Volcanism & Tectonics on Earth, Venus and Mars: A Planetological Approach

Eric B. Grosfils, Project Director
Department of Geology, Pomona College, Claremont, CA 91711

Linda A. Reinen
Department of Geology, Pomona College, Claremont, CA 91711

Martha S. Gilmore
Department of Geology, Washington and Lee University, Lexington, VA 24450

Samuel J. Kozak
Department of Geology, Washington and Lee University, Lexington, VA 24450

-- Dedicated to the memory of the late Sam Kozak: mentor, colleague and friend. May the generosity and love for learning he exhibited continue to inspire us all.

INTRODUCTION

Data returned by NASA missions flown during the past two decades have significantly improved our ability to decipher the intriguing and complicated geological histories preserved on Venus and Mars. Each of these planets can be thought of as a unique natural laboratory within which the values of many basic physical parameters (*e.g.*, temperature, atmospheric pressure, gravity) differ from the "settings" found on Earth. These variations can affect the behavior of geological systems, and analysis of digital images returned by planetary spacecraft such as Magellan (Venus) and Viking (Mars) has revealed a wealth of volcanic and tectonic features which differ, both strikingly and subtly, from those we see on Earth. By assessing the physical characteristics of these features and evaluating how they form, planetary geologists gain fresh insight into the nature of volcanic and tectonic processes and the evolution of the terrestrial planets.

During the summer of 1997 a Keck Geology Consortium sophomore project based at Washington and Lee University in Lexington, Virginia, introduced students to several fundamental components of planetary geology. Through study of the most recently released NASA data, student teams investigated the formation and evolution of specific volcanic and tectonic features on Venus and Mars, thereby improving our understanding of how and why volcanic and tectonic processes can operate differently on these planets than on Earth.

PARTICIPANTS

The Planets project was guided by four faculty: Eric Grosfils and Linda Reinen from Pomona College, and Martha Gilmore and Sam Kozak from Washington and Lee University. The visiting faculty sponsors were Bob Carson from Whitman College and John Cooper from California State University, Fullerton.

The student participants in the Planets project were: Carrie Brugger, Colorado College; Nick Chambers, Beloit College; Dave Cook, University of Texas, El Paso; Javier Cruz, University of Puerto Rico, Mayaguez; Lena Fletchér, Smith College; Reina Foxx, California State University, Fullerton; Holli Frey, Franklin & Marshall College; Robbie King, College of Wooster; Erin Kraal, Washington & Lee University; Alix Krull, Pomona College; Bill Pike, Carleton College;

Shannon Ristau, Smith College; James Sammons, Washington & Lee University; Martin Wong, Williams College; and Heather Wright, Whitman College.

PROJECT ORGANIZATION AND ACTIVITIES

The Planets project was organized into three primary phases. In the first, several days of intensive lecture introduced students to remote sensing techniques, common planetary processes, basic mathematical methods used in the geosciences (including fractal and fourier analyses), and the geology of Mars and Venus with a focus upon existing research opportunities. Using NIH Image and Adobe Photoshop, students also learned the basic skills required to load and process Magellan and Viking satellite image data. With this preparation, faculty and students then worked together over a two day period to define seven student teams and formulate each team's research project; ultimately, two teams focused their attention upon Mars, while the remainder explored aspects of venusian geology. The first phase of the project concluded with each team submitting to the faculty a formal proposal defining a research question, the steps necessary to resolve it, and the potential significance of the outcome.

During the second phase of activity, which lasted approximately three weeks, each student team: (1) explored extensively in the literature to learn about and absorb the lessons from previous research efforts, (2) produced geologic maps to gain insight into pertinent stratigraphic relationships and morphological characteristics, (3) collected all data needed to address their research question, and (4) analyzed the data, a process which in all cases involved some degree of mathematical analysis. Throughout this phase, each team also wrote the bulk of its final paper in an iterative fashion. After meeting an initial deadline by submitting its Introduction, each team then met a second deadline by handing in a revised version of the Introduction and a new section describing Methods, and so on. This process was of necessity very fluid as ideas changed and evolved during the process of performing the research, but it helped identify potential difficulties on an ongoing basis and kept each project focused and moving forward by periodically encouraging team members to put their ideas into writing.

Throughout the three weeks of the second phase, students were able to interact with a diverse array of talented scientists who took the time to visit, tell us about their research, and work with the teams on their projects. These visitors included (in order of their visitation): *Dr. Susan Keddie* from SAIC, who discussed the selection and organization of future "better, faster, cheaper" Discovery class missions; *Dr. James Zimbelman* from the Smithsonian's Center for Earth and Planetary Studies, who shared with us his considerable experience making geologic maps of Mars; *Dr. Patrick McGovern* from the Carnegie Institute's Department of Terrestrial Magnetism, who presented his latest attempts to improve our understanding of volcano growth on Venus; *Dr. James Farquhar* from the Carnegie Institute's Geophysical Laboratory, who introduced the group to oxygen isotope geochemistry and its application to meteoritics; *Dr. David Sparks* from the Lamont Doherty Earth Observatory, who briefly returned us to Earth by talking about his work on mantle dynamics beneath oceanic spreading centers; *Dr. Phillip Sakimoto*, a physicist from NASA Headquarters who described current directions in space science research and the variety of opportunities young geologists have to become involved; and, *Dr. Susan Sakimoto* from the Goddard Space Flight Center, who talked both about her ongoing attempts to decipher the mechanics of lava flow movement in long lava tubes and, as a former Whitman student, about her path from Keck project participant to successful NASA scientist.

In addition to the activities revolving around our visiting speakers, the regular schedule of project activity was punctuated by a variety of different events. The saddest of these was the unexpected death of Dr. Sam Kozak during the second week of the project. I have nothing but the highest of praise for the humanity and personal character exhibited by all members of the project during this difficult time. Later that same week, we watched in awe as the Pathfinder lander became the first US spacecraft to visit the surface of Mars in more than twenty years (the entire lifetime of the students!), an event which proceeded so smoothly we couldn't help but wonder if Sam's spirit was out there lending a hand. In the wake of the landing, the Planets students were visited and interviewed by several media representatives, and pieces about the project aired on the regional news and appeared in two newspapers. Finally, all members of the project, at the invitation of Dr. Zimbelman, visited the Center for Earth and Planetary Studies, where we received a behind-the-scenes tour of this prestigious research group's facilities in the Smithsonian Air and Space Museum and had a chance to interact with several of the Center's other planetary scientists.

In the third phase of the project, each team worked hard to prepare high quality figures and to complete their research papers. In addition, each team designed and constructed a poster explaining the results of its research. These posters were presented to the community of faculty and students at Washington and Lee University during an open poster session on the final day of the project, and all teams subsequently presented their posters in March at the *29th Lunar and Planetary Science Conference* at the Johnson Space Center in Houston, Texas. I am especially proud to report that the final phase of activity was representative of the Planets project spirit as a whole—all members of the group worked together during this intensive period to ensure that every project was concluded on time in a polished, professional manner.

STUDENT PROJECTS

I. MARS.

Erin Kraal (Washington and Lee University) and **Martin Wong** (Williams College) spent their summer assessing the origin of a spectacular, flat-floored trough, approximately 550 km in length and 10-30 km wide with near-vertical walls several hundred meters high. The trough cuts across Noachian-age rock in the Nili Fossae region near the border between the heavily cratered southern highlands of Mars and the lowland plains to the north, extending northeast from the highland volcanic province of Syrtis Major to the Utopia Planitia lowlands in a slightly arcuate configuration concentric to the 600 km Isidis Basin, a Noachian-age impact site. Given the geologic setting, proposed explanations for formation of the trough include: catastrophic flooding, perhaps induced when volcanic activity in Syrtis Major melted an extensive permafrost layer; tectonic processes related to formation of the Isidis Basin; thermal erosion by volcanic flows; glacial scouring; mass wasting that widened a narrower trough; and, aeolian activity [*Craddock*, 1994; *Baker et al.*, 1992]. Martin and Erin constructed a detailed map of the Nili Fossae trough and its immediate surroundings, looking in particular for evidence of morphological features which would help them constrain how the trough formed and assess any secondary modification.

Reina Foxx (California State University, Fullerton) and **Carrie Brugger** (Colorado College) conducted the first detailed test of whether an extensive system of enigmatic, kilometer-scale domes situated in the Arrhenius region of Mars could be of volcanic origin. In order to understand the geological setting and set the stage for a detailed study of the domes' morphologies, initial mapping of the Arrhenius region focused upon the distribution of features such as infilled craters (depositional), pedestal craters (erosional), undulating scarps (erosional), rampart craters (indicating the probable presence of shallow subsurface volatiles) and the appearance of the background plains (smooth, flat and featureless versus rough, undulating and textured). Using their mapping results, Carrie and Reina chose to focus their attention upon the morphologies of domes in Viking Orbiter frames 586B34 and 586B36. For the 640 domes in this area, they collected physical data including the diameter of the domes, the elongation direction of individual domes and dome clusters, the presence or absence of a summit pit, and the spatial density distribution within the field. These data were then compared with analogous data from volcanic fields on Earth [*Tibaldi*, 1995] to assess the origin of the domes.

II. VENUS

Javier Cruz (University of Puerto Rico, Mayaguez) and **Robbie King** (College of Wooster) mapped a region at the edge of the heavily deformed equatorial highland Ovda Regio, deciphering the complex sequence of volcanic and structural events preserved there. At present, much of the scientific energy focused upon understanding the geology of Venus revolves around resolving whether or not the majority of the planet was catastrophically resurfaced during a brief interval of time 300-500 million years ago [*Strom et al.,* 1994].. The crux of this issue involves answering two questions: were the planet's extensive volcanic plains really emplaced in a short geological interval, and what is the origin of the older, heavily deformed highlands? Within the area selected, Robbie and Javier examined the characteristics of the ridges, extensional fractures and graben, and both highland and lowland volcanic plains. Their data were then compared with model predictions in order to constrain the primary mechanism responsible for the highland's formation.

Lena Fletcher (Smith College) and **Heather Wright** (Whitman College) evaluated the origin of an unusual volcanic flow located in Atalanta Planitia. Previous researchers have suggested that this flow might best be classified as a festoon [*Head et al.*, 1992], but the validity of this assertion has never been rigorously tested. Resolving this issue is potentially of great importance because festoon flows may represent more evolved compositions than those thought typical for Venus, and thus may provide important insight into the volcanological evolution of the planet. Heather and Lena mapped the Atalanta Planitia flow and evaluated (1) ridge spacing and other morphological characteristics, (2) the surface area and thickness, and (3) the radar emissivity, reflectivity and RMS slope, then used these data to constrain flow volume, density, yield strength and viscosity. These data permitted direct comparison with the two previously identified venusian festoons and classification of the Atalanta Planitia flow.

Holli Frey (Franklin and Marshall College), **Alix Krull** (Pomona College) and **Bill Pike** (Carleton College) mapped and then calculated the fractal dimension of 72 lava flow margins on Venus at a variety of altitudes and geographic locations. The fractal dimension provides insight into the sinuosity of the flow margin, with higher viscosities yielding lower fractal dimensions and vice versa [*Bruno and Taylor*, 1995]. Thirteen of the flows studied lie within the landing ellipses of the Soviet Venera and Vega landers, where instruments collected major element chemistry and/or radioisotope data permitting evaluation of the flows' compositions. Using these compositional data Alix, Bill and Holli estimated a range of viscosities for each lander site which they then correlated to the calculated fractal dimensions of the flows measured within each landing ellipse. Using the relationship established at the lander sites, they then predicted the composition of the remaining 59 flows for which only the fractal dimension was known.

Shannon Ristau (Smith College) and **James Sammons** (Washington and Lee University) conducted a systematic global study of the altitude distribution of two distinctive styles of intermediate-sized volcanoes on Venus, "ticks" and "anemones." This study was designed to provide new insight into the neutral buoyancy conditions thought to promote formation of these magma reservoir-derived edifices [*Head and Wilson,* 1992]. Previous studies of similar reservoir-derived features, including large volcanoes [*Keddie and Head,* 1994] and radiating dike swarms [*Grosfils and Head,* 1995], support the contention that magma reservoir formation and depth on Venus will be sensitively dependent upon atmospheric pressure and thus altitude. After mapping examples of each style of intermediate volcano to improve their understanding of the associated morphologies, James and Shannon determined the basal altitude for the 39 ticks and 23 anemones and compared these data with both theoretical predictions and analogous data for other features.

Nick Chambers (Beloit College) and **Dave Cook** (University of Texas, El Paso) designed a research project to explore whether magma reservoir size varies with altitude in order to gain further insight into the neutral buoyancy model [*Head and Wilson,* 1992] and to improve our understanding of large volcano growth on Venus. Their study consisted of two parts. In the first, they measured caldera diameter for each of the 15 large volcanoes on Venus which exhibit this structure, then plotted these data as a function of altitude to constrain the plan view diameter of the underlying reservoirs [*Wood, 1984*]. In the second part of the study, Dave and Nick selected three of the large volcanoes and evaluated the three dimensional magma reservoir geometry for each by determining the average volume of each volcano's individual lava flows.

ACKNOWLEDGMENTS

I will begin by thanking the Keck Foundation and the NSF for providing the support which made this project possible; it is my hope that the results from this project justify the faith these institutions have in the Keck Geology Consortium's ability to involve undergraduate students in significant and exciting geologic research. I would next like to offer my sincerest thanks to the faculty and staff of the Geology Department at Washington and Lee and to *Mata Mcguire* and *Anne Davis*: the support and selfless efforts of all these individuals contributed significantly and directly to the success of the Planets project during the challenging summer weeks. I would also like to offer special thanks to *Dr. Ed Spencer* for teaching us about Appalachian geology and for taking us out into the field to see some of the wonders of Virginia first-hand! Finally, in addition to again thanking all of our visiting speakers, I wish to thank *Dr. Tracy Gregg* of the Woods Hole Oceanographic Institute for her assistance formulating the Arrhenius dome field project on Mars, *Dr. Ken Tanaka* of the United States Geological Survey's Branch of Astrogeology for his generous donation of a set of martian geologic maps, *Dr. Barbara Bruno* from the Hawaii Institute of Geophysics and Planetology for her advice during the fractal project, and *Dr. Jim Zimbelman* for graciously hosting our visit to the Center for Earth and Planetary Studies.

REFERENCES CITED

Baker, V.R., M.H. Carr, V.C. Gulick, C.R. Williams, and M.S. Marley, Channels and valley networks on Mars, in *Mars*, edited by H.H. Kiefer, B.M. Jakosky, C.W. Snyder and M.S. Matthews. Tucson: University of Arizona Press, 1992.

Bruno, B.C., and G.J. Taylor, Morphologic identification of venusian lavas, *Geophysical Research Letters*, *22*, 1897-1900, 1995.

Craddock, R., Geologic history of Isidis Planitia and Syrtis Major Planum, Mars, *Lunar and Planetary Science Conference*, *XXV*, 291-292, 1994.

Grosfils, E.B., and J.W. Head, Radiating dike swarms on Venus: Evidence for emplacement at zones of neutral buoyancy, *Planetary and Space Science*, *43*, 1555-1560, 1995.

Head, J.W., L.S. Crumpler, and J.C. Aubele, Venus volcanism: Classification of volcanic features and structures, association and global distribution from Magellan data, *Journal of Geophysical Research*, *97*, 13153-13197, 1992.

Head, J.W., and L. Wilson, Magma reservoirs and neutral buoyancy on Venus: Implications for the formation and evolution of volcanic landforms, *Journal of Geophysical Research*, *97*, 3877-3903, 1992.

Keddie, S.T., and J.W. Head, Height and altitude distribution of large volcanoes on Venus, *Planetary and Space Science*, *42*, 455-462, 1994.

Strom, R.G., G.G. Schaber, and D.D. Dawson, The global resurfacing of Venus, *Journal of Geophysical Research*, *99*, 10899-10926, 1994.

Tibaldi, A., Morphology of pyroclastic cones and tectonics, *Journal of Geophysical Research*, *100*, 24521-24535, 1995.

Wood, C.A., Calderas: A planetary perspective, *Journal of Geophysical Research*, *89*, 8391-8406, 1984.

Large volcanoes on Venus: volume, geometry and depth of magma chambers

Nicholas W. Chambers
Department of Geology, Beloit College, 700 College St., Beloit, WI 53511-5595
Faculty sponsor: Cameron Davidson, Beloit College

David L. Cook
Department of Geology and Geological Engineering, University of Idaho, Moscow, ID 83844
Faculty sponsor: Jerry Hoffer, University of Texas at El Paso

INTRODUCTION

Venus, because of its striking similarity in mass, density and size to Earth, provides a unique opportunity to test our understanding of fundamental volcanic processes. It is assumed that on Venus, as on Earth, a volcanic edifice forms only after an initial magma chamber is established. Predictions based on neutral buoyancy theory state that there is a point at which a rising magma body reaches equilibrium with the surrounding country rocks such that their respective densities are equal (Ryan, 1987). It is at this neutral buoyancy zone (NBZ) that the rising magma collects and grows laterally to form the magma chamber that feeds the volcano (Head and Wilson, 1992).

Because of the extreme atmospheric surface pressure exerted on the lowlands of Venus, volatiles do not exsolve from rising magma bodies as readily as they would on Earth. In addition, because erupted lava has a density that is about equal to the surrounding substrate on Venus, a layer of low density material does not form, and the rising magma body does not stall in the Venusian crust. However, as altitude on Venus increases, the atmospheric pressure decreases significantly (Head and Wilson, 1992). At higher altitudes, volatiles are exsolved more readily and the density of the resulting rock is relatively low due to the higher amount of vesiculation. Unlike at the lower altitudes, these conditions allow a NBZ within the crust and, hence, the formation of a magma chamber. Head and Wilson (1992) conclude that magma reservoirs on Venus grow larger than they do on Earth because they linger in the substrate, and do not migrate rapidly upwards into the edifice as the volcano gets taller. This slow migration is also a consequence of the enormous atmospheric pressure on Venus.

Using Magellan data, we examined 15 of 18 known large volcanoes with calderas to determine if a relationship exists between altitude and magma chamber volume and geometry, and if a uniform geometry exists between magma chambers, or if several shapes are needed to explain the observed surface features. The presence of a magma chamber is assumed from features such as volcanic edifices, lava flows and calderas. The measurements from the latter two features can be used to constrain a model for describing the magma chamber volume and depth (Blake, 1981; Wood, 1984). The three-dimensional geometry of the magma chamber can be estimated from the surface geometry of the caldera, assuming that the chamber is an ellipsoid, and the volumes of the surface flows erupted from the chamber. Therefore, three volcanoes, Shiwanokia Corona (Fig. 1), an unnamed volcano located at 9N029 (Fig. 2), and Hatshepsut Patera (Fig. 3), and their associated lava flows and calderas were mapped to gain insight into the associated reservoir geometries. These volumes were then used to approximate the total volume of the magma chamber for each of the volcanoes. Finally, we determined the basal altitude, caldera diameter, and height of all 15 volcanoes (Table 1). These type of data provide a way to test predictions based on neutral buoyancy theory and its application to Venus, and may help to identify fundamental differences between volcanic processes operating on Earth and Venus.

DISCUSSION

Basal height, caldera diameter, and basal altitude. The caldera diameter of a shield volcano is approximately equal to the map view diameter of the associated magma chamber (Wood, 1984). Therefore, the caldera diameter can be used as an indicator of the relative size of the magma chamber. The magma chamber volume calculations of the three mapped volcanoes were based on lava flow volume in relation to eruptive percentage of the magma chamber (Blake, 1981); they did not consider the caldera diameter. Hatshepsut Patera, which has the largest caldera, also has the largest magma chamber, while Shiwanokia Corona, which has the smallest caldera, also has the smallest magma chamber (Table 1 & Fig. 4). These two independent approximations confirm that a larger caldera corresponds to a greater magma chamber volume. The basal altitudes of Shiwanokia Corona, the unnamed volcano, and Hatshepsut Patera are 6051.9 km, 6051.5 km, and 6051.1 km respectively. Thus, for these three volcanoes, magma chamber volume does not appear to be dependent on basal altitude.