by open-system degassing. Up to 35 - 40 % of intital dissolved sulfur may have been lost through preeruptive degassing.

Hydrogen isotope and total H_2O analyses of rhyodacitic obsidians and vitrophyres spanning the climactic pumice fall deposit have δD values from -103$^o/_{oo}$ to -53$^o/_{oo}$ with H_2O concentrations of 0.23 wt. % to 1.74 wt. %, respectively. The δD values and wt. % H_2O of obsidians and vitrophyres tend to decrease towards the top of the climactic fall deposit. Matrix glasses in climactic pumice samples have low δD values of -144$^o/_{oo}$ to -102$^o/_{oo}$ and 1.80 to 3.42 wt. % H_2O due to rehydration by deuterium depleted meteoric water. Fresh obsidians and vitrophyres collected from the preclimactic Llao Rock pumice fall, and Cleetwood pumice fall, have δD values and H_2O concentrations that decrease with stratigraphic height in outcrop, consistent with open-system degassing. .

V41C-11 1115h

An Experimental Approach Using Vesicle Size Distribution (VSD) to Investigate the Kinetics of Vesiculation

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The exsolution of volatiles in magma initiates the formation of gas bubbles as a result of the development of a state of supersaturation from either magma ascending in the conduit, decrease in temperature, or the crystallization of anhydrous solid phases. In this analysis bubble-free rhyolitic glasses were isothermally decompressed in a series of controlled nucleation experiments to investigate the kinetics of bubble nucleation and growth. A two-fold approach was used to synthetically saturate the high silica melt. The first method is based on using blocks of solid obsidian placed in gold capsules with > 10 wt.% H_2O and saturated for 72 hours. The second technique uses powdered obsidian that was saturated with H_2O at a given pressure and temperature for 48 hours, quenched, reground, and then repeated one more time. The use of powdered obsidian in the second method evenly saturates the melt by minimizing the volume to surface area ratio, hence the diffusion distance. In all experiments glass charges were saturated with H_2O at 100 MPa and 850^{o}C, and than isothermally decompressed at a rate of approximately 0.26 MPa/sec to a final confining pressure of 30, 50, and 70 MPa. Samples were held at the final pressure for a period ranging from 5 to 300 seconds (residence time) to allow for nucleation to take place. Bubble-bearing glass charges were cut, polished, imaged under SEM and Nikon petrographic microscopes, and digitally analyzed with "Scion Image".

All glass charges produced by the block method contained either no bubbles or only a few bubbles. The only indication of bubble nucleation was limited in a zone on the outer periphery of the glass charges. This leads us to believe that in the block method the time given for hydration was insufficient for homogeneous saturation of the melt.

We directed our attention to the bubble-bearing glasses generated by the powder experiments. Vesicle Size Distribution (VSD) was used to determine the kinetic behavior of bubbles at the onset of nucleation and their development in the melt within the known residence time. The more even bubble distribution in the melts using the powder method gave rise to nuclei density populations ranging from 10^9 - 10^{11} bubbles/cm^4. Mean vesicle size for all experiments was 0.009 mm in diameter. Using a residence time of 300 seconds growth rates were calculated and show to be approximately 3.8 x 10^{-2} cm/s. Nucleation rates of 10^7 - 10^9 bubbles/cm^3 s illustrate how minor fluctuation in pressure can drastically increase the onset of bubble formation in viscous silicate melts. The data generated by VSD (bubble nuclei density, bubble growth and nucleation rates, and mean bubble size) was then applied to a conceptual model used to describe explosive volcanic eruptions.

V41C-12 1130h INVITED

Sources of Magmatic Volatiles Discharging from Subduction Zone Volcanoes

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Subduction zones are locations of extensive element transfer from the Earth's mantle to the atmosphere and hydrosphere. This element transfer is significant because it can, in some fashion, instigate melt production in the mantle wedge. Aqueous fluids are thought to be the major agent of element transfer during the subduction zone process. Volatile discharges from passively degassing subduction zone volcanoes should in principle, provide some information on the ultimate source of magmatic volatiles in terms of the mantle, the crust and the subducting slab. The overall flux of volatiles from degassing volcanoes should be balanced by the amount of volatiles released from the mantle wedge, the slab and the crust.

Kudryavy Volcano, Kurile Islands, has been passively degassing at 900C fumarole temperatures for at least 40 years. Extensive gas sampling at this basaltic andesite cone and application of $CO_2/^3He$, $N_2/^3He$ systematics in combination with C and N- isotopes indicates that 80% of the CO_2 and approximately 60% of the N_2 are contributed from a sedimentary source. The mantle wedge contribution for both volatiles is, with 12% and 17% less significant. Direct volatile flux measurements from the volcano using the COSPEC technique in combination with direct gas sampling allows for the calculation of the ^{3}He flux from the volcano. Since ^{3}He is mainly released from the astenospheric mantle, the amount of mantle supplying the ^{3}He flux can be determined if initial He concentrations of the mantle melts are known. The non-mantle flux of CO_2 and N_2 can be calculated in similar fashion. The amount of non-mantle CO_2 and N_2 discharging from Kudryavy is balanced by the amount of CO_2 and N_2 subducted below Kudryavy assuming a zone of melting constrained by the average spacing of the volcanoes along the Kurile arc. The volatile budget for Kudryavy is balanced because the volatile flux from the volcano is relatively small (75 t/day (416 Mmol/a) SO_2, 360 Mmol/a of non-mantle CO_2 and 5.4 Mmol/a of non-mantle N_2).

Other subduction zone volcanoes are currently degassing a much more substantial amount of volatiles. Popocatepetl, Mexico, has degassed approximately 14 Mt of SO_2 to the atmosphere over the past 6 years (Witter et al. 2000). Satsuma-Iwojima, Japan, has degassed for longer than 800 years and is currently releasing 500-1000 tones/day (Kazahaya et al. 2000). At these volcanoes CO_2 and N_2 discharges from the magma should also be balanced by the supply from slab and crustal sources. The rate of subduction off Mexico and Japan, however, is similar to the rate at the Kuriles. Therefore, large amounts of slab derived volatiles must be, in some fashion, stored in the "subduction factory" to supply the large amounts degassing passively from these volcanoes.

Kazahaya et al. (2000) Seventh Field Workshop on Volcanic Gases, IAVCEI.

Witter et al (2000) Seventh Field Workshop on Volcanic Gases, IAVCEI.

V41C-13 1145h INVITED

Constraints on the Cl Content and Water Isotopic Composition in High-Temperature Volcanic Gases. Implications for the Shallow Magma Degassing

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Chemical composition of major species in volcanic gases with an emphasis on the water isotopic composition and Cl-content is discussed on the basis of a worldwide compiled data set for high-temperature volcanic gases collected from about 40 volcanoes during the last three decades. Gases from volcanoes of different tectonic setting are divided on three groups: A-gases form andesitic and more acid magmas of subduction (arc)-type volcanoes; AB-gases from basaltic magmas of arc volcanoes; B-gases from basaltic magmas of intraplate (rift and hot-spot) volcanos. Most of the A-gases display as the main geochemical trend an increase in the HCl content with increasing temperature of the gas vent with a limit of 10 mmol/mol, and isotopic composition of volcanic vapor in the range of dD=-15 to -25 permil, d18O=5 to 7 permil (andesitic water box). AB-gases, which were collected mainly from lava flows and cinder cones of erupting volcanoes, are often characterized by the higher, up to 30 mmol/mol, HCl-content and lower dD due to degassing of lava. There is not enough data for B-gases to constrain their HCl-content and dD-values. The usual relationship between dD and HCl in A-gases is a positive correlation indicating a mixing of meteoric water with a magmatic end member (Kudryavy-type behavior). The negative dD-HCl correlation may be caused by magma degassing (Colima-type) or by interaction with a high-temperature brine inside a magmatic-hydrothermal system (Vulcano-type). Hot meteoric-seawater-magmatic systems (White Island-type) display a wide range of the Cl-dD trends due to the HCl partition and isotope fractionation between acid saline brine and vapor.

Volcanic gas condensates are strongly acidic, so their principal Cl-bearing specie is HCl, not alkali chlorides. Independent of the scenario of the fluid separation from magma at the surface (where this fluid after mixing and interaction with other material became a volcanic gas) almost all alkali chlorides should be hydrolyzed to HCl. A possible mechanism includes equilibrium between H2O-vapor, halite and Al-silicates if one assumes that the vertical pressure gradient in the fumarolic conduit is lower than the lithostatic and hydrostatic gradient.

V42A CC: 203 Thursday 1330h

New Views of Mars Volcanism: Extrusive, Explosive, and Possible Influences of H2O *(joint with P)*

Presiding: **S Sakimoto,** NASA - GSFC**; T Gregg,** Univ. of Buffalo**; L Glaze,** Proxemy Research

V42A-01 1330h INVITED

The Mineralogy of Mars: Results from the Thermal Emission Spectrometer

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The mineralogy of Mars has been mapped globally by the MGS Thermal Emission Spectrometer (TES) instrument at a resolution of 5 km. These data show that the mineralogic composition of volcanic materials is basaltic, composed primarily of plagioclase feldspar and clinopyroxene with minor olivine, in the ancient, southern hemisphere highlands, and andesitic, dominated by plagioclase feldspar and volcanic glass, in the younger northern plains. Aqueous mineralization has occurred in limited regions under ambient or hydrothermal conditions. Gray, crystalline hematite is found in three unique locations that are interpreted to be in-place sedimentary rock formations, indicating that liquid water was stable near the surface for a long period of time. There is no evidence for carbonates at a detection limit of ∼10%; large-scale (10's km), moderate-grained (>50 m) deposits of >10% carbonates are not currently exposed at the martian surface. Unweathered volcanic minerals (pyroxene and feldspar) dominate the spectral properties of martian dark regions. Weathering products, such as clays, have not been observed above the TES detection limit (10%). This lack of evidence for significant chemical weathering of the martian surface indicates a geologic history dominated by a cold, dry climate in which mechanical, rather than chemical, weathering was the dominant form of erosion and sediment production.

V42A-02 1350h

New Views of Volcanism on Mars: Recent Observations and Computer Simulations

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The Mars Global Surveyor spacecraft has provided an unprecedented new view of Mars in general, and of volcanism on Mars in particular. The Mars Orbiter Camera (MOC) has obtained thousands of images showing the texture and relief of Martian volcanic terrain at scales down to the 1.4 m/pixel resolution of the mapping images. These new images have not changed many of the Viking-based interpretations of the origin of individual volcanic constructs (Mons, Tholus, Patera, etc.), but they have revealed an abundance of new detail about lava flows and other volcanic deposits on the planet. The Mars Orbiter Laser Altimeter (MOLA) has quantified the relief of the Martian surface with precision down to the 30-50 cm vertical accuracy of the individual MOLA measurements. MOLA data have shown that surface gradients and slope orientations based on Viking data are sometimes in serious error, which can affect interpretations of how lava flows become emplaced on the planet. MOLA data have recently revealed the first strong evidence for lava tubes on Mars, to add to the channelized flows observed since

Mariner 9. MOLA data also provide new Digital Elevation Model (DEM) representations of the Martian surface over which computer-simulated lava flows can be emplaced. We have carried out preliminary simulations of flow emplacement in the Tharsis Montes area of Mars on released MOLA DEM data, which are providing new insights into the likely conditions present when the lava flows were emplaced in this area. As more detailed MOLA data are released, we will refine these early simulation results.

V42A-03 1410h INVITED

Recent Flood Volcanism on Mars: Implications for Climate Change, Layered Deposits, and Lava-Water Interactions

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In many ways, the high-resolution imaging of volcanic features on Mars has been disappointing due to the significantly degraded state of the ancient surfaces. One major exception has been the recent volcanism in the Cerberus Plains and Amazonis Planitia (Keszthelyi et al., 2000). Crater counts suggest some lava surfaces are less than 10 Ma (Hartmann and Berman, 2000), though rapid burial and very recent exhumation would allow for somewhat older eruptions. Investigation of the platy-ridged portion of the 1783-1784 Laki flow field in Iceland revealed that these lava flows have a morphology unlike any in Hawaii. We have called this form of lava "rubbly pahoehoe" and find it in several terrestrial flood basalt settings (Keszthelyi and Thordarson, 2000). Rubbly pahoehoe on Iceland and Mars transitions into undisrupted inflated pahoehoe flows at their margins. These flows are hypothesized to form as surges in flow rate travel through large inflating sheet flows. This allows emplacement underneath a thick mobile insulating crust, permitting lava to travel great distances in a rapid but laminar manner. Thermal modeling suggests eruption rates on the order of 10^5 m^3/s feeding these sheets of lava, a rate about an order of magnitude larger than typical for terrestrial flood basalt eruptions.

These huge eruptions potentially have significant climatic implications. If the dissolved volatile content of the Martian flood lavas were similar to that of large terrestrial basaltic eruptions (Thordarson and Self, 1996; McSween et al., 2001) we would expect on the order of 300 Gt of highly acidic gas to be released. Simultaneously, several thousand cubic kilometers of highly vesicular basaltic ash should be produced. Further gas release and ash production would come from the rootless cone fields found on the lavas (Lanagan et al., submitted). The acid-laced ash may be deposited to form the Medussae Fossae Formation and perhaps other finely layered sedimentary deposits seen on Mars. There is evidence from MOC and MOLA that recent floods of both water and lava originated from Cerberus Rupes, a fracture system which has been active very recently (it cuts the young lavas). This may be the very best place on Mars to search for current geothermal activity.

Keszthelyi et al. (2000) JGR 105, 15027-15049. Hartmann and Berman (2000) JGR, 105, 15011-15025. Thordarson and Self (1996) JVGR 74, 49-73. Keszthelyi and Thordarson, (2000) GSA Ann. Meet. Abst. #5293. McSween, et al. (2001), Nature 409, 487-490. Lanagan et al., (submitted) GRL.

V42A-04 1430h

Key Trends in Volcanic Activity in the Hesperian Period of Mars: New Insights From MOLA Data.

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The Hesperian Period is a critical phase in the evolution of volcanic processes and new MOLA data provide insight into their nature and evolution. During the Hesperian, globally distributed ridged plains of volcanic origin were emplaced and deformed, significant regional volcanism took place in Tharsis, Syria, and Elysium, radial and concentric deformation occurred around Tharsis, the majority of the outflow channels formed, and extensive resurfacing and infilling of the northern lowlands took place. Formation of regional volcanic plains and associated paterae occurred in Alba, Hesperia Planum, Syrtis Major Planum, and Malea Planum. Important unanswered questions include: Does the global formation of ridged plains (Hr) represent a specific phase of volcanic activity or simply the tail end of declining global volcanism related to early high heat flux? What is the relationship between the global volcanism of Hr and the regional volcanism of Tharsis and Elysium? What is the temporal and genetic relationship of highland paterae, Syria Planum and Tharsis Montes? Is there a genetic relationship between highland paterae and basin structure as suggested by their location? Do changes in highland paterae morphology and inferred environment reflect near-surface volatile depletion? What is the relationship of the apparent global contraction, represented by wrinkle ridges, to the change in style of volcanism from widely distributed to regional? What is the relationship of the Tharsis tholi and small paterae to the Late Hesperian Tharsis plains? Why is Syria Planum so prominent topographically, but so subtle in terms of patera or caldera-like structures? What is the relationship between the activity at Syria and Tharsis Montes? What is the relationship of the activity in Tempe Terra to that of the rest of Tharsis at this time? What is the relationship between the earlier (Hesperian) and later (Amazonian) stages of volcanism in Tharsis and Elysium in terms of volume, area, and style? Mars Global Surveyor data have provided an opportunity to reassess the nature of geological units and their stratigraphic relationships. Information from MOLA on the geometry and volumes of these deposits, their stratigraphic relationships, and the morphometry of landforms, has lead to new insight into the flux and resurfacing history during this critical time.

V42A-05 1445h

Martian Lavas: Emplacement Parameters Using MOLA Data and Numerical Models

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An active Martian lava flow has yet to be observed, so that eruption and emplacement parameters must be inferred from the resulting lava flow morphologies. Mars Global Surveyor (MGS) has provided a wealth of new information about Martian lava flows, and has allowed us to refine our interpretations of Martian volcanic behaviorand how this behavior varies in time and space. Somewhat surprisingly, MOC high-resolution images provide information on lava flow surface textures only for extremely young flows; typically, Martian lavas are covered with dust and/or dunes. MOLA data also reveal several details of lava flow morphologies that were not apparent in Viking Orbiter (VO) images, but at larger scales and also for more weathered flows than can be resolved in MOC images. MOLA data show that true lava flow boundaries (identified by topographic profiles) tend to lie outside those identified in VO images. Additionally, MOLA exposes central channels in lava flows that were believed to be flat-topped on the basis of VO images. As a result, flows previously labeled flat-topped are often slightly wider channel-fed flows, and flows previously identified as containing discontinuous channels or depressions are revealed to contain a subtle ridge with axial collapse structures characteristic of lava tube-fed flows. Using lava channel or tube collapse dimensions and underlying slopes obtained from MOLA, we have estimated the flow velocities and effusion rates for a range of flow lobes across Mars: Tyrrhena Patera, Syrtis Major, Elysium Mons, Arsia Mons, and Olympus Mons. In general, Martian lavas appear to have effusion rates and flow velocities that are at least 10 times higher than the highest basaltic effusion rates yet observed on Earth (Mauna Loa, Hawaii, 1984 eruption). However, the rates obtained are comparable to those estimated for mid-ocean ridge eruptions. Lava flow lobes at Tyrrhena Patera were emplaced at rates similar to those observed for Mauna Loa and Kilauea volcanoes, Hawaii. The relatively low rates for the Tyrrhena Patera flows may be related to the low underlying slopes there, or perhaps to a unique lava composition and/or emplacement style.

V42A-06 1500h

Testing the Hypothesis of Young Martian Volcanism: Studies of the Tharsis Volcanoes and Adjacent Lava Plains

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The post-Viking view of Mars was of a planet virtually volcanically inactive for the last 2.5 Ga. This paradigm persisted in spite of early indications from crater counts that some Tharsis and Elysium volcanism might be as young as 300 Ma. More recently, several studies have independently offered evidence which can be interpreted to suggest volcanic activity late in Martian history. The current emerging hypothesis of young Martian volcanism is based on these lines of evidence. Included in this are analyses of Martian meteorites, photogeologic examination of the planet's surface and detailed crater count studies of high resolution images from MGS/MOC. Possible indications of liquid water present on Mars late in its history may be tied to recently active volcanism as a heat source. Early MGS/MOC crater data from Elysium Planitia suggested some lava flows are as young as 100 Ma and possibly much less. These crater count studies can however be questioned on the basis of two major uncertainties: very small sampling of counts on young flows, and poor absolute surface age estimates on Mars. We have therefore initiated a two-pronged attack to address these uncertainties. The first task is to improve the detailed crater statistics on the large Martian shield volcanoes and their surrounding lava plains. This work builds on studies of the lightly cratered terrains of Elysium Planitia. The second task is to determine the absolute ages of the units using new estimates of the crater production rate on Mars. Theoretical advances and new numerical tools now allow for a better determination of the orbital and size-frequency distribution of the Mars-crossing asteroid population. These results can then be directly compared to recent estimates of the nature of all near-Earth asteroids so that known lunar surface ages can be calibrated to the Martian case. Our initial crater counting work on the flanks of Olympus Mons gives calibrated ages as low as 5-50 Ma for the very youngest flows. Our study will continue for the next three years and will include detailed mapping of individual lava flows, crater density measurements, and age calibration based on estimates of the size and number of Mars and Earth crossing asteroids. This multi-discipline investigation will therefore help to constrain the nature of volcanism on Mars and its geothermal and hydrothermal history.

V42A-07 1530h

Modeling of Small Martian Volcanoes: A Changing View of Volcanic Shield and Cone Fields

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The small volcanic features on Mars (channels, flows, shields, and cratered cones) are key to understanding eruption styles, rates, and volumes because they are ubiquitous and simple enough to attempt modeling. Several of these small features have been suggested to be geologically recent [1,2,3]. This study measures and models small (3-50 km) volcanic edifices. Recent Mars Global Surveyor data reveal that these small features are more common that we had previously thought from the lower resolution Viking mission data (e.g., [3,4]). Furthermore, there are clear geometric differences in the Mars Orbiter Laser Altimeter (MOLA) data between regions suggesting local and regional eruption styles may vary with latitude. While a few of the pre-MGS construction models predict the martian mid-latitude volcanic shield shapes fairly well, the small explosive volcanic edifice shapes were not well predicted by existing models (see[5]), and there are a host of typesmostly polarthat are not well described by prior modeling. We compare small edifice construction model results for a percolation style model of effusive and mixed effusive and explosive edifices to prior model results for several martian volcanic regions. While mid-latitude edifices match well to predicted cross-section shapes, steeper flank slopes (See [6]; Glaze and Sakimoto, this volume) for the polar edifices suggest that the magma supply rate or the edifice permeability may be higher in the polar regions for some edifices types. However, polar edifice flank slopes do not commonly reach the greater than 10 degree flanks expected from prior explosive edifice models. Additionally, we do not observe shallow flank slope shields in the polar regions. This suggests that simple shield building may be significantly influenced or modified by volatile involvement near the martian poles, while a range of poorly understood explosive activity may be active in both regions.

V

[1] Keszthelyi et al. JGR 105, 15027-15049, 2000. [2] Hartmann and Berman, JGR, 105, 15011-15025, 2000. [3] Garvin, et al., Icarus, 145, 648-652, 2000. [4] Sakimoto, et al., LPSC XXXII, CDROM, abstract #1808, 2001. [5] Glaze and Baloga LPSC XXXII, CDROM, abstract #1209, 2001. [6] Wong, et al., LPSC XXXII, CDROM, abstract #1563, 2001.

V42A-08 1545h

Martian Rootless Cones as Indicators of Recent Deposits of Shallow Equatorial Ground Ice

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Small, cratered cones have been identified in high-resolution Mars Orbiter Camera images of the Cerberus Plains and Amazonis Planitia, Mars [1].These cones occur in small clusters independent of obvious fissures, are superimposed on fresh lava flows, and do not appear to issue lavas themselves. Observed cones have basal diameters <250m and large summit craters. The structures are similar in both morphology and dimensions to the larger of Icelandic rootless cones,or pseudocraters [2], which form due to phreatomagmatic explosions caused by mechanical mixtures of tube-fed lavas with near-surface water-saturated substrates[3]. If the martian cones form in a similar manner as terrestrial rootless cones,then they may provide constraints on the spatial and temporal distribution of martian ground ice. Lavas associated with the western Amazonis cone fields(24N, 171W) show well-preserved surface morphologies and few superimposed impact craters. Impact crater statistics indicate that these lavas and superimposed cones may have been emplaced less than 10 Ma, indicating near-surface ice must have been present at the time.

The presence of young rootless cones helps constrain the origins of ground ice. Relic ground ice is unlikely to be a volatile source for rootless eruptions as regolith in equatorial regions is likely to be desiccated to a depth of 200-m [4]. Vapor exchange between the regolith and atmosphere due to obliquity variations [5] may input enough water into the subsurface to reproduce martian cones of observed diameters calculated by explosion models[6]. However, surficial waters released in outflow events may be required to recharge requisite quantities of ground ice. Most proposed rootless cone fields appear in or close to fluvial features of the Cerberus Plains and Marte Valles[7]. Nested summit craters of some cones indicate a multi-stage constructional process, which would require recharge of aquifers beneath the erupting cones. Such a process would require the substrate to be permeable and contain enough ground ice to allow water to flow to the explosion point.

[1]Lanagan, P. D. et al.(2001)Geophys Res Let, submitted. [2]Thorarinsson, S.(1953)Bull Vol, 14, 3-44. [3]Thordarson, T.(2000)Volcano-Ice Interactions on Earth and Mars, 36. [4]Clifford, S. M., and Hillel, D.(1983)J Geophys Res, 88, 2456-2474. [5]Mellon, M. T., and B. M. Jakosky.(1995)J Geophys Res, 100, 11781-11799. [6]Fagents, S. A. and R. Greeley.(2000)Volcano-Ice Interactions on Earth and Mars, 13. [7]Burr, D. M. et al.(2001)Geophys Res Abs.

V42A-09 1600h INVITED

Terrestrial Subice Volcanism and Pre-flood Basalt Hydrovolcanism as Models for Magma-Volatile Interaction on Mars

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Sub-ice basaltic volcanism on Earth produces distinctive edifices including flat-topped volcanoes (tuyas) and fissure-fed cone-and-ridge structures (tindars). These edifices mostly represent subaqueous to emergent sequences constructed within ice-bound lakes, but some deposits from eruptions beneath thin ice are deposited by meltwater streams. Tuyas are often associated with lava-fed deltas, which are constructed when subaerial lava flows fragment on entering relatively deep water. Such deltas record the former water level(s) and a minimum ice thickness. Important controls on eruption and emplacement mechanisms include vent geometry and distribution, magma volume, viscosity, vesiculation state and cooling rate, glaciostatic, hydrostatic and magmastatic head, magma-water/slurry interaction processes, ice structure and surface gradient, bedrock topography, meltwater volume and meltwater drainage mechanism(s). Terrestrial basaltic subice volcanoes are associated with catastrophic flood deposits, are subject to glacial erosion and resedimentation, and may be buried or partly buried by subaerial lava flows from the same vents, following ice sheet withdrawal. Subglacial rhyolite edifices are distinctly different in lithofacies and architecture to basaltic ones, reflecting differences in magma rheology and glacier hydraulics. Flat-topped volcanic landforms in the Utopia, Acidalia and Elysium areas of the northern plains of Mars and some of the interior deposits of Valles Marineris have been interpreted as analogs to terrestrial tuyas. Ridges without resistant caprock occur in Utopia Planitia near Elysium Mons, and follow the same northwest trend as known volcanic features on the flanks of the Mons. Their rough texture, topography and similarity to Icelandic features suggest that they may be formed from friable materials, and could be possible tindar analogs. On the opposite side of the planet, many chasmata are nearly filled with freestanding interior layered deposits (ILDs). Recently, it has been suggested they may represent englacially erupted subaerial tephra that was deposited in lakes. Sub-ice volcanism may also have generated the catastrophic floods from the Valles Marineris chasmata.

Little known voluminous eruption-fed lahars record the onset of flood basalt volcanism in the Karoo, Ferrar, East Greenland and possibly Siberian Traps flood basalt provinces. The flows infilled large collapse structures and generated widespread outflow sheets. Study of the Karoo examples suggests that they were probably erupted following mingling of magma and fluidised wet sediment, during underplating of large areas of sediment by voluminous and constantly replenished high-level sills. Martian deposits interpreted as the products of enormous outburst floods may have formed by an analogous mechanism of sill intrusion into ground-ice cemented sediment

V42A-10 1615h

Use of Slopes of Small Martian Edifices to Discriminate Between Formation Mechanisms

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We have looked at Mars Orbiter Laser Altimeter (MOLA) topographic profiles of several small Martian edifices (3 - 50 km in size) in a variety of volcanic regions from the mid-latitudes to the poles. Viking and Mars Observer Camera (MOC) images and recent MOLA gridded topography data reveal a wide range of small edifice geometries (e.g., Garvin et al., 2000; Won et al., 2001), and a larger number of edifices than previously detected (e.g., Sakimoto, et al., 2001). We have attempted to characterize the average slopes of these edifices using a variety of statistics. Because of the curvature of many of the slopes, simple unweighted and weighted averages are not adequate for characterization. However, most of the flanks can be well described by a parabolic regression (R squared values greater than 90%). As a starting point, we have used the 'slope' term from the parabolic regression for comparison between the various features. The parabolic regression has the form: elevation = a - b sqrt(distance), where the constant 'a' is a vertical offset and 'b' is analogous to the slope. The true instantaneous slope at any point on the flank is found by taking the derivative of the expression above and is necessarily a function of location on the flank. The following table contains values of 'b' for the South and North facing flanks of several volcanic features found in different geologic settings:

Feature: (South) (North)moderate cratered cone (large crater) B1: (8.588) (7.46)steep cratered cone (small crater) B5: (9.90) (10.613)-latitude Tempe Terra shield TS1: (2.158) (1.964)-latitude Tempe Terra cone TC1: (4.934) (4.591)

As can be seen from the table, the individual features are very consistent between their South and North facing flanks. There is also a clear distinction between B5, TS1 and TC1. The uncertainty (standard error) in the 'b' values given above is typically less than 1, suggesting the possibility of at least three separate feature types represented above. In addition to this simple comparison between parabolic slopes, we can also compare the actual shapes of the features. For example, the TS1 shield-type feature has less curvature than the others and may be better characterized by a linear fit. This also distinguishes it from the other features purely by the shape of its flanks. These comparisons allow us to quantitatively document the differences between the small Martian shield volcanoes as a feature class from their more explosive counterparts.

Garvin, J.B., et al., Icarus, 145, 648-652, 2000. Wong, M.P., et al., LPSC XXXII, CDROM, abstract #1563, 2001. Sakimoto, S.E.H., et al., LPSC XXXII, CDROM, abstract #1808, 2001.

V42A-11 1630h

Styles of Phreatomagmatic Activity Adjacent to Volcanic Constructs on Mars

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Early in the analysis of Viking Orbiter data, it was recognized that there were numerous sites on Mars where igneous intrusions may have interacted with ice near the surface. Hrad Vallis (34N, 142E) in Western Elysium Planitia, and Olympica Fossae (25N, 245E) to the southwest of Ceraunius Fossae, were two such candidate areas. New images from the Mars Orbiter Camera show striking differences between these two sites, revealing a wide diversity of depositional and erosional features. We are therefore exploring several potential terrestrial analogs to better constrain models of heat transfer from the igneous intrusion, the style of "eruption" of the water/sediment mixtures, and the hydrologic conditions in the substrate at the time of emplacement. We have found layering at the source of Hrad Vallis, and several nearby impact craters 270 - 530 m diameter that are almost totally mantled, consistent with the deposition of 20 - 30 m of sediment around the source graben. Prominent sub-radial ridges occur within this 8,400 km^2 deposit; close to the source, these ridges have a spacing of 100 - 120 m but grade to smaller ridges 60 m apart within 2 km of the source. No "de-watering" features are visible on this unit. In contrast, Olympica Fossae displays no depositional features near the source graben. We interpret these morphologic differences to be due to a higher sediment load of the fluid that reached the surface at Hrad Vallis compared with Olympica Fossae. At neither site are there signs of "weeping" graben walls, indicating that the source of the water was probably at a depth greater than that of the graben (about 60 - 100 m). With due allowance for bulking and for errors of measurement, the volumes of the deposits are comparable to the volumes of their parent source depressions. We envisage that these deposits were created by phreatomagmatic explosions in which heat from a sill-like intrusion melts ice occupying pore space in crustal rocks and boils the resulting water. Calculations show that steam pressures of 1-3 MPa can readily loft the overburden from depths of a few hundred meters and lead to ejecta speeds greater than 100 m/s. Condensation of the water vapor during the explosion process leads to emplacement of a wet deposit, and plausible variations in ice content of the crustal rocks explain the sediment load variations.

V42A-12 1645h

Magmatically Driven Catastrophic Erosion on Mars

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Geomorphic observations on Mars indicating the interaction of volcanism and H_2O have long been recognized. Now, Mars Orbiter Laser Altimeter topographic data reveal what appear to be even more dramatic examples of magmatically driven erosion. Three regions of Early Hesperian plateau volcanism, each $>10^6$ km^2, occur within topographic lows on the rims of large impact basins. Older basin inner-slope topography, including prominent massifs, is largely missing where the volcanic rocks occur. At Syrtis Major Planum, lavas

lie ~200 m on average below the inner rim of Isidis basin. Similarly, Malea and Hesperia Plana respectively lie ~700 and ~400 m below the inner rim of Hellas basin. Missing rock volume is in the range of 10^5 -10^6 km^3. We propose that magmatic activity at these sites began with shallow sills that drove catastrophic erosion of friable, upper crustal Noachian rocks. The rocks likely were charged with H_2O ice and water and perhaps CO_2 ice and CO_2 clathrate; dry ice is more volatile than water ice and may better explain why such huge volumes of rock could be readily disrupted, eroded, and transported many hundreds of kilometers. The deposits would have each infilled the basins by tens to a few hundred meters on average. In Hellas basin, a large lobe of what may be such material extends from below Hesperia Planum westward across much of the basin floor. Further volcanism covered the eroded plains with sheet lavas, and broad low shields and volcanic subsidence structures formed at eruptive centers. Other possible erosional features related to shallow intrusion on Mars include large troughs at Valles Marineris, Tempe/Mareotis Fossae, Elysium Fossae; deep, broad canyons and chaotic terrain associated with large outflow channels; and many smaller enclosed depressions associated with the Tharsis and Elysium volcanic regions. Most of the largest features formed during the Hesperian, few if any are recognized in the Noachian, and generally smaller, local features developed during the Amazonian. These relations indicate that typical magmatism and perhaps crustal conditions evolved over time on Mars, making the relatively short Hesperian Period most favorable for catastrophic erosion driven by magmatic heating.

V51A CC: 203 Friday 0830h

Petrological and Geochemical Constraints of the Formation of Archean Cratons I *(joint with GS, T)*

Presiding: **T L Grove,** MIT**; S B Shirey,** Carnegie Institution of Washington

V51A-01 0830h INVITED

The Cool Early Earth: Oxygen Isotope Evidence for Continental Crust and Oceans on Earth at 4.4 Ga

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Zircons preserve the best record of U-Pb crystallization age and oxygen isotope ratios of igneous rocks. The d18-O of non-metamict zircon is unaffected even by hydrothermal alteration and high-grade metamorphism.

Ion microprobe analysis of detrital zircons from the ~3 Ga Jack Hills metaconglomerate (Narryer Gneiss Terrane, Yilgarn Craton, Western Australia) yield U-Pb ages from 3.1 to 4.4 Ga (SHRIMP II, Wilde et al. 2001 Nature) and d18-O from 5 to 8 permil (Cameca 4f, Peck et al. 2001 GCA). The d18-O of these zircons averages 6.3, and is 1 permil higher than that in equilibrium with the mantle and that of normal Archean granitic zircons (5.3+-0.3, 5.5+-0.4, respectively; King et al. 1998 Pre-C Res, Peck et al. 2000 Geology). The distribution of mantle-like vs. mildly elevated d18-O values for magmas is constant from 2.7 to 4.4 Ga, and on 4 continents.

The age of 4.404+-0.008 Ga from one 200 micron zircon is >99% concordant and represents the oldest recognized terrestrial material. This crystal is zoned in d18-O (5.0+-0.7 vs. 7.4+-0.7) and REEs (La=0.3 to 13.6 ppm), and contains inclusions of SiO2. REE patterns are HREE enriched with positive Ce and negative Eu anomalies; calculated melts are LREE enriched. Taken together, these results suggest crystallization from a quartz-saturated granitic magma and thus the existence of continental crust, possibly in a setting like Iceland. The high d18-O portion of the crystal would be in equilibrium with a magma at d18-O(WR)= 8.5-9.5. There is no known mantle reservoir with such high values. d18-O(WR) values above 8.5 are typical of 'S-type' granites that have melted or assimilated material that was altered by low temperature interaction with water at the surface of the Earth (i.e., weathering, diagenesis, low T hydrothermal alteration). Thus the high d18-O value of the 4.4 Ga zircon suggests that surface temperatures were cool enough for liquid water suggesting that the early steam-rich atmosphere condensed to form oceans at that time.

The evidence for liquid water and possibly oceans at 4.4 Ga suggests a Cool Early Earth. This contrasts with the Hot Early Earth and global magma oceans envisioned at 4.5-4.3 Ga based on: an impact origin of the Moon (4.45-4.50 Ga), core formation, higher Hadean radioactive heat production, and intense early meteorite bombardment. Magma on the surface of the Earth cools quickly by radiation to form a crust, but a magma ocean caused by these processes might persist beneath the initially thin crust for up to 400 m.y. and might erupt as massive flood basalts in response to major meteorite impacts, boiling surface waters. The thermal contrasts presented by these lines of evidence are minimized if the Moon and core formed earlier (~4.5 Ga), if the Moon formed by a process not involving a Mars-size impactor, or if the early meteorite bombardment was less intense or irregular in timing. It is possible that periods of Cool vs. Hot Early Earth alternated, with boiling of early oceans after major impact events followed by periods of cooler surface conditions. If life evolved in these seas, multiple extinctions before 3.9 Ga are suggested.

V51A-02 0855h INVITED

In-situ Measurements of Sedimentary Graphites and Sulfides in Early Archean (>3.7 Ga) Banded Iron-Formations from West Greenland: Biological and Atmospheric Influences

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Stable isotopes of carbon [^{13}C, ^{12}C] and sulfur [^{32}S, ^{33}S, ^{34}S and ^{36}S] are used as tracers for igneous, hydrothermal and biological processes on Earth. Carbon and sulfur are abundant in marine systems and they have been utilized as biomarkers in ancient sediments. Kinetic isotope fractionations between inorganic and bioorganic carbon and sulfur during metabolic cycling results in a marked enrichment of the light isotope in the biological component by several percent. Graphitic inclusions from early Archean banded iron-formations are isotopically light [range $\delta^{13}C_{VPDB}$ = -20 to -50$^o/_{oo}$]; these results are consistent with a biological origin. Bacterial sulfate reduction has been linked to the range of over 150$^o/_{oo}$ in $\delta^{34}S$ from sulfate and sulfide in the rock record. Mass-dependent sulfur isotope fractionations, commonly expressed as $\delta^{34}S_{CDT}$ values for sulfur-containing minerals, exhibit a small range centered at ~0$^o/_{oo}$ for terrestrial igneous [0±5$^o/_{oo}$] and hydrothermal [0±10$^o/_{oo}$] systems. Atmospheric chemical reactions on the low pO_2 early Earth are implicated in non-mass-dependent sulfur isotope anomalies [expressed as: $\Delta^{33}S=\delta^{33}S-0.520\delta^{34}S$] reported from whole-rock analyses of sulfur-containing phases in Precambrian sediments. Only atmospheric processes in planetary environments, and nucleosynthetic, spallation or ion-molecule reactions in the stellar or near-stellar environment, appear capable of producing non-mass-dependent isotope fractionations. To explore how sulfur signatures are preserved in early Archean BIFs new techniques have been developed to obtain precise ^{32}S, ^{33}S and ^{34}S measurements in situ of sulfide grains from sedimentary rocks ranging in age from early Archean [~3.83 Ga] to Proterozoic [~1.8 Ga]. High-precision simultaneous measurements of multiple sulfur isotopes enable $\Delta^{33}S$ to be evaluated at the sub-grain scale [<30 μm]. These results may then be compared with previous carbon isotope measurements from the same rocks. How might atmospheric and biological evolutionary links be evaluated by studying the carbon and sulfur isotope compositions of ancient sediments? New data reveal well-resolved non-mass-dependent $\Delta^{33}S$ anomalies in an early Archean [3.77-3.83 Ga] banded iron-formation and a metapelite from West Greenland [total range in $\Delta^{33}S$=+1.10±0.07$^o/_{oo}$ to +1.23±0.05$^o/_{oo}$, 2σ] previously analyzed for carbon isotopes. Data from sulfides in a diverse collection of stromatolithic cherts, banded iron-formation and shales of Proterozoic to late Archean age [1.8-3.2 Ga] displayed only mass-dependent [$\Delta^{33}S$~0$^o/_{oo}$] sulfur isotope relationships within the precision of the measurements [typically ±0.06$^o/_{oo}$, 2σ]. Results reveal that non-mass-dependent sulfur isotope anomalies [i.e. $\Delta^{33}S$>0] are preserved in sulfide phases contained in the oldest known rocks of sedimentary origin. That these rocks contain a record of gas-phase reactions in an early atmosphere would support the interpretation that atmospheric partial pressures of oxygen were low and the effects of UV-photolysis on atmospheric sulfur from a UV-active young Sun were widespread and commonplace on the Archean Earth. This might also be reflected in the long-term [billion-year timescale] changes to the isotope composition of bioorganic carbon. Further studies warrant coupling sulfur, carbon [and nitrogen] measurements in ancient sediments to explore this relationship.

V51A-03 0910h INVITED

Testing Models for the Formation of Archean Cratons: An Example from the Western Superior LITHOPROBE Transect, Canada

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The Western Superior Lithoprobe transect provides a rare opportunity to integrate a multitude of petrological, geochemical, geochronological and structural studies within a geometric framework based on deep (32 s) vibroseis seismic reflection and refraction/wide-angle reflection data, acquired along a 600 km N-S corridor across the prominent E-W trending structural belts of the Western Superior Province. Previous models suggested accretion of Neoarchean (<2.8 Ga) oceanic crust, island arcs and sedimentary prisms with almalgamated Mesoarchean continental fragments against the southern margin of the more than 3 Ga composite North Caribou terrain during the ca. 2.7 Ga Kenoran orogeny. At surface, the southern margin of the North Caribou terrain shows Neoarchean convergent-margin magmatism. Outboard (south) from the protocraton margin, beneath the "accreted" terranes, two lower crustal sutures are identified, where the reflection Moho is offset by several kilometers, consistent with north over south displacement. Along the northern suture, a Mesoarchean continental fragment of the eastern Wabigoon Subprovince is thrust beneath the North Caribou terrain. This fragment is underplated from the south by a basal crustal layer with high sub-horizontal reflectivity, very high crustal p-wave velocities (7.6-7.7 km/s) and intermediate density (3.0-3.1 gm/cc), that tapers northward, truncating the reflection Moho and extending into the upper mantle to at least 16 s TWT. The velocity and density constraints of this layer can be satisfied by amphibolitic rocks with a sub-horizontal N-S lineation, and the layer may thus represent a tectonically underplated slab of Archean oceanic crust. Below the Moho, a north-dipping, 20 km thick layer at 50 to 60 km depth is characterized by 5to tectonic strike). This anisotropy is interpreted as an Archean fossil fabric associated with LPO of olivine. All these observations are consistent with the previously predicted northward subduction of Late Archean oceanic lithosphere.

V51A-04 0935h INVITED

Source and Mechanism of Archean Lithosphere Formation

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Chemical analyses and Re-Os model ages have been obtained for approximately 140 peridotite xenoliths from on and off craton kimberlites widely distributed across southern Africa. Peridotites erupted through Proterozoic basement have slightly lower Mg/Fe and display no Archean Re-Os model ages compared to peridotites from on-craton kimberlites that generally are very Fe, Ca, and Al depleted with Re-Os model ages > 2.5 Ga. The one exception on craton is the Premier kimberlite where magmatism associated with formation of the Bushveld intrusion at 2.05 Ga introduced Proterozoic peridotite into the underlying mantle.

The mean Re-depletion and Re-Os model ages for xenoliths from all on-craton localities, excluding Premier, are 2.59 +/- 0.49 Ga and 3.9 +/- 4.2 Ga, respectively. The large error on the Re-Os model age reflects recent Re addition to some samples due to host kimberlite contamination or metasomatism in the mantle. Excluding samples with 187Re/188Os > 0.1 (approximately half of the data set) gives mean Re-depletion and Re-Os model ages of 2.69 +/- 0.23 Ga and 2.99

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