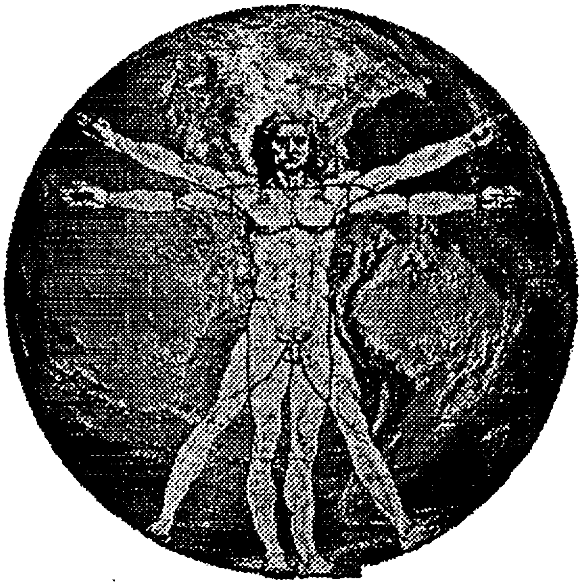

Proxemy Research
Grant NAS5-7251
Closeout Report

Author: Dr. Stephen M. Baloga

Proposal Title: Quantitative Studies in Planetary Volcanism
(Grant No. NAS5-7251)

Submitted to: Dr. David Senske
Code SR
NASA Headquarters

June 30, 2001

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PROPOSAL TITLE:: Quantitative Studies in Planetary Geology

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1. Introduction

Proxemy Research had a grant from NASA to perform science research of quantitative studies of planetary volcanism. **This grant (NAGS-7251) closed on April 30, 2001.** Here we summarize the scientific progress and accomplishments of this grant. Scientific publications and abstracts of presentations are indicated in the final section.

This was a very productive grant and the progress that was made in each year is summarized below. The Full Proposal originally identified four tasks related to geologic features associated with planetary volcanism. The problems presented in the full proposal were selected because of their significance to planetary geology and our ability to make a unique contribution. The specific topical areas were: 1) Rapidly emplaced lava flows, 2) The emplacement of pahoehoe flows, 3) Volcanic debris flows on Mars and Venus, and 4) Lava flows and bright deposits on Io. Attention is drawn to the publications, abstracts, and talks given in each year.

2. FY 01 ACCOMPLISHMENTS

Bright deposits on Io. This research focused on the bright annular deposits volcanic plumes and the bright conforming margins of lava flows, known as "auras". During the last year, our manuscript on volcanic plumes on Io appeared [Glaze and Baloga, 2000, **"Stochastic-ballistic plumes on Io"**, JGR/Planets,105,E7 17,579-588]. This work presented a theory for volcanic plumes on Io and applied it to the bright cylindrically symmetric annular deposit at Prometheus. The stochastic-ballistic model divides a plume into a small region near the vent, where random effects occur, and a larger region where the transport of plume particles is purely ballistic. For data/theory comparisons we have assumed that the brightness observed in imaging data is proportional to the areal concentration of plume particles. This theory was found to provide very good agreement with the profiles at Prometheus, provide plausible compositional constraints, and explain why annuli are observed for some eruptions, but not others.

Since the publication of the plume paper, we have focused on adapting the theory for the auras at Talos Patera. Three plausible alternative hypotheses for the formation of auras were investigated. **Hypothesis 1:** Heat from the flow releases volatiles from the regolith beside the flow. The volatiles are then transported above the surface and deposited to form the aura. **Hypothesis 2:** Volatiles are derived directly from the surface of the flow itself. Once liberated, they follow ballistic trajectories to the surface. **Hypothesis 3:** Heat from the fresh lava flow propagates through the regolith, locally mobilizing the volatiles throughout the entire lateral extent of the aura, where they condense immediately at the surface. We have reformulated the stochastic-ballistic model so that it can be applied to the auras. We have also developed compositional constraints by assuming 3 different styles of volcanism for the flow itself: basalt, ultramafic, and sulphur. Results of this analysis were reported at the recent LPSC [Baloga and Glaze, 2001, Potential mechanisms for the formation of lava flow auras on Io, Abstract, LPSC XXXII].

The random walk model for pahoehoe lavas. Our approach to modeling the emplacement of pahoehoe has been to treat lava transport as a random walk. Initially, we considered simple uncorrelated random walks. Our results for small lobes of toes were conceptually very encouraging. When we scaled up the theory to flow fields and lobes of hundreds or thousands of parcels, we found that no form of correlated random walk could reproduce the shape of isolated Hawaiian lobe transects. Consequently, we invoked a very challenging form of a correlated random walk. Here the correlation is thought to come from the momentum of lava parcels in motion and a "chain of memory" connection with vent conditions. There was no useful information in the literature for this type of random walk, but we were able to obtain a new solution that gives pahoehoe lobes transects that agree with field observations. The mathematical formalism of this new correlated random walk has been completed and the predictions have been compared with approximately a dozen transects of lobes in Hawaii. (See abstract in final section.)

The influence of degassing and channel formation in planetary flows. We have recently published a model for lava flows that explicitly considers the loss of volatiles while a flow is active [Baloga et al.,**"The influence of degassing on thickness and density profiles in active basalt flow lobes"** to appear shortly in JGR Solid Earth, 2001]. We have applied the density change theory to almost two dozen lava flows on Mars and the Moon for which we have thickness information from either Viking, MOLA, or the Apollo images. It is also well-known that levee-building and other similar types of lava volume and mass loss while a flow is active has a signficant effect on estimates of viscosity, lengths of flows, and advance rates. We have recently combined both of these models to obtain a new set of equations to describe a mass loss to stationary margins concurrent with a density change along the path of the flow. We have shown that the nature of the viscosity change along the flow path has a major influence on the shape of the profile when density change and levee building are included. These profiles can be readily compared to planetary data for lava flows on Mars and the Moon. This confirmed our suspicions that the formation of stationary margins, combined with a density change along the flow path, has a dramatic effect on the thickness profile.

Miscellaneous collaborations. Collaborations with PIs in the PGG program resulted in 3 additional abstracts presented at the last LPSC conference. One addressed a statistical analysis of coronae on Venus (by Stofan et al). Another investigated the growth of the lunar regolith (by PD Spudis and SM Baloga), and a third investigated the validity of volcanic plume models on Mars (by LS Glaze and SM Baloga).

3. FY 00 ACCOMPLISHMENTS

Modeling pahoehoe lava. We made significant progress developing a stochastic model that explicitly incorporates random effects. To date, we have statistically characterized the dimensions of pahoehoe toes [Crown and Baloga, 1999] and we have collected other field data intended to distinguish the different types of random walks. Recently, we investigated models for uncorrelated random walks, with and without bias, and spatially-correlated random walks [Baloga and Glaze, 2000]. We presently believe that pre-existing large scale topographic slope can be expressed as a "bias" in the random walk. On the basis of preliminary field observations, we have obtained broad qualitative agreement between predicted and observed shapes of isolated lobate deposits emplaced in the toe regime.

The uncorrelated random walk describes a number of qualitative features observerd in the field, such as the meandering of isolated filaments and the budding of toes in the upslope direction. Figure 1.1 shows the resulting cross-sections of such a flow at different time steps. The flow spreads and gently thins as it advances. A discrete binning of these curves can be compared to field data.

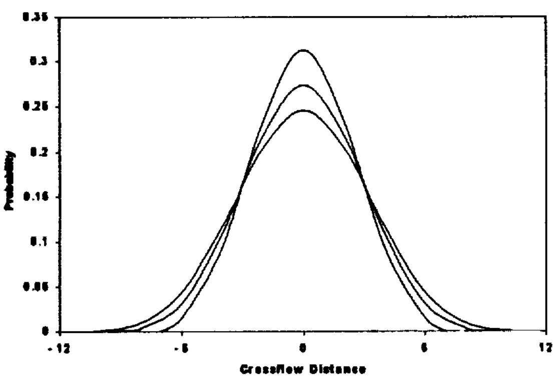

Figure 1.1 Cross-section of flow at time steps N = 6, 8, & 10 (top, middle, bottom).

We were initially encouraged by the applicability of the uncorrelated random walk for large numbers of parcels. However, a number of issues arose. First, this classical random walk minimizes the interaction between parcels during transport. Thus, the limited influence of neighboring parcels precludes conventional fluid dynamic influences throughout the active lobe. In effect, we would have to abandon conventional viscous fluid dynamics except for a parcel-by-parcel application at the margin and front of the lobe. A second problem with the uncorrelated random walk became evident from computer simulations of many uncorrelated random walks. These simulations superimposed many monofilaments. They reproduced broad, amorphous flow fields of many thousands of parcels, but were far too diffuse to represent solitary or multiple lobes. Finally, we had collected thickness transects across a dozen or so small isolated lobes at Mauna Ulu and Hualalai (e.g., Figure 1.2). On the basis of this exploratory study, it was ambiguous, at best, whether such profiles actually fit the theoretical predictions.

We addressed these issues by considering a correlated random walk and by the collection of additional field data. With a correlated random walk, some "memory" of what happened to a parcel at prior steps is retained. Correlation is a manifestation of the momentum of the flow, inertial effects, and fluid dynamic pressure, when there are many contiguous parcels in a flow lobe.

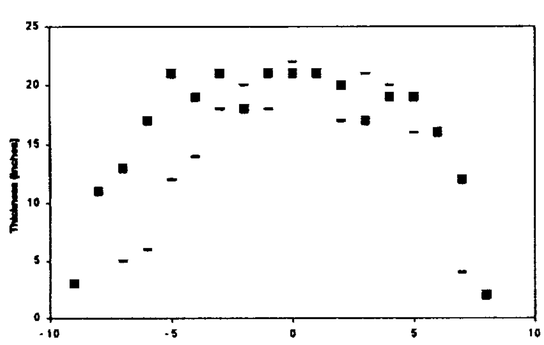

Figure 1.2 Measured pahoehoe lobe transects

In broad amorphous fields of toes, there is often a clear loss of connection between the source of lava supply and the formation of toes. As a toe forms in one location, other toes can be simultaneously budding and forming, at random, at other locations. This does indeed suggest a lack of correlation.

However, in lobes, sheets, and channelized flows, there is a definite, overall flow and forcing of parcels that is the direct result of continued lava supply and fluid dynamic effects.

The development of the correlated random walk model proved to be an unexpectedly difficult challenge. We were not able to directly use any of the correlated random walks that have appeared in the literature or any of several initial attempts we developed. Based on field observations, it is clear that the formalism must include perfect correlation, its absence, and the full range of intermediate cases. We also wanted the capability to simulate the full range from a few toes to thousands of pahoehoe parcels. We desired a general analytic formalism that would allow us to relate the predicted features to conventional fluid dynamics. Finally, we wanted to avoid having to manually derive the probability distribution for each time step for different degrees of correlation.

Io Plumes and Auras In Glaze and Baloga [2000], we developed the stochastic-ballistic theory for volcanic plumes on Io and applied it to the bright annular deposit at Prometheus. The stochastic region is considered to be a hemisphere near the vent with a radius that is small compared to the overall dimensions of the plume. Within this region, the random effects associated with collisions of particles, thermalization, irregu-larities in vent conditions, and perhaps phase changes, dominate the dynamics. The theory assumes that the important transport variables (e.g., energy, momentum, ejection angles) have probability distributions. Once particles leave the stochastic region, the randomizing influences on particle motions cease and the subsequent trajectories are purely ballistic. In the Prometheus application, it was found that a narrow Gaussian exit energy distribution (RSD=8%) and a modestly truncated ejection cone (75° from the vertical) are required to produce an annulus similar in size and shape to the image data. Only small changes in the nature of the energy distribution, dispersion, and angular ejection distributions were found to be admissible if the annulus is to be preserved.

We also used the constraint on the energetics to determine admissible compositions of the annulus. Plume temperatures at the vent were chosen to be representative of three plausible styles of volcanism (sulfur, basaltic, and ultramafic). For each style of volcanism, it was found that only a limited range of atomic weights (32-64 for sulfur volcanism, 64-128 for basaltic volcanism, and compositions in a range greater than 64 and less than 256 for ultramafic volcanism) were permitted by the size and brightness distribution of the Prometheus annulus.

Lava density changes during emplacement. We developed a model for lava flow with density and rheology changes during emplacement. This manuscript has been submitted to the Journal of Geophysical Research. In that work, we used detailed studies of the Mauna Loa 1984 flow and we considered two endmember form for the volume flowrate. We have applied the density change theory to a number of lava flows on Mars and the Moon for which we have thickness information from either Viking, MOLA, or the Apollo images. The results were based on data presented in Mouginis-Mark and Tatsumura Yoshioka (Elysium, [1998]), Zimbelman (Ascraeus, [1985] and Imbrium [pers com]), Schneeberger and Pieri (Alba, [1991]), Baloga et al. (Mauna Loa, [2000]), Glaze and Baloga (Puu Oo, [1998]). Many of the most interesting planetary flows show significant channelization. Systematic dimensional data is readily available for some flows. The loss of lava volume from an active flow was treated in Baloga et al., [1998] and applications to planetary flows appears in Glaze and Baloga [1998].

Recently we combined both of these models to obtain a new set of equations to describe a mass loss to stationary margins concurrent with a density change. We have also investigated a linear viscosity increase and it is clear that the nature of the viscosity change along the flow path has a major influence on the shape of the profile when density change and levee building are included. These profiles can be readily compared to planetary data for lava flows on Mars and the Moon. This preliminary study confirmed our suspicions that the formation of stationary margins, combined with a density change along the flow path, has a dramatic effect on the thickness profile. These processes can almost completely mask a 1000-fold increase in viscosity.

4. FY 99 ACCOMPLISHMENTS

Manuscript published: "Pahoehoe toe dimensions, morphology, and branching relationships at Mauna Ulu, Kilauea volcano Hawaii", David Crown (U. Pitt) and Stephen Baloga was published by the Bulletin of Volcanology. This manuscript describes field measurement of pahoehoe toes, investigates the basic statistical characteristics of their distributions, and determines the importance of a variety of factors (e.g., pre-existing topography, character of the substrate, etc) on controlling emplacement. This work focused exclusively on small flow units that were composed exclusively of toes, very small sheets, and small channels. It has set the stage for the development of detailed stochastic models that capture the relative influence of random process variables.

Manuscript published: "Dimensions of Puu Oo lava flows on Mars", Lori Glaze (Proxemy Research) and Stephen Baloga, was published in JGR/Planets, 1998. This paper looks at the new "volume-loss" model for a Newtonian rheology in laminar flow and examines how the model scales for a different gravity (e.g. that of Mars). Previous scaling relationships are extended to embrace the influence of a changing rheology along the path of a flow. The dimensions and emplacement characteristics of Puu Oo flow are determined as they would be on Mars with all eruption parameters remaining the same as their terrestrial values. Applications to lava flows at Ascraeus Mons, Elysium Planitia and Alba Patera were also given.

Manuscript published: "New statistics for estimating the bulk rheology of active lava flows: Puu Oo examples", Baloga, SM, LS Glaze, JA Crisp (JPL), and SA Stockman, was published in JGR/ Solid Earth. Three emplacement models were considered, appropriate statistics developed, and results were applied to terrestrial examples. The highlight of this paper is the derivation and application of the new "Volume-loss model" that allows a flow to have both stationary (e.g., levees, stagnant zones) and active components concurrently. This agrees with visual observations of many flows and has profound implications for estimates of rheology from dimensional and topographic data.

Manuscript submitted: "Indirect solutions of volume conservation models for flows of geologic materials I: Theory", Baloga, SM and LS Glaze, was submitted to JGR/Solid Earth in 1998. This will unfortunately require significant, as yet undetermined, revision prior to resubmission. However, a companion paper that addresses the application of the theory to lava flows and lahars has been drafted (LS Glaze and SM Baloga) and is expected to be more appealing to the reviewers.

LPSC Abstracts and Supporting Research. We participated in 3 abstracts for the LPSC in 1999. These abstracts addressed 3 different topics: 1) The stochastic ballistic model for the emplacement of bright deposits by active plumes on Io (co-authored with Lori Glaze), 2) The emplacement of the ejecta blankets of rampart craters on Mars as modeled by a continuum flow approach (co-authored with Jim Garvin/GSFC), and 3) Scaling relationships for different pahoehoe morphologies on Mauna Ulu (co-authored with David Crown/ U Pitt).

5. PUBLICATIONS AND ABSTRACTS FROM GRANT:

SELECTED RESEARCH PUBLICATIONS: Baloga, SM, LS Glaze, MN Peitersen, and JA Crisp, 2001, "The influence of volatile loss on the emplacement of lava flows", to appear in JGR, Solid Earth, 105, E12 (July, 2001); **Glaze, LS and SM Baloga**, 2000, "Stochastic-ballistic plumes on Io" JGR/Planets, 105,E7, 17,579-588; **Lang, HR and SM Baloga**, 2000, " Validation of airborne visible-infrared imaging spectrometer (AVIRIS) data at Ray Mine, AZ", GSA Env and Eng Geosciences, In Press; **Crown, DA and SM Baloga**, 1999, " Pahoehoe toe dimensions, morphology, and branching relationships at Mauna Ulu, Kilauea volcano, Hawaii", Bull. Volc, 61:288-305; **Glaze, LS and SM Baloga**, 1998, "Dimensions of Puu Oo lava flows on Mars", JGR/Planets, 103, 13,659-13,666; **Baloga, S, LS Glaze, JA Crisp, and SA Stockman**, 1998, "New statistics for estimating the bulk rheology of active lava flows: Puu Oo examples", JGR/ Solid Earth 103, 5133-5142; **Glaze, LS, SM Baloga and L Wilson**, 1997, "Transport of atmospheric water vapor by volcanic eruption columns" Jour. Geophys. Res. /Atmos 102: 6099-6108; **Sakimoto, SEH, SBaloga and JCrisp**, 1996, "Eruption constraints on tube-fed planetary lava flows", Jour. Geophys. Res, 102: 6597-6613; **Glaze, LS and S Baloga**, 1996, "Sensitivity of buoyant plume heights to ambient atmospheric conditions: Implications for volcanic eruption columns", JGR/Atmos., 101: 1529-1540; **Bruno, BC, S M. Baloga and GJ Taylor**, 1996," Modeling gravity-driven flows on an inclined plane" Jour. Geophys. Res., 101, 11,565-11577;

RECENT ABSTRACTS: Baloga, S.M. and L.S. Glaze (2001) Potential mechanisms for the formation of lava flow auras on Io. *Proc LPSC XXXII.* **Glaze, L.S. and S.M. Baloga** (2001) Validity of convective plume rise models for volcanic eruptions on Mars. *Proc LPSC XXXII* . **Spudis, P.D. and S.M. Baloga** (2001) Mixing of the mare regolith: A Clementine test *Proc LPSC XXXII.* **Stofan, E.R., S.M. Baloga, L.S. Glaze and S.E. Smrekar** (2001) An updated database of coronae on Venus. *Proc LPSC XXXII.*

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE June 30, 2001	3. REPORT TYPE AND DATES COVERED Final Report

4. TITLE AND SUBTITLE
Quantitative Studies in Planetary Volcanism

5. FUNDING NUMBERS
NAS5-7251

6. AUTHORS Dr. Stephen M. Baloga

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
NASA
Code SR
Washington, D.C. 20548

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
Closeout Report

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)* Scientific research was conducted on volcanic processes on Mars, Venus, Io, the moon, and the Earth. The achievements led to scientific advances in the understanding of volcanic plumes, lava flow emplacements, coronae, and regoliths on the solid surfaces. This research led to multiple publications on each of the main topics of the proposal. Research was also presented at the annual Lunar and Planetary Science Conference at Houston. Typically, this grant contributed to3-4 presentations each year. This grant demonstrated, numerous times, the usefulness of NASA mission data for advancing the understanding of volcanic processes on other planetary surfaces and the Earth.

14. SUBJECT TERMS

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	SAR