

RESEARCH IN VOLCANIC GEOLOGY
PETROLOGY AND PLANETARY SCIENCE
AT M.I.T.

1969 to 1974

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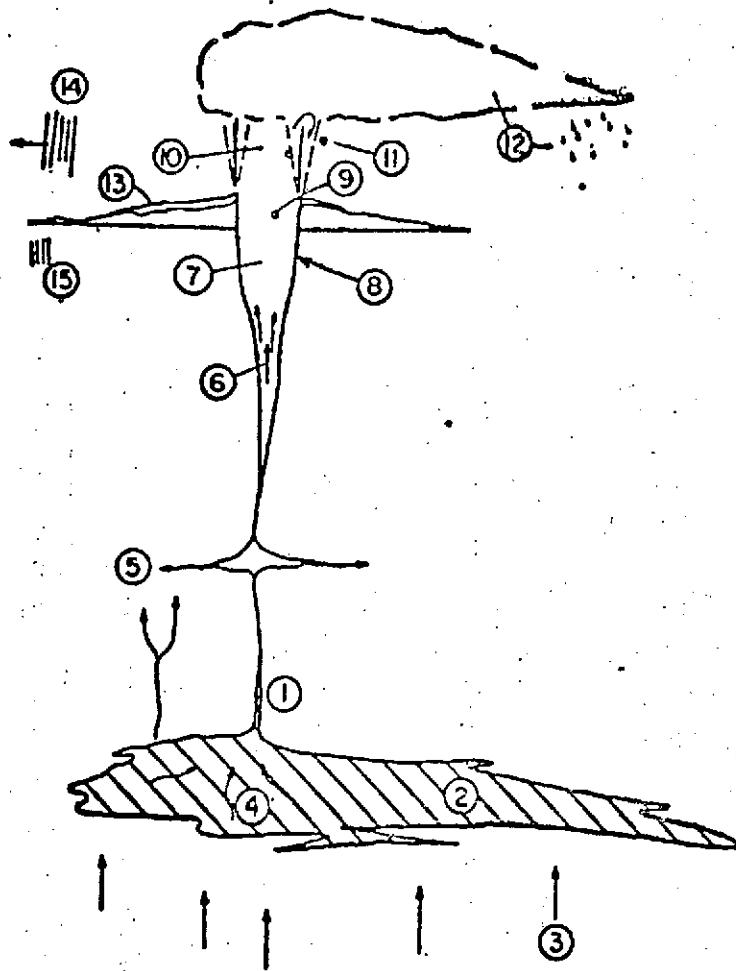
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1. OPERATING PHILOSOPHY

Volcanoes are landforms resulting from the transport of fluid and solid material from the earth's interior to the surface. The chemical and physical processes involved, while complicated, can be defined individually and so treated. Yet, it is our view that volcanoes are best and only truly understood when viewed as a system. Hence coordinated observations of volcanic geology, petrology, chemistry and physics provide important clues in understanding the behavior of volcanoes. Such observations are more powerful taken together than separately. We have developed a mode of operation which attacks volcanism in several ways - by geologic mapping, petrologic investigations of lava and xenoliths, physical measurements, and theoretical modelling. Our approach always begins with detailed field observations - and the lab work breaks either of two ways, one toward petrological studies, the other toward eruption mechanism and related processes. Some of these problems and approaches are illustrated in the figure on the following page.

One basic practical goal of volcanic research concerns eruption prediction. For particular volcanoes we need answers to some simple questions concerning eruptions: when, where, and how big? Our curiosity, however, also drives us to seek to understand eruption mechanisms in detail, to use volcanoes as research tools to probe the interiors of the earth and terrestrial planets in efforts to understand their compositions, physical and dynamic states. Some people are very interested in possible use of volcanoes as energy sources through geothermal power. Many ore deposits are associated with volcanic rocks. The processes of alteration and enrichment occurring within volcanoes during the terminal stages of their activity are known to be important in the formation of ore bodies. As certain critical resources, such as heavy metals, become increasingly short in supply the economic aspects of volcanic geology will become an increasingly central point of interest as the geological sciences are called upon to meet national needs. Understanding volcanic and igneous processes will play a key role in developing new approaches to mineral and ore exploration and possibly new extraction techniques as well. Finally, we feel truly privileged to work in a relatively undeveloped part of our science, in natural settings which are commonly beautiful, sometimes truly spectacular, and always exciting and challenging.

Some Problems in
Volcanology



1. Composition and thermal state of the mantle as revealed by xenolith investigations
2. Origin and localization of magma in the mantle; evolution of magmas
3. Mineralogical sites, diffusion and localization of volatiles in the mantle
4. Migration of magma; physical properties of multi-phase systems; reservoir performance
5. Fracture propagation; deformation (strains and measurable till)
6. Hydrodynamics of flow; heat and mass transfer (viscous effects important)
7. Hydrodynamics of expanding complex multiphase media (vesiculation, fluidization, etc)
8. Mechanical stability and heat transfer to wall rocks; contact metamorphism
9. Ballistics, thermal and comminution history of entrained fragments
10. Hydrodynamics of the exhaust jet; interaction with atmosphere or vacuum
11. Exterior ballistics of fragmental ejecta; atmospheric drag
12. Ash distribution by wind; fall out
13. Mechanics of emplacement of lava and ash flows (heat and mass transfer)
14. Volcano acoustics; airwaves and atmospheric shocks.
15. Seismicity
16. Other

Sources of Data (Constraints on all models)

Direct field observation of active volcanoes

Reconstruction of events using:

Geological relations to reconstruct a detailed sequence of events (or direct data).

Petrology (P, T, H₂O..... physical and chemical history revealed by mineral chemistry, textures, etc.).

2. SUPPORT

The present level of support was approximately \$50,000 per year, about equally split between the NSF, which supports petrologic studies, and NASA, which supports volcanological and planetary surface investigation. Nominal - but important - support was provided by M.I.T. and U.S. Geological Survey.

1. NASA - (NGR-22-009-522) Photogeologic investigations of Mariner 6 and 7 photographs. 1 April 1970 to 30 March 1972. \$25,000.

2. NASA - (NGR-22-009-637) Volcanic Field Studies 1 June 1971 to 30 May 1973. \$57,000.

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4. U.S. Geol. Survey - Apollo 16 and 17 Field Geology Experiment.

5. M.I.T. - Various means including: Undergraduate Institute funds, Teaching Assistantships, Fellowships and Tuition Scholarships.

3. PARTICIPANTS

T.R. McGetchin

Assistant Professor of Geology, M.I.T.
Ph.D., California Institute of Technology, 1968
Volcanic geology; petrology of ultramafic and
volcanic rocks; planetary surfaces and interiors.

B.A. Chouet

Graduate student, M.I.T. (NASA)
S.M., Massachusetts Institute of Technology, 1972
(Aero-Astro Engineering); 1973 (Geology)
Physical volcanology; data acquisition and pro-
cessing methods; field methods.

D. Francis

Graduate student, M.I.T. (NSF)
B.A., Univ. British Columbia, 1970
Genesis of basaltic and ultramafic rocks; field
geology and petrology.

M. Settle

Graduate student, M.I.T. (NASA)
B.S., Massachusetts Institute of Technology (1973)
Petrology and geology of volcanic rocks; volcanic
eruption prediction by empirical statistical
means; cratering models, applied lunar geology.

G. Wayne Ullrich (Capt., USAF)

(NASA)
Graduate student, M.I.T.
M.S., Air Force Institute of Technology, Wright-
Patterson Air Force Base, Ohio, 1969
Shock hydrodynamics; cratering by explosives;
hydrodynamics of volcanic eruptions.

Masaaki Obata

(NSF)
Graduate student, M.I.T.
M.S. Kanazawa University, 1972
Petrology of ultramafic rocks, particularly
eclogites.

N.M. Hamisevicz

B.S., M.I.T. (Electrical Eng.) 1973 (NASA, UROP)
Computer methods applied to data acquisition
processing of volcano eruption photography;
ballistics.

Gordon Woulff

Undergraduate student, M.I.T. (1973) (Mathematics
and Geophysics) (NASA, NSF, UROP)
Geological field assistant to Don Francis in
Alaska (June-July, 1972); volcanic geology;
fall-out from volcanic ash eruptions and the
effect of crosswinds on ejecta and resulting
volcano morphology; volcano noise.

M. Scott Baldrige (NSF)
Div. Sponsored Research, employee, M.I.T.
Graduate student, California Institute of
Technology (beginning Sept., 1972)
Chemical evolution of volcanic rocks; Hekla rocks.

Robert Hart
B.S., M.I.T., 1972 (Geophysics) - Currently a
graduate student at California Institute
of Technology
Acoustic methods for analysis of volcanic exhaust
jets.

Carli Pieters
Graduate student, M.I.T. (Planetary Science)
B.A., Antioch College, 1968, M.S., M.I.T.
(Planetary Science) 1973
Geology of volcanic landforms and diffuse spectral
characteristics of volcanic ash and cinders

Beverly Carrol
Graduate student, M.I.T. (Geology)
B.S., U. Calif., San Diego, 1970
Petrology and petrography of volcanic rocks

William Baan
Graduate student, M.I.T. (Physics)
Numerical models for large-scale eruptions of
the Katamai, Hekla, Krakatoa (blast) type.

Support Personnel

Douglas Hopkins
Division Sponsored Research (NASA)
Photographic technician

Susan Hall
B.A., Univ. of Illinois, 1970
Secretary

4. FIELD ACTIVITIES

Our work begins with field observations. During the period 1970-1973 members of our research group visited sites in Alaska (Nunivak, Katmai), Iceland, Hawaii, Italy (Etna, Stromboli, Vesuvius), Arizona, Guatemala, Chile, and Ecuador and have published on most and have manuscripts approaching completion on each locality. The localities, data and participants are listed below:

<u>Date and Participants</u>	<u>Feature</u>	<u>Publications</u>
A. Arizona, June 1970 Jim Cole Jim Besancon Rudy Hon Jasi Nikhanj Scott Baldrige Paul Pelke Tom McGetchin	Kimberlite pipes and Upper Mantle Symposium in Flagstaff	McGetchin and Besancon (1972) McGetchin, Nikhanj, Chodos (1972)
B. Iceland, May 1971 Fred Frey Scott Baldrige Kate Hadley Suzanne Sayer Richard Naylor Tom McGetchin	Harvard Geology Club trip covering all of Iceland	Baldrige, McGetchin Frey (1972)
C. Italy, August 1971 Tom McGetchin Bernard Chouet Mark Settle Douglas Hopkins Richard Birnie (Harvard)	Mapping and Photographic experiment on Etna and Stromboli	McGetchin, Settle, Chouet (1972) McGetchin and Head (1972) McGetchin, Head, Chouet and Settle (1972) Chouet, Hamisevicz and McGetchin, (1972) Chouet's M.S. Thesis
D. Hawaii, March 1972 Doug Luther Bob Hart Nick Hamisevicz Don Francis Mark Settle Bernard Chouet Carli Pieters Larry Lebofsky Tom McGetchin	MIT Seminar; Topical studies of the cinder cones of Mauna Kea	3 papers in preparation

- E. Nunivak Island, Alaska, June-July, 1972
 Don Francis
 Gordon Woulff
 Geologic mapping and field petrology of xenolith bearing cones on Nunivak Island
 Francis' Ph.D. thesis
 Francis and McGetchin 1973, 1974
- F. Central America
 Guatemala, Jan '73
 B. Chouet
 N. Hamisevicz
 G. Woulff
 M. Settle
 D. Francis
 N. Apter
 R. Birnie, Harvard
 P. Lyttle, Harvard
 Coordinated physical observations of active volcanism (seismicity, acoustics, eruption photography) at Pacaya, Acatemango and Santiagaiyo. Trip built an MIT Seminar Fall Term 1972-73, on physical methods and 19 participants
 Woulff and McGetchin 1974
 2 abstracts
- G. Chile, Poge hue Volcano January 1973
 T. McGetchin
 M. Settle
 D. Francis
 B. Chouet
 Mapping and petrologic collection of a recent maar observed in a state of eruption, 1960.

5. PROJECTS AND RESULTS

A. Mt. Etna - Cinder Cone Growth Models

Field and photoballistic observations and theoretical eruption modelling using data acquired during Sept. 1971 field trip to Italy produced some interesting results, summarized in JGR, in press. Photographs analysed show ejecta exits Etna's northeast crater at median velocity of 51 m/sec, maximum of about 80 and exit angles vary about uniformly in a cone between 70° and vertical. A mathematic model for cinder cone growth follows from ejecta distributions which include the effect of atmospheric drag on particles trajectories. The model predicts four stages of cinder cone growth quantitatively defined, which are in good agreement with field observations. Models permit prediction of lunar and Martian cone shapes, given exit conditions. Predicted Martian and lunar cones are quite unlike terrestrial cinder cones and very much like the dark blanketing deposits near Apollo 17 site on the moon. Results show that inferences about look-alike features in photographs of planetary (i.e. so-called terrestrial analogs) is hazardous, unless inferences are based on sound models for the processes involved in the formation of specific features. Conversely, where such models are strong, landforms can be used to infer conditions of their formation by inversion. One example is the inversion of pyroclastic cone shape to exit velocity of the erupting ejecta (and its volatile content); another is the asymmetry of cone shape to the crosswind environment.

Publications

p 10, p 16, A 13, A 15, A17

B. Stromboli - Eruption Mechanism Studies

High speed movies were taken of the eruption of Stromboli during September 1972. A Hulcher 102 ballistic movie camera was used which provided excellent quality 70 mm images which have been processed using a computer interfaced digital film processed by Nick Hamisevicz provide a very detailed description of two Strombolian eruptions and was the subject of B. Chouet's M.S. thesis and has been accepted by JGR. We have mapped the time variation of particle velocity, mass flux, energy flux, particle size and exit angle through two complete eruptions and have used these data to constrain the hydrodynamics of the eruption (i.e. to describe how the plumbing system of the mountain operates in detail). Also, we have good quantitative estimates of the ratio of gas to solid ejecta emitted. These data are important from the viewpoint of the origin and evolution of the atmosphere and ocean.

Statistical analysis of an eruption chronology compiled by M. Settle who observed the five summit vents over a three day period has revealed a strong correlation between the eruption of two of the vents and the activity of the others. Presently these data were subjected to stepwise regression analysis which yields an expression of the time to the next eruption at an individual vent as a function of the previous period duration, and activity of neighboring vents in a general linear equation. Possible electrical analogs in switching circuit theory are also being investigated. We believe statistical treatment of the eruption history of volcanoes generally may lead to much improved models. This result points up the usefulness of studying "laboratory" cases such as Stromboli, which erupts about every 20 minutes. We intend to test the model on volcanoes with longer periods of eruption such as Kilauea and Hekla, and feel we have an important statistical tool to be applied to the important problem of eruption prediction.

Publications

p 18, A 13, A15, A18

C. Hekla - Evolution of its lavas

During 1971, Harvard's Geology Club sponsored a field trip to Iceland during which samples of the 1970 Hekla lavas were collected by Scott Baldrige, McGetchin and Fred Frey. Hekla is a particularly interesting volcano because it's andesitic lavas may be related to the oceanic tholeiites of the mid-Atlantic ridge, hence the nature of this evolution is of some interest. The volcano erupts episodically and characteristically these eruptions begin as violent tephra (ash) producing blasts which evolve with time during each eruption to more-and-more basic lavas; the mode of eruption becomes progressively more quiescent with time. Also careful work on the tephra by Icelandic geologists have shown that the silica content of the first erupted tephra is directly proportional to the repose time since the last eruption; hence, Hekla is a lava differing machine which performs linearly in time. We are intrigued by these relationships and investigated several Hekla rocks including some collected during the 1970 eruption supplied by Wm. Melson, Smithsonian Museum, Washington.

We obtained probe data on phenocryst olivine, magnetite and plagioclase and the groundmass (glass). Our data show that the evolution of the Hekla lavas is dominated by olivine and magnetite separation - the precise time of appearance of magnetite is apparently controlled by PO_2 and explains the evolution of the Hekla lavas and those at Thingmuli, Iceland. Most interesting from the eruption viewpoint are the data regarding PH_2O which indicate very high water pressures in the magma chamber in which the plagioclase phenocrysts formed (2 to 4 kb). This is an important physical constraint on the pre-eruption conditions and will permit quantitative treatment of the tephra-producing blast by a modified shock-tube model. This is important because Hekla is one of the best understood of the truly dangerous andiesite, ash-producing volcanoes whose eruption frequency is so low that empirical data are poor, yet potentially are the most destructive (Krakatoa, Relee, Thera, and examples).

Publications

p 15

D. Mauna Kea, Cinder Cones and Petrology

During Spring vacation 1972, 10 M.I.T. students and McGetchin spent four field days investigating the cinder cones on the NW flank of Mauna Kea, Hawaii. Our interests included planetary surfaces, petrology, volcanology and geophysics. We worked in 4 teams concerned with the following: (1) reconnaissance characterization and sampling of the field, (2) internal cone structure, (3) ballistics and geomorphology and (4) petrology of ejecta and xenoliths.

Cone structures are interpretable and consistent with the mathematical model evolved at Mt. Etna. The geomorphic state of the cones precluded interesting results from a ballistic viewpoint, although good quantitative descriptions were obtained of the cone material. Many of the cones are asymmetrical and show the effects of crosswind on the distribution of ejecta. The studies of xenoliths and lavas have revealed that the color (oxidization) of the lavas is reflected in the xenoliths in the formation of iddingsite (from olivine and orthopyroxene) and these reflect PH_2O and PO_2 changes in the reservoir prior to eruption. A variety of xenoliths including dunites, peridotites and plagioclase-bearing rocks which appear to be cumulates from the lavas and not mantle derived xenoliths, in general. The diffuse reflection spectra of xenoliths and lavas (0.34 to 1.8 microns) show three distinct spectral types correlated with black, maroon and red ash. These curves are remarkably similar to those observed on Mars and we think the Mauna Kea results may be quite significant in that context.

Two other aspects of the Mauna Kea cones are being investigated by students who did not participate in the field trip. First, the spacial distribution and cone volumes are being compared with the apparent cones in the vicinity of the Apollo 17 landing site, by Mike Charette. Secondly, Alan Goldberg set about mathematically modelling a tectonic model for the hot-spot hypothesis which we hope to use as one model for petrogenesis of the lavas.

Publications

E. Nunivak Island, Alaska

Nunivak Island lies about 100 km north of the Aleutian chain just off the west coast of Alaska. Young alkali- and tholeiite-basalts overly Cretaceous sediments. In 1968 McGetchin and two USGS geologists visited the island for 3 weeks, mapped the distribution of blocks around recent maars. The size of blocks decreases with range and these field data were inverted in an AFIT M.S. thesis by K. Rohlf to the eruption properties. McGetchin published analysis on a mantle-derived mica-bearing spinel-peridotite from one of the maars.

Several interesting problems are being investigated by Don Francis (Ph.D. thesis, with field assistance by Gordon Woulff). Peridotite xenoliths vary from olivine-clinopyroxene to dunite, plagioclase-olivine (troctolites) granular textured grade into pyroxene-spinel rocks (possible basalt-eclogite rocks). As at Mauna Kea, xenoliths of all types vary in the degree of alteration by iddingsite formation, from those with pristine-olivines to completely iddingsitized types. The degree of alteration is directly correlated with oxidation effects in the lavas, as at Mauna Kea, reflecting conditions in the reservoir.

Francis is particularly interested in attempting to relate the petrology and petrography of the xenoliths and the basalt genesis to the geographical distribution of cones on the Island to see if any zonal distribution similar to that observed on Oahu is present. This was interpreted by Jackson and Wright in terms of the upper mantle petrology hence is of considerable interest. Also of possible significance is the unusual tectonic setting of Nunivak, behind the active Aleutian arc. (Specifically, could any of the basalt-eclogite transition rocks be fragments of the down-going lithosphere, transported to the surface by the diatremes?). The similarities to the Mauna Kea rocks provide interesting grounds for comparisons because Nunivak is underlain by continental crust. Also strain effects in the peridotites from Nunivak are being investigated by other MIT workers and may be a clue to their origin - i.e. cumulates should be unstrained, true xenoliths may retain strain effects. Francis has also shown that basalt genesis may be closely tied to hornblende breakdown in hornblende peridotite. Using chemical and textural data he has shown that hornblende may be an important constituent of the upper mantle under the Bering Sea.

Publications

A 4, A 22, A 23

F. Colorado Plateau Kimberlite and Carbonatite Pipes

Arizona-Utah kimberlite and carbonatite diatremes provide some interesting clues to the nature of processes operating in the upper mantle as well as samples (xenoliths) derived from the vent walls by the eruptions. The Colorado Plateau experienced epirogenic uplift during the Tertiary and the pipes are dated at 30 m.m., hence the association of kimberlite, carbonatite and exotic basaltic rocks (sanadine-bearing lamprophyre reflect the upper mantle conditions associated with platform tectonics. (McGetchin's Ph.D. thesis was concerned with the composition of the crust and mantle, and the emplacement of kimberlite as revealed by geological field investigations, petrologic studies of kimberlite and xenoliths and hydrodynamic models for the kimberlite emplacement).

Beyond attempting to clear the deck of ideas and data accumulated during the thesis, several new things have appeared. During a field trip during June 1970, Jasi Nikhanj and McGetchin collected samples of intrusive carbonate containing biotite and chrome-chlorite. Probe studies on these minerals led to a model for their genesis by reaction of mantle volatiles (H_2O and CO_2) with R_2O_3 -rich diopside in upper mantle peridotite. A product of the reaction is carbonatite. The genesis and association of carbonatite and kimberlite is thereby explained by reaction of volatiles and mantle peridotite. This supports an earlier suggestion by McGetchin and Silver, that the Colorado Plateau epirogenic event reflects a volatile-rich mantle - the source of the volatiles remains an interesting mystery. This result also constitutes a new model, for the genesis and association of carbonatites and kimberlites. On the same field trip garnets were collected by Jim Besancon and McGetchin which contained carbonate the amphibole inclusions. The garnets are pyropes believed to be derived from disaggregated upper mantle, garnet peridotite. Hence, these inclusions are direct evidence for upper mantle carbonate and amphibole. Phillip Oreville in a seminar at M.I.T. during 1972 made the interesting suggestion that potassium might exist in the upper mantle as K_2CO_3 (at sufficiently high pressure), so we investigated the carbonate inclusions in detail. We found negligible amounts of potassium but widely varying Ca/Mg ratios, and significant amounts of Sr, approaching 1%.

Also, whole rock data in Moses Rock xenoliths were plotted during work on the Hekla lavas. The plutonic rock of clearly near surface origin were found to define a calc-alkaline differentiation trend from gabbro to rhyolite, whereas the eclogite and high rank rocks with meta-igneous textures form a clearly defined but different trend culminating in jadeite-rich, sulfide bearing rocks. The latter group may reflect a high pressure differentiation trend. Hence we believe the eclogite and granulite nodules in the kimberlite pipes represent trapped basaltic magmas formed and possibly differentiated at depth which were formed in the lower crust as dikes and sills.

Publications

Many -- See bibliography

G. Lunar and Planetary Surface

Three ideas have been pursued in support of the Apollo field geology experiment team for Apollo 16 and 17. All of these have been carried along in close cooperation with Dr. Jim Head, Brown University, W.R. Muehlberger, USGS, and the flight crews. Results are equitably applicable to Mars.

The first, we are attempting to rationalize the observed sequence of events recorded on the moon's surface with thermal evolution models, petrologic and chemical results on samples remote sensing data, and the local geology of each Apollo site. In early lunar history there are two major processes operating; first, igneous activity in the interior and second, the large impacts. This is the whole-moon problem and it serves as a worthwhile context in which to view the local geology of each site.

Secondly, the Stromboli and Etna results suggest that the dark blanketing deposits near the Apollo site are the lunar equivalent of terrestrial pyroclastic cones. Both the detailed morphology of individual cones and the areal distribution of cones is consistent with this view. Because the dark mantling deposits are very young (based crater count data and simple superposition) it means Apollo 17 may provide relatively young volcanic rocks of pyroclastic origin, hence samples will be of great interest from the viewpoint of the thermal and igneous evolution of the lunar interior. Also, pyroclastic eruptions on the earth are driven by some volatile phase. The nature and abundance of this material, some small part of which is probably trapped in ejecta, is also important. The orange soil at the Apollo 17 site is believed by most investigators to have a pyroclastic origin, although the dark mantle unit remains an enigma.

We also have been investigating explosion and impact cratering in attempts to assess the detailed nature of the ejecta blankets from impact craters. The lunar surface is dominated by impact features, and the major events in the evolution of the lunar surface are the large basin-producing impacts. The sequence in which these basins formed is now well known - Nubium, among the oldest; Imbrium and Orientale among the youngest. The lunar front-side (the part not buried by mare) consists of a sandwich of ejecta from each of the front-side basins. So, if one had a good working model to describe the ejecta from craters, then it could be applied to each basin in succession to describe the nature of the ejecta at a given location on the moon. We have discovered that many such interesting properties of ejecta blankets are described by a simple power function of the form $t = A(r/R)^{-B}$ where A and B are empirical constants, r is range, and R is crater radius. Ejecta thickness turns out to be scale dependent, i.e. $A \approx 14R^{0.74}$ but B is about 3.0. We have used this to calculate the stratigraphic column at all the Apollo sites and several other localities of interest. The thickness contributed

to each of the Apollo sites derived from the 10 large frontside basins varies from about 100 to 200 meters. The predicted thickness of the Imbrium ejecta at the Apollo 14 site is about 33 m; data from the active seismic experiment suggests 35 to 65 m. Many other physical properties such as maximum and median particles size appear to be described by similar simple power functions. We are exploring the many properties of ejecta blankets thereby predicted such as impact velocity, shock state, initial and final temperature, secondary crater frequency and size, to name a few. This model has proved to be quite useful to several sample investigations and is currently the topic of a lively debate concerning the conditions of formation of the large lunar (mare) basins and the associated ejecta blankets which form the lunar upland rocks.

Publications

P 13, (P 20), A 19, I-6, I-7

H. Mars - Volcanic Geology and Implications

Photographs of the Martian surface by Mariner 6, 7 and more recently by Mariner 9, have revealed a truly spectacular array of volcanic landforms, including the largest single known volcano in the solar system, Nix Olympica. The age of the volcanoes is unknown, but the low crater frequency on the surfaces near the obvious centers indicates a relatively young (flux) age for the volcanism. Our view of the Martian interior has changed radically as a consequence of the new radius determinatives and it is now clear that Mars has a sizable core, probably approaching 40 to 50% of the planet's radius. Current thermal evolution models suggest that Mars may still be in its core-formation processes; hence, the nature and timing of the volcanism is an important factor in the context of Martian thermal evolution.

We have pursued several problems relating to the volcanism and Mar's surface and interior. The current views of the evolution of Mar's interior could logically result in virtually any type of igneous rock at its surface - granite to iron rich peridotite. If the production of pyroclastic rocks, particularly ash, on Mars is similar to earth's, then it is reasonable that 10 meters, and perhaps as much as 100 m, of volcanically contributed material may occur on the surface. This swamps the meteoritic contribution and could dominate remote sensing observations. Also current planetary accretion models suggest that the amount of volatiles initially trapped in Mars may significantly exceed the earth and moon, hence if Mars is currently actively forming its core, then the release of volatiles from its interior (and resulting volcanism) may be at a peak or at least relatively high. In attempting to assess the thermal state of Mars interior we found an interesting relationship between planetary mass and surface heat flow -specifically, a simple hueristic model suggests that surface heat flux may be proportional to the cube root of the mass of planets. (This is clearly not true for stars because the energy production rate is strongly mass dependent). Earth's heat flow scaled to the moon is in excellent agreement with the average of 32 calculated values; the predicted heat flow for Mars is 45% of the earth's. Various thermal gradients are possible within Mars and we investigated the implications of various models by superimposing these thermal gradients on the stability relations (in pressure, temperature, and PH_2O space) for basalt and peridotite. We found that partial melting does not occur within a wet peridotite Mars, if the surface heat flux is earth-like (i.e. 45% of the earth's). A basaltic Mars melts if $\text{PH}_2\text{O} < \text{PT}$ at about 300 km depth. If saturated it melts at about 200 km, but a higher heat flux is implied, about 71% of the earth's.

One of the implications of a higher thermal gradient is that the phase boundaries shift to greater depths - hence in a

basaltic Mars the basalt-eclogite transition is deeper, the crust will have a lower density and (if isostatically balanced) will stand higher. The height will be simply related to the heat flux. We noticed that the detailed topography revealed by radar studies showed that one possible volcanic center (Iapagia) should be topographically high, by about 4 km, above the surrounding terrain, and that its photogeology suggested, at least, a central volcanic complex and possible massive flows. (We were struck with the question of how Iceland might appear if the Atlantic Ocean didn't exist). Combining these observations and inferences we found that the radar topography, photogeology, petrologic models for the interior and estimated surface heat flux make a self-consistent picture, and suggests that the following properties of Mars may be correlated - high surface heat flow, volcanism, and elevation.

Another specific problem under investigation is the inversion of the form of asymmetrical pyroclastic cones to infer exit conditions and crosswind magnitude. This is one extension of the Stromboli-Etna and Mauna Kea field work and is currently being carried on by Gordon Woulff and Nick Hamisevicz.

We have collaborated with Dave Johnston and Nafi Toksoz in some thermal history calculations of Mars. One of the interesting results was a petrologic model for the Martian mantle suggesting that its composition is quite unlike the earth's. The predicted martian mantle is an ore-bearing, garnet dunite in which the olivine and garnet are very iron-rich (olivine, fo⁵⁶). Lavas produced by partial melting of such a system should be a very iron-rich picritic basalt having a very low viscosity. This is of considerable interest to both astronomers interested in remote sensing and to volcanologists interested in the huge martian shield volcanoes.

Publications

P10, P11, P17, A14, A16, A17, A19, A20, I4.

I. Miscellaneous Studies

I.1. Fallout of Volcanic Ash

Don Francis, in a term paper, showed that the decrease of thickness and particle size from large ash eruptions is described by patched power functions. Using data from 11 large eruptions he showed that ash thickness decreases with a slope of -1 to -2 from the vent to a range of about 100 km, but beyond, the decrease is much faster, described by a power function of slope approximately -5. We don't know why. We are interested in applying two approaches to this problem - first, the calculations of the penetration of the atmosphere by a high velocity upward directed jet and second, solution of the fallout problem using empirical data from atom bomb testing, and atmospheric models. Volcanic clouds penetrate to great altitudes, some as high as 100,000 feet, so the problem has implications for air pollution, Martian geology, as well as volcano eruption mechanisms.

Gordon Woulff investigated this as a part of crosswind effects on volcanic ejecta.

Publications

I.2. Shape of Asteroids and Decay of Topography on Planetary Surfaces

We were interested in the ability of simple model bodies to support topography under loads imposed by the topography itself. We find that the time-scale of the stability of topography is critically dependent on temperature where creep is considered and that ice-rock bodies such as satellites and asteroids are quantitatively ambiguous with respect to whether or not topography would last for geologically long times. Hence, their surfaces might be useful clues to their thermal history.

Publications

P11, A16

I.3. Diatreme Hydrodynamics

McGetchin initiated a program of numerical hydrodynamic calculations of erupting kimberlite diatremes, and made quantitative estimates of the flow properties in the Moses Rock dike. Wayne Ullrich extended these models to include many more effects including basalt models involving exsolution of volatiles from the melt. Ullrich's results were used to calculate the distribution of blocky ejecta around possible lunar and Martian diatremes. One of the principal uncertainties in these models is the drag law for multi-phase flow in ducts - and our knowledge of such systems at high mass ratios of solid-volatiles is really weak. The models should be extended to explore a range of possible drag laws, and to a more general formulation of the conservation equations for two phase flows.

Publications

P1, P8, P9, A6, A12

Field Methods for Volcano Research

We're interested in developing new and imaginative techniques for use in the field, on volcanoes, to augment studies by classical geological, geophysical and petrological means. Although we're interested in both surveillance and topical studies, for the moment we're primarily pursuing the latter, and are looking for light weight, portable, but good experiments.

J.1. Photography

We have demonstrated, to our own satisfaction, the significance of very high quality, high speed ballistic movie photography. The Hulcher 102 provided excellent images at Stromboli - and we've developed data retrieval techniques and solved the major geometry and statistical problems required to extract the physically interesting data. We've also learned how to improve our field experiments - and we need our own Hulcher. At Stromboli we also tested a Hasselblad equipped with a mechanical time-chopping mechanism and obtained useable images. A twin stereo-based Hasselblad (or Nikon) system, time-synchronized and time-chopped would provide another powerful tool for studying individual eruptions. Data obtained provide detailed time history of eruption events and permit models of eruptions to be tested.

J.2. Acoustics

Photography provides direct data on the character of volcanic jets. The sound associated with eruptions, like the visual effects, is spectacular but also contains much information. The total power radiated from a (simple) jet source is proportional to the eighth power of the gas velocity; its power spectrum also varies with velocity. A moderate quality tape recorder and moderate quality microphone are sufficient to provide quantitative data for acoustic analysis, provided a calibration source is included during the field experiment. The results will be an independent means of investigating the properties of the volcanic exhaust jet - particularly the time dependence of velocity and perhaps mass flux. This idea was field tested by Gordon Woulff at Acatenango, Jan. 1973, and a manuscript describing the results is being submitted.

J.3. Spectroscopy

Volcanic jets are generally incandescent and flames are commonly visible. Several scientists have studied the radiation emitted by these jets and have inferred the composition of the gases, in their pristine (unoxidized or partially oxidized state), (for example, Naughton and Kruckshank, in Hawaii). Several experimental configurations suggest themselves. The first is a passive one in which the vent gases act as a source and the emitted spectra recorded

and analyzed. The second requires an active source behind the vent and would measure the absorption of radiation by the volcanic gases. Both techniques suffer by the influence of atmospheric gases in the path between the source and recorder. This problem suggests the possible usefulness of a differential measurement technique in which a comparison would be made between a reference beam which might travel nearly the same path as the test beam, in either an active or passive experiment. The nature of both the source and receiver are problems. High resolution spectrometers (Fourier transform interferometers) exist with sufficient spectral resolution to separate, not only molecular bands, but potentially splitting due to light isotopes, particularly H and D, such as in H₂O and HCL. Such systems are delicate and require liquid N temperatures, hence severe experimental problems separate the concept and its field use. Never-the-less, we are most interested in this experiment because it would provide valuable data on some quite general problems - the flux and composition of volcanic gases, the ratio of juvenile to recycled gaseous components, hence the present rate of evolution of the earth's atmosphere. We are currently exploring the possibility of using backscattered tuned (CO₂) lasers as a means of analyzing volcanic gases and we feel this technique holds great promise.

J.4. Several-channel analog memory - AD converter

At very active sites such as Stromboli, a simple several-channel memory (about 6) with the capacity of storing continuous information, generally in binary form, would permit collection of important statistical data by a single individual (or ultimately by remote automated means). Such data are required in construction of empirically based eruption prediction schemes and are also necessary for evaluation of hazards during field operations.

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