate should form as submicron coatings on regolith particle grains.





Carbonate growth as a function of P_{CO_2} . Measurements are of samples from 54-hour experiments including $20 \mu\text{m H}_2\text{O}$. A transitory aqueous H_2O phase was promoted in experiments having $P_{CO_2} > 200$ mbar. Weighted average carbonate abundances in samples are denoted by solid squares. The average value from the 250-mbar experiment employing soil A has been adjusted so as to relate to experiments using soil B on the basis of powder BET surface area. Distribution of points at each pressure primarily reflects carbonate distribution among sample fractional layers.



Carbonate growth as a function of time. Experiments employed soil B and possessed 250-mb CO_2 and $30 \mu\text{m H}_2\text{O}$. Carbonate is plotted versus cumulative illumination time. Time involving warm temperatures ($297^\circ \pm 2^\circ\text{K}$) is somewhat shorter than the illumination time because of a 1-hour period at the start of each 6-hour illumination period, during which samples warm from night temperatures.

WEATHERING IN THE ABSENCE OF LIQUID H₂O

R. Huguenin

Two principal environmental factors that make Mars chemical weathering different from Earth weathering are (1) H₂O occurs only as frost and vapor and (2) UV penetrates to the surface at $\lambda > 1.95\mu\text{m}$. The absence of liquid H₂O prevents the formation of protective precipitate layers on grain surface - thus exposing surface ions directly to atmospheric gases and frost, and direct atmosphere/surface interactions take place. UV-illumination drives two principal surface reactions ($\text{CO} + \frac{1}{2}\text{O}_2 \rightarrow \text{CO}_2$) and (2) photooxidation of Fe²⁺ in minerals to Fe₂O₃-FeOOH. Absorption of H₂O results in the hydrolysis-reduction of silicates, with the resultant surface production of O₂ gas and oxidative species. Absorption of CO₂, SO₂, NO₂, and Cl may produce salts, but this is still being tested. The weathering products are probably amorphous, since there is no liquid water to polymerize them into clay minerals. Mars weathering is a huge sink for outgassed volatiles, removing the equivalent of 3m - 3km of water. It also could have produced chemical etching on micro and regional scales.

3. SUBGROUP SUMMARIES

MARS SURFACE WEATHERING SUBGROUP

One of the most exciting discoveries of the Viking mission was the unusual surface chemistry discovered by the lander biology experiments. The discovery of the highly magnetic nature and remarkably high sulfur and low alumina contents of the soil were equally unexpected. The Viking mission in fact raised a myriad of new questions about surface weathering and regolith processes on Mars, and stressed the need to expand research efforts in several important problem areas.

Chemical Weathering Processes. It is now apparent that the differences in surface environments on Earth and Mars have resulted in two quite different sets of chemical weathering processes on the two planets. On Earth, chemical weathering is dominated by solution processes and biogenic activity. On Mars it appears that photochemical weathering, direct surface/atmosphere interactions, and palagonization probably dominate. These two sets of processes produce distinctly different weathering products, and they have probably had very different effects on regolith composition, physical properties, and surface morphology over geologic time.

Future research efforts should focus on determining the mechanisms, rates, and products of chemical weathering processes that occur in the unique martian environment (UV radiation, absence of liquid H_2O , low temperatures, etc.). Laboratory studies clearly need to be expanded, and remote observations of surface composition continued. Terrestrial and planetary analogs have proven useful in the past, but attention needs to be focused on the uniqueness of the martian environment.

Physical Weathering Processes. Physical weathering processes are also not adequately understood in the unusual surface environment of Mars. Probably the dominant processes have been impact, host disintegration, fluid abrasion, spallation, exfoliation, explosive volcanism, dessication cracking, and glaciation. It is unknown, however what the relative importance of each has been for forming the regolith over geologic time. It is also uncertain how the unique chemical weathering processes may have affected the physical weathering rates, or to what extent physical processes could have produced chemical fractionations.

Research efforts should focus on laboratory studies in simulated martian environments, and on modeling of atmosphere history. Terrestrial and planetary analog studies, as well as orbiter and lander image analyses should continue to be useful.

Regolith Transportation Processes. The Viking mission stressed the need to understand martian regolith transportation processes. Vast regions of the surface appear to be blanketed

by remarkably homogeneous dust, based on Viking lander analyses and Earth-based reflectance spectra. It is unknown how deep the dust mantle and regolith are, and to what extent these depths vary regionally. It is also uncertain to what extent compositional heterogeneities exist and reflect regional associations. Answers to these questions are critical to studies of regional petrology, and to estimates of the potential for regolith storage of volatiles as ground ice, adsorbed gas, and chemically combined volatiles.

Future research should stress laboratory studies of transport processes in simulated martian environments, and observational programs to map the regional variations in surface mineralogy (spectral reflectance). Terrestrial and planetary analog studies and image interpretation should also be continued.

Lithification and diagenesis. The discovery of sulfur-rich duricrust and lithified clods in the Viking soil samples raised several new questions about cementation and lithification processes. Can they form in the present-day highly desiccated environment, or do they reflect past changes in martian climate?

Laboratory studies of chemical weathering processes as they relate to salt and evaporite formation and Mars-like environments need to be expanded. Modeling of atmospheric history, and terrestrial and planetary analog studies will also be very useful.

Depositional and erosional forms and surface morphology. The Viking lander and orbiter images revealed the presence of apparent depositional and erosional forms on the surface that were not seen before. Laboratory modeling and terrestrial analog studies need to be undertaken to determine the origin of the features. These studies along with photogeologic mapping of the distributions and associations of the features will permit constraints to be placed on the processes that formed the regolith.

SUBGROUP REPORT - IGNEOUS PETROGENESIS

There are two problems of principal concern in martian igneous petrogenesis - each has some intriguing aspects:

The origin of the ancient cratered uplands. Were they produced by plagioclase floatation in a manner commonly proposed for the lunar uplands (and possibly the primitive earth)? Were they differentiated from an early mantle? Could they be representative of relatively primordial accretion products little altered by igneous processes?

Origin in time and place (depth) of the surface igneous rocks forming the plains and shields. Almost certainly these rocks are volcanic flows; are they similar to the lunar mare basalts or to the lunar upland (Fra Mauro) basalts or even KREEP. Are they analogous to terrestrial komatiites? Did the composition of these rocks change with time, reflecting a changing upper mantle as suggested by thermal models in which the core formed late in martian time. Is there evidence for large amounts of volatiles as predicted by homogeneous accretion models? Is the sulfur in the Martian soil of igneous origin or is it a sedimentary concentrate. If primary, how did the sulfur arrive as an immiscible sulfide liquid? Are martian sulfide ores plausible? What is the significance of the differences observed from Viking orbiter mapping? What is the meaning of the ferric-iron bearing pyroxene spectra obtained from earth based observations?

The subgroup proceeded by identifying five more specific problems which could be approached more directly. For each, we attempted to define the status of the existing data base, the most important constraints, what was most reasonable to do next and policy and program issues related to each. The specific problem areas were:

- the chemical composition of the surface igneous rocks
- their distribution in time
- the present composition of the mantle, exclusive of volatiles
- volatiles in the mantle
- present internal structure and thermal state of the mantle

The Data Base

The data base which bears on these problems is remarkably diverse and most of the essential clues from each is missing, so the definitive constraints on martian petrogenesis are yet to be established. None-the-less among the available martian data are: Viking XRF data (high S, low Al and Si content - unlike terrestrial or lunar basalts), Viking imagery (a variety of volcanic landforms viewed from orbit), Viking lander imagery (showing rocks, many with prominent vesicles suggestive of fragmented lava flow material), Viking thermal mapping (showing wide variability correlated with age but no straightforward interpretation), Viking atmospheric chemistry (perhaps consistent with low crustal K abundance), moment of inertia, C/Mr^2 (probably consistent with a high mantle density but still very model dependent), bulk planetary density (suggestive of a lower bulk Fe content than the earth, but a smaller core also), spectral reflectance measurements from earth (which show uniform light areas with a strong ferric iron absorption and differences in dark areas, including possible band splitting consistent with Fe^{+3} bearing pyroxene), models of accretion and thermal conditions in the early solar system (which suggest Mars accreted significantly larger amounts of volatile than the earth per unit mass), a deep regolith (perhaps capable of storing large quantities of volatiles), large gravity anomalies over the volcanic shield complexes and the regional domes on which they occur (which have negative Bouguer anomalies suggestive of a low density root, but not total compensation implying some lithospheric strength), global geologic mapping (showing an ancient cratered upland which may or may not be like the moon's, old volcanic plains, and the young, possibly Recent, shields), thermal evolution models (with or without magma coeans - take your pick! - but which show global expansion through much of martian history consistent with global tensional features such as Valles Marineris and the Tharsis fracture system), to name some of the most prominent.

Important Constraints and What to Do Next

Surface Composition. The most important existing constraints on the surface composition are the Viking XRF analyses, spectral reflectance (observations from Earth and color filter data from Viking orbit), Viking orbiter and lander imagery (which show a variety of features of possible volcanic origin, some of which may yield information about composition) and magnetic properties of the soil from Viking. Interpretation of all of these data are tied up directly with the surface weathering processes. (Hence, the question of martian igneous petrogenesis can not be divorced from surface processes, and probably will not be even after sample return.) The tasks defined as timely were, proceed with refinement of the Viking XRF data - some numbers can be improved by a factor of two; experimental petrology on iron-rich basaltic and ultramafic rock melts to determine liquidus phase compositions should proceed, and this work should be

closely coordinated with laboratory measurements of reflectance spectra of igneous mineral phases, mixtures and their weathering products. The Soviet γ -ray data should be examined in detail - there may be valuable data to be extracted. Several theoretical and synthesis tasks are important - synthesis of orbital and earth based remote sensing data with regional geology; thermal modeling should proceed, also theoretical petrologic models using existing phase diagrams will be a useful guide to further experimental, observational and theoretical work.

Time Sequence of Igneous Rocks. The time sequence of igneous rocks and time dependent-compositional changes was the second topical problem discussed. The current data base is photogeologic - it consists of superposition relationships and crater frequency data. There is substantial disagreement about the flux history through martian time - which, of course, will remain unresolved until several absolute age dates are obtained on proper surfaces and the flux history can be calibrated. Relative ages are useful to be sure, and this may be especially true for the young surfaces on the shields. There is no agreement at present regarding the age of the shield's surfaces - estimates range from zero to half a billion years, hence the volcanoes may be active or the activity may have ceased in Cambrian time. Analysis of high resolution Viking imagery may resolve this question by yielding statistically significant crater counts on these young surfaces. The crater frequency data on the older surfaces bears on rapidly developing dynamic and thermal models of the early solar system and accreting planets.

Composition of the Mantle. The problems of the present bulk composition of the martian mantle and the present physical properties and thermal state of the martian interior are so closely related and interwoven that they can not be separated. The most important existing constraints on the composition of the interior are (1) the bulk geophysical properties - the moment of inertia, the estimates of core size and density compared with the bulk planetary density, (2) the surface igneous rocks, and (3) clues from gravity.

There was general agreement that the virtual absence of hard geophysical constraints on the structure and seismic velocities of the martian interior is crippling to attempts to model the petrology of the interior. It is indeed likely that the mantle of Mars is substantially denser than the Earth's but even that conclusion is model dependent. A great deal of important petrologic inference would follow from some reasonably firm bounds on basic properties of the upper mantle - density, p and S wave velocity, the location of seismic discontinuities, and regional (horizontal) variations related to major (global) structural-tectonic elements of the planet (Tharsis, Hellas, the uplands-plains contrasts). Hence, any tasks which will improve our knowledge of the geophysical constraints are of first order interest to petrologists, such as (1) continue tracking the Viking orbiter for high resolution gravity and (2) maintain the one functioning Viking seismometer - and pursue the possibility of a contrived active experiment.

Another major point of agreement was that the high pressure, subsolidus phase relationships most probably relevant to Mars do not exist. In plain language, that means that if we were told the bulk chemical composition of the martian mantle, we would not be able to describe the mineral assemblage which made up the mantle rocks. Probably it would consist of familiar mineral phases in terrestrial peridotites (olivine, garnet, pyroxenes, spinels of various kinds) but the relevance of iron-rich compositions have not been investigated at high pressure and our inferences are just that - best guesses. Our "best guesses" may be quite wrong. This sample space, alone is enormous even when constrained by models and inference, and its only part of the problem. The liquidus compositions also should be determined and the role of volatiles, particularly oxygen, sulfur and water need to be evaluated. This work will satisfy other motives, such as relevance to terrestrial sulfide ore deposition and certain iron-rich basaltic rocks.

Volatiles in the Interior. The Viking atmospheric experiments have contributed much data about the martian atmosphere but there is serious disagreement about their fundamental meaning. The argon and neon isotope ratios suggest either a volatile-poor or a very incompletely outgassed planet. Equilibrium condensation models for the origin of the planets predict a volatile-rich Mars. The polar caps are now acknowledged to be water ice. A large amount of volatiles could be stored in the regolith as ice (or liquid at greater depth). The Viking XRF analyses revealed substantial amounts of both sulfur and carbon (probably present as sulfate and carbonate) but there is no consensus about what the volatile abundances are at depth. An important related topic is the light element in the cores of the Earth and Mars - oxygen, sulfur and silicon are given serious consideration. The volatiles present in the mantle clearly will be affected by subtraction during core formation and outgassing of the atmosphere. If Mars has had a mild thermal evolution involving passive core formation and only modest heating during accretion, then it is possible its mantle is volatile rich, and it could be rich in chemical constituents found in the Earth's core or crust, or both! It is well known that volatiles have a first order effect on the physical as well as chemical properties of silicate solids and liquids - the solidus curves can be affected by hundreds of degrees, in wet relative to dry systems; strength, electrical conductivity and viscosity vary by orders of magnitude; the composition and properties of melts, especially for low degrees of partial melting, are likewise drastically altered. It appears that the oxygen fugacity in the earth's mantle may be buffered by reactions involving elemental carbon - if so, a similar situation may exist in the mantles of the other planets. If true that would provide a possibly very important simplifying constraint.

There was universal agreement that volatiles - their identity and abundance - in the martian mantle are of first order importance; they will largely determine the principal properties of the lithosphere, subsolidus and melting relations. It was also universally agreed that the volatile inventory of the martian mantle is a nearly completely open question.

Regarding the directions of future research, there was general agreement that the modeling studies of accretion would benefit from an experimental foundation. They are currently based on thermodynamic properties of simple end-member mineral compositions which are used to predict the sequence of formation of condensates from a complex composition (solar or meteoritic approximations to the primordial soup). Data are important at lower temperatures (where the differences between Venus, Mars Earth and the Moon - if it becomes clear where it accreted - are inferred to have originated), and at high temperature. Furthermore, evaporation and condensation kinetics may be very important. Outgassing models are not well developed nor is the experimental base - solubilities of gases over a wide pressure and temperature range and diffusion properties.

The consensus on the volatile question was that 1) it is a key point, 2) it is perhaps the worst constrained part of the igneous petrogenesis question, 3) more experimental underpinning for planet accretion modeling would enhance confidence in them, 4) if one were to hazard intelligent guesses - Mars is volatile rich relative to the earth, its sulfur abundance may be higher and the f_{O_2} may be buffered by graphite reactions, all weakly based!, 5) there are experimental petrology tasks to undertake which have multiple purposes, Mars being only one, and which would yield valuable results, and 6) unraveling the Viking atmospheric composition experiment data is very important - is Mars wet or dry, out-gassed or not, etc.

Summary and Conclusions - Policy and Program Recommendations

The subgroup reached agreement relatively easily on the list of items of principal importance and what needs to be pursued - which translate directly into suggested program commitments. These were:

- Modeling will help as a guide to further experiments and observational work. While the data base is incomplete, it is ripe for synthesis and theoretical approaches. It is an appropriate time to aggressively pursue ideas.
- Experimental petrology of systems (e.g. iron and sulfur-rich) likely to be important for Mars has not been done. There are practical reasons - these compositions are corrosive and very difficult to deal with experimentally. Also, magnesium-rich systems are a fair approximation to the earth's interior. In particular, high pressure relations relevant to Mars are unexplored, but could be if investigators are encouraged.

- Spectral reflectance observations and experiments need to proceed; it appears likely that very useful data will emerge regarding primary igneous mineralogy of the surface rocks. Both lab and telescope work should proceed; space telescope time was discussed favorably, because greater spatial and spectral resolution would be valuable. This work should be coordinated closely with the experimental petrology described above and also surface simulation and weathering experiments.
- Volatiles are a crucial part of the question of petrogenesis of igneous rocks - and their abundance and character in the martian interior is virtually unknown. Furthermore, the role of volatiles in physical properties and processes is equally important - melting point depression, viscosity and creep behavior, lithosphere thickness and properties, electrical conductivity, convection etc. are drastically influenced by volatiles. Experiment and theory will help but new data are probably essential to resolve this problem.
- Geophysical constraints on the most fundamental interior properties of Mars are very weak. Petrologists naturally are most interested in the upper mantle - the upper asthenosphere and the lithosphere, where igneous rocks originate and evolve. Any firm data on density, v_p and v_s and the location of discontinuities within Mars will have first order effects on how petrologists view the planet. Hence, refined (high resolution) gravity from Viking Orbiter tracking, and any data from the Viking seismometer, are examples of potential sources of new geophysical data.

4. COMPILATION OF HOMEWORK QUESTIONNAIRE

HOMEWORK DUE BEFORE
YOU LEAVE ON WEDNESDAY

6-8 February 1978

Name

1. The major unresolved problems in Martian petrology and surface chemistry are:

2. Some potentially fruitful approaches to the solution of these problems are:
 - Theoretical/Modeling Studies:

 - Experimental Studies/Laboratory Simulation

 - Observational Studies:

3. Some suggestions for future Mars exploration programs:
 - What is most important to do now in earth based work (theory, lab, observations, Viking)?

 - What answers are most important to obtain in the next generation of flight experiments; suggest how if you can?

 - What are some important policy considerations in the long view (role of geology, SR&T/DA support, ROP and MSSR options, manned flight,...)?

4. Any suggestions for follow-up workshops? Criticism of this one.

WORKSHOP ON MARS PETROLOGY

COMPILATION OF HOMEWORK

1. The major unresolved problems in Martian petrology and surface chemistry are:

Petrology: source, nature of S in regolith; effect and abundances of dissolved gases in magmas, composition
 Surface chemistry: source of O₂ in Viking biology experiments; nature of volatiles CO₂ & H₂O in soil

What do surface analyses and properties tell us of the interior e.g. is S a property of the planet as a whole, what is fO₂ of interior, we have no idea of mineralogy inside or out so we don't know nuthin'.

- a) Major and minor element chemistry in surface rocks and bedrock
- b) Chemical and mineralogic significance of IR differences detected in dark areas.
- c) Surface chemistry relationship to mantle chemistry
- d) Confirmation or refutation of montmorillonite clays and soluble salts in regolith fines.

- a) compositions of the rocks observed on the surface
- b) compositions of the surface materials, weathering products and their evolution
- c) compositions and nature of the cratered uplands
- d) compositional variations of martian lavas thru time
- e) changes in planetary atmospheres T, P thru time.

- a) composition and mineralogy of Martian lavas
- b) relation of Martian soil chemistry to a)

What are the major chemical (for major and trace elements) isotopic and mineralogical features of martian igneous sedimentary and metamorphic rocks?

Mantle composition and mineralogy. What if pO₂ and pS. Are there mineral hydrates in the mantle and to what degree have they dehydrated over geologic time to free up H₂O for mantle and surface processes. How extensive has weathering modified surface composition? How are the atmosphere and surface chemistry coupled? What is surface mineralogy (reflectance spectroscopy) and how does it correlate with geologic features.

Reliable composition/mineralogy of unweathered "basalt(s)"
 Regional variations in "basalt" chemistry/mineralogy
 Nature of weathering; explanations for unusual chemical features

Has the bulk chemistry of surface lavas changed with time?
What is the bulk chemistry and mineralogy of the surface lavas?
Has it changed with time, reflecting growth of lithosphere
evolution of the core
change in volatiles in the
mantle

Volatile inventory of the mantle

Composition of rocks, interior processes which form magmas
Surface process which erode, weather, transport, deposit, and
lithify rocks

Origin of the magnetic phase in Martian soil. Is it primary, or
a weathering product, or both. If primary, supplies a
mineralogical constraint

Rock composition, mineralogy on surface

- A) To what extent is the current surface material regionally
or globally homogeneous? Does any "primary" material exist?
Where?
- B) Are the Viking "vessicles" real?
- 1) Composition and mineralogy of mantle
 - 2) Chemical variation's of fresh lavas
 - 3) Amount and type of volatiles in lavas and mantle

Chemical composition of Martian lavas. Variation with location
and time. Viscosity. Where are the volcanic gases. Extent
of Martian volcanism. Reactivity of surfaces to UV, gases.

The consequences of varying pO_2 regimes within Mars are enormous
and need to be explored theoretically and experimentally.
 H_2O abundance in sorts
Time sequence of evolution of crust

The sequence of weathering between parent rocks and the "final"
alteration products. The ability to infer rock types from
alteration products.

What properties of the lavas (if any) are responsible for the
immense size of the volcanoes.

- 1) Range of composition of igneous rocks, and their distribution
- 2) Volatile content, oxidation state of mantle
- 3) Are Viking fines likely igneous rocks, and if not how are
are they related to igneous parents?
- 4 a) Degree and nature of weathering processes and products
b) Mechanisms involved in anomalous surface chemical properties
(Viking "biology" results)
c) Mechanism for cementation of fines

Will we see any rocks that are not so degraded as to be useless?
If we find rocks can we get enough of a suite to sort out
complicated fractionation processes?

Composition of the surface rocks and 'soils'

Mechanism of weathering and the formation of eolian debris

2. Some potentially fruitful approaches to the solution of these problems are:

a. —Theoretical/Modeling Studies:

One experiment is worth a thousand theories. The less the experimental evidence, the less accepted the model.

Model interior al la McGetchin-Smyth and partially melt and play clever weathering and surface chemistry games to see if we can produce Viking analyses. accretion and condensation games.

Thermal Models

Accretion composition models

Petrologic differentiation models as effects 1) surface chemistry esp. behavior of Al, K, S. 2) volatile release

Modeling of atmosphere using the few hard pieces of data (present abundance and isotopic compositions)

- 1) Intensive review of weathering processes in order to reason backwards from Lander chemical analysis to possible source rocks (i.e., lava compositions)
- 2) Review of all available experimental data to see what is currently known about melting in other than "standard formats"

Continue work on hot and cold, homo and hetero accretion models to derive bulk composition.

Continue mantle thermal and basalt petrogenesis modeling

Continue thermal modeling but constrained

Evaluation of volatile abundances in model mantles

Continue mantle mineralogy/petrology models + density of planetary members - no crust +Al-garnet

Laboratory weathering of realistic martian simulant materials under simulated martian surface conditions

Improvement of data reduction techniques to get better analytical data from Viking remote sensing experiments

Long-duration support if necessary

Improved thermal models integrated with chemical models bases on phase relationships

Effect of composition on viscosity. Effect of viscosity on geomorphology

Extend modeling to explore consequences of a) varying pO_2
b) varying pS in mantle/crust evolution models.

After quantitative studies of earth analogues - the isolation of biological activity - then martian models

Gravitational & rheologic properties of the large shield volcanoes
Role of advection of heat during outgassing on thermal history
both of planets and lavas.

Thermodynamic models of Fe effect on high-pressure melting
equilibria
Perhaps same on volatiles, esp. sulfur

Proceed with present $\bar{\rho}$ & $c/Ma^2 \rightarrow$ Fe rich mantle
What are the compatibilities at high P and high Fe?

2b. Experimental Studies/Laboratory Simulation:

The best alternative/choice if feasible. In the absence of access to planetary surfaces, laboratory simulation best alternative if conditions are standardized so that results of analysis can be compared.

Test the more promising of the above.

Weathering studies under simulated contemporary Martian climate
Same under simulated paleoclimate environmental conditions
Laboratory IR spectra of soil models (fully mixed -- not individual components).

Laboratory simulation studies can provide useful data on weathering, volatile entrapment, atmospheric evolution

- 1) Specifically design and carry out experimental melting studies at 30 kbar or Fe-rich systems at intermediate and f_{O_2} and then at high f_{S_2}
- 2) More low temperature weathering studies involving bulk chemistry as determined by Lander

Better distribution coefficients for trace elements

Expand experimental petrology to include Mars mantle P, T, pO_2 , pS and composition - stability of hydrated minerals
Expand lab and theoretical studies of Mars weathering and surface chemistry

Expand lab and theoretical studies of reflectance spectra of minerals to improve interpretation of Mars reflectance spectra

Possible study of Fe-bearing systems at high pressures
Further lab. weathering studies

Continue studies in Fe-rich silica deficient ultramafic systems to determine subsolidus relations in high p mantles
Determine liquidus phases
Explore S and O rich mantles

Physical weathering- sand blasting, etc.
Chemical weathering - UV, proper PT, proper mix of gases - important to use correct simulant.

Simulate weathering to ascertain if magnetic phases are produced during or as a consequence of weathering

Peridotite solidus + work with Fe^{2+} , CO_2 , S_2

Weathering experiments designed to predict expected surface material - to what extent are these processes globally effective?

Studies of iron-bearing model systems with and without volatiles at high pressures

Measurement of viscosity of potential Mars lavas including volatiles (S, H₂O, Cl, ...)

Experimental petrologic investigations of Fe-rich systems at 20-30kb and varying pO₂ regimes

Characterization of earth alteration, moon and remote sensing of earth alteration and investigate problems of coating (e.g. Desert varnish) and evaporites

Further data on desert varnish, weathering on Mars/Earth. Morphology of craters in permafrost-combination of impact, blow out craters, especially in moderate size ranges

High-pressure melting studies of more "realistic" Mars mantle compositions

SO₄⁻ solubility in silicate melts

Liquidus-solidus separation for XRFs "fines" composition (tricky - must handle pressure, oxidation, sulfur)

Simulation of leaching and cementation by "moist" films on grain surfaces

Studies of smectite formation from glass

Find low melting composition in CMAS + Fe

Photosimulation experiments - palagonization of glasses of differing compositions - particularly of a hypothetical Fe-rich (our best guess) Martian lavas

Spectral reflectance measurements of such a hypothetical lava and its palagonized product in a simulated Martian environment

2c. Observational Studies

With improving techniques, observational studies are a definite plus in the study of petrology. Of little application with respect to surface processes.

Spectroscopy development, viscosity versus topography studies, gravity and isostasy modelling for observed features.

Additional IR observations in all λ 's possible. (earth-based).
More use of Ames airborne observatory?

Remote sensing of O at better resolutions and longer wavelengths

Comparisons of spectra data of Mars with simulated laboratory materials in order to obtain potential mineralogy and rock type data.

Good photogeological study to attempt to constraint lava viscosities thru geomorphology, etc.

We need hard data to define the problems for the above two items.
Especially we need orbital geochemical data and returned samples.

Expand Earth-based observations of surface spectral reflectance to obtain broader coverage of dark area mineralogies

Improved remote spectral measurements
Better moment of inertia value

Continue EB SR observation and relate to geology
Better determination of I
Any hard data on internal structure

Continued spectral studies including spacecraft-based telescopic observations (Shuttle)

Sample return mission equipped with core drill, sent to volcanic terrain. Need ability to pick and choose glassy (fresh) samples.

Heat flow studies \rightarrow present thermal state

High precision, high resolution, (spatial) remote sensing studies.
Space telescope observations could help to a resolution of ~ 80 km - Orbital measurements seem essential to define areas of distinct primary or secondary surface material

Sampling program, with either remote or in-laboratory chemical analysis preferably the latter

If a returned sample is not possible, perhaps chemistry and mineralogy could be done on Mars using spectral reflectance, etc

Photo-geologic interpretation of large volcanoes to see if physical constraints can be placed on viscosity or density of evolved lavas,
Refinement of C/mr^2 values

Earth weathering
Photogeology

Design of better signal processing devices, either in electronics on fly by craft or on data analysis to increase resolution of spectra

Mineralogic-petrologic study of subglacial "palagonite"

Radar on flows for block size -

Earth based spectral imaging studies (using LANSAT for example) of palagonized rocks in Iceland; similar types of studies of ultramafic lavas where exposed in the absence of biological or weathering effects (if this is possible)

3. Some suggestions for future Mars exploration programs:
 What is most important to do now in earth based work
 (theory, lab, observations, Viking)?

Evaluate Viking data (and other) to set objectives of future missions and instrumentation. Laboratory simulation can be used to study surface chemistry, set objectives and test capabilities of instrumentation, i.e. a soil chemistry experiment.

Theory and lab to match Viking analyses plus spectroscopic observations

All in 2 above

Keep the present ball rolling and increase its momentum!
 The S.R. & T. program on Martian analogs must be expanded. Push for the development of methods which can produce useful info on rock/mineral compositions. Better XRF equipment, GCMS modification to produce slow heating capability

All of the above could be carried out simultaneously (but of course by different groups working on separate topics). The only thing that requires very much additional funding would be the experimental studies. These could be gotten for about \$100,00/yr (divided among 3 to 5 different research groups).

Spectral reflectance obs. and supporting studies

See 2 above; all can be done now

Rock chip analysis; attempts at correlation of observed color differences at Viking sites with composition; lab. weathering of basalts; high P experiments on model compositions probably premature; even if unweathered comp. is known, volatiles activities must be independently specified; solidus curves of peridotites of varying Fe/Mg with different volatile activities

Theory - thermal model, tectonic-photo geology, history are likely to yield important model context for MSSR
 Observations - extend experimental petrology of iron-rich, silica-poor, variable volatile systems

Lab. simulation of plausible surface processes

Laboratory simulations of weathering processes and studies of iron-rich phase equilibria

Continued experimental exploration of synthetic basalt systems, with emphasis on parameters thought to be important a_{Fe} , a_S , a_{CO_2} , P, T

Very important to push over a vesicular rock and see if the bottom is the same as the exposed surface.

Basic need is more observational data - perhaps look in detail at morphology, reflectance spectra, etc. of certain critical areas.

Correlate in detail remote sensing with geological units (including surficial units). Include landing sites V I, II

Models for Mars

Improve remote sensing techniques, sensitivity
Careful characterization of earth and moon weather of wind tunnel for physical weathering

Figure out what the hell the seismometer is seeing by putting the JPL simulated seismometer on a craft and then looking at signal from seismic event.

Map tectonic features not rock types.

Finish refinement of Viking XRFS data.

Liquidus-solidus determination for Viking "fines" composition (after preceding)

Begin Mars Mantle melting experiments

Ad hoc studies of cementation, "palagonization"

Lab

Terrestrial analogue studies of palagonization

3b. What answers are most important to obtain in the next generation of flight experiments; suggest how if you can?

Nature of surface chemistry; position of volatiles in the soil. Compositions of Basalt. Organics? Better idea of dating of the surface

- 1) Return of a range of samples - range of rocks, weathering processes, chronology (you know the game plan)
- 2) Seismic net-interior structure & ρ
 - a) Higher resolution chemical measurement + diffractometer analyses of surface fines and rocks. Limited mobility (~ 10 -100 meters) extremely useful. Need rock saw or chipper or grinder. Sample return of highest priority; remote spacecraft if budget constrains.
 - b) X-ray and IR orbiter mapping
 - 1) good compositional data about Mars
 - a) surface materials and their evolution
 - b) remote sensing info. e.g. γ -ray, I.R.
 - 2) sample returned to earth for detailed analysis

New data sources from Mars. Probably does need a sample return rather than doing analysis there. Also probably should design a drill or digging mechanism for sample from perhaps 1 to 10 meters depth, if possible (*land on one of the big volcanoes)

- 1) Good chemical, mineralogical, textural, isotopic data for martian surface materials
- 2) Internal structure

What is the nature and extent of chemical weathering and surface chemistry

What is the distribution of primary and weathering minerals across the planet?

We need more constraints on interior structure, density, thermal properties, etc., orbiting geochemistry, in situ geochemical analysis, sample return; orbiting geophysics

Mars orbit spectral sensing of Tharsis volcanics and other distinctive regions; γ -ray orbiter

Ages and petrology of the principal surface rock units
Better constraints on the thermal state and internal structure

Composition of martian rock types (mineralogical and chemical)
Type and intensity of surface processes as deduced from returned soil samples. Sample return is necessary next mission.

Active species on martian surface; ESR spectrometer on a lander

What is the scale of surface geochemical units that can be measured? - orbital measurements

Documentation of chemical, mineralogical, and age variations of surface rocks - need a sampling program designed to go after fresh rocks.

- 1) Geochemical mapping (γ , X, IR) orbiter
- 2) sample return

Surface reflectance spectra mapping, particularly $Fe^{2+} - 3+$ ratios, from Mars orbit.

Refinement of gravity profiles over Tharsis to estimate crustal density

Surface mineral distribution and characterization gamma, UV, visible, near IR, mid IR radar etc

1. Heat flow and composition from bore hole. Better the latter.
2. Develop narrow, band, tuned fly by experiments for remote sensing.

Igneous rock composition - range & distribution. Best by in situ rover-based labs. Geochem. orbiter of help in late stage, for distribution.

Mineralogy of fines, XRD, DATA/EGA, better XRF/ α -BS. (applies to rocks, too)

Look for chill margin samples from cooling units on top of Olympus Mons. Look for volcanic ash.

More and better chemical composition information at various localities - particularly and assessment of volatile inventory of soils, rocks, etc (using Ge (Li) detector or rover instrument?)

x-ray diffraction data on soils to place restrictions on mechanism of soil formation

- 3c. What are some important policy considerations in the long view (role of geology, SR&T/DA support, ROP and MSSR options, manned flight,...)?

Biology work must be subordinate to geological, mineralogical objectives. We are not yet ready for a return mission. Rovers preferred for survey. Penetrators don't provide enough data - money better spent on rovers. After MSSR mission, it would be a logical next step to have a manned survey mission.

Early commitment to: 1) returned sample 2) manned mission (>50% for the soul side) 3) continued SR & T support

Geology should be prime motivator, but meteorological and biological measurements important adjuncts. Combined ROP too ambitious. If Rover, settle for shorter ranges (<1 km). If MSSR, grab sample not defensible. Must sample large rocks, loose fines, duricrust fragments. Not clear that a drill would obtain significantly different samples

Based on the fact that funds will be limited, we must demand the best possible science for the dollar spent. The sample return mission must be sold as a national commitment and work initiated now for a late '80 mission

Biological experiments should now take a back seat to petrological/physical ones.

The very longest term goal should be to put men on Mars - not especially for geologic reasons - but it will capture the excitement of the world.

Can we get any more flights to Mars?

Will "geochemical orbiters" be dropped? How can we strengthen their position?

We need to greatly expand our Earth-based laboratory and modeling studies of petrology and weathering processes.

We also need to develop geochemical remote sensing experiments applied to Mars

Earth based observations (remote sensing) should be expanded

Any type of sample return is essential, preferably from Tharsis volcanics

Relevant experimental petrology for Mars does not exist; this activity is important and is worthy of support

There is rich (but incomplete) data base

SRT should support extensive experimental work

MSSR is only useful mission option

Maintain a balanced program

Perhaps the most politically viable program is to aim for a stretched out, gradually escalating program, as in the deep sea drilling program. This would also have a stabilizing influence on the science and it might actually be possible to rationalize missions on scientific merit

Whenever doing future Martian mission studies the question of biology and life should be addressed in a positive way

"Grab" sample might not be too useful and should not be viewed as a primary objective.

Frame scientific questions to provide information while soothing the public. Why is public apathetic to geology, planetology of NASA

Define the factors which make Mars unique (comparative planetology) and don't oversell the value of petrology results

SRT support for background studies apparently needs facilitation or advertisement

Vital importance of rational sample selection on basis of maximum geologic/petrologic understanding means MSSR should be preceded by program of in situ analyses, rovers, perhaps probes.

4. Any suggestions for follow-up workshops? Criticism of this one.

Oxygen fugacity and volatiles in planetary mantles
 Good workshop, well-run, good talk/discussion ratio, more experts on Mars would have helped, but they're rare

Allowance for adequate presentation time and questioning periods was a strong plus. Informality a plus.
 A repeat workshop or symposium in about one year would be very appropriate since most work reported is on-going or in infancy.

Martian regolith development - surface processes, both chemical and physical
 Planetary atmospheres workshop

Break low temp. and igneous pet. into two separate workshops.
 Continue these for at least several years. Enough flux in data and ideas so that some topics can be gone over profitably on a repeat basis.

This one - too much scheduled. As long as audience relatively small, have few well chosen speakers to lead discussion

No discussion of information to be gained from trace element and isotopic data was a serious omission

Mars surface chemistry
 Martian atmosphere
 Atmosphere/surface interactions
 Martian petrogenesis

SR and geology of Mars
 Martian volatile inventory
 Martian weathering

Workshop should be held every 6 months
 Good workshop - too broad - igneous petrology not terribly useful at this stage of our knowledge about Mars

Very informative workshop

Suggest having Dwornik, Quaide, or French at future workshops of this sort

Chemical weathering of the martian surface

Organized on too short notice - no isotope or surface morphology people present - otherwise excellent - especially stimulating for me.

Useful and fairly intense and fruitful experience
 Should have photo-geologic types for additional constraints

Review of work done started etc. from this session at a future workshop.

Compile list of what work is being done by who.

In a limited way bring the exobiology and biogeochemical or organic problems under the fold of geology. In other words control it etc. Include photogeologists. Make list available for available support to work on these problems through LSI & JSC

Send out suggested reading list for preparation

Shorter talks, organized discussions by panels

Re-configure tables. Current format is good for eye contact during discussions, not so good for listening to talks

Would favor follow-ups as Viking data analysis and experimental work proceed

More workshops of specialty topics might be useful - an example might be: Martian Surface Weathering - petrogenesis of hypothetical martian magmas

After discussion of these specialty topics, general group meetings could be arranged to provide a forum of communication to a broader spectrum of people.

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