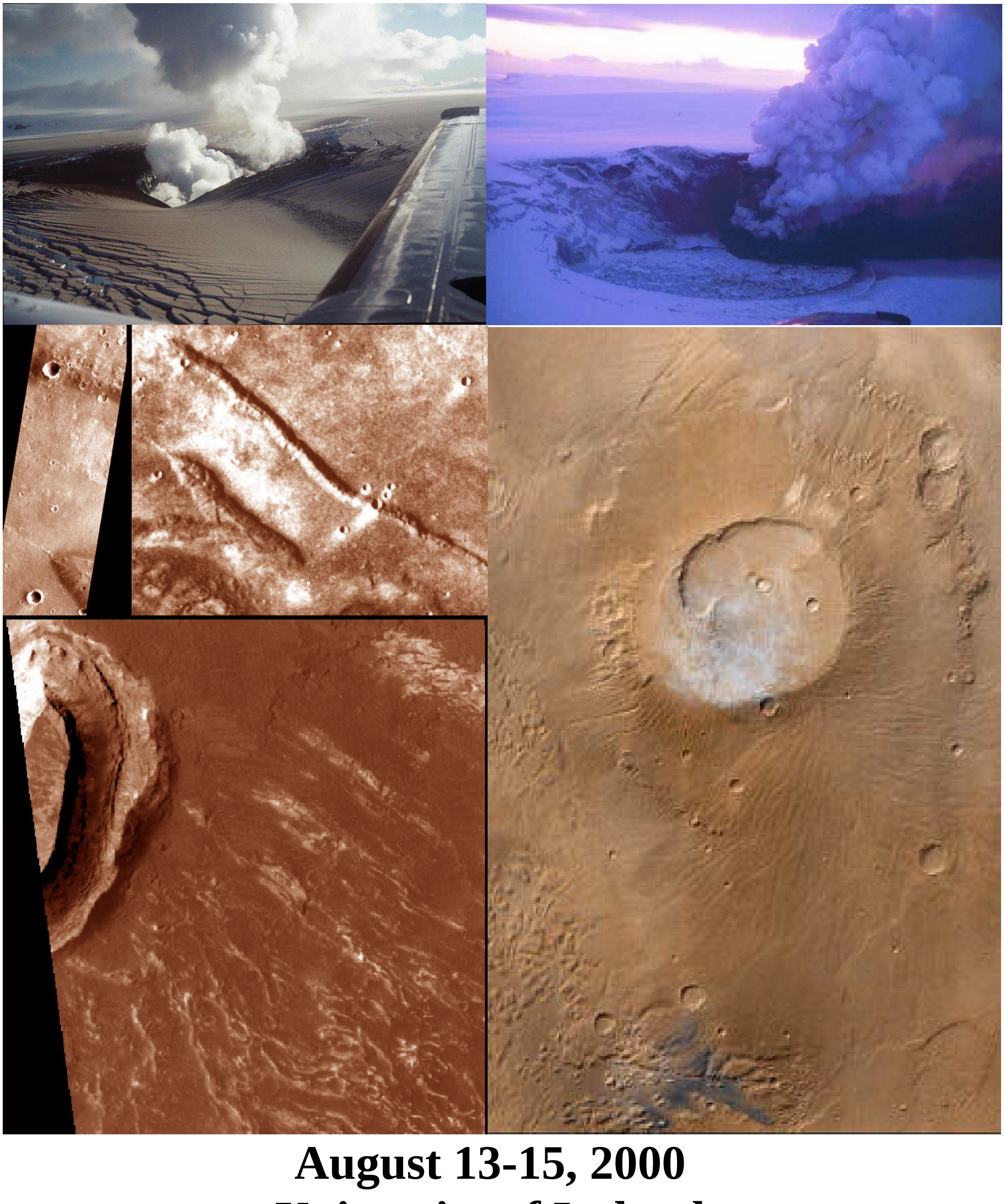
# VOLCANO/ICE INTERACTION ON EARTH AND MARS



**August 13-15, 2000**
**University of Iceland**
**Reykjavík, Iceland**

*On the cover:* Upper left: Gjálp eruption, Iceland 1996; photo taken by Magnús T. Gudmundsson. Upper right: Grímsvötn eruption, Iceland 1998; photo taken by Magnús T. Gudmundsson. Lower left: false color images of possible subice volcanoes on Mars: near Elysium Mons (MOC SP247504 and VO 541A20) and in Melas Chasma (MOC 3-00945; MOC images courtesy of Malin Space Science Systems/NASA) Lower right: possible volcano/ice interaction landforms surrounding Apollinaris Patera volcano, Mars (MOC2-119; MOC images courtesy of Malin Space Science Systems/NASA).

# Volcano/Ice Interaction on Earth and Mars
## Abstract Volume

*Edited by:*
Virginia C. Gulick and Magnús T. Gudmundsson

*Conveners:*
Mary Chapman, USGS, Flagstaff, Arizona, USA
(mchapman@flagmail.wr.usgs.gov)

Magnús T. Gudmundsson, Science Institute, University of Iceland, Reykjavík, Iceland
(mtg@raunvis.hi.is)

Virginia C. Gulick, NASA-Ames Research Center/SETI Institute, Moffett Field, California, USA
(vgulick@mail.arc.nasa.gov)

Sveinn Jakobsson, Icelandic Institute of Natural History, Reykjavík, Iceland
(sjak@ni.is)

Ian Skilling, University of Southern Missisippi, Hattiesburg, Mississippi, USA
(Ian.Skilling@usm.edu)

John Smellie, British Antarctic Survey, Cambridge, UK
(jlsm@pcmail.nerc-bas.ac.uk)

*Collaborator:*
Carlton Allen, Johnson Space Center, Houston, TX, USA

*Conference Organizer:*
Iceland Travel/Conference Department
Lagmuli 4, 108 Reykjavík
Phone: 354-585 4300
Fax: 354-585 4490
E-mail:
congrex@icelandtravel.is
bjorkb@icelandtravel.is

*Hosted by:*
University of Iceland
Icelandic Institute of Natural History

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University of Iceland
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## VOLCANO/ICE INTERACTIONS ON EARTH AND MARS

### *MEETING PROGRAM*

***Sunday 13th August***

Arrival of Participants
3.00-5.00 Registration at Oddi, University of Iceland
5.00-7.00 Ice-breaker Reception at I›nó Restaurant, Reykjavík

***Monday 14th August***

**SESSION 1. Terrestrial Volcano-Ice Sheet Interaction (Chairs: John Smellie, Ian Skilling, Magnús T. Gudmundsson)**

8.10-8.15 OPENING ADDRESS: Dr Jón Gunnar Ottósson (Icelandic Institute of Natural History)

8.15-8.45 Lithofacies architecture and construction of volcanic sequences erupted subglacially (J.L. Smellie) *invited talk*

8.45-9.05 The icebreakers: historical eruptions of subglacial volcanoes in Iceland (Larsen)

9.05-9.25 The hyaloclastite ridge formed in the subglacial eruption at Gjálp, Iceland in 1996 (M.T. Gudmundsson, F. Pálsson, H. Björnsson and Th. Högnadóttir)

9.25-9.45 Icelands largest subglacial rhyolite eruption (D.W. McGarvie, H. Tuffen and A.G Tindle)

9.45-10.05 Upper Pleistocene subglacial volcanic activity in the region SW of Vatnajökull Icecap, Iceland (E.G. Vilmundardóttir, and S.P. Snorrason)

10.05-10.25 Subglacial volcanism in the Langjökull Region, Western Volcanic Zone, Iceland (S.P. Jakobsson)

10.25-10.45 **COFFEE BREAK**

10.45-11.05 Subglacial Volcanoes (Tuyas) of north-central British Columbia, Canada (C.C. Allen)

11.05-11.25 Middle to Late Cenozoic Volcanic Record of the West Antarctic Ice Sheet. (T.I. Wilch and W.C. McIntosh)

11.25-11.45 Intense Volcanism associated with crustal rebound: recharging of a volcanic centre and subsequent petrological evolution (G. E. Sigvaldason)

11.45-12.05 Bed roughness as an indictor of relative eruption frequency (K. Langley)

12.05-1.05 **LUNCH BREAK**

1.05-1.35 Hydrology of ice caps in volcanic regions (H. Björnsson) *invited talk*

1.35-1.55 Volcano/Ice Interaction at Bláhnúkur, Torfajökull, Iceland: a Quaternary subglacial rhyolite eruption (H. Tuffen, J.S. Gilbert, D.W. McGarvie )

1.55-2.15 Pillow lava sheets: origins and flow patterns (S.P. Snorrason and E.G. Vilmundardóttir)

2.15-2.35 Rootless eruptions and cone groups in Iceland: products of authentic explosive water to magma interactions (Th. Thordarson)

2.35-2.55 Volatiles in basaltic glasses from a subglacial volcano in northern British Columbia: Implications for mantle volatiles and ice sheet thickness (J.E. Dixon, J. Filiberto, J.M. Moore and C.J. Hickson)

2.55-3.15 Jökulhlaups and rapid depressurization of pillow basalts (Á. Höskuldsson, M. Carroll, and R.S.J. Sparks)

3.15-3.35 The 1969 subglacial eruption on Deception Island (Antarctica): events and processes during an eruption beneath a thin glacier (J.L. Smellie)

3.35-3.55 **COFFEE BREAK**

3.55-4.15 Basaltic pahoehoe lava-fed deltas: clast-generation, emplacement and criteria to distinguish englacial/lacustrine deltas from submarine examples (I.P. Skilling)

4.15-4.35 The interplay between ice thickness, water pressure and eruption style in subglacial eruptions: effects of ice subsidence, deformation and meltwater drainage (M.T. Gudmundsson)

4.35-4.55 Removal of subglacially erupted volcanic edifices beneath the divide of the West Antarctic Ice Sheet interpreted from Aeromagnetic and Radar Ice Sounding (J.C. Behrendt, D.D. Blankenship, C. Finn and R.E. Bell)

4.55-5.15 Middle and Late Wisconsian Expansion of the West Antarctic Ice Sheet at Mt Takahe Volcano (T.I. Wilch, S. McCuddy and W.C. McIntosh)

5.15-6.15 **POSTER VIEWING WITH DRINKS**

***Tuesday 15th August***

**SESSION 2. Planetary Volcano-Ice Interaction (Chairs: Mary Chapman and Ginny Gulick)**

8.00-8.30 Relations of Surface Water, Ice and Volcanism on Mars (J. Head) *invited talk*

8.30-9.00 Volcano/Ice Interactions on Mars: An Overview (C.C. Allen) *invited talk*

9.00-9.20 Comparative glaciology and active phenemona in the solar system (N.I. Koemle)

9.20-9.40 Mars: geologic setting of magma/water interactions (J. Head and L. Wilson)

9.40-10.00 The role of volcano/magma-H2O interactions in valley and channel formation on Mars (V.C. Gulick)

10.00-10.20 Martian analogs of terrestrial sub-ice volcanoes support ancient ocean (M.G. Chapman)

10.20-10.40 **COFFEE BREAK**

10.40-11.00 Possible tuya origin of interior layered deposits in Valles Marineris, Mars (M.G. Chapman and K.L. Tanaka)

11.00-11.20 Well-preserved volcanic and fluvial landforms in the Cerberus/Amazonis Region of Mars (A.S. McEwen, L. Keszthelyi, P.D. Lanagan, R. Beyer and D. Burr)

11.20-11.40 Mega-lahars of Elysium, Mars (K.L Tanaka, I.P. Skilling and J. Skinner)

11.40-12.00 Analysis of Rootless eruption model for origins of small cones of Elysium Basin and Amazonis Planitia, Mars (P.D. Lanagan, A.S. McEwen, L.P. Keszthelyi and Th. Thórdarson)

12.00-12.20 Formation of pseudocraters on Earth and Mars (S.A. Fagents and R. Greeley)

12.20-1.20 **LUNCH BREAK**

1.20-1.30 ANNOUNCEMENT ON FIELD TRIP AND OVERFLIGHT LOGISTICS (Magnús T. Gudmundsson/Sveinn Jakobsson)

**SESSION 3: Volcano-Snow/Ice Interaction on Terrestrial Stratovolcanoes (Chair: Dave Lescinsky)**

1.30-2.00 Landform development and fracturing during lava-ice interaction at stratovolcanoes with alpine glaciers (D.T. Lescinsky and J.H. Fink) *invited talk*

2.00-2.20 Possible linkage between laharic events and glacier ice melting at Popocatapetl volcano, Mexico (H. Delgado, A.E. González-Huesca and B. Oropeza-Villalobos)

2.20-2.40 Subglacial eruptions at Sierra Madre Oriental, Mexico (Á. Höskuldsson)

2.40-3.00 Subglacial evolution of Hoodoo Mountain volcano, northwestern British Columbia, Canada (B.R. Edwards and J.K Russell)

3.00-3.20 **COFFEE BREAK**

**SESSION 4: Alteration of Volcanic Glass and Exobiologic Implications of Planetary Volcano-Ice Interaction (Chair: Gudmundur Sigvaldason)**

3.20-3.50 Bio-alteration of basaltic glass in the oceanic crust (H. Furnes) *invited talk*

3.50-4.20 Alteration of the tephra of the Surtsey Tuya, Iceland (S.P. Jakobsson) *invited talk*

4.20-4.40 Palagonitization of the Keanakakoi Ash Member, Kilauea Volcano (P. Schiffman R.J. Southard and H.J. Spero)

4.40-5.00 Mineral identification in palagonitically-altered volcanic material as an indictaor of geochemical history (J.L. Bishop)

5.00-5.20 Exploring for evidence of extant martian life in polar ice deposits (J.D. Farmer)

5.20-5.30 **MEETING PUBLICATION ANNOUNCEMENT (John Smellie)**

5.30-5.35 **CLOSING ADDRESS (Magnús T. Gudmundsson)**

**EVENING: Conference Dinner in Videy**

**POSTER SESSION (on display for whole conference)**

1. Architecture and evolution of hydrovolcanic deltas in Marie Byrd Land, Antarctica (W.E. Le Masurier)

2. Fragmentation mechanism in Icelandic subglacial rhyolite eruptions: evidence from ash shard morphologies (Tuffen, McGarvie and Gilbert)

3. Rhyolite tuyas at Torfajökull, Iceland (H. Tuffen, D.W. McGarvie and J.S. Gilbert)

4. The products of subglacial volcanism: examples from the Eyjafjallajökull volcano, southern Iceland (S.C. Loughlin)

5. The Tindaskagi hyaloclastite ridge, SW Iceland (Herdís H. Schopka, Jakob fi. Gudbjartsson and S.P. Jakobsson)

6. Radar Mapping of the Hoodoo Mountain Volcano Ice Cap: assessment of hazards associated with jökulhlaups (J.K Russell, M. Kelman J. Schmok and B.R. Edwards)

7. Simulation of melting of permafrost layer by dyke intrusion: estimate of melting speed and water flux (Y. Yamagishi, G. Ogawa and K. Kurita)

8. Holocene jökulhlaup activity at Entujökull, Iceland (K. Smith, A. Dugmore and G. Larsen)

9. Volcanism and ice in West candor Chasma, Valles Marineris, Mars (B.K. Lucchitta)

10. Searching for recent volcanism in the Valles Marineris, Mars (R.A. Beyer and A.S. McEwen)

11. Complex Sedimentary Responses to explosive eruptions at a snow-capped stratovolcano: 1995-96 Ruapheu, New Zealand (V. Manville, B.F. Houghton, K.A. Hodgson and J.D.L. White)

12. Satellite based analysis of erupting ice-capped volcanoes in Alaska (K.G. Dean, K.R. Engle and J. Dehn)

13. Glacial/Holocene Magma Production Rates in the Thingvellir-Langjökull Area, SW Iceland (M.T. Gudmundsson, S.P. Jakobsson and Th. Högnadóttir)

14. Radar sounding survey of Eyjafjallajökull, Iceland: subglacial topography, ice thickness, and derived relative permittivities (S.M. Strachan)

**VOLCANO/ICE INTERACTION ON MARS: AN OVERVIEW.** Carlton C. Allen, Lockheed Martin Space Operations, Houston, TX 77058, USA carlton.c.allen1@jsc/nasa.gov

The interactions of volcanic eruptions with ice and/or water produce a characteristic suite of landforms and minerals. Landforms include flood channels, distinctive mountains and ridge systems, and explosion craters. Morphologically similar features have been identified on Mars and may prove to be valuable indicators of the history of water on that planet. A major product of volcano/ice interaction is the pseudo-mineral palagonite, which bears strikingly similarities to martian soil.

Rapid melting of ice by subglacial volcanic eruptions, as well as slower meltwater buildup due to moderate heating, produces some of the largest floods on Earth. The highlands of Mars contain a variety of channels, many apparently formed by massive floods. Melting of ground ice by elevated heat flow, particularly in volcanic regions, may explain these channels.

Central-vent eruptions beneath glaciers build flat-topped or conical volcanoes composed of pillow lava, glassy tuff, and in some cases capping flows. Subglacial fissure eruptions produce ridges of pillow lava and tuff. Analogs to these mountains and ridges occur on the northern plains of Mars, particularly in the Chryse, Acidalia, and Elysium regions. These features can be modeled as the products of volcanic eruptions through ground ice or into an ancient ocean.

Phreatic craters result from steam explosions caused by lava flowing over water-saturated ground or ice. Phreatic craters generally resemble cinder cones, though they are not formed above a vent but confined to a lava flow. Groups of small cones, suggested to be of phreatic origin, have been recognized in Chryse and Acidalia.

Hydrous alteration of basaltic tuff at elevated temperatures produces palagonite, a poorly-crystalline, yellow-orange gel with a characteristic pattern of elemental enrichment and depletion. The surface soil of martian bright regions closely resembles palagonitized tuff in terms of visible and near-infrared reflectance spectra and, to a lesser extent, major element composition.

**SUBGLACIAL VOLCANOES (TUYAS) OF NORTH-CENTRAL BRITISH COLUMBIA, CANADA.** Carlton C.Allen, Lockheed Martin Space Operations, Houston, TX 77058 USA carlton.c.allen1@jsc.nasa.gov.

Ten flat-topped volcanoes and eight volcanic cones, all attributed to subglacial volcanism, occur in the Jennings River area of north-central British Columbia (latitude 59°N, longitude 131°W, altitude 1200 to 2900 m). Volcanoes of the first type are flat-topped piles of hyaloclastite overlain by subhorizontal basalt flows. Those of the second type are lapilli cones overlying pillow basalt units. These mountains are collectively designated "tuyas". Field observations, photo analysis, and microanalysis of samples support the contention that the tuyas of British Columbia were formed by eruption of basaltic magmas through Pleistocene glacial ice.

The flat-topped mountains are analogous to most Icelandic subglacial volcanoes in size, form, and construction. The exposed units, namely pillow basalts, sideromelane tuff, and caprock basalt flows, indicate that each eruption proceeded until the level of the surrounding englacial lake was surpassed. These mountains were subsequently covered by glacial ice, which eroded cirques and deposited erratic boulders. Minor eruptive activity followed the melting of the glaciers.

The lapilli cones represent an eruption style that is relatively uncommon in Iceland. These volcanoes were erupted in englacial lakes deep enough (several hundred meters) to cause the formation of basal pillow basalt layers. The bases of some cones are topped by units composed of vesicular sideromelane glass shards, indicative of explosive eruption near to the water surface. The uppermost units are formed of black vesicular lava. This material was also erupted within a meltwater lake, though water had only limited access to the rising magma. None of the lapilli cones has a caprock, either because none grew high enough to breach the water surface or because the upper portions were removed by erosion. Their distinctive compositions and morphologies appear to be due to relatively minor differences in the contributions of magmatic and phreatomagmatic eruption to the production of tuff and cinders.

**REMOVAL OF SUBGLACIALLY ERUPTED VOLCANIC EDIFICES BENEATH THE DIVIDE OF THE WEST ANTARCTIC ICE SHEET INTERPRETED FROM AEROMAGNETIC AND RADAR ICE SOUNDING.** J.C. Behrendt[1,3], D. D. Blankenship[2], C. Finn[3] and R.E. Bell[4]. [1]Institute of Arctic and Alpine Research University of Colorado Boulder, CO 80309-0450, USA (behrendj@stripe.colorado.edu), [2]University of Texas Institute of Geophysics Austin, TX 78759-8345, USA, [3]USGS, Denver, CO 80225, USA, [4]Lamont Doherty Earth Observatory Columbia University Palisades, N.Y. 10964, USA

The West Antarctic Ice Sheet (WAIS) flows through the West Antarctic rift system characterized by exposures of bimodal alkaline Neogene volcanic rocks. The 1800m high divide of the WAIS is underlain by the 400km long, volcanic, Sinuous Ridge, which rises well above sea level. A 1995-96 aeromagnetic and radar_ice_sounding survey over part of the Sinuous Ridge beneath the WAIS divide shows a 70km diameter circular pattern of 400-1200-nT anomalies, suggesting one of the largest caldera(?) complexes on earth. Radar-ice-sounding shows that the northern part of this pattern overlies the Sinuous Ridge and extends south over the Bentley Subglacial Trench; however comparison of the radar and magnetic maps shows only minimal correlation. Modeling shows that sources of the caldera anomalies and other anomalies over the Sinuous Ridge interpreted as caused by volcanic centers are at the base of <1-2km thick ice and that their volcanic edifices have been glacially removed. Modeled thicknesses of the magnetic sources vary from 2 to >6 km. The 300 to 500-nT background area surrounding the caldera is possibly caused by a shallow Curie isotherm. Within this negative anomaly area there is a 400-nT positive anomaly, northeast of the caldera pattern, correlated with the shallowest, most rugged bedrock topography in the surveyed area (+380 m). We interpret this volcanic edifice to comprise subaerially erupted flows at a time when the Sinuous Ridge area was deglaciated. We suggest uplift of the Sinuous Ridge forced the advance of the WAIS. The evidence of glacial removal of probable hyaloclastic volcanic edifices over the Sinuous Ridge area beneath the present WAIS divide indicates that this divide has not been stationary, but has migrated to its present position as snow accumulation has varied over time.

**SEARCHING FOR RECENT VOLCANISM IN THE VALLES MARINERIS, MARS.** R. A. Beyer 1 and A. S. McEwen 1 , 1 Lunar and Planetary Laboratory, the University of Arizona (1629 E. University Blvd. Tucson, AZ 85721-0092, rbeyer@lpl.arizona.edu).

Volcanic activity in the Valles Marineris that was concurrent with or postdates canyon formation has been pos-tulated, but not proven. Many dark patches of material with basaltic spectra have been supposed to be volcanic con-structs or recent flow features [1,2,3]. Additionally, one of the most attractive hypotheses for formation of the inte-rior layered deposits is that of subaqueous volcanic processes [4]. From these observations and the analogy to ter-restrial rifting centers, recent volcanic activity is expected to have occurred within the Valles Marineris. High-resolution images from the Mars Orbital Camera (MOC) have not revealed anything that is clearly a recent volcanic construct or feature in the Valles Marineris. Previous MOC coverage of the areas proposed as volcanic by the above authors has been sparse. However, the dark patches along the north wall of Coprates Chasma interpreted to be volcanic [1] are in fact just a series of dark dunes marching down a gully at the base of the wall. Now that more MOC data has been acquired, the coverage at high resolution (1.4 meters/pixel) of the Valles Marineris is greatly improved. Additionally, high-quality Mars Orbiter Laser Altimeter (MOLA) data for many of these images has been released as well. We will survey these data for volcanic features, especially in those areas suggested by previous authors as possible volcanic areas.

References: [1] Lucchitta, B. K. (1987) Science 235, 565-567. [2] Geissler P. E. et al (1990) JGR 95, 14,399-14,413. [3] Lucchitta, B. K. (1990) Icarus 86, 476-509. [4] Nedell, S. S. (1987) Icarus 70, 409-441.

**MINERAL IDENTIFICATION IN PALAGONITICALLY ALTERED VOLCANIC MATERIAL AS AN INDICATOR OF GEOCHEMICAL HISTORY.** Janice L. Bishop, SETI Institute, (jbishop@mail.arc.nasa.gov) NASA-Ames Research Center, MS-239-4, Moffett field, CA 94035.

Determining the mineralogy of the Martian surface material provides information about the past and present environments on Mars which are an integral aspect of whether or not Mars was suitable for the origin of life. Mineral identification on Mars will most likely be achieved through visible-infrared remote sensing in combination with other analyses on landed missions. Therefore, understanding the visible and infrared spectral properties of terrestrial samples formed via processes similar to those thought to have occurred on Mars is essential to this effort and will facilitate site selection for future geology and exobiology missions to Mars.

Altered tephra/ash samples have been studied from a variety of terrestrial environments including the high elevation, low-humidity conditions at the Haleakala summit basin on Maui [1]. Palagonitization is an important process in this environment. Mineralogical analyses of the palagonitically altered tephra/ash in Iceland are important for Mars as well in that the formation conditions in Iceland may be similar to alteration of volcanic material on Mars in ice-rich permafrost regions.

The volcanic alteration samples studied previously [1] exhibited a range of chemical and mineralogical compositions, where the primary minerals typically include plagioclase, pyroxene, hematite, and magnetite. The kind and abundance of weathering products varied substantially due to the environmental conditions. The degree of weathering of these tephra was evaluated by assessing changes in the leachable and immobile elements, and through detection of phyllosilicates and iron oxide/oxyhydroxide minerals.

Identifying regions on Mars where phyllosilicates and many kinds of iron oxides/oxyhydroxides are present would imply the presence of water during alteration of the surface material. Tephra samples altered in the vicinity of cinder cones and steam vents contain higher abundances of phyllosilicates, iron oxides, and sulfates and may be interesting sites for exobiology.

**References:** [1] Bishop J. L. et al. (1998) JGR , *103*, 31457-31476.

**HYDROLOGY OF ICE CAPS IN VOLCANIC REGIONS**. Helgi Björnsson, Science Institute, University of Iceland, Hofsvallagata 53, 107 Reykjavík, Iceland.

Water plays an important role in glacier-volcano interactions. Its presence and production before and during volcanic eruptions determines the exchange of thermal energy, the types of volcanic products created.

In general, subglacial drainage systems are controlled by the thermal conditions, the composition and topography of the substratum, the thickness and slope of the overburden ice, and the water supply. Theoretical analyses and field observations suggest the existence of two main types of subglacial drainage systems. In the first type, water is conducted through a river-like system of widely spaced tunnels. In the second type of system, water is dispersed across the bed through a distributed network of passageways. Thirdly, water may accumulate in subglacial lakes under depressions created at geothermal and volcanic areas. The relatively low basal pressure potential under depression causes meltwater to accumulate in subglacial lakes which grow in size until they become unstable and burst out in jökulhlaups.

Volcanic eruptions are a violent disturbance of the normal hydrological conditions in glaciers, but the course of events following the eruption is none the less dependent on the initial state of the system prior to the eruption. The volcanic regions of Iceland form a suitable natural laboratory for a study of the interaction of glacial and volcanic phenomena. Examples are discussed and models described of glaciological and hydrological effecs of the geothermal and volcanic activity in Vatnajökull.

**MARTIAN ANALOGS OF TERRESTRIAL SUB-ICE VOLCANOES SUPPORT ANCIENT OCEAN.** M. G. Chapman[1], [1]U.S. Geological Survey, 2255 N. Gemini Drive, Flagstaff, AZ 86001, USA, mchapman@usgs.gov.

Mars Orbiter Laser Altimeter (MOLA) data are consistent with hypotheses that suggest large standing bodies of water in the northern lowlands in the past history of Mars [1]. Because an equipotential surface with a mean elevation of –3760 ± 560 m [1] closely matches a mapped shoreline [2]. However, all Mars Orbiter Camera (MOC) images acquired to test these hypotheses have provided negative or ambiguous results [3]. Perhaps the sought-after shoreline features (e.g. wave cut terraces, spits and bars) are not well developed in likely Martian transient pondings of water- or ice- dominated coasts [4,5]. In the absence of classic coastal features to test the paleo-ocean hypothesis, the heights of submarine tuyas and hyaloclastic ridges may be used as rough estimates for ice thickness. Some Martian geomorphic features have been interpreted to be analogous to terrestrial tuyas and hyaloclastic ridges. For example, northwest of Elysium Mons, Early Amazonian landforms interpreted to be hyaloclastic ridges occur on the flanks of the volcano [6]. A preliminary study of MOLA data show that 3 of those ridges are about 150 m high, reaching an elevation of -3778. The 3 ridges appear to be piles of submarine hyaloclastites without caps of subaerial lava. A minimum ice height of –3778 is well within the standard deviation of the MOLA equipotential surface and supports a northern ocean filled to a depth of 1490 m.

**References:** [1] Head et al., 1999, Science 286, 2134-2137. [2] Parker et al. 1989, Icarus 82, 111-145. [3] Edgett and Malin, 2000, LPSC 31th CD, #1054. [4] Baker, et al., 2000, LPSC 31th CD, #1863. [5] Rice, 2000, LPSC 31th CD, #2067. [6] Chapman, 1994, Icarus 109, 393-406, 1994.

**POSSIBLE TUYA ORIGIN OF INTERIOR LAYERED DEPOSITS IN VALLES MARINERIS, MARS.** M. G. Chapman[1] and K. L. Tanaka[2], [1]U.S. Geological Survey, 2255 N. Gemini Drive, Flagstaff, AZ 86001, USA, (mchapman@usgs.gov, ktanaka@usgs.gov).

Viking Orbiter and Mars Orbiter Camera images show mesas having horizontal to angled layers in many Valles Marineris chasmata. Several chasmata are filled nearly to the plateau rim with Late Hesperian to Early Amazonian [1] interior deposits, many of which are separated from the chasmata walls by a moat. A lacustrine origin was suggested because of their apparent horizontal continuity and similarity in connected troughs [2,3,4,5,6,7]. Others prefer a volcanic origin based on the volcano-tectonic setting, layer diversity, low albedo and high competence of some layers, tuff-like weathering, and location of dark materials [1,4,8,9]. The interior deposits of Gangis and Juventae Chasmata were suggested to be similar to the ideal tuya form (table-like) [10] and eroded flutes and variable albedo of Hebes Chasma deposits bear an uncanny resemblance to tuyas [11]. We note that Mars Orbiter Laser Altimeter data show interior deposits that locally (1) reach 4-km in height, (2) rise above sections of plateau, and (3) in the case of Hebes, have the distinctive tuya form. Their morphologies include local resistant caps [12], ridged forms, and possible deltas. Based on the dimensions, morphologies, and associated catastrophic floods and other geologic events (glacial, tectonic, and mass flows) we support the suggestion that the interior deposits are hyaloclastic ridges and tuyas.

**References:** [1] Witbeck et al., 1991 USGS Map I-2010. [2] McCauley, 1978 USGS Map I-897. [3] Carr, 1981 Yale Univ. Press, New Haven, 232 pp. [4] Peterson, 1981, Proc. LPSC 12th, 1459-1471 [5] Lucchitta, 1982, NASA TM 85127, 233-234. [6] Nedell, 1987, *Icarus* 70, 409-441. [7] Weitz and Parker, 2000, LPSC 31th CD, # 1693. [8] Lucchitta, 1990, *Icarus* 86, 476-509. [9] Weitz, 1999, LPSC 30th CD, # 1279. [10] Lucchitta et al. 1994, *JGR* 99, 3783-3798. [11] Croft 1990, NASA TM 4210, 539-541. [12] Lucchitta, B.K., 1999, USGS Map I-2568.

**SATELLITE-BASED ANALYSES OF ERUPTING ICE-CAPPED VOLCANOES IN ALASKA: VENIAMINOF AND WESTDAHL.** K.G. Dean[1], K.R. Engle[2] and J. Dehn[3] Geophysical Institute, University of Alaska Fairbanks, P.O.Box 757320, Fairbanks, Alaska 99775-7320; ken.dean@gi.alaksa.edu [1], kevin.engle@gi.alaska.edu [2], jdehn@gi.alaska.edu [3]

Satellite data and field observations were used to analyze physical changes on two recently active, ice capped volcanoes in Alaska, Westdahl and Veniaminof.

Westdahl Volcano, 1200 km southwest of Anchorage, erupted in 1978 and in 1991/92. In 1978, an explosive eruption formed a crater 500 m deep through glacial ice. Plumes and a lahar were observed. Seasat, a Synthetic Aperture Radar (SAR) satellite imaged the crater and three reflecting surfaces, radiating 3 km from the vent. The 1991/92 eruption resulted in a 8-km-fissure in the ice cap and was the source of ash and steam emissions, lava fountaining and lava flows. This eruption was recorded on Advanced Very High Resolution Radiometer (AVHRR) and SAR satellite data. The AVHRR data showed plumes and elevated surface temperatures related to the lava flow and fountaining. SAR data showed the fissure, melting ice, the new lava flow, the snow-filled 1978 crater, and older flows and cones. The 1991/92 and 1978 vents were offset by approximately 2 km.

Veniaminof Volcano, 500 southwest of Anchorage, erupted in 1993 from a cone within the 10 km wide, ice filled caldera. Lava flows melted an ice pit adjacent to the cone that had also been active in 1984 eruption. AVHRR data detected elevated surface temperatures related to the lava flow and steam and ash plumes. SAR data recorded the melt pit and variations in the surface properties of the snow cover likely related to an ash fall.

At these two volcanoes, AVHRR, and SAR data record surface volcanic processes and the interaction between volcanoes and ice caps that complement ground and aerial observations. Time sequential SAR data showed variations in source vents, eruption styles and long-term effects of snow burial on landform detection and seasonal changes at the volcano. Multi-temporal SAR data were combined forming color composite images to study environmental effects.

**POSSIBLE LINKAGE BETWEEN LAHARIC EVENTS AND GLACIER ICE MELTING AT POPOCATEPETL VOLCANO, MEXICO.** H. Delgado, A. E. González -Huesca, and B. Oropeza-Villalobos, Instituto de Geofísica, UNAM, Circuito Exterior, C. U., Coyoacán 04510, México, D. F. (hugo@tonatiuh.igeofcu.unam.mx)

**Introduction:** The laharic event at Nevado del Ruiz (Colombia) in 1985 is one of the best known examples of eruptive forcing of lahars at glacier-clad volcanoes. In this case, pyroclastic flows produced melting of snow and glacier ice triggering the lahar. In the case of Icelandic jökuhlhaups subglacial eruptive activity (i. e. subglacial injection lava flows) produce glacier-ice melting at its base supplying the water needed to trigger laharic events. Small-scale jökuhlhaups are less known. They may occur at high-altitude glaciers where runoff immediately mobilizes debris on steep slopes to form small- to medium- size lahars.

**Recent lahars at Popocatépetl volcano:** In spite of the presence of unconsolidated ashes on the slopes of the volcano and the heavy rainfall in recent years, important debris and/or hyper-concentrated flows have not occurred to present in connection with the current eruptive activity. On the other hand, Ventorrillo glacier (<0.2 $km^3$) is nested on the northern flank of Popocatépetl volcano, the size and regime of this hanging, retreating ice body has been strongly affected by the eruption of the volcano. The ice mass has been repeatedly covered by ashes and hit by incandescent bombs. However, none of these volcanics have produced laharic events. Most lahars at Popocatépetl have occurred during the ablation season in the summer, when extensive ice melting occurs all over the glacier. Nonetheless, these lahars are mainly hyper-concentrated flows with ranges of less than 4 km from the source. In May-June 1997 and again in May this year moderate- size laharic events have occurred almost reaching Santiago Xalitzintla, the nearest town to the volcano. In these cases, the lahars have consisted of non-cohesive debris flows. We present evidences that may establish a linkage between the laharic events and subglacial melting.

**VOLATILES IN BASALTIC GLASSES FROM A SUBGLACIAL VOLCANO IN NORTHERN BRITISH COLUMBIA: IMPLICATIONS FOR MANTLE VOLATILES AND ICE SHEET THICKNESS.** J. E. Dixon[1], J. Filiberto[1], J. M. Moore[2], and C. J. Hickson[3], [1]RSMAS/MGG, University of Miami, 4600 Rickenbacker Cswy, Miami, FL 33149-1098, jdixon@rsmas.miami.edu, [2]U.S.G.S., MS-910, 345 Middlefield Road, Menlo Park, CA 94025), [3]Geological Survey of Canada, 101-605 Robson Street, Vancouver, British Columbia, V6B 5J3.

We measured dissolved water and carbon dioxide concentrations in glasses from Tanzilla Mtn., an exposed subglacial volcano from the Tuya region, north central British Columbia. Tuya formation begins with non-explosive eruptions of pillow basalt and interpillow hyaloclastites. As the volcano grows, the ice/water depth progressively decreases until the overlying ice melts through to form a lake. The eruption then changes to phreatic or explosive resulting in layers of glassy tephra on top of the pillows. If the eruption continues, crater walls build up above the water level and subaerial lava flows cap the sequence. Based on S analyses, Tanzilla is the least degassed of the 8 tuyas studied and did not reach the subaerial phase. Dissolved water (0.49-0.92 wt%) and carbon dioxide (0-72 ppm) are similar to those observed in shallow oceanic islands, such as Loihi. Vapor saturation pressures calculated from dissolved water and carbon dioxide contents range from 35 to 200 bars with glasses collected at the base of the tuya yielding the highest estimated equilibration pressure. A pressure of 200 bars corresponds to an ice thickness of ~2 (±~0.5) km overlying the nascent Tanzilla tuya, consistent with Cordilleran ice thickness predicted by the ICE-4G model. Water concentrations correlate positively with other incompatible elements, such as P2O5. The Tanzilla data overlap data from other Pacific seamounts (e.g., Loihi) and enriched-MORB implying that metasomatic enrichment of the mantle source regions for the tuyas involved a melt and not a hydrous fluid phase.

**SUBGLACIAL EVOLUTION OF HOODOO MOUNTAIN VOLCANO, NORTHWESTERN BRITISH COLUMBIA, CANADA.** B.R. Edwards[2] and J.K. Russell[2], [1]Dept. of Geology, Grand Valley State University, 1 Campus Drive, Allendale, MI 49401-9403, edwardsb@gvsu.edu, [2]Igneous Petrology Laboratory, Dept. Earth and Ocean Sciences, University of British Columbia, 6339 Stores Road, Vancouver, B.C. V6T 1Z4, russell@perseus.geology.ubc.ca.

Hoodoo Mountain is a trachytic/phonolitic volcano located in northwestern British Columbia, ~ 100 km south of Mount Edziza, and ~300 km southeast of Mount Edgecumbe, Alaska. It is one of the largest peralkaline subglacial volcanoes in Canada, which is second only to Iceland and Antarctica in numbers of subglacial volcanic deposits. The evolution of Hoodoo Mountain is dominated by eruptions that were partly to entirely subglacial. The initial stages of eruption (at ~80 ka; [1]) generated thick, trachytic lava flows covered by deposits of monolithologic breccia, interpreted as hyaloclastite. The flows (units Qvap1,2) were eventually blocked by valley glaciers and form cliffs up to 210 m high around the volcano. These flows and breccias account for the lowermost 1/2 of the edifice. Between 80 and 54 ka [1], a thick sequence of pyroclastic debris erupted. The resultant poorly to strongly welded pyroclastic deposits are grouped stratigraphically into one unit (Qvpy). The explosive eruptions responsible for the formation of these deposits may have been in part subglacial or hydroclastic. Unit Qvpy is overlain by a series of apparently subaerial lava flows at ~54 ka (unit Qvap4 [1]). Subsequent eruptions formed a thick sequence of subglacial lava flows and hyaloclastite (unit Qvap5). This upper section of subglacial lava flows forms the bulk of the upper 1/4 of the volcano and comprises a variety of morphologic deposits, including large, lava lobes that are enclosed by hyaloclastite. Unit Qvap6 resulted from emplacement of dikes through Qvap5 into the overlying ice at 40-30 ka [1]. The most recent activity at Hoodoo Mountain (9-7 ka [1]) comprises highly porphyritic, phonolite/trachyte, subaerial lava flows (Qvpp). The present summit of the volcano (1800 m) is covered by a small icecap, which is ~ 3 km in diameter.

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**FORMATION OF PSEUDOCRATERS ON EARTH AND MARS.** S. A. Fagents[1] and R. Greeley[1], [1]Department of Geology, Arizona State University, Tempe, AZ 85287-1404; fagents@asu.edu.

The Mars Orbiter Camera has provided high-resolution views of candidate pseudocraters (rootless volcanic cones) in Amazonis and Elysium Planitia, and in the Isidis basin. Similar structures had previously been proposed for Mars based on Viking data [1]. Icelandic analogs are interpreted to form when lava flows over a saturated substrate [2]. Pressurization of water vapor overcomes the confining pressure due to the weight and strength of the overlying lava, and an explosion excavates the flow. Lava fragments ejected by repeated cycles of vaporization and pressurization eventually form a cone structure. In the martian case, melting and vaporization of crustal ice stores might lead to a similar process.

In order to understand pseudocrater explosion conditions and volatile requirements, we have characterized the morphology of Icelandic and martian examples to use as constraints on a model of the excavation process. Cones in the Landbrot and Alftaver districts of Iceland have modal diameters of ~20 m. By comparison, the cones in Amazonis Planitia average 100 m in diameter.

Results from modeling the explosion dynamics indicate that differences in gravity and atmospheric pressure explain the difference between Icelandic and martian cone sizes, and easily compensate for the potentially lower availability of $H_2O$ in the martian regolith. For example, to excavate a 5 m thick flow and eject material to the typical 20-m Icelandic cone size requires ~700-2000 kg of superheated vapor. A typical 100-m martian cone requires only 160-360 kg. Identification of further candidate pseudocraters will help to constrain the distribution and amount of crustal $H_2O$ on Mars.

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**EXPLORING FOR EVIDENCE OF EXTANT MARTIAN LIFE IN POLAR ICE DEPOSITS.**
Jack D. Farmer (jfarmer@asu.edu), Department of Geology, Arizona State University, Tempe, AZ 85287-1404

The exploration for extant Martian life has not received much emphasis in the current Mars exploration program, because of the perceived need to access the deep (multiple km) subsurface where habitable zones of liquid water may exist (Clifford 1993). It is generally assumed that such deep drilling can not be accomplished robotically and will require humans.

However, it is generally conceded that liquid water oases might also exist locally in the shallow Martian subsurface where upwelling hydrothermal systems (developed above magmatic intrusions) would allow warm, convecting water to reach the surface. In addition, models suggest that zones of basal melting could exist within the beneath the North polar ice cap of Mars (Clifford 1987), providing long-lived aqueous habitats for life. Subglacial volcanic eruptions may have periodically released such melt water along the margins of glaciers carrying along a subsurface biota (or prebiotic chemistry) and sequestering it in near-surface ground ice (Farmer and Des Marais 1999).

The growing data base of high resolution images from MOC, along with high spatial resolution thermal imaging from the THEMIS experiment to be flown in 2001, could eventually provide a basis for identifying high latitude sites where water has been recently brought to the surface either by regional hydrological processes, or by localized magma-cryosphere interactions. Spatially-restricted anomalies in temperature and/or atmospheric volatiles (e.g. water vapor, reduced gases such as methane, etc.) could be used to pinpoint the locations of near-surface hydrothermal systems and orbital sounding could locate zones of basal melting within polar caps or ground ice deposits formed by outfloods of subsurface water along polar margins. Landed missions targeted to such sites could provide robotic access to an extant subsurface biota and organic chemistry cryopreserved in ground ice.

**BIO-ALTERATION OF BASALTIC GLASS IN THE OCEANIC CRUST.** Harald Furnes[1], [1].Geological Institute, University of Bergen, Allegaten 41, 5007 Bergen, Norway, Harald.Furnes@geol.uib.no

Bio-alteration of Quaternary to Early Cretaceous basaltic glass from pillow lavas of the upper oceanic crust, can be documented in DSDP/ODP samples from shallow to deep drill holes from the north to central Atlantic Ocean, Lau Basin and Costa Rica Rift. Bio-generated textures are rooted in fractures and appear as individual and/or coalesced spherical bodies, mostly 1-3 microns in diameter. Tubular or branching bodies, mostly 20-30 microns long, also occur, and are more common at deeper levels. The degree of bio-alteration shows large within- and between-section variations, related to depth (and temperature), fracture density of the glass, and the age of the crust. Within sections the degree of bio-alteration generally increases from the top of the volcanic basement downwards, reaches maximum values of c. 27 - 28% of the total glass at depths of about 50-300 m, and thereafter decreases. The degree of abiotic alteration generally increases downwards. Bio-alteration starts at the constructional stage of the crust, but is most effective at the near-axis, hydrothermal stage, when effective cooling, due to high water flux through the rocks, creates the most favourable environment for microbes at the deepest levels within volcanic sequences. During later stages fractures become progressively sealed with authigenic minerals and bio-alteration slows down.

**THE INTERPLAY BETWEEN ICE THICKNESS, WATER PRESSURE AND ERUPTION STYLE IN SUBGLACIAL ERUPTIONS. EFFECTS OF ICE SUBSIDENCE, DEFORMATION AND MELTWATER DRAINAGE** M.T. Gudmundsson, Science Institute, University of Iceland, Hofsvallagata 53, 107 Reykjavik, Iceland (mtg@hi.is)

In most cases water at the bed of temperate glaciers is driven towards the glacier edge. It flows down the gradient of the water-flow potential which is mainly controlled by the ice surface slope. Water accumulation rarely occurs except where basal melting at active geothermal areas has created surface depressions [1]. Thus, in most cases meltwater will drain from an eruption site, leading to formation of cauldrons in the ice surface. Cauldrons were observed in Gjálp in 1996, subsiding at a rate of ~100 m/day. To explore the conditions within a cauldron we consider the force balance on a subsiding central block. The three forces acting are: 1) Force of gravity, i.e. the weight of the subsiding central block, 2) buoyancy force exerted by the pressure of water beneath the block, and 3) a shear force acting on the sides of the block, opposing the ice deformation. Forces 2) and 3) act upwards and together they are equal and opposite to force 1). The shear force appears of comparable size to the buoyancy, implying that water pressure beneath the central block is considerably less than the weight of the overlying ice, and much less than the ice overburden pressure surrounding the depression. Rate of water drainage away from a cauldron, along a subglacial tunnel, is dependent on the temperature of the meltwater [2, 3]. For conditions and water temperatures inferred at Gjálp, T =15-20°C [4], tunnel wall melting rate and the creep closure rate will be in balance when water pressure is 20-30 bars below the ice overburden pressure. This suggests that during subglacial eruptions, drainage tunnels will be enlarged until the water pressure within a cauldron becomes much less than the surrounding ice overburden pressure. This low water pressure may be a major factor in causing early fragmentation of magma under thick ice during subglacial eruptions.

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**GLACIAL/INTERGLACIAL MAGMA PRODUCTION RATES IN THE THINGVELLIR-LANGJÖKULL AREA, SW-ICELAND.** M.T. Gudmundsson[1], S.P. Jakobsson[2] and Th. Högnadóttir[1], [1] Science Institute, University of Iceland, Hofsvallagata 53, 107 Reykjavík, Iceland [2] Icelandic Institute of Natural History, Hlemmur 3, 105 Reykjavík Iceland

The Western Volcanic Zone between lake Thingvallavatn and the Langjökull ice cap is characterised by hyaloclastite ridges, tuyas, and postglacial and interglacial lavas. Many of the ridges and tuyas are partly buried by Holocene and possibly interglacial lavas. In order to study rates of production of Holocene and interglacial lavas on the one hand and subglacially formed hyaloclastite mountains on the other, a gravity survey has been carried out covering an area of about 1000 $km^2$. Several profiles traversing lava fields, ridges and tuyas were measured. The density contrast between subaerially erupted lavas and subglacially formed tuffs and pillow lavas is used as a basis for modelling the thickness of lava fields in which the hyaloclastite mountains are buried. Buried ridges and tuyas may be located and the true size estimated. The gravity modelling is tied to detailed geological mapping with chemical analyses being used to identify individual eruption units.

The results obtained so far suggest that several of the hyaloclastite ridges and tuyas are deeply buried, in places the lava pile is 200-300 m thick. Thus, these mountains are much larger than previously thought. As suggested earlier [1], the large lava shield of Skjaldbreidur conceals a large hyaloclastite mountain. When the total volume of hyaloclastites and lava is compared, it appears that total magma production during the Holocene and interglacials has been similar or greater than during the glacials. In the absence of absolute ages, we have only considered the least eroded pre-Holocene formations, believed to from the Weichselian and Saale glacials and the Eem interglacial. Considering the much shorter duration of the interlacials, these results suggest that the magma production rate in the area during the Saale and Weichselian glacial periods was roughly an order of magnitude less than during the Eem interglacial and the Holocene.

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**THE HYALOCLASTITE RIDGE FORMED IN THE SUBGLACIAL ERUPTION AT GJÁLP, ICELAND IN 1996**. M.T. Gudmundsson, F. Pálsson, H. Björnsson and Th. Högnadóttir. Science Institute, University of Iceland (Hofsvallagata 53, 107 Reykjavík, Iceland mtg@raunvis.hi.is, fp@raunvis.hi.is, hb@raunvis.hi.is, disah@raunvis.hi.is)

The eruption at Gjálp in Vatnajökull in October 1996 allowed several aspects of subglacial volcanism to be observed. Data on heat transfer rates, ice cap response, eruption mechanisms and effects on subglacial hydrology were obtained [1]. The ice thickness along the 6 km long fissure varied from 500 m to 750 m. Meltwater flowed southwards along the fissure for the duration of the eruption. Direct observations of the top of the edifice could be done in June 1997 while the form of hyaloclastite ridge was studied with radio echo soundings in 1997 and 1998, and with gravity measurements in 1998-2000. The edifice formed in the eruption is remarkably varied in shape and height. The central part, where the subaerial crater was located, is the highest, rising 500 m above the pre-eruption subglacial bedrock. In the northern part, where ice thickness was greatest, the ridge is only 150 m high but up to 2 km wide. Lateral spreading of the erupted material must have occurred at this place during the latter stages of the eruption. In the southern part, where subglacial eruption was vigorous during the first 24 hours, the edifice is low and narrow. It is likely that a large part of the material erupted at this place was transported with the meltwater into Grímsvötn. The volume of the edifice is 0.6-0.7 $km^3$. Geophysical surveying within the Grímsvötn caldera shows that deltas of volume 0.07 $km^3$ formed during the eruption, constituting about one tenth of the total volume of erupted material. It seems that variations in hydrological conditions along the fissure are the main reason for the differences in edifice form and preservation. Relatively high water pressure was probably maintained in the northern part, with the subaerially erupting crater in the center impeding flow of water southwards.

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**THE ROLE OF VOLCANO/MAGMA H2O INTERACTIONS IN VALLEY AND CHANNEL FORMATION ON MARS.** Virginia C. Gulick, Mail Stop 239-20, Space Science Division, NASA Ames Research Center, Moffett Field, CA 94035, vgulick@mail.arc.nasa.gov.

Magma interactions with groundwater and groundice likely played a critical role in the formation of fluvial landforms on Mars. Catastrophic floods responsible for carving the outflow channels issued from the subsurface in areas of ground collapse and from large fractures. The catastrophic release of groundwater may have been triggered by the build up of magmatic gases in the subsurface and/or an increase in hydraulic pressure associated with large-scale magmatic hydrothermal systems from the Tharsis volcanism [1,2,3]. $CO_2$ and other gases likely migrated from the cooling magma over time and dissolved into the surrounding groundwater. An overlying ice-rich permafrost would have allowed the dissolved magmatic gases to accumulate over time. Upwardly flowing hydrothermal waters carried sufficient thermal energy to the base of the overlying ice to thin it and this may have created an instability that led to the break up of the overlying confining layer. Viking topographic and MGS MOLA data indicate that the outflow channels are located in low regions adjacent to the Tharsis volcanic region, where hydraulic pressures would have been greatest.

Volcano/magma ground $H_2O$ interactions were likely also important in the formation of many fluvial valleys on Mars particularly on the volcanoes [4]. Other likely sites of such interaction are where fluvial valleys formed in association with magmatic intrusions (e.g., Warrego valles), as well as very young fluvial valleys that apparently formed from melt water released from the distal portions of lava flows (e.g. Mangala Valles region, [5]). While Mars Global Surveyor images have supported evidence for fluvial processes, in most cases the high-resolution views provide little evidence for widespread erosion or greater dissection of interfluve regions and therefore little indication of more clement climatic conditions in the past. However, stream channel segments have been identified in both Viking and MGS images [6].

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**MARS: GEOLOGIC SETTING OF MAGMA $H_2O$ INTERACTIONS.** J. W. Head[1] and L. Wilson[1,2], [1]Geological Sciences, Brown University, Providence, RI 02912, James_Head_III@brown.edu; [2]Environmental Science, Lancaster University, Lancaster, LA1 4YQ, UK.

The geological context for ascent and eruption of magma shows that a wide range of eruption conditions and deposits are likely [1]. A very important subset is the interaction of intrusions and extrusions (e.g., plumes, plutons, dikes, sills, flows, pyroclastic eruptions) with ground water, cryosphere/ground ice, surface standing water, surface frozen water (snow, glaciers, polar deposits). 1) Plutons: A 30 km diameter pluton intruded to a typical neutral buoyancy depth should have its top at about 6 km depth, and will initially increase heat flow and decrease cryosphere thickness by a factor of ~10; this could melt the base of thick ice rich deposits such as those presently at the poles. Unless resupplied, the pluton will cool significantly in only a few Ma. Thus, significantly shallower or larger plutons would be required to melt the cryosphere. 2) Dikes: The vertical and lateral emplacement of magma filled cracks (dikes) provides much more efficient heat transfer to the cryosphere. Dike intrusions to shallow depth can create a near-surface stress field resulting in faulting of the cryosphere and large-scale release of groundwater (e.g., Mangala Valles). Dikes intruding into the cryosphere will cause local melting, and incorporation of ground water and melted ground ice into magma, to produce lahars, explosive eruptions and widening of the vent system (e.g. Elysium channels). 3) Sills: The presence of a low density cryosphere can enhance density contrasts in the shallow crust and favor intrusion of sills, which are extremely efficient in melting near-surface ice and releasing groundwater. Our calculations show that sill intrusion provides plausible models for several outflow channels.

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**RELATIONS OF SURFACE WATER, ICE AND VOLCANISM ON MARS.** J. W. Head, Brown University, Dept. of Geological Sciences, Providence, RI 02912, James_Head_III@brown.edu.

**Introduction:** Water has occurred in a variety of environments on Mars in solid and liquid states, and interacted with the ascent and eruption of magma in a host of different ways. Mars Orbiter Laser Altimeter (MOLA) data are providing detailed documentation of present polar ice deposits, past polar volatile-rich deposits, deposits from possible ancient standing bodies of water perhaps even at the oceanic scale, outflow channel timing and extent, and evidence for ground water reservoirs. MOLA data are also revealing the topography of volcanic edifices and deposits in a much more quantitative way. Quantitative measurements of flows, surface manifestations of dikes, regional slopes, and morphometry of edifices, together with improved topographic information revealing stratigraphic relationships, are greatly improving our knowledge of volcanology. Together, these data reveal a much more comprehensive picture of the ways in which ascending magma interacts with water and ice throughout the history of Mars. Examples of new data showing edifices and deposits representing volcano/ice interactions include the north and south polar regions, dikes radial to Tharsis and Elysium, edifices, and regional plains deposits. Important are the implications of magma-water interactions for the production of fine-grained sedimentary material and deposits in martian history.

**THE TINDASKAGI HYALOCLASTITE RIDGE, SW ICELAND.** Herdis H. Schopka, Jakob Th. Gudbjartsson and Sveinn P. Jakobsson, Icelandic Institute of Natural History, P. O. Box 5320, 125 Reykjavík, Iceland

Tindaskagi, an 8 km long basaltic hyaloclastite ridge in southwest Iceland, was apparantly constructed by subglacial volcanic activity during the Upper Pleistocene (0.01-0.78 Ma). It lies in the Western Volcanic Zone and has been partly buried by Holocene lavas.

The primary object of our study was to reconstruct by structural and lithofacies analysis the main stages of the volcano's history of formation. We mapped the principal facies of the volcano and used the data to make inferences about the eruption sequence, the eruption centers and the general environment of the volcanic and sedimentary facies.

Tindaskagi is primarily made up of hyaloclastites, vitroclastic sediments of short transport and subaerial lavas. The bulk of the hyaloclastites was formed by subglacial phreatomagmatic eruptions. The sedimentary sequences appear to have been deposited mainly in flowing water, both during and after the eruptions. Irregular, small basaltic intrusions are numerous, some with apophyses that can be traced into lenses of pillow lava. No true basal pillow lava could be located, which is in agreement with recent geophysical studies, indicating that the exposed part of Tindaskagi is the top of a much larger structure. Only minor hydrothermal alteration of the hyaloclastites was observed. Two separate environments could be determined in which basaltic glass was altered to palagonite, a steam-dominated system close to the eruption centers and a water-dominated system within the sedimentary sequences.

We conclude that Tindaskagi probably consists of two main structural units, separated by sediments, a northern and a southern unit. Sediments from the northern unit overlie the southern unit, indicating that they were not formed in the same eruption event. This may even mean that the mountain was not formed during just one stadial but that the ice sheet grew and waned several times while the volcano was being built up by numerous eruptions. Our investigations suggest that the glacier around Tindaskagi was approximately 600-700 m thick when it was constructed.

**SUB-GLACIAL ERUPTIONS IN SIERRA MADRE ORIENTAL, MEXICO** A. Höskuldsson, South Iceland Institute of Natural History, Strandvegur 50, 900 Vestmannaeyjar, Iceland (arm@eyjar.is).

The Trans Mexican Volcanic Belt crosses Mexico from the Pacific to the Gulf of Mexico. The easternmost part of the TMVB is dotted by a north-south lying volcanic chain made up of the volcanoes Cofre de Perote, La Gloria, Cerro las Cumbres and Pico de Orizaba-Sierra Negra volcanic complex. During the last glacial maximum, ice caps covering these volcanoes did reach down to the altitude of some 3000 meters, the Altiplano being at the altitude of 2500 meters. The summits of the volcanoes are at the altitude of 4000 to 6000 meters, the highest being the volcano Pico de Orizaba. Currently only Pico de Orizaba is covered by a permanent ice cap. Field studies within the volcanic chain have positively identified at least two major sub-glacial volcanic eruptions at the volcanoes of Cerro las Cumbres and Pico de Orizaba.

The volcanic products in both eruptions are highly fragmented, indicating a water magma reaction during the eruption. The most spectacular observation in the LC eruption is the distribution of the deposits. The bulk of the deposits are observed below the altitude of 3000 m and then within the caldera. The area between 3000 m altitude and the caldera rim is believed to be deposits free since it was covered by an ice cap at the time of the eruption. Similar distribution of deposits has been observed in relation to the large Z1 eruption in Myrdalsjökull, Iceland.

The eruption of Cerro Colorado formed a tuff cone at the altitude of some 4000 m in the SW slopes of Pico de Orizaba. Today the cone has been extensively eroded by glaciers, deduced from glacial scours on, and in the surroundings of its remains. The tuff is fully palagonitized. Fine stratification of the tuff shows a repetition of airfall and surge like deposits.

## JÖKULHLAUPS AND RAPID DEPRESSURIZATION OF PILLOW BASALTS

A. Höskuldsson[1], M. Carroll[2] and RSJ Sparks[3]. [1]South Iceland Institute of Natural History, Strandvegur 50, 900 Iceland. [2]Dipt. di Scienze della Terra, Via Gentile III da Varano, Universita' di Camerino, 62032 Camerino, Italy. [3]University of Bristol, Wills Memorial Bld. Queens_road, BS1_8RJ, Bristol UK.

In this presentation we report results from analysis of pillow basalt formations in Kverkfjöll, NE-Iceland. These formations record the eruption under glacial conditions. Confining pressure influences degassing of the magma and degassing is further limited by the actual amount of volatiles in the magma prior to eruption. The outer crust of the pillows consists of well-formed basaltic glass with thickness ranging from 7 cm to 0.1 cm. The joints do not penetrate into the vesiculated cores of the pillows. The pillows are slightly flattened. Measurements indicate that the pillows in Virkisfell are in general larger than those that have been previously described from southern Iceland. Vesiculation in the pillows is present from the rim to the core. The glassy sideromelane rim shows vesicularity of 10-20%. When reaching the core of the pillow vesicularity increases drastically. About 79% of pillows measured in Virkisfell contained a vesiculated core. Vesicularity of the cores was measured as low as 40% and as high as 60% with an average of 49±5%. Vesicles in the cores are spherical in shape and in general larger than vesicles observed in the sideromelane rim. The FTIR measurements were carried out to determine the amount of water in the glassy rim of Mount Virkisfell. For the Virkisfell pillow margins the average wt% $H_2O$ content is 0.89±0.03. Infrared measurements of glassy pillow rim material showed no $CO_2$ above the detection limit (<30 ppm). We calculate the following pressures from the measured $H_2O$ contents of glassy pillow rims with no $CO_2$ and with 30 ppm $CO_2$: Virkisfell 78±6 to 133±4 bars. This indicates that Virkisfell erupted under an ice sheet 863±67 to 1481±45 m thick. We can estimate the drop in water level during depressurization from the initial pressure estimate of 78 to 133 bars. This represents about 29 to 44 bar depressurization or a drop in the water table of 290 to 440 m.

**SUBGLACIAL VOLCANISM IN THE LANGJÖKULL REGION, THE WESTERN VOLCANIC ZONE, ICELAND.** S. P. Jakobsson, Icelandic Institute of Natural History, P. O. Box 5320, 125 Reykjavík, Iceland

About 220 Upper Pleistocene (0.01-0.78 Ma), subglacial, basaltic volcanoes have been identified by reconnaissance mapping in the Langjökull Region, the northernmost part of the Western Volcanic Zone in Iceland. These volcanoes are often of complicated structure, but most of them are considered to be monogenetic. Three main eruption phases can be distinguished, pillow lava, hyaloclastites and subaerial lava. Compositionally the eruption products are olivine tholeiites or tholeiites.

Basal pillow lava was tentatively identified in 32 cases but may be present in many more volcanoes, although not exposed. Hyaloclastites (hyalotuffs) are found in all but twelve volcanoes and can be subdivided into two main types, (1) a poorly bedded, unsorted hyaloclastite that probably was quenched and rapidly accumulated below water level without penetrating the surface, and (2) a more fine grained, layered hyaloclastite, formed by phreatomagmatic eruptions at shallow water depths and deposited by air fall on land, ice, or in shallow water. Subaerial lavas, either sheet flows or simple massive flows, cap 64 of the volcanoes. The depth of transition between basal pillow lava and hyaloclastite is difficult to determine because of poor exposures, but may generally be of the order of ≥200 m.

The volcanoes divide into two morphological types, ridges and tuyas. The ridges, which measure up to 16 km in length and 1.3 km in width, clearly erupted from fissures. Lava caps 19% of the ridges thus calling for a modification of the definition of subglacial ridges. The main part of most tuyas appears to have erupted from one crater, although it seems likely that they all initially erupted from fissures, albeit short. Most of the tuyas are capped by lavas. The largest volcano is the monogenetic tuya Eiriksjökull, which is 11 x 7 km2 in area and has a volume of about 50 km3. It is therefore the largest eruption unit so far identified in Iceland.

**ALTERATION OF THE TEPHRA OF THE SURTSEY TUYA, ICELAND** S. P. Jakobsson, Icelandic Institute of Natural History, P. O. Box 5320, 125 Reykjavik, Iceland.

Surtsey is a marine tuya that was constructed from the sea floor by phreatic submarine and effusive subaerial volcanic activity during 1963-1967. The island (0.8 $km^3$) consists of alkali basaltic air fall and base surge tephra/tuff deposited during 1963 -1964 and lava flows of 1964 - 1967, that produce foreset breccias where they enter the sea. Drilling and geophysical measurements indicate that pillow lava is nonexistent or of insignificant volume at the base of Surtsey.

The consolidation and palagonitization of the tephra has been monitored closely since 1967. A hydrothermal system was developed due to intrusive activity within the tephra cones in early 1967. Hydrothermal activity caused rapid alteration of tephra producing the first visible palagonite tuff in 1969. In 1998 it was estimated that 80-85 percent of the volume of the tephra pile above sea level was converted to palagonite tuff.

The chemistry and mineralogy of samples collected at the surface as well as drill core samples from a 181 m-deep hole, have been investigated. The tephra was altered at temperatures up to 100° C above sea level and up to 150° C below sea level. It appeares that with the exception of addition of water and $CO_2$ and oxidation of iron, there has only been a minor change in the bulk chemistry as the tephra was converted to tuff. On the microscale, however, a considerable leaching of elements has occurred when sideromelane was transformed to palagonite. This alteration is primarily a function of temperature. Ten hydrothermal minerals have crystallized in the tephra, the dominant species are smectite, analcite, phillipsite, and tobermorite.

Signs of microbial activity have been found in many tuff samples from Surtsey. There is, however, still no evidence for the involvement of microbes during the main phase of palagonitization. The present data from Surtsey are best explained if the microbes are considered to have entered the samples after the main phase of alteration. The microbes appear only to have caused a minor local alteration of the basaltic glass.

**COMPARATIVE GLACIOLOGY AND ACTIVE PHENOMENA IN THE SOLAR SYSTEM.** N. I. Kömle[1], [1]Institut für Weltraumforschung, Österreichische Akademie der Wissenschaften, Elisabethstrasse 20, A-8010 Graz, Austria. Email: norbert.koemle@oeaw.ac.at.

We give an overview of various 'active phenomena' observed at the surface of solar system bodies. Roughly, two major driving factors for activity can be identified:

- Endogenic processes, as in the case of ice-volcano interaction.
- Solar radiation energy, responsible for the activity of comets and (possibly) for the geysir-like eruptions on the Neptunian satellite Triton, discovered by Voyager 2 [1].

In both cases burst-like, violent activity is caused by the fact that energy is accumulated below the surface over a longer time and then suddenly released by some 'catastrophic' event. We describe analogies and differences between the various activity phenomena and propose an extension of the classical sciences 'glaciology' and 'volcanology' in the sense that they include analogous phenomena on other solar system bodies.

Led by our experience concerning the understanding of comet nuclei with the aid of laboratory experiments under space conditions [2], a similar approach is suggested for the investigation of processes controlling ice/volcano interaction, not only on earth, but also under the environmental conditions of Mars, Europa, Triton, and other bodies. To be more specific, the question of energy transfer between a geologically active surface and a glacial ice mass could be investigated on a small scale in the laboratory. We propose dedicated experiments to investigate this question.

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**ARCHITECTURE AND EVOLUTION OF HYDROVOLCANIC DELTAS IN MARIE BYRD LAND, ANTARCTICA.** W.E. LeMasurier, Department of Geology, CB 172, University of Colorado at Denver, PO Box 173364, Denver, Colorado, 80217-3364, USA

Some of the largest hydrovolcanic structures in Marie Byrd Land occur in the basal sections of large shield volcanoes. The best preserved of these exposures are somewhat delta-like in form, with gentle distal slopes, and foreset bedded deposits composed of hyaloclastites, pillow breccias, and occasionally, nested pillows. Three broad categories of processes related to their evolution are well displayed. (1) Flow of lava from a subaerial to a sub aquatic environment with accompanying development of pillowed flows (kubbaberg), nested pillows, pillow breccias, and hyaloclastite, the latter being the most abundant. (2) Intrusion of dikes, some of which develop pillowed structures, while others are bounded by thick (e.g. 1 m) intensely fragmented glassy margins, and terminate either in wholly clastic dikes or in hyaloclastite beds. (3) Edifice settling, which takes place by downslope movement of debris flows and internally cohesive glide blocks, by soft sediment flowage and diapirism, and by distributive displacement along multiple conjugate fractures.

These deposits vary in composition from alkaline basalt in some deltas to trachyte in others. Vitric clasts are invariably rich in microlites, indicating sub-liquidus temperatures of eruption. There is a wide range in the vesicularity of clasts and pillows that seems related to both lava composition and the environment of lava-ice interaction (i.e. air to water, water to air, etc). The interpretation of these structures can yield information about ice levels and ice level fluctuations at the time of eruption, and because they deform so easily, they may influence the behavior of ice sheets when they occur in the glacier bed.

**ANALYSIS OF ROOTLESS ERUPTION MODEL FOR ORIGINS OF SMALL CRATERED CONES OF ELYSIUM BASIN AND AMAZONIS PLANITIA, MARS.** P. D. Lanagan[1], A. S. McEwen[1], L. P. Keszthelyi[1], and Th. Thordarson[2], [1]Lunar and Planetary Laboratory, University of Arizona, Tucson AZ 85721, USA, planagan@lpl.arizona.edu. [2]CSIRO Magmatic Ore Deposit Group, Division of Exploration and Mining, Floreat Park Laboratories, Wembley, W.A., 6014, Australia.

High-resolution images from the Mars Orbiter Camera (MOC) have revealed the presence of small, cratered cones in the Elysium Basin and Amazonis Planitia. These structures are possibly of volcanic origin, formed by explosive rootless eruptions, as they occur in small clusters independent of any obvious structural patterns, are superimposed on fresh lava flows, and do not appear to issue lavas themselves. The cones observed in Amazonis Planitia and southern Elysium Basin have basal diameters <250m, which is consistent with terrestrial examples. Rootless cones, also known as pseudocraters, form as a result of phreatic explosions due to the emplacement of a lava flow over a volatile-rich surface [1], possibly involving mechanical mixtures of tube-fed lavas with water- or ice-laden substrate [2].

Lavas associated with one cone field near the mouth of Marte Valles show well-preserved surface morphologies and few superimposed impact craters. Crater statistics indicate that these lavas and superimposed cones may have been emplaced less than 10 Ma. In order to form the cones by rootless eruptions the subsurface ice must have been present at a depth of not more than half the thickness of the overriding lava flow [3]. Lava flows in this field are ~10m thick [4], so ground ice in these areas would have been present at comparable depths, much less than the 100-300m generally expected for near-equatorial regions of Mars [5]. It is possible that relatively recent late Amazonian floods replenished the ground water in these areas.

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**BED ROUGHNESS AS AN INDICATOR OF RELATIVE ERUPTION FREQUENCY.** K. Langley, Science Institute, University of Iceland, Hofsvallagata 53, 107 Reykjavík, Iceland. kirsty@raunvis.hi.is.

Introduction: Subglacial volcanism creates a very distinct topography, which, on a regional scale, appears as an irregular or rough surface. Roughness related parameters, determined from the number of volcanic remains within an area, can be used to compare volcanic provinces. Radio echo sounding data from Western Vatnajökull, southeast Iceland, covers several volcanic systems that can be compared in this way. The roughness frequency ($r_{freq}$) and the roughness factor ($R_{fac}$) give an indication of the amount and style of volcanism. For example, frequent small eruptions are implied for the Grímsvötn-Laki system whilst infrequent large eruptions appear to characterise the Kverkfjöll system. But this is not a direct indication of the intensity of volcanic activity since each peak is not necessarily the result of a separate eruption. Where two or more peaks are part of a single ridge they presumably formed during a single eruption. The relative spatial eruption frequency ($E_{fr}$) gives an indication of the number of eruptions that have occurred per unit area over an unspecified length of time. This parameter suggests that the Grímsvötn-Laki system is at present the most active system beneath Vatnajökull, a conclusion that has been reached in other studies [1]. To compare regions of different sizes, an area independent factor, termed the eruption factor ($E_{fac}$), is used and is a measure of the total number of eruptions that have occurred. This factor was calculated for the area of simplified drainage basins of Western Vatnajökull and indicated that the greatest number of eruptions has occurred within the Dyngjujökull area.

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**THE ICEBREAKERS: HISTORICAL ERUPTIONS OF SUBGLACIAL VOLCANOES IN ICELAND.** G. Larsen, Science Institute, Univ. of Iceland, Dunhagi 3, IS-107 Reykjavík, Iceland. E-mail glare@raunvis.hi.is.

Three of the most active volcanic systems in Iceland are partly overlain by ice-caps that cover their central volcanoes and parts of the associated fissure swarms. Ice thickness ranges from tens to hundreds of meters with maximum thickness of +850 and +700 meters in the calderas of the Bardarbunga and Katla central volcanoes, respectively, while a subglacial lake occupies the caldera of the Grimsvotn central volcano[1]. Several other volcanic systems have partial ice-cover but only Oeraefajokull and Eyjafjallajokull have erupted in historical time.

Beginning as subglacial eruptions, the majority of the eruptions break through the ice in minutes, hours or days, depending on magma extrusion rates, ice thickness and meltwater drainage. A single vent or the whole length of a fissure may then emerge to emit highly fragmented tephra in hydromagmatic explosions of varying strength. With a few exceptions the magma is basaltic and would erupt as lava in dry subaerial environment. Volume and dispersal of airborne tephra varies greatly, in some cases tephra fall does not extend outside the ice-caps while occasionally it has reached mainland Europe[2].

Tephra layers deposited on accumulation areas of ice-caps are buried by snow and preserved as distinct horizons in the ice, later exposed as dark bands in the ablation areas. The ice thus preserves the volcanic record of the subglacial volcanoes[3], while the tephra layers provide internal time markers that can be correlated to known eruptions to accurately date the ice. The Vatnajokull tephrostratigraphy extends back to 12th century but basal ice dates at least back to 11th century AD[4].

Over 120 eruptions have broken through the ice on the glaciated parts of the five volcanic systems during the past 11 centuries and left tephra layers in ice and soil. About 2/3 of these originate within the Grimsvotn system which has the highest eruption frequency. Eruptions of subglacial volcanoes constitute nearly 60% of known historical eruptions in Iceland.

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**LANDFORM DEVELOPMENT AND FRACTURING DURING LAVA-ICE INTERACTION AT STRATOVOLCANOES WITH ALPINE GLACIERS.** D.T. Lescinsky[1] and J. H. Fink[2], [1]Dept. Earth Sciences, University of Western Ontario (London, ON N6A 5B7, Canada; dlescins@julian.uwo.ca), [2]Dept. Geology, Arizona State University (Box 871404, Tempe, AZ 85287-1404, USA; jonathan.fink@asu.edu).

Lava eruptions at glaciated, temperate, stratovolcanoes produce characteristic landforms and fractures. The alpine glaciers on these volcanoes are thin (<150 m thick), permeable, and have steep underlying slopes (>20º). Meltwater produced during eruptions travels away from the vent area freely, eroding cavities in the ice by thermal and kinetic processes. These voids, tunnels, and trenches commonly act as confining channels for lava that flows into them, producing unbranched flows with steep glassy margins, that have polygonal fractures. Examples of these landforms found in the Cascades Range include: flat-topped lava mountains, steep-walled ridge flows, smaller lava flows and one variety of lava dome.

Landforms may also be produced by lava filling glacial voids containing small volumes of ponded meltwater. In this case, in addition to steep glassy margins, these landforms have pseudo-pillow fractures (a second type of lava dome) or isolated lava pillows (esker-like lava flows) indicating the presence of water. Landforms resulting from by lava flow into an englacial lake (pillow-lobe flows), have pseudo-pillow fractures, but show no evidence of flow confinement.

Fractures formed during lava-ice interaction can be morphologically characterized as: polygonal, sheet-like, pseudo-pillow, hackly, and shard-forming, and these correspond to increasing lava cooling rates. Pseudo-pillow, hackly and shard-forming fractures form during cooling by a mixture of steam and water penetrating the lava flow. Polygonal and sheet-like fractures may represent cooling by convecting steam.

The presence of the different fracture types can be used to infer and locate the former presence of ice and trapped meltwater at the time of eruption. By combining large and small-scale field evidence with historical observations of glacial modification, it is possible to reconstruct past environmental conditions and describe various aspects of the eruption.

**THE PRODUCTS OF SUBGLACIAL VOLCANISM: EXAMPLES FROM THE EYJAFJALLAJOKULL VOLCANO, SOUTHERN ICELAND.** S. C. Loughlin[1] [1]British Geological Survey, West Mains Road, Edinburgh, EH9 3LE, Scotland. s.loughlin@bgs.ac.uk

The Eyjafjallajökull volcano has been active for over 800Ka and is composed of complex, intercalated deposits of diamictite, lava, pillow lava, hyaloclastite and reworked volcaniclastic sediments. After detailed succession and lithofacies analysis it has been shown that these diverse deposits often occur in distinctive assemblages or 'lithofacies associations'. The constituent lava and volcaniclastic lithofacies of these associations are typically genetically related. The form of each lithofacies association depends on the local topography, the thickness of ice/ depth of water at deposition, the volume and rate of eruption, the physical properties of the magma and the depositional environment.

Volcanic successions deposited between about 600Ka and 800Ka at Eyjafjallajökull volcano formed stacked, laterally extensive, flat to gently sloping associations of diamictite, lava, hyaloclastite and volcaniclastic sediments consistent with eruption beneath a waxing and waning ice sheet, although some deposits may have been emplaced in a shallow marine environment. Lava facies commonly intrude cogenetic sedimentary successions and there is abundant evidence of fluidisation of wet sediments [1] around some intrusions. Some irregular-shaped lava bodies have a mantle of hyaloclastite breccia and evidence suggests that the lava continuously interacted with the breccia during flowage and also after deposition if a continuous feeder system was maintained. As the volcano grew in size, a summit ice cap and valley-confined glaciers developed and consequently valley-confined subglacial volcanic deposits are abundant in younger successions. Such deposits typically include a basal diamictite, and volcaniclastic successions may show abundant evidence of mass flow processes. Rapid erosion at the margins of such valley-confined volcanic deposits may ultimately lead to topographic inversion which appears to be a feature diagnostic of subglacial valley-confined volcanism. Some lava facies, interpreted to have been emplaced subglacially, have a high aspect ratio and were emplaced on relatively steep slopes, implying ponding within ice.

Similar deposits have been described elsewhere, especially in Antarctica (eg [2], [3]).

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**VOLCANISM AND ICE IN WEST CANDOR CHASMA, VALLES MARINERIS, MARS**.
Baerbel K. Lucchitta, U.S. Geological Survey, 2255 N. Gemini Dr., Flagstaff, AZ 86001, blucchitta@usgs.gov

Deposits in West Candor Chasma may consist of volcanic materials emplaced in an ice-covered lake. West Candor Chasma is a 6 km deep rectangular trough, about 150 km wide and open to the east. It contains a freestanding mesa composed of flat lying, light and dark layers, bordered locally by steeply dipping units. The top of the mesa is about 5 km above the trough floor and 1 km below the plateau into which the trough is entrenched. Very dark deposits with mafic spectral signatures occur in the depression between mesa and trough walls. The composition of the material forming the mesa is unknown, but some interbeds are also very dark and probably of mafic composition. Furthermore some of the dark interbeds spawn dunes; and massive, somewhat lighter layers are fluted by wind erosion. Both observations are consistent with a composition as ash. Some very light, even layers, however, may represent lacustrine interbeds. Massive flows, including some light colored lobes up to 30 km long, emerge from the mesa in places. These flows are probably, likewise, not volcanic; a high-resolution Mars Global Surveyor image shows that one of these flows disrupts and rafts away segments of layers, suggesting that the lobes are debris flows. To explain all of the observations, I propose that the layered sequences are composed of lava, palagonite, an admixture of sediments, and ice, originally filling the trough wall to wall. Later structural depressions formed near the trough walls and tilted the beds bordering the mesa. Icy layers in the mesa were then able to mobilize and flow. Continued volcanism may have melted some of the ice, giving rise to the youngest light colored debris lobes.

**COMPLEX SEDIMENTARY RESPONSES TO EXPLOSIVE ERUPTIONS AT A SNOW-CAPPED STRATOVOLCANO: 1995-96 RUAPEHU, NEW ZEALAND.** V. Manville[1] , B.F. Houghton[2] , K.A. Hodgson[3] and J.D.L. White[4] , [1]Institute of Geological & Nuclear Sciences, Bag 2000, Taupo, New Zealand, [2]University of Hawaii, 1680 East-West Rd, Honolulu HI96822, USA, [3]Lincoln University, Private Bag, Christchurch, New Zealand, [4]University of Otago, Private Bag, Dunedin, New Zealand.

The 1995 and 1996 explosive eruptions of Ruapehu volcano, Taupo Volcanic Zone, New Zealand ejected approximately 0.1 km 3 of tephra onto snow cover and ice fields on the 3000m volcano. Syneruptive sedimentary responses included snow-rich lahars, snow avalanches and icefalls. Lahars were triggered by the explosive ejection of hot crater-lake water, lake floor sediments and andesitic scoria onto the steep upper slopes of the cone where they re-mobilized entraining large volumes of snow and ice. A total of 28 lahars were triggered directly by explosive activity. The posteruptive response has operated on a wide range of scales and has included rain-triggered lahars causing more than $US9M in damage, ash-induced avalanches, wind-reworking, diurnal freeze-thaw, creep, sheet wash and rilling. The extent of these processes has depended on a complex interplay of factors such as slope angel and aspect, primary ash thickness and sand rainfall. Estimates of sediment yield indicate that nearly of the 1995 tephra will be removed rapidly from the cone, whereas the coarser and more permeable 1996 tephra will reside longer.

**WELL-PRESERVED VOLCANIC AND FLUVIAL LANDFORMS IN THE CERBERUS/AMAZONIS REGION OF MARS.** A. McEwen[1], L. Keszthelyi[1], P. Lanagan[1], R. Beyer[1], and D. Burr[2], [1]Lunar and Planetary Lab, University of Arizona (Tucson, AZ 85721, USA, mcewen@lpl.arizona.edu), [2]Department of Geosciences, University of Arizona.

High-resolution (1.4-20 m/pixel) images from the Mars Global Surveyor spacecraft have revealed well-preserved volcanic and fluvial features on the Cerberus plains (~5 N, 190 W), central Amazonis Planitia (~25 N, 160 W), and Marte Vallis (connecting Cerberus and Amazonis regions). Most of Mars' surface has been extensively modified by eolian or other processes, obscuring fluvial and volcanic morphologies on the scale of meters. The Cerberus/Amazonis region (covering ~4 x $10^6$ $km^2$) is the largest region on Mars revealing what appear to be primary volcanic and fluvial morphologies at the scale of meters. Much of the plains are covered by lava flows with a distinctive platy/ridged morphology similar to portions of high effusion rate flows on Iceland [1]. Marte Vallis and other channels reveal terraces, longitudinal grooves, and streamlined islands, similar to some of the paleoflood channels in Iceland [2]. The major channels originate in ancient highland terrains, but the water may have been released as the result of recent volcanic activity. Some of the lava flows appear to be younger than 10 Ma based on crater counts [3], and the channels are probably younger than 500 Ma [2]. In places the flows are being exhumed from beneath weakly indurated sediments of the Medusae Fossae Fm.; these sediments may be volcanic tephra from basaltic lava fountains or from phreatomagmatic explosions where the magma interacted with ice-rich highland terrains. The best evidence for volcano-ground ice interactions in this region are the features interpreted as rootless cones [4]. Polygons about 50 m diameter are common, probably from cooling and contracting lava flows but perhaps related to shallow ground ice. Many morphologies are puzzling, possibly due to mudflows, transient shallow lakes, or lava-ground ice interactions.

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**ICELAND'S LARGEST SUBGLACIAL RHYOLITE ERUPTION.** D.W. McGarvie[1], H. Tuffen[1,2], A.G.Tindle[1]. [1]Department of Earth Sciences, Open University, Milton Keynes MK7 6AA, UK. (e-mail: d.mcgarvie@open.ac.uk) [2]Department of Environmental Science, Lancaster University, Lancaster LA1 4YQ, UK.

Torfajökull is Iceland's largest active rhyolite volcanic complex and was the locus of numerous subglacial rhyolite eruptions during the Pleistocene [1]. We believe that one eruptive event, which formed a group of prominent subglacial massifs (the Kirkjufell Formation), is the largest subglacial rhyolite eruption yet documented in Iceland [2].

The Kirkjufell Formation (total volume of 11-17 $km^3$) consists of five separate massifs which form a discontinuous ring around the margins of the Torfajökull volcanic complex [2]. The northern massifs are preferentially aligned along linear fissures whereas the southern massifs are aligned along arcuate fissures [3]. Each massif contains one or more tuyas which rise up to 520 m above surrounding terrain. The largest tuyas have massive lava caps which can be subdivided into two facies: a lower tier of steeply-ramped lavas, and an upper tier of sub-horizontal lavas. We suggest that the steeply-ramped lavas represent ice-constrained flows erupted within ice cauldrons, whereas the sub-horizontal lavas represent unconstrained flows [4]. This facies change may allow a reconstruction of the ice thickness at the time of eruption.

It was first suggested back in 1984 that the massifs of the Kirkjufell Formation were the products of one rhyolite eruption [2]. A recent and more thorough study has confirmed that there are indeed narrow geochemical and mineralogical variations within the Kirkjufell Formation rhyolites, with (for example) Zr varying only from 822 ppm to 999 ppm [3]. We are presently exploring this further, to determine whether the pre-eruptive chamber was un-zoned, or whether a pre-eruptive compositional zonation existed and was destroyed during the eruption.

The similar morphologies of the five massifs together with their closely-related geochemical and mineralogical characteristics, all suggest that they were formed during one subglacial rhyolite eruptive event – Iceland's largest.

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**RADAR MAPPING OF THE HOODOO MOUNTAIN VOLCANO ICE CAP: ASSESSMENT OF HAZARDS ASSOCIATED WITH JÖKULHLAUPS.** J.K. Russell, M. Kelman, J. Schmok*, and B.R. Edwards, Igneous Petrology Laboratory, University of British Columbia, 6339 Stores Road, Vancouver, British Columbia, Canada V6T 1Z4, russell@perseus.geology.ubc.ca, *Golder Associates, Vancouver

Hoodoo Mountain is a Quaternary volcano located in the Coast Mountains of northwestern British Columbia. The edifice comprises mainly phonolitic lavas with minor pyroclastic material and is largely a product of subglacial volcanism. Its summit is 1850 m, and an ice cap 3-4 km across obscures the volcanic stratigraphy above 1700 m. Lava flows originating from beneath the present day ice cap may be as young as 9000 BP. Although isolated, the nearby Iskut River drainage is the site of substantial economic activity in the form of mines, fisheries, timber harvesting, and potential hydroelectric development. The greatest hazard posed by renewed volcanism at Hoodoo is large-scale, rapid melting of the ice cap and subsequent flooding of the Iskut drainage by jökulhlaups. The principal aim of our 1997 field program, therefore, was to map the shape of the summit ice sheet using radar. We completed a multiple-traverse radar survey using a low-frequency monopulse radar unit with a 1000 V transmitter designed by Narod and Clarke (UBC) for glaciological studies. Radar data were collected in step and free mode and all surveys were located using GPS data tied to two local control points. GPS positions and individual radar traces were linked by time tags. Results show the ice cap to be 100-150 m thick; excluding marginal areas, it maintains a relatively uniform thickness. Minimum ice volume is estimated at 0.32 cubic kilometers. These results delineate the shape of the volcanic summit and show it to be flat; there is no evidence of a caldera or any substantial craters. This shows the potential for a jökulhaup to be low. Renewed volcanism at Hoodoo Mountain would generate substantial volumes of water but they would tend to be released continuously and in all directions. This behaviour is inconsistent with the generation of jökulhaups.

**PALAGONITIZATION OF THE KEANAKAKO'I ASH MEMBER, KILAUEA VOLCANO.** P. Schiffman[1], R. J. Southard [2] and H. J. Spero [3], [1] Department of Geology, University of California, Davis, California 95616, PSchiffman@UCDavis.edu ; [2] Department of Land, Air and Water Resources, University of California, Davis, California 95616; [3] Department of Geology, University of California, Davis, California 95616

Three end-member scenarios have been invoked for palagonitization of tephra produced from hydrovolcanic erup-tions: a syn-depositional model [1], a hydrothermal, post-depositional model [2] and a low temperature, post-depositional model [3]. We have been investigating the feasibility of these models to account for the palagonitiza-tion of the Holocene Keanakako'i Ash Member at Kilauea Volcano. These tephra deposits are distributed across a region of Kilauea Caldera which experiences pronounced variations in rainfall (<50 to > 300 cm/yr), soil pH (3.5 to 7.5), and hydrothermal input (active steam vents along circumferential faults at temperatures between 55 and 79° C). Palagonitization of the Keanakako'i tephras by a dominantly hydrothermal mechanism is suggested because: (1) palagonitization, as opposed to other forms of tephra alteration (e.g., weathering to form pedogenic mineral suites), is found only adjacent to caldera-bounding faults, and (2) the stable isotopic composition of calcite intergrown with palagonitized glass is indicative of a hydrothermal origin. Specifically, d 18 O of these calcites (16.5 to 19.6 ‰ SMOW) suggest isotopic exchange with local meteoric fluids at temperatures between 33 and 49°C. Moreover, the d 13 C of these calcites (1.8 to 4.3 ‰ PDB) imply that approximately 30 to 80% of their carbon is of magmatic origin. As ubiquitous alteration minerals, carbonates are potentially powerful indicators of environments for palagonitization.

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**INTENSE VOLCANISM ASSOCIATED WITH CRUSTAL REBOUND: RECHARGING OF A VOLCANIC CENTRE AND SUBSEQUENT PETROLOGICAL EVOLUTION.**

G.E. Sigvaldason, Nordic Volcanological Institute, University of Iceland, Grensásvegur 50, Reykjavík, Iceland.

Crustal deformation by repeated glaciations causes rapid, large scale vertical movements of the diverging plate boundary through Iceland. Theoretically the glacier thickness over Central Iceland will reach 1500-2000 meters, causing 400-500 meter subsidence of the plate margin [1]. Crustal rebound is associated with intense volcanism along the plate boundary. Semiquantitative estimates indicate lava emission 30-40% higher than the present rate of production [2,3].

The Dyngjufjöll volcanic complex in Central Iceland is known as the location of the Askja depression that formed at the end of the Younger Dryas period [4]. Eruptive fissures within the Askja depression produced a large volume of lavas that filled the depression and escaped through a mountain pass forming a wide, 30-40 km long apron. Intermittent volcanic activity has since added to the lava apron displaying variations in volume and composition with time. Volume changes from about 4 $km^3$ at the beginning of Holocene to 0.1 $km^3$ during the present century [3]. Composition changes from an olivine tholeiite, typical of some monogenetic lava shields, to a quartz tholeiite, typical of continuously active volcanic centers of the rift zone. The compositional variation within the lava apron (10 000 years) matches the entire compositional range of basalts from the Dyngjufjöll complex (300 000 years).

Basalts within volcanic centers in Iceland are evolved quartz tholeiites indicating prolonged crustal residence [5]. Recharging of crustal magma containers with mantle derived olivine tholeiite occurs normally in frequent (200-500 years interval) rifting episodes [6]. A major tectonic disturbance, during crustal rebound, amounting to 400-500 meters uplift within a period of 1000 years [7], appears to provide pathways for large amounts of mantle derived olivine tholeiite into the crust, recharging and even replacing previously existing magma containers of volcanic centres. The Holocene lava apron from the Askja depression displays changes in volume and composition as the crustal magma containers return to normal after the climatic impact.

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**BASALTIC PAHOEHOE LAVA-FED DELTAS: CLAST GENERATION, EMPLACEMENT AND CRITERIA TO DISTINGUISH ENGLACIAL/LACUSTRINE DELTAS FROM SUBMARINE EXAMPLES** I.P Skilling, Box 5044, Dept of Geology, University of Southern Mississippi, Hattiesburg, MS 39406, USA. Email: Ian.Skilling@usm.edu

Basaltic pahoehoe lava-fed deltas have been described from submarine, lacustrine (including englacial) and fluvial settings. This paper discusses examples from the James Ross Island Volcanic Group (Antarctica), Hawaii and west Greenland. Processes that generate clasts include downslope pinching of active pillow lavas, quenching, mechanical stress, hydromagmatic explosions and peperite formation. Lava flow velocity and volumetric flux, the development of lava tubes, wave energy and delta collapse are important variables affecting these processes. The largest foreset clasts are derived from pinching of pillows, from subaqueous fallout and resedimentation of littoral spatter and from break-up of jointed lava during collapse. Plastic clasts commonly deform and adhere during loading and downslope movement. Delta collapse is an extremely common process, triggered by seismic activity, oversteepening of the foresets, large variations in bottom gradient during active progradation, ice failure and melting, delta lobe interference and tube inflation(?). Collapse generates chaotic and folded slumps, which often include subaerial lava breccias. Foreset emplacement is dominated by density-modified grain flows, but also includes slump deposits, littoral tephra deposited by subaqueous fallout and redeposited by sediment and fluidal gravity flows, and coherent pillow and sheet lavas. Detailed facies analysis of the littoral zone and marginal facies is useful to distinguish englacial/lacustrine deltas from submarine equivalents. Lacustrine deltas display large differences (>50m?) in the passage zone heights of penecontemporaneous lobes, poor sorting and no wave reworking in the littoral zone, redeposition of littoral tephra dominantly by turbidity currents, and an absence of beach deposits. Lacustrine deltas are typically more constrained than submarine examples due to smaller basin geometries. Englacial examples may also display marginal facies related to ice collapse or melting.

**LITHOFACIES ARCHITECTURE AND CONSTRUCTION OF VOLCANIC SEQUENCES ERUPTED SUBGLACIALLY.** J.L. Smellie, British Antarctic Survey, High Cross, Madingley Road, CAMBRIDGE CB3 0ET, UK; email: JLSM@bas.ac.uk

Volcanic sequences erupted subglacially are common in parts of the world with extant glaciers or evidence for the former presence of glaciers. Glacier thickness, structure and hydraulics exert a dominant influence on the way in which the volcanic sequences are constructed englacially. Three empirical models for the hydraulic evolution of glacio-volcanic systems can be deduced, with distinctly different implications in each case for the resultant lithofacies architecture. The models are illustrated using natural examples of monogenetic and polygenetic volcanoes investigated mainly in Antarctica. Eruptions beneath thin glaciers result in generally thin sequences (individually a few tens of metres) of interbedded glacier bedload, eruption-related volcaniclastic sediments and cogenetic lava–hyaloclastite breccia, which are usually bounded above and below by sharp glacially-modified unconformities. By contrast, volcanoes erupted beneath thicker glaciers (> c. 200 m) are much thicker (many tens to hundreds of metres) and are constructed within leaky water-filled vaults. The lithofacies types and their architecture will depend on whether the vault is predominantly top-draining, resulting in the familiar mesa or table mountain landforms, or if it drains by sudden basal release of meltwater. In the latter case, for which there are no currently described examples, the lithofacies are predicted to be mainly subaqueous and chaotic, but they could be hard to distinguish from those formed in early stages of vent construction in a top-draining vault. Subglacially erupted volcanic sequences are important yet largely neglected repositories of palaeoenvironmental information. With their high potential for precise isotopic dating, correct interpretation of those volcanic sequences is essential and will prove to be important for reconstructing past environments and enabling geologists to contribute even more to current controversies on the effects of global change, past and future.

**THE 1969 SUBGLACIAL ERUPTION ON DECEPTION ISLAND (ANTARCTICA): EVENTS AND PROCESSES DURING AN ERUPTION BENEATH A THIN GLACIER**.
J.L. Smellie, British Antarctic Survey, High Cross, Madingley Road, Cambridge CB3 0ET, UK; email: JLSM@bas.ac.uk.

A short-lived eruption of basaltic andesite to andesite magma on Deception Island in 1969 occurred from a series of fissures underneath a glacier. The glacier was thin (only about 100 m) yet, contrary to predictions based on existing hydrological models, the eruption created a large and sudden discharge of meltwater that overflowed the glacier, severely damaging a British scientific station on the island. The eruption was unusually well documented and it illustrates several features of subglacial eruptions that are only poorly known and not well understood. These include the formation of unusual cylindrical ice chimneys and overflowing englacial vaults. Both features were observed on Deception Island and have been described elsewhere only during the considerably more complicated 1996 subglacial eruption at Gjálp, Iceland. The eruption is analysed in this paper, and used to interpret the fluid dynamics and thermodynamics of eruptions beneath a thin glacier mainly composed of impermeable ice. Results of the study are also important for reconstructing the shapes of englacial cavities melted above a vent.

**HOLOCENE JÖKULHLAUP ACTIVITY AT ENTUJÖKULL, ICELAND**. K. Smith[1*], A. Dugmore[1] and G.Larsen[1+2], [1]The Department of Geography, University of Edinburgh, Drummond Street, Edinburgh, EH8 9XP, Scotland [*]kts@geo.ed.ac.uk, [2]Science Institute, University of Iceland, Dunhagi 3, IS 107 Reykjavík, Iceland**.**

This poster presents new evidence for jökulhlaup activity at Entujökull, western Myrdalsjökull, south Iceland. M‡rdalsjökull is an ice cap in south central Iceland, covering the caldera of the Katla Volcanic System. Three large outlet glaciers, Kötlujökull (also known as Höfdabrekkujökull), Sólheimajökull and Entujökull flow through breaches in the caldera rim and drain ice from the central volcanic complex of Katla. On average, Katla has erupted twice a century during historical times, and produced jökulhlaups with fine grained basaltic pumice that have generally flowed east from under Kötlujökull. While good historical jökulhlaup records exist for Kötlujökull and a detailed geomorphic record has been established for the Sólheimajökull area, little is known about jökulhlaup activity from below Entujökull and down the Markarfljót valley. Determining patterns of activity from Entujökull is necessary to gain a fuller understanding of past jökulhlaup activity from Myrdalsjökull, fundamental to future hazard planning. Geomorphic maps of the proglacial area of Entujökull show three major glacial stages associated with at least two substantial basaltic jökulhlaup events. The oldest identified episode of Holocene glacial expansion filled the current proglacial valley forming a terminus 4700m from the present glacier snout. This was followed by a period of glacial retreat of at least 1280m, emplacement within the valley of lava from a nearby fissure and a subsequent major jökulhlaup from Entujökull. A later episode of glacial retreat, lava emplacement and a second major jökulhlaup was followed by terminal moraine formation 1910m from the present glacier. A further innermost moraine complex represents the so-called ‘Little Ice Age’ (1600 – 1900AD). These findings are significant because they show that Entujökull has been a route for successive Holocene jökulhlaups. Future activity of Katla could produce flooding to the west of the ice cap with potential impacts on the Markarfljót valley and the Landeyjar and Fljótshlíd districts.

**PILLOW LAVA SHEETS: ORIGINS AND FLOW PATTERNS.** Snorri P Snorrason Almenna Verkfrædistofan hf, Consulting Engineers, Fellsmula 26,108 Reykjavík, Iceland snorri@almenna.is. Elsa G. Vilmundardóttir Orkustofnun, National Energy Authority, Grenasvegi 9 108 Reykjavík, Iceland egv@os.is

The past 20 years the authors have mapped subglacial eruptions on the Eastern Volcanic Zone in Iceland, some 2000 $km^2$.

The most common form, if not the most obvious of a subglacial eruption in the western half of the study area, is the basaltic pillow lava sheets. They are series of thin pillow lavas or pillow lava breccias. The flow front of these volcanic units may be as thin as 30 m (comparable in thickness to rhyolitic subareal lavas in Iceland) and may flow several km from its parent eruptive fissure.

The formation of these lava's occurs in both large and small volcanic units **(**0.1-7 $km^3$) and also in all types of basalt in the area. The pillow lava sheets most often originate from short eruption fissures in relation to the size of the volcanic unit.

Pillow lava sheets have a very large cooling surface compared to thicker units. High intensity of the magma flow is therefore needed to overcome the cooling effect of the surrounding meltwater. Lower eruption rate is thought to result in a thicker unit, often in the shape of a narrow ridge directly above the erupting fissure.

The shape of pillow lava sheets is partly governed by the subglacial landscape and partly by the flowpath of meltwater. The meltwater created in the eruption may follow the lowest path of the glacier subsurface, like a river. In this case the pillow lava would tend to follow the meltwater stream and form a long and narrow eruptive unit very similar in shape to subareal lava flows. On the other hand if the path of least resistance (hydrostatic pressure) does not coincide with the lowest path in the bedrock the pillow lava flow cannot follow the path of the meltwater stream and the shape eruptive units tends to spread

Pillow lava sheets appear to be concentrated in Central Iceland where the ice cap was thickest during the last glaciation.

**RADAR SOUNDING SURVEY OF EYJAFJALLAJOKULL, ICELAND: SUBGLACIAL TOPOGRAPHY, ICE THICKNESS, AND DERIVED RELATIVE PERMITTIVITIES.**
Sara M. Strachan, Department of Geography Drummond St., University of Edinburgh, Edinburgh EH8 9XP UK, sms@geo.ed.ac.uk

Point data from low-frequency radio-echo soundings are interpolated to produce maps of the ice thickness and subglacial topography of Eyjafjallajokull. This study adds Eyjafjallajokull to the growing archive of surveyed glaciers in Iceland. Experimental data provide the means to determine the relative permittivities of the ice at representative sites on the ice cap: flank, caldera, and the foot of Gigjokull, the main outlet glacier. Relative permittivities of the ice are calculated from the measured velocities, giving site-specific accuracy to the depth determinations. Precision error of radar sounding interpretation is quantified by taking multiple frequency soundings at each point. This dataset will be useful for a variety of applications, including flow model input, hazard assessment, and mass balance studies. The aim is to reveal the bed topography with a view to determining the past system fluctuations from the volcanic bed morphology.

**MEGA-LAHARS OF ELYSIUM, MARS.** K. L. Tanaka[1], I. Skilling[2], and J. Skinner[1], [1]U.S. Geological Survey, 2255 N. Gemini Dr., Flagstaff, AZ 86001, USA, ktanaka@usgs.gov, [2]Dept. of Geology, University of Southern Mississippi, Box 5044, Hattiesburg, MS 39406-5044, USA, Ian.Skilling@usm.edu.

On Mars, huge lobate deposits covering 1.45 x $10^6$ $km^2$ in Utopia Planitia were emplaced by outflows originating from deep canyons on the northwest flank of Elysium Mons. These rugged deposits include smooth medial deposits and large channels and have been interpreted to be lahars generated by the heating of ground ice from magmatism [1]. Their complex morphologies seen in Viking and high-resolution Mars Orbiter Camera images indicate many flow units of variable thickness and ruggedness and processes such as seepage, piping, block rafting, deposit settling, collapse, and secondary flow generation similar to those associated with terrestrial lahars. Low ridges and troughs suggestive of glacial-like flow bound many of the flow lobes and thus may have formed after fluid flow ceased and the lubricating water froze. Some of the circular features appear to be related to differential settling across buried topography or perhaps to secondary, phreatic venting. Also, some domical structures may be pingos. Surprisingly, the lahars appear to have been impacted by few craters, indicating that they may be much younger than previously recognized [2]. New altimetry data provided by the Mars Orbiter Laser Altimeter enable more precise measurement of the volumes of the deposits and canyons; previously, the lahars were estimated to be 10 to 100 times the volume of the canyons [1]. Our results indicate that the volume of the eroded canyons is ~$10^4$ $km^2$. Cumulative thickness of the lahars probably varies considerably, and the deposit margin is not detected in MOLA profiles. Based on channel depths, the lahars are probably tens of meters thick and may locally exceed a hundred meters thick. Thus the volume of the lahars probably exceeds that of the troughs by a factor of a few to several. The excess volume must therefore have a magmatic origin.

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**ROOTLESS ERUPTIONS AND CONE GROUPS IN ICELAND: PRODUCTS OF AUTHENTIC EXPLOSIVE WATER TO MAGMA INTERACTIONS.** Thorvaldur Thordarson, CSIRO Magmatic Ore Deposit Group, DEM, PO Box 5 Wembley, WA 6913, Australia. E-mail: t.thordarson@per.dem.csiro.au

Rootless cone groups (i.e. pseudocraters) are closely packed group of circular tephra cones that are found within pahoehoe flows where the lava advanced over wetlands. They are formed by phreatomagmatic eruptions that are fed by lateral conduits (i.e. lava tubes) and driven by explosive interaction between molten lava and water-saturated substrate. Cone types range from small hornito-like spatter cones to tuff cones with basal diameter ranging from 5-450m. Individual cones typically exhibit a well-bedded lower sequence, consisting of alternating layers of lapilli scoria and red-baked lacustrine muds, and a crudely bedded upper sequence of brick red agglutinates. The upward increase in grain size emulates the attenuation of explosive power during the eruptions and goes hand in hand with decrease in the abundance of lacustrine mud incorporated into the deposits by the explosive activity.

A conceptual model on the formation of rootless cone groups has to account for the following:

- The cone groups rest directly on the host lava but the cones show no evidence of having been deformed by moving lava,
- The random distribution of the cones and that the lava continued its advance despite the rootless eruptions,
- The occurrence of lacustrine muds as distinct beds in the cone sequence, which is a clear indication of their involvement in generating the steam explosion by providing the water, and
- Internal stratification of the cones, which demonstrates sustained explosive activity of decreasing intensity,

In short, the lava has to be able to flow across the wetlands and initiate rootless eruptions, forming cones on top of the lava that are not deformed by its movements. It will be shown that this can only be accomplished by tube-fed pahoehoe flows formed by insulating lava emplacement and inflation.

**FRAGMENTATION MECHANISMS IN ICELANDIC SUBGLACIAL RHYOLITE ERUPTIONS: EVIDENCE FROM ASH SHARD MORPHOLOGIES.** H. Tuffen[1,2] , D. W. McGarvie[1], J. S. Gilbert[2]. [1]Department of Earth Sciences, Open University, Milton Keynes MK7 6AA, UK. [2]Department of Environmental Science, Lancaster University, Lancaster LA1 4YQ, UK.

Rhyolitic ash shards from Quaternary subglacial volcanoes at Torfajökull, Iceland have distinctive shapes and surface textures that relate to a variety of fragmentation mechanisms and alteration processes. Ash shards from the margins of in-situ subglacial lava lobes at Bláhnúkur [1] are relatively vesicle-poor and have blocky morphologies typical of magma-water interaction [2,3]. From field observations we postulate that small-scale phreatomagmatic explosions occurred when lava lobes encountered meltwater-saturated breccias under ice >300 m thick. Arrested vesiculation may attest to a high glaciostatic confining pressure (c. 3 MPa). Ash shards within green, indurated debris flow deposits on Bláhnúkur [1] are similar, but have abraded corners and pitted surfaces, suggestive of transport and alteration [3].

Very different ash has been found in northern Raudufossafjöll, in a thick (>10 m) sequence of bedded ash which we interpret to have been deposited in an ice-dammed lake at the northern margin of a large (>6 $km^3$) subglacial-to-emergent volcano. Shards are highly vesicular, with delicate bubble walls, and show no sign of alteration or abrasion. In this case, fragmentation was probably driven by volatile exsolution in a 'dry' magmatic eruption [3]. Assuming that this ash came from the Raudufossafjöll massif, we infer that the rhyolite magma was sufficiently volatile-rich to generate an explosive eruption once the glacier surface had been breached and meltwater was no longer available [4]. This raises the possibility that Raudufossafjöll generated a widespread tephra layer.

A recent study of historic basaltic tephra layers in Iceland [5] has found a quantitative difference between the morphology of subglacially and subaerially erupted ash shards. However, rhyolitic tephra appears more difficult to interpret. Our preliminary observations at Torfajökull suggest that rhyolitic ash shard morphologies may indeed yield information on eruption mechanisms.

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**VOLCANO/ICE INTERACTION AT BLÁHNÚKUR, TORFAJÖKULL, ICELAND: A QUATERNARY SUBGLACIAL RHYOLITE ERUPTION.** H. Tuffen[1,2], J. S. Gilbert[2], D. W. McGarvie[1]. [1]Department of Earth Sciences, Open University, Milton Keynes MK7 6AA, UK. [2]Department of Environmental Science, Lancaster University, Lancaster LA1 4YQ, UK.

Bláhnúkur is a 350 m high subglacial rhyolite volcano emplaced during the last glacial period at the Torfajökull volcanic complex, south central Iceland. We present field evidence for complex volcano/ice interaction beneath a glacier >400 m thick. Reworked basal till is intercalated with juvenile-dominated sandstones in an incised subglacial meltwater channel at the base of the sequence. This suggests that meltwater was draining from the vent area during the eruption, as predicted for subglacial rhyolite eruptions [1].

Much of the subglacial deposits consist of 5-10 m lava lobes set in pumice breccia [2,3]. Columnar jointing patterns may indicate that some lobes reached the glacier base, where they were moulded within steep-sided conical cavities in the ice [3]. Explosive magma-water interaction probably contributed to fragmentation at lobe margins, forming blocky ash shards typically 10-100 μm in diameter. Mass flow deposits on the volcano flanks consist of portions of lava lobes and pumice breccia [3]. They appear to have been hot when emplaced and were possibly formed by syn-eruptive instability of lava lobes and breccia, triggered by melting of the supporting ice walls (e.g. [4]).

Larger lava flows (>20 m thick) were extruded towards the end of the eruption. The orientation of columnar joints suggests that lava flowed within subglacial tunnels [3,4,5]. The lack of fragmentation at lava flow margins may indicate that these tunnels were largely empty of meltwater. We propose that the eruption mechanism was strongly influenced by the evolving subglacial cavity system. This emphasizes that an understanding of subglacial hydrology is the key to hazard assessment at active ice-covered volcanoes.

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**RHYOLITE TUYAS AT TORFAJÖKULL, ICELAND.** H. Tuffen[1,2], D. W. McGarvie[1], J. S. Gilbert[2]. [1]Department of Earth Sciences, Open University, Milton Keynes MK7 6AA, UK. [2]Department of Environmental Science, Lancaster University, Lancaster LA1 4YQ, UK.

A large subglacial eruption of peralkaline rhyolite at Torfajökull, Iceland has created at least ten tuyas with a total volume of 11-17 km3 [1,2]. These tuyas, which rise 370-520 m above the surrounding land, are the rhyolitic equivalent of basaltic tuyas such as Herdubreid [3].

Lithofacies record three distinct phases: (1) an early subglacial phase, (2) an ice-constrained subaerial lava phase, and (3) an unconstrained subaerial lava phase. The products of the early subglacial phase (1), which consist of lava lobes and pumice breccia [c.f. 4,5] are mostly concealed by scree. Products of the next eruptive phase (2) consist of steeply ramped lava flows up to 1.2 km long and 150 m thick. Where preserved, flow tops are pumiceous and glassy; closely resembling those of subaerial rhyolite lava flows nearby. The nature of these lava flows appears consistent with subaerial emplacement within an ice cauldron. The final eruptive phase (3) occurs on volcanoes above 1000 m in elevation, where the ice-constrained lava flows (2) are overlain by subhorizontal and unramped lava flows only 10-25 m thick, which locally drape down the volcano flanks (c.f. [6]). These may have flowed above the glacier surface, before entering a bergshrund-like gap between the volcano and the encapsulating glacier.

The high viscosity of rhyolite lava has lead to the development of ramped structures not seen in the subaerial lava flows of less silicic tuyas. The morphology and stratigraphic position of the ice-constrained rhyolite lava flows reported here may provide evidence for both ice cauldron geometries and palaeo-ice thickness. We estimate that the subaerial lava cap of one rhyolite tuya at Torfajökull (Kirkjufell) was emplaced within an ice cauldron 150 m deep and ~1.2 km in diameter that had developed in a glacier ~400 m thick. These dimensions are strikingly similar to those of the ice cauldrons that developed during the Gjálp eruption - but is this purely a coincidence?

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**UPPER PLEISTOCENE SUBGLACIAL VOLCANIC ACTIVITY IN THE REGION SW OF VATNAJÖKULL ICECAP, ICELAND**. Elsa G. Vilmundardóttir Orkustofnun, National Engergy Authority, Grensásvegur 9, 108, Reykjavík Iceland. e-mail: egv@os.is Snorri Páll Snorrason Almenna Verkfrædistofan, Consulting Engineers, Fellsmúli 26, 108, Reykjavík, Iceland. e-mail snorri@almenna.is

Subglacial volcanic activity was common in the neovolcanic zone in Iceland during the Upper Pleistocene (< 0.8 m.y.). The products, hyaloclastites (named móberg in Icelandic), are dominating morphologic features in the móberg regions, which cover about 20% of the total area of the country.

The region to the west and southwest of the Vatnajökull Icecap is a good example of this activity. It has been mapped geologically by the authors in scale 1:50.000 in connection with hydropower projects in the area. The fieldwork began in 1981 and is still going on.

The bedrock map includes 87 volcanic units of basaltic hyaloclastite of different chemical composition in an area of some 2000 $km^2$, and in addition there are 28 basaltic holocene lava flows (<10.000 years B.P.) originating within the same area. The Upper Pleistocene erupting fissures vary in length from being very short (< 1 km) and up to at least 48 km. The fissures are strongly oriented in NE-SW direction, most often near N 45° S.

The research area can be divided into three subsections with different characteristics:
1) The Gjáfjöll area
2) The Thórisvatn area
3) The Breidbakur area

The Gjáfjöll area is characterized by relatively short eruption fissures (0.5-20 km) and the distance between them is often very short (0.5 km or less). In the Thórisvatn area the fissures are 10-30 km in length and the distance between them can be up to 3-4 km. The most interesting features are pillow lava sheets which have flowed out from the eruption centers. The Breidbakur area is characterized by very long ridges, up to 50 km in length which can be seen as outstanding features on maps and satellite photos. Often the eruption fissures are close together, less than 0.5 km apart.

Only the approximate and relative age of the móberg is known. Most of the volcanic units are believed to date from the last glaciation between 10.000-100.000 years B.P., the oldest most likely from the second last glaciation. Age groups (sequences of volcanic units whose relative age is known) normally comprise only a few units, up to 8 but more often only 2-4. Glacial erosion seems to be light or very light in the area.

**MIDDLE AND LATE WISCONSINAN EXPANSIONS OF THE WEST ANTARCTIC ICE SHEET AT MT. TAKAHE VOLCANO.** T.I. Wilch 1 , S.M. McCuddy 1 , and W.C. McIntosh 2 , 1 Department of Geological Sciences, Albion College, Albion MI 49924 (twilch@albion.edu), 2 Department of Earth and Environmental Science, New Mexico Tech, Socorro, NM 87801.

Vertical expansions of the West Antarctic Ice Sheet ~400 m, 413 m, and 575 m above the present ice level are recorded in three Wisconsinan volcanic passage zones at Mt. Takahe in eastern Marie Byrd Land, West Antarctica, 150 km inland from the Amundsen Sea. The horizontal passage zones at Stauffer Bluff, Gill Bluff and Moll Spur formed where late-stage lower flank volcanoes emerged above the level of ice-magma interaction and are inferred to represent approximate paleo-ice-levels. Rocks below the passage zones consist of pillow lava and hyaloclastite breccia that form flow-foot delta sequences. Above the passage zones, rock outcrops consist of oxidized and welded breccia and lava at Gill Bluff and Moll Spur and hydrovolcanic tuff at Stauffer Bluff. Descending and climbing passage zone sequences at Gill Bluff may indicate the draining and refilling of an ice-marginal lake during the eruption interval. Field observations are corroborated by extensive petrographic and geochemical data. A precise 40 Ar/39 Ar chronology of elevated ice-sheet levels at each location is presented below.

| Site | Paleo-ice Thickening | Age (±1 sd) |
|---|---|---|
| Gill Blu | +413 m | 21.9 ±1.8 ka |
| Moll Spu | +575 m | 15.2 ± 2.4 ka |
| Stauffer Bluff | +400 m | 66.4 ± 4.7 ka |

The age of the ~400 m above present ice-sheet level at Stauffer Bluff corresponds to an early Wis-consinan global ice volume increase (marine isotope stage 4) inferred from deep-sea marine isotope records. The 413 and 575 m higher inland ice levels indicate that there was significant volumetric, not just lateral, ex-pansion of the West Antarctic Ice Sheet during Late Wisconsinan time. The ice-level record at Mt. Takahe provides key inland data points for paleo-ice-sheet reconstructions in West Antarctica, which are important for understanding global sea-level records and the sensitivity of West Antarctica to past climate changes.

**MIDDLE TO LATE CENOZOIC VOLCANIC RECORD OF THE WEST ANTARCTIC ICE SHEET.** T.I. Wilch[1] and W.C. McIntosh[2] , [1]Department of Geological Sciences, Albion College, Albion MI 49924 (twilch@albion.edu), [2]Department of Earth and Environmental Science, New Mexico Tech, Socorro, NM 87801.

Paleo-environmental reconstructions and 40 Ar/39 Ar geochronology of nineteen large polygenetic volcanoes and numerous smaller monogenetic volcanoes in Marie Byrd Land, West Antarctica provide proxy records of changing ice levels of the West Antarctic Ice Sheet since the Oligocene. Interpretations of eruptive and depositional environments are based on lithofacies studies and indicate whether the volcanoes erupted below, near, or above the level of the ice sheet. A new conceptual model of glaciovolcanism in Marie Byrd Land differentiates volcanic records of local ice levels from records of West Ant-arctic Ice Sheet levels. The model builds upon the traditional Icelandic table mountain model but addresses several complicating features of the glaciovolcanic environment of Marie Byrd Land. Specific complications include: ice-level feedback effects caused by obstructions to ice-flow, changes in ice level in coastal regions caused by rises or falls of sea level, glaciovolcanic interactions with slope ice, and volcanism on interfluves between regions of fast-flowing ice. The Oligocene to Pleistocene volcanic history provides a proxy record of ice level changes in West Antarctica, with the following major conclusions: 1) the first indications for ice in West Antarctica are the early Oligocene (29-27 Ma) emergent tuff sequences at Mt. Petras, where limited local syneruptive glaciation is inferred; 2) the first evidence for a widespread West Antarctic Ice Sheet is Late Miocene (~9.3 Ma) glaciovolcanic sequences from across Marie Byrd Land; 3) paleo-ice-level ex-pansions of the WAIS were more extensive at coastal sites than at inland sites; 4) the West Antarctic Ice Sheet is in a near maximum configuration that existed at several times since 9.3 Ma but was rarely exceeded; and 5) significant thickening events of the West Antarctic Ice Sheet above its present-day level are recorded only in middle and latest Pleistocene glaciovolcanic sequences.

**SIMULATION ON MELTING OF PERMAFROST LAYER BY DYKE INTRUSION: ESTIMATE OF MELTING SPEED AND WATER FLUX.** Y. Yamagishi, Y. Ogawa, and K. Kurita, Department of Earth and Planetary Science, University of Tokyo, 7-3-1 Hongo Bunkyo-ku Tokyo 113-0033, JAPAN.

When dykes intrude in the upper part of crust, resultant high heat flux promotes the melting of the permafrost layer, which is estimated as an origin of the outflow channel on Mars [1]. The ability to produce large amount of water in a relatively short time is a key criterion for the cause of the outflow channel. In this study, we calculate the production rate of liquid water by melting of permafrost when the dike reaches near the bottom of the permafrost layer. We model the permafrost by porous media in which the matrix is rock and ice fills the pore. The natural convection in the porous media is incorporated in the phase change problem. The numerical simulations are performed in two ways. One is based on 1D rigorous Stefan formulation, and the second one is 2D simulation with heterogeneous heat flux on the enthalpy formulation. We take notice of the change of the speed of the melting front and the liquid volume produced ultimately with variation of ice content/porosity and the size of the dike. By using the numerical results, we inspect the interactions between the size of the dike, the state of the permafrost and the landforms formed consequently. Particularly we model formation of the closed depressions such as the Hebes Chasma. We also compare the features to those suspected to be produced by the melting of ice under the surface on the other planetary bodies, Earth and icy satellites.

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