Pyroclastic passage zones in glaciovolcanic sequences

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Passage zones are diachronous surfaces marking transitions between subaqueous and subaerial depositional environments during volcanic eruptions. The elevations of passage zones have long been considered to record unequivocally the heights and depths of paleo-lakes at a specific point in time and space, and are particularly useful in glaciovolcanic settings. However, previous workers have only identified glaciovolcanic passage zones within effusive volcanic sequences where the passage zone separates subaqueous lava-fed delta lithofacies from overlying subaerial lavas. Here we present the first documented description of a new type of passage zone within an entirely explosive glaciovolcanic sequence in a subglacial volcano (i.e. tuya) near Kawdy Mountain in NW British Columbia, Canada. Kima'Kho tuya is a highly dissected, small volume (4-6 km^3), early Pleistocene (1.82 Ma $\pm$40 ka) basaltic volcano. The edifice forms a high relief structure covering 28 km^2 and rising to an elevation of 1946 m.a.s.l. on a regional plateau situated at 1470 m.a.s.l. The volcano features a 476 m high, 3 km diameter, eroded tephra cone (1.1-1.5 km^3) formed by an initial phase of explosive eruption through an enclosing ice sheet. The cone comprises mostly vent-proximal (<1 km from vent) volcaniclastic deposits; distal deposits are absent or not preserved. The pyroclastic cone comprises massive to crudely bedded lapilli tuffs deposited subaqueously below the level of the englacial lake, overlain by coarsely to well bedded subaerial deposits, characterised by abundant armoured lapilli, that were deposited once the cone became emergent. The transition between subaqueous and subaerial facies occurs at 1850 m.a.s.l. and defines a passage zone within pyroclastic deposits. Subsequent eruptions formed an onlapping lava-fed delta comprising steeply-dipping (5 to 30°) beds of pillow lava, pillow breccias and pillow lava derived hyaloclastite capped by subaerial lava sheets. Our discovery requires extension of the passage zone concept to accommodate explosive volcanism and should guide future studies of hundreds of terrestrial and non-terrestrial glaciovolcanic edifices. We suggest that the geometries of pyroclastic passage zones will be sensitive recorders of dynamic changes in englacial lake levels, and will differ fundamentally from effusive passage zones. Edifice growth and lake level fluctuations will be recorded by the morphology of the pyroclastic passage zone surface, e.g. a concave upwards surface represents the simultaneous growth of the edifice whilst the lake level is rising due to trapped meltwater. Our recognition of pyroclastic passage zones increases the potential for recovering transient paleo-lake levels, improving estimates of paleo-ice thicknesses on Earth and Mars, and providing new constraints on paleoclimate models that consider the extents and timing of planetary glaciations.

A model for recent magmatism on Mars

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On Mars young-aged lava flows have been identified in several locations such as Central Elysium Planitia and Amazonis Planitia. This raised strong curiosity whether the present Mars is still active like the Earth or not. At the same time another significant question has been raised, whether this magmatism is essentially different from those which had been active for long time because the surface morphology is so different.The young lava flows are characterized by extremely smooth plane, which indicates flooding of low viscosity lava(for example, Voucher et al 2009 about Central Elysium Planitia and Fuller and Head 2002 about Amazonis Planitia). The activity seems short and persistent repeated discharges of lava flow are not recognized. On the other hand long-lived magmatism is characterized by formation of huge volcanic edifice such as Olympus Mons.To build such a huge edifice continual supply of magma at the same locality fro long time is necessary, which reminds us terrestrial hot spot magmatism by deep-rooted thermochemical plumes. We would like to discuss existence of two contrasting styles of magmatism, huge edifice building magmatism and lava-flooding magmatism and their origins. Particularly we present a working hypothesis of delamination-induced magmatism as an origin of lava-flooding magma.

The martian crust is significantly heavy compared with the terrestrial lower crust.Crustal density of 2900 to 3100 kg/m3 is estimated by analysis of gravity anomaly and admittance analysis(Wieczorek and Zuber 2004).This is consistent with the chemical composition of the martian meteorites. Basaltic shergotite contains twice amount of FeO than terrestrial MORB. In such iron-rich system Ohmori 2013 estimate phase boundary of basalt-eclogite transition based on the thermodynamical calculation and obtained lower transition pressure such as the depth range of 60-80km in Mars. If the crust thickens gradually by accumulation of lava the lower-most part of the martian crust possibly transforms to eclogite. Since the iron-rich eclogite is heavier than iron-rich mantle peridotite transformed lower crust is expected to delaminate and sink in the mantle. Associated with this delamination mantle compensating flow should be induced. During the adiabatic rise melting should occur if the mantle temperature below the lithosphere is close to the solidus. In this situation the locations of magmatism are expected at near the dichotomy boundary, where the crustal thickness largely changes. This seems consistent with the localities of young lava flooding (Noguchi and Kurita 2013 in this meeting).

At last part we would like to discuss probable sites of terrestrial analog for the lava-flooding magmatism. We propose Garrotxa volcanic zone at the periphery of Pyrenees Mountains as a such analog.

Thermal, geological and glaciological constraints on past volcano-ice interactions

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Volcano-ice interaction takes on many forms in terrestrial settings. One end member is the eruption under a thick ice sheet, another is an eruption on a stratovolcano with thin or limited ice cover. Many eruptions fit somewhere on the spectrum between the two extremes. For many Pleistocene tuyas and other hyaloclastite mountains found at mid to high latitudes such as Iceland and Canada, the large ice sheet case seems to fit the environmental conditions at the time of formation. By applying thermodynamics and simplified ice mechanics, considerable inferrences can be made on the size and thickness of the glacier at the time when a subglacial volcano was formed. The thermodynamic principles applied are calorimetry and data on thermal properties of the rock, ice and liquid water. Magma type is important because of the variations in thermal properties with composition. Geological information includes e.g. evidence for the presence or absence of a lake level at the time of eruption and whether a volcano ever became emergent. Morphological parameters include volume, bulk density and thickness/height of subglacial part of volcano. Other important input parameters for such simple modelling are partitioning between crystalline rocks (pillow lavas) and pyroclastic glass. When combined with empirical constraints on heat transfer efficiency obtained from recent eruptions, equations can be derived that provide estimates of (1) the likely depth of ice depression over an eruption site at time of eruption, (2) the size of a depression in a glacier surface over a subglacial volcano, and (3) the maximum thickness of ice melted during the formation of a subglacial volcano. If something is known about the mass balance of the glacier at the time of formation of a volcano, the time for healing of the overlying ice sheet after an eruption can be estimated. The equations derived need to be applied with due care, and by considering fully the available geological data. However, when these conditions are met, the equations should in favourable cases provide realistic estimates of Pleistocene glacier extent and thickness in a volcanic region at the time of eruption.

Overview of recent findings regarding the fumarolic ice caves of Erebus volcano, Antarctica

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Fumarolic ice caves and towers on Erebus are the surface expression of flank degassing on the world's southernmost active volcano. The caves act as windows into magmatic processes, host extremophiles, and are analogues for extraterrestrial systems. Over the past four Austral summers, mapping, gas and thermal monitoring conducted under the Erebus Caves Project has elucidated relationships between cave structures, underlying magmatic processes, and surface weather.

A newly compiled database and map of cave locations demonstrates that their locations reflect the underlying magmatic system as imaged by recent seismic tomography and scattering survey, but are also affected by shallow features including lava flow edges and remnant caldera rims.

Heat transport into the caves occurs primarily by advective transport through discrete vents, as revealed by distributed temperature sensing (DTS) campaigns. Long time series of temperature data reveal vent temperatures to be nearly constant over observed periods (up to two years), implying a stable effusive degassing process. Despite constancy on long timescales, vent gas have transient changes, dropping by as much as 15℃ for one to three days, several times a month. These sudden drops in temperature are thought to represent sudden changes in cave geometry, such as the opening of a new entrance or collapse of an ice tower. Small temperature changes (on the order of 1℃) in vent temperature on the scale of hours to days correlate with barometric pressure measured at surface weather stations and reveal barometric pumping of gas from the volcano edifice through the caves. At that scale in temperature and time, relationships between vents on Ice Tower Ridge suggest subsurface gas-permeable pathways connecting the vents.

Vent gases contain up to 3% CO_2 but lack the S, Cl, and F gases that are soluble at lower magma pressure and released at Erebus' convecting lava lake. This suggests that the cave gas exsolves from a deeper source than the degassing that occurs at the crater. FTIR measurements conducted in Warren Cave showed significant absorption in methane bands. This is the first evidence of volcanic gas other than CO_2 in the caves. Results will be presented for analysis of recently collected gas samples using mass spectrometry and gas chromatography.

Frozen martian lahars? Evidence from Utopia-Elysium flows

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The Utopia-Elysium flows originate on the northwest of Elysium rise and extend more than a thousand kilometers into the Utopia Basin. They have been interpreted as evidence for mega-lahars triggered by intrusions; either by melting ground ice or by cracking the cryosphere, allowing drainage of confined aquifers.
However, little focus has been placed on the emplacement properties of lahars under martian conditions, though martian temperature and pressure may have had a significant impact on the lahar emplacement and morphology. Based on regional high-resolution data from the CTX camera (6 m/pixel) this study investigates the emplacement mechanisms of the proposed mega-lahars in the Utopia-Elysium region (138-145E; 30-40 N) and how they affected the subsequent geologic development in the area.

The outflow deposits are composed of four units, which display very different morphology in the proximal, medial and distal areas. The central part consists of a channel deposit, CD (1,890 km2), with well-defined tear-drop shaped islands and it incises the surrounding flood plain deposit, FPD (13,730 km2), and the elevated terrace deposit, TD (4,200 km2). All three units are recognizable by their very flat appearance, flow-like textured albedo variations and normal impact craters. On the contrary, the distal deposits called smooth flow, SF (45,400 km2), have diagnostic steep, lobate flow fronts with upward convex snouts, variable thickness (10-100m), enclosed depressions pits and hollows, crenulated rims and internal fractures. Distinct crater morphologies are observed including thermally distinct craters, ring-mold-like craters (RMCs), and ice-cauldron −like features. All four deposits are stratigraphically similar and originate abruptly at approximately -3750 m elevation on the flank of the Elysium rise in association with ridges, fractures and troughs, which we interpret as morphologic evidence of dikes.

We suggest that the diverse morphologies express varying degrees of water drainage and freezing within the outflow deposit. Normal channel and flood plain deposits are found in the central part of the outflow deposit and resemble terrestrial lahar deposits. The overbank deposits create the distal deposits; SF (∼75% of the total outflow deposit in the Galaxias region) show morphologic characteristics similar to ice-rich deposits. This suggests that, unlike terrestrial lahars, the water within these slower moving overbank flows froze due to the cold martian conditions, creating an ice-rich deposit. Furthermore, seventeen mounds resembling moberg ridges (linear, distinct ridge-crests and associated with linear ridges) are found within the ice-rich distal deposits and imply that later volcanic activity was highly affected by the presence of the ice-rich lahar deposits, generating ground-ice-volcano interactions and resulting in a secondary suite of ice-volcano morphologies.

The style and characteristics of young magmatism on Mars

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On Mars, very young magmatic activity has been identified in several places such as Central Elysium Planitia (CEP, Keszthelyi et al., 2010, Jaeger et al., 2010) and Amazonis Planitia (AP, Hartmann, 2003, Harman et al., 2012). The existence of such young activity places a strong constraint on the thermal structure of the present Mars as well as its thermal evolution. A key question arises as for this; whether the young magmatism is different from those lasting for long period in the Martian history, which are characterized as huge-edifice building magmatism such as the formation of Olympus Mons. Both CEP and AP are well known to have very smooth surface characteristics (Kreslavsky & Head, 2000, Aharonson et al., 2001), which is interpreted as a result of flooding of low-viscosity lava. The landscape seems quite different between young ones and long-lasting ones. Is this also true for the magmatic activity?; this question is a starting point of our investigation. To answer this, we have conducted geomorphological surveys at CEP and AP to characterize young volcanism.

In this study, we have picked up these two regions as the survey area to conduct comparative investigations on the morphology. In both areas the smooth plains are interpreted as lava flows mostly because of the existence of small cones, which are identified as rootless cones caused by magma-water interaction. Particularly in CEP, Noguchi & Kurita, 2012 reported existence of peculiar cone morphology (Double Cone Structure, DCS), which strongly indicates of the magmatic origin. Since the smooth lava plains are featureless, existence of cones should be an unique criterion for the magmatic identification. In CEP, flooding lava emanated from Cerberus Fossae (Plescia 2003) and flowed into Athabasca Valles. On the other hand, in AP the extent of lava flow units are not precisely determined and the source regions are not specified. Fuller and Head, 2002 showed that southern AP lava was derived from Tharsis Montes. By contrast, Harmon et al., 2012 suggested that Southern AP (SAP) lava has the local source, and Northern AP (NAP) lava flow was derived via Marte Valles, west of AP. We conducted mapping of lava flow units in AP to constrain the extent and the source regions by focussing two morphological features in CTX and HiRISE images: 1) decelerating ridges whose strikes are perpendicular to the flow direction, and 2) linear alignment of cones which are parallel to the flow direction.

As a result, we found most of AP cones locate in SAP, and few cones exist in NAP. There are 2 cone regions in SAP, eastern area and western area. Diameter of cones in western area of SAP is larger than those of eastern area. The direction of linear alignment of cones in SAP is different between eastern area and western area. This difference suggests that there are 2 lava sources in SAP, and shows that magmatism in AP is more complicated than CEP.

A new detailed glacio-eruptive history for Tongariro National Park, New Zealand: Results from mapping, geochronology, geochemistry and glaciology currently underway

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We present and discuss preliminary findings of a project to develop an integrated volcanic and glacial history for the composite volcanoes of Tongariro National Park. This collaboration with New Zealands Department of Conservation will publish the first detailed (1:50,000 scale) volcanic geological map and bulletin for the park. The park includes the iconic active vents of Ngauruhoe and Ruapehu, last eruptive in 1975 and 2007, respectively, and the reactivated Te Maari vent of Tongariro, which erupted twice in 2012. Ruapehu and Tongariro are at least 250,000 years old, having erupted multiple times from overlapping centres. Compositions are predominantly basaltic andesite to andesite and both centres have been host to ice caps during glacial periods, representing a significant proportion of their eruptive history.

A large amount of geological mapping and geochemical work has been conducted over past decades, focussed mainly on lava and pyroclastic units. Past moraine mapping has been limited and the extent of glacial landforms has been under-appreciated; the frequency, extent and precise timing of past glacier fluctuations remained unknown. Consideration of the influence of glacial processes with primary volcanism has largely been absent. The volcanoes are surrounded by a substantial laharic ring-plain, and we are integrating these sediments into the glacial and volcanic history of the peaks. Tongariro and Ruapehu volcanoes have now been geomorphically mapped from aerial photos and fieldwork, showing extensive complex moraine and lava sequences over much of the area. Distributions of lava flows and pyroclastic deposits have been heavily controlled by ice distributions during eruption. We now recognise widespread ice-contact textures including fine-scale lateral columnar jointed lava (sometimes grading into till); intercalated stacked moraines and perched lavas, often with lobes of lava dipping and thickening into the valleys toward now-missing ice; lava tubes and sheets apparently emplaced under ice; stalled lava flows inferred as bounded by valley-filling ice; Holocene valley bottom lavas mantling glacial features; and eruptive textures and landforms possibly due to sub-glacial lacustrine volcanism.

New high-precision groundmass Ar-Ar age dates are being produced on suitable lavas. We are achieving 1.2 kyr (1 s.d.) uncertainties on Holocene lavas and less than 1 kyr on c.40 kyr lavas. The tephra cover on moraines is being analysed in detail; stratigraphic constraints are being combined with cosmogenic 3He surface exposure dating of moraines to ascertain the relative and absolute timing of volcanic events and their relationships to past ice configurations and thus the till units. The dating is shedding new light on the timing of growth of late Pleistocene cones, and about the Holocene lavas and their relationships to the regional fall and flow deposits (see Cowlyn et al., this volume) previously documented from the east side of Ruapehu.

Widespread lava–water interactions in Elysium Plantia, Mars: Implications for paleoenvironments during the Middle to Late Amazonian Epochs

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The Elysium Volcanic Province (EVP) includes the youngest and best preserved eruptive products on Mars. These young (Middle to Late Amazonian) eruptive products are dominated by extensive lava flows that provide insight into the planet's thermal evolution and volcanic history. The Cerberus Fossae 2 and 3 units, located in the southeastern portion of the EVP, include regionally extensive flood lavas that host numerous cratered cone groups. These cratered cone groups are generally interpreted to be the products of explosive lava–water interactions (i.e., volcanic rootless constructs) and provide evidence of near-surface water or ice at the time of lava flow emplacement. This study focuses on the Cerberus Fossae 2 unit and uses imagery from the Mars Reconnaissance Orbiter to demonstrate that the cratered cone groups cover 15,000–20,000 km^2. The Cerberus Fossae 2 unit also includes pitted terrains that are interpreted to be thermokarst, which was generated by lava-induced melting of near-surface ground ice followed by foundering of the overlying lava. If these landforms were associated with lava–ground ice interactions, then their distribution implies an extensive near-surface H_2O reservoir at the time of lava flow emplacement approximately 125 Ma ago (with a factor of ± 2 uncertainty). The region also includes annular depressions around high-standing knolls and mesas of the Noachian-age Nepenthes Mensae unit. These features are interpreted to be the result of another form of lava–ice interaction, with lava flows embaying ice-bearing lobate debris aprons that were subsequently removed by sublimation and deflation to form an annulus around the high-standing topography. When lava flows associated with the Cerberus Fossae 2 unit were emplaced, the inferred paleo-distributions of near-surface ground ice and ice-bearing debris aprons are consistent the ice accumulation zones predicted by Mars climate models with approximately 35° obliquity.

Lava lake volcanism on Io: Insights from Erta Ale observations

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Jupiter's moon Io hosts dozens of erupting volcanoes, many of them lava lakes. Lava lake volcanism is an important mode of heat release for Io's interior, though the dynamics of heat transfer through lava lake systems are not fully characterized. Remote observations of the Erta Ale lava lake system inform our studies of Io's Pele volcano.

The Pele volcano is the source of a large plume of sulfur and mafic pyroclastics and has been observed to be active nearly continuously from 1979 (for the Voyager flyby) through the present (via ground-based observations). Night side observations of Pele by the Galileo spacecraft in 2001 indicate much of the 30 km diameter volcano-tectonic depression, and perhaps to an outer 60 km depression, is a lava lake. Hotspots had brightness temperatures on average 1100-1200 C, similar to hawaiian basalts. The hotspots are distributed such that a central, bright region 10 km across is surrounded by an arcuate distribution of smaller, isolated hotspots, all separated by cool material.

The Erta Ale lava lake has been observed by many groups to be active at least intermittently since the early 1900s. We observed the lake in early 2010 to be 10 m below the rim of a 45 m pit crater and in a particularly actively fountaining phase. Despite the appearance of fountains of varying size, one every 1-2 minutes over about 90 minutes, the lake was dominated by a cool (though rolling) crust that formed rapidly over newly exposed material. Most fountains were found near the lake margin, where the crust interacted with the crater walls. Thermal images obtained near 1 micron using a handheld camcorder reveal brightness temperatures of 1150 C at the center of the fountains, which are likely eruption temperatures, since they reflect temperatures from collected samples and because many pixels were filled by exposed lava. Slightly lower temperatures were found at cracks in the lake surface and cool temperatures were observed in the insulating lava lake crust. Some experiments with an inexpensive three-channel radiometer are also described, analogous to many spacecraft observations where hot lava only fills a small fraction of the beam footprint.

The hotspot distribution at Erta Ale lava lake, with a large, actively fountaining region surrounded by cool crust and an arcuate distribution of smaller hotspots at the crater margins, is similar to that observed at Pele. The dimensions of Pele, however, are almost two orders of magnitude larger than those of Erta Ale, and reflect a much greater heat flow through the lake system. Temperatures obtained by the handheld camcorder reveal it is possible to obtain eruption temperatures of lavas if there is enough exposed material to completely fill pixels. That similar temperatures were obtained for Pele indicates similar compositions for the volcanoes and that lava was exposed in great volumes by large-scale fountaining, observed by the more distant and lower-resolution Galileo observations.

The role of volatiles in volcanism on Io

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Sulfur and sulfur dioxide volatiles play a significant role in the volcanism on Io, the innermost of the large moons of Jupiter. However their abundance appears to vary greatly from one location to another, for reasons that are as yet poorly understood. At Pele the volatiles are abundant enough to drive plumes which carry material hundreds of kilometers above the surface. At Loki their abundance is smaller yet the activity, while less violent, may still be strongly influenced by volatiles. In the foundering-lava-lake-crust model for recurrent activity, developed by Rathbun, the volatiles and their vesicles provide the required buoyancy for the crust and therefore control the timing of the eventual foundering. Volatiles may also act to modify the temperature distribution we see with thermal infrared measurements. We have been conducting a detailed analysis of spacecraft data to quantify the amount and the role of the volatiles at these and other sites.

At Loki numerous small bright features, which for historical reasons are colloquially known as bergs, are distributed across the dark patera surface. Modeling of colors in the best available images (from Voyager I) shows that small parts of the patera are bare basalt but much of the background patera is covered by 20 to 40 percent sulfur, with the exact coverage depending on assumed sulfur grain size. At the bergs, most of which are only partially resolved, coverage is at least 33 percent, probably ranging up to 100 percent. The bergs may in fact be fumarole deposits on the basalt crust. However the largest bergs appear to survive successive resurfacings, which implies they represent something less ephemeral than simple surface deposits, and are perhaps higher standing kipuka.

In addition to Pele and Loki, we are analyzing the volatile distribution at other hot spots such as Tupan. Tupan shows an overall morphology similar to Loki, with a central island and one straight margin. However rather than showing bright bergs in a dark patera it shows a more complex pattern which varies across the patera. However a detailed analysis of the reflectance shows that sulfur is abundant on many of the surfaces within the patera.

Morphometric extraction of the passage zone: Broad scale analysis of subglacial edifices in Iceland

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Glaciovolcanic landforms and sequences can be used as a proxy for paleo ice caps. The passage zone, marking the junction between the lava cap and breccia, is of particular interest. It records the englacial water level coeval with the delta formation and thereby provides important paleoenvironmental parameters regarding ice thickness, paleo ice surface and the paleo eruption environment.

Since the very beginning of investigation of subglacial edifices, tuyas have been known for their morphometric characteristics being roughly equidimensional, steep-sided, flat topped mountains. In particular, the passage zone is morphometrically diagnostic and already in 1969 Jones [1] described that the passage zone for the tuya Skrida, Iceland, was noticeable by a conspicuous break in slope marking the transition from steep scree flanks to low sloping lava cap.

Strangely, these morphometric characteristics have never been exploited for broad scale analysis of subglacial edifices based on geomorphometry. Therefore, we initiated a pilot study on Reykjanes Peninsula, Iceland to make a purely morphometric characterization of subglacial landforms based on IS 50V digital elevation model (20 m/pixel). The edifice boundaries were delimited by concave breaks in slope around their bases and morphometric parameters such as volume, slope, base area, base width, edifice height, ellipticity and irregularity were calculated for each edifice [2,3]. Further analysis of topographic profiles correlated with geologic maps and aerial photographs, showed that it is possible to resolve individual land elements based on slope discontinuity. The passage zone is especially clearly defined by a convex break in slope.

This study utilizes the fact that volume, edifice height and the passage zone for tuyas can be extracted to make geomorphometric broad scale investigation of tuyas from the Icelandic neovolcanic zone. Furthermore, aerial photographs will be used to investigate if lavas drained down the tuya edifice providing information on the stability of the englacial lake during the eruption. The correlation of the passage zone heights, volumes and information regarding englacial lake stability allows us to investigate several aspects of tuya formation. This includes examination of; (1) spatial distribution of tuya sizes in rift and plume dominated volcanic systems (2) approximate estimate of paleo ice surface height based on passage zone elevation and (3) relationship between eruption size, approximate paleo ice surface height and meltwater drainage.

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Rapid growth of a basaltic volcano beneath an ice sheet: Askja, Iceland

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New high-precision K-Ar unspiked ages of basalts of the Austurfjöll glaciovolcanic massif at Askja provide insights into the rapid growth of a basaltic central volcano during the last (Weichselian/Wisconsin) glacial period.

The ice-free Askja central volcano comprises a number of separate glaciovolcanic massifs (constructed of pillows, pillow breccias, and tuffs) which have been dismembered by multiple calderas, and which are surrounded by copious outpourings of Holocene basaltic lavas. Austurfjöll is the largest of Askja's glaciovolcanic massifs and prior to caldera collapses had an estimated area of c.60 km^2 and volume of c.25 km^3. (Current values are c.50 km^2 and c.20 km^3). The massif rises from surrounding plains at c.640 m elevation to a high point at 1510 m on a caldera rim.

Two Austurfjöll basalts yielded K-Ar unspiked ages of 29±8 ka and 71±7 ka, which are within the Weichselian (Wisconsin) glacial period. The 71 ka date comes from a subglacial pillow basalt close to the base of Austurfjöll, and this suggests that the vast bulk of the massif was constructed during one glacial period. This is a surprising finding given that the lifespans of Icelandic central volcanoes are considered to the 0.5-1.0 Ma, and suggests that Askja is a very young central volcano.

Using values of 20 km^3 DRE and a period of 60 ka yields a Weichselian production rate of 0.33 km^3 per ka for Austurfjöll alone. This is similar to estimated Holocene production rate of 0.32 km^3 per ka for Askja from 2.9 ka till the present.

It can be concluded that despite the presence of the Weichselian ice sheet, Askja's Weichselian basaltic magma productivity was equivalent to that of the present-day. Which begs the question: what really triggered production rates at Askja of up to 9.4 km^3 per ka during the early Holocene?

Suppression of lateral collapses at glaciated volcanoes in the South Sandwich arc by high rates of erosion and formation of sediment wave fields on the lower slopes of edifices.

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Flank instability producing landslides of various types is common in almost all volcanic island arcs. These landslides range from small, thin-skinned events comparable to non-volcanic landslides; through larger events at the edges of platforms around islands; to large (1 to > 10 cubic kilometres) and deep-seated (thicknesses of 100s of metres) lateral collapses. In some island arcs, such as the Bismarck arc in Papua New Guinea, a majority of the volcanoes show evidence for recent occurrences of even these largest and least common lateral collapse landslides, in the form of collapse scars and offshore debris avalanche deposits. In strong contrast, recent British Antarctic Survey mapping cruises around the South Sandwich arc have shown that lateral collapse debris avalanche deposits from the active subaerial volcanoes of this arc are extremely rare. Only one, relatively small, subaerial lateral collapse structure is known (on Zavodovskii Island), whereas the several seamounts also mapped do show a number of lateral collapse features and deposits. The subaerial islands are subject to small-scale thin-skinned landslides and the margins of the submerged platforms on which they stand show scallop-shaped scars from platform margin landslides.

The slopes below these platform margins are formed by unusually large and well-developed sediment wave fields, which extend up to several tens of kilometers and contain sediment waves up to 200 m high. Such large sediment wave fields are only found around caldera volcanoes in other island arcs. We propose that the suppression of large scale, deep seated lateral collapses in the South Sandwich arc is linked to rapid coastal and glacial erosion of the glaciated subaerial volcanoes that, coupled with subglacial phreatomagmatic eruptions and ice-melt floods, generates large fluxes of coarse sediment to feed the sediment wave fields. The rapid removal of material from the summits and upper slopes of the volcanoes, and its deposition on the lower flanks, appears to have stabilized the edifices against occurrence of the large-scale flank collapses found in other arcs. The contrast in patterns of flank instability between the South Sandwich arc and other arcs may provide insights into the underlying mechanisms of, and controls upon, lateral collapse occurrence.

Are Mars volcanic rocks dominated by primary melts and why?

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The 4 Ga-record of Martian volcanic activity has been well characterized over the last decade by various instruments, including remote sensing gamma ray spectroscopy, visible/near-infrared and thermal spectroscopy, and in-situ measurements. These instruments have revealed trends in surface chemistry and mineralogy such as variations in SiO_2 concentration and the relative abundance of high-calcium and low-calcium pyroxene end-members. These variations are found to show trends as a function of age, and petrogenetic modeling indicates that they can be explained in terms of variable degrees of partial melting of the Martian interior (Baratoux et al., 2011, 2013). In detail, the results of the modeling provide evidence for cooling of the mantle and associated thickening of the lithosphere. The scenario is constrained by data spanning the Noachian-Hesperian-Amazonian periods and indicates high production rates of crust on early Mars, implying that Noachian rocks exposed at the surface may be petrological expressions of this volcanism rather than being associated with mantle overturn following the crystallization of a magma ocean. This situation may be compared to the Earth highlighting the differences between the thermal evolution of a stagnant-lid planet and a planet with plate tectonics. This simple scenario, which relates the composition and mineralogy of surface rocks to conditions of melting in the mantle, relies on the assumption that the signature of surface igneous rocks is largely dominated by primary melts extracted from the mantle and emplaced at the surface without significant fractional crystallization or contamination by crustal rocks. Such a situation is necessarily intriguing for terrestrial petrologists, and contrasts with a widely used concept in planetary science suggesting the existence of a neutral buoyancy zone that is mainly controlled by surface gravity (Wilson and Head, 1994). A series of factors that may favor the rapid ascent of magma to the surface will be reviewed, including the large density contrasts between primary melts and crustal material, and the viscosity of iron-rich liquids produced by the partial melting of an iron-rich mantle. Estimated crustal densities range from 3200 to 3580 kg/m^3 (Grott and Wieczorek, 2012) suggesting that magma buoyancy may be a sufficient driving force for its ascent to the surface. In addition, experimental estimates of the viscosity of iron-rich liquids (Chevrel et al., 2013) indicate values at the liquidus as low as 1 Pa s. Magma ascent could be therefore faster than 10 m/s, limiting fractional crystallization as long as the magma remains buoyant.

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Evaluating methane clathrate destabilization by heat from lava flows as a mechanism for supplying Titan's atmospheric methane

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As previously noted [1-3], Titan may have an upper crust rich in methane clathrates which would have formed early in Titan's history [3]. Uncertainty prevails as to how methane, a major atmospheric component, and ^{40}Ar are replenished from Titan's interior. One possibility is that volcanic processes release these gases from Titan's interior. We have investigated the destabilisation of methane clathrates by the thermal interaction with cryolava flows and intrusions as a way of replenishing atmospheric methane and liberating trapped argon. We have adopted models of lava flow cooling and solidification [4] to chart the penetration of the thermal wave from such volcanic events and the evolving release of methane as clathrates are destabilised. For example, a 10-m-thick cryolava covering 100 km^2 of the surface would raise 3 x 10^8 m^3 of substrate methane clathrates to the destabilization temperature in $\sim 10^8$ s, releasing 4 x 10^{10} kg of methane. This is an impressive amount, but it would take 5 million similar events to yield the current total mass of atmospheric methane, requiring the completely resurfacing of Titan with cryoflows six times just to produce the current methane inventory. If all the flows were, instead, $\sim$60 m thick, then Titan only needs to be completely resurfaced once. The idea of initially supplying all of Titan's atmospheric methane through the destabilization of clathrates by flow substrate heating seems to be unlikely. However, the potential reservoir of methane clathrates is sufficient to resupply present day losses of atmospheric methane, and requires only one such 10-m flow event about 40% of the time to do so. A somewhat lesser amount of intrusive activity would also release sufficient methane. In conclusion, we find that a near-global-scale resurfacing event some 0.5 BYa [5] involving cryolavas hundreds of meters thick, or perhaps widespread crustal foundering, would be required to yield sufficient methane from the thermal destabilisation of clathrates to explain current atmospheric abundances. However, meeting the current global methane replenishment rate is certainly feasible from thermal interaction between cryolavas and methane clathrate deposits on a relatively modest scale, one that might be hard to detect by remote sensing. References: [1] Choukroun, M. and Sotin C. (2012) GRL, 39, L04201. [2] Tobie, G. et al. (2006) Phil. Trans. R. Soc. A., 367, 617-631. [3] Lunine, J. I. et al. (2009) Origin and Evolution of Titan, in Titan From Cassini-Huygens, ed,. R. Brown et al., pp. 35-59, Springer. [4] Davies, A. G. et al. (2013) LPSC-44 abstract 1681, available online. [5] Sotin, C. et al. (2012) Icarus, 221, 768-786. Acknowledgements: This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract to NASA. © 2013 Caltech. We thank NASA's OPR Program for support.

Cryovolcanism on Titan

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Volcanism is a fundamental geologic process in the solar system, as it has occurred on most solid planetary bodies. Planetary volcanism is manifested across a range of morphologies, driving conditions, and compositions, including ices (cryovolcanism). Understanding volcanism in space and time on a planet provides vital constraints on the transfer of heat and mass from the interior, and can also provide insights into the composition of a planet or moon. Comparing eruption and emplacement mechanisms on other planets to those on Earth better constrains how terrestrial magmatism behaves under present and past conditions. Planetary volcanism has been defined as an eruption from an opening on a planetary surface from which magma, defined for that body as a partial melt product of mantle or crustal material, is erupted. Volcanism that occurs on the satellites of the outer solar system, sometimes known as cryovolcanism, is primarily the eruption of aqueous or non-polar molecular solutions or partly crystallized slurries, derived from partial melting of ice-bearing materials. Observations from the Cassini mission have revealed that the moon Titan is a complex world in which interior, surface and atmospheric processes interact to create and modify geologic features. In terms of active or recent surface-shaping processes, Titan is one of the most Earthlike worlds in the Solar System. Among the varied surface features observed by Cassini instruments are vast dune fields, lakes of liquid methane and ethane, fluvial channels, and mountains. However, the existence of features formed by cryovolcanic activity has been the subject of controversy. Here we use observations from the Cassini RADAR, including SAR imaging, radiometry, and topography data, plus compositional data from the Visible and Infrared Spectrometer (VIMS) to re-examine several putative cryovolcanic features on Titan in terms of likely processes of origin (fluvial, aeolian, cryovolcanic, or other). We present evidence to support the cryovolcanic origin of some features, which includes the deepest pit known on Titan, Sotra Patera, and some of the highest mountains, Doom and Erebor Montes. We interpret this region to be a cryovolcanic complex of multiple cones, craters, and flows. Elsewhere, a circular feature, approximately 100 km across, is morphologically similar to a laccolith, showing a cross pattern interpreted to be extensional fractures. However, we find that some other previously supposed cryovolcanic features were likely formed by other processes. We discuss implications for eruption style and composition of cryovolcanism on Titan. Our analysis shows the great value of combining data sets when interpreting the geology of Titan and in particular stresses the value of topographic data.

Observational and Theoretical Limits on Present-Day Cryovolcanic Activity on Titan with application to Planetary Protection

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The search for evidence of recent and present-day cryovolcanic activity on Titan continues. While a positive detection would be of extraordinary interest in its own right, the nondetection is also significant. Should areas of present-day activity be found, they may need to be designated as special regions for planetary protection purposes, in that they would constitute microenvironments where terrestrial biota conveyed on a spacecraft might inoculate bodies of liquid water. It is thus important in planning future missions to Titan to consider what constraints the current and planned Cassini observational coverage may place on the existence of such regions.

With reasonable assumptions, a recent cryolava flow with thin enough ice cover to constitute a special region (i.e. thin enough for an impacting spacecraft could break through) can be equated with an area with a given surface temperature. This can be estimated by equating the conductive heat flow through the ice lid to the convective loss to the atmosphere (radiation loss is negligible at these temperatures) and would be 5-25K above ambient, using convective heat transfer coefficients estimated from the cool-down of the Huygens probe. Such warm surfaces could be detectable in Radar radiometry and in thermal IR measurements. The radiometric resolution of the RADAR radiometer and CIRS instruments is of the order of 1K and thus temperature anomalies filling a significant fraction of the beam footprint (typically tens to hundreds of km across) would be detectable. In practice, emissivity variations raise the radar radiometry threshold by a factor of a few, so we adopt the footprint size as a convenient feature scale. To date about a third of Titan has been observed with close RADAR observations (20-80km resolution) and nearly all of it at 200km resolution. Bayesian calculations, combined with lava spreading and cooling models could be employed to derive a probabilistic constraint on smaller regions of interest.

A tighter theoretical 'constraint' can be derived from the expected geothermal heat flow (6 mW per m2). If (as on Earth) a tenth of this is expressed as latent heat in magma, and noting from the calculation above that a region of interest cools at 50 W per m2, an a priori estimate emerges that less than 1E-5 of Titan's surface (i.e. 1000km2) should be covered in such areas. Some additional information (e.g. from geological interpretation) would be required to revise such an estimate upwards to the level (1E-4) of concern for planetary protection.

Multiple fissure-fed construction of a glaciovolcanic complex at the Askja volcano, Iceland

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Austurfjoll is the largest glaciovolcanic complex at Askja, and the bulk was constructed by eruptions during the last (Weichselian) glacial period. Recent detailed mapping, logging, and chemostratigraphy has demonstrated that the bulk of the c.800 m thick Austurfjoll complex was constructed by at least 15 vents situated along formerly ice-confined fissures which follow three structural trends: rift-parallel (NE-SW), rift-perpendicular (E-W) and concentric to the margin of Askjas largest caldera. The cross-cutting nature of the closely-spaced eruptive fissure generated a large volume, broadly equidimensional massif, rather than a typical elongate Icelandic "tindar", though the processes and products are similar.

The complex rests in the south-east on a diamict, of probable glacial origin, that overlies a small area (0.7 km2) of glacially scoured subaerial aa lavas, that may be of "interglacial" (Eemian?) age. The oldest glaciovolcanic products are dominated by sheet-like units (to 400m in width, 60 m thick) of micro-porphyritic pillow lava, and associated pillow-fragment breccias, which were emplaced beneath thick ice. The sheet lavas are draped by explosively generated vitriclastic lapilli tuffs, that were emplaced by subaqueous density currents and mass flows. The maximum thickness of these tuffs is about 350m, with individual massive or slump-bedded units to about 100m. The uppermost (in altitude) pillow lavas and clastic deposits tend to be more coarsely porphyritic (plagioclase) than lower altitude lavas and tuffs. However, this is not a systematic trend across the whole complex, but may rather be restricted to individual fissure eruptions. The youngest deposits at Austurfjoll, exposed near the rim of Oskjuvatn caldera, include a variety of coarse, indistinctly parallel-bedded volcaniclastic breccias with subaerial lavas clasts and heterolithic lapilli tuffs that include rhyolitic pumice and reddened scoria clasts. These lithofacies imply that at least some of the fissure eruptions became emergent in the west of the massif. The entire massif is also intruded by a wide variety of dike-like and irregular intrusions, that were emplaced into consolidated (including ice-cemented) and wet, unconsolidated clastic deposits.

See the companion presentation by McGarvie for new K-Ar dating, and by Graettinger for environmental conditions of the eruptions.

Environmental reconstruction of basaltic glaciovolcanic deposits at Askja Volcano, Iceland, using lithofacies and geomorphology

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Askja volcano, Iceland, consists of basaltic glaciovolcanic complexes, at least three calderas, and numerous Holocene lava flows. The deposits of the glaciovolcanic Austurfjöll complex, the eastern most massif of the volcano, have been described in detail in order to reconstruct the environmental conditions during its construction. This complex was constructed by two phases of Pleistocene ice-confined volcanism indicating maximum ice thicknesses for both phases between 600-900 m. (Ages are presented in companion abstract by McGarvie and eruptive evolution of the massif is discussed by Skilling). Ice thickness calculations are based on morphological constraints (i.e. elevation and distribution of subaqueous lithofacies) and volatile analysis of pillow lava glass rinds. Key deposits for environmental reconstruction of the glaciovolcanic Austurfjöll complex include subaqueously emplaced effusive and explosive volcanic deposits, subaerial pyroclasts and lavas and lava breccias, glacial erratics, and putative glacial tillites. The massif is dominated by subaqueously emplaced sequences; consequently, it is the subaerial and glacial deposits that are critical indicators of variability within the ice-confined system. Subaerial lavas are identified as having scoriacious tops (which can be glacially scoured), iron (reddened) oxidation, and characteristic at Austurfjöll, high density relative to subaqueous lavas. Subaerial pyroclastic deposits contain red scoria and armored lapilli. Blocks of subaerial lavas occur in both subaerial pyroclastic deposits, and subaqueous / emergent breccias. Glacial tillites are composed of poorly sorted massive deposits with rounded, and scoured clasts of varying compositions in a ashy matrix. The occurrence of such units allows the reconstruction of periods of ice presence and associated water levels around the complex.

The timing of these events relative to the overall growth of the massif is reconstructed based on their facies associations with subaqueous units. Subaerial deposits between two subaqueous units likely represent temporary periods of exposure including rapid drainage events. Those subaerial and subaerial-component deposits on top of subaqueous units near the top of the complex (along the Öskjuvatn caldera rim) suggest the emergence, or near-emergence of the complex. Additionally, the position of glacially scoured lavas with putative tillites at the base of the sequence allows the reconstruction of ice advance prior to the major eruptive periods of the Austurfjöll eruptive activity. Such detailed mapping and lithofacies investigations reveal the dynamic nature of ice-confined lake water levels produced by a long lived basaltic ice-confined volcano. These data, in conjunction with new K/Ar dates,provide important new data on the thickness of the ice sheet in this part of central Iceland during the early to mid-Weichselian.

Eruptive gap during the Last Glacial Maximum at Nevado de Toluca Volcano, Mexico.

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The Nevado de Toluca Volcano (NdT) is a 4600 m a.s.l. stratovolcano, situated 80 km SW of Mexico City and 20 km S of Toluca town, at the boundary between the central and eastern sectors of the Trans Mexican Volcanic Belt (TMVB). The activity at NdT started 2.6 Ma ago and was dominated by the extrusion of mainly andesitic lava flows and domes that ended approximately 1.2 Ma ago. After a long period of quiescence, characterized by erosive processes and sector collapse, the magmatic activity re–started at 42 ka BP (Macias et al., 1997). The Pleistocene–Holocene period was characterized by different eruptive phases, including five dome collapses dated at (14C ages) 37, 32, 28, 26.5 and 13 ka (Macias et al., 1997) and four plinian eruptions at 36, 21.7 (Lower Toluca Pumice), 12.1 (Middle Toluca Pumice) and 10.5 ka (Upper Toluca Pumice) (Macias et al., 1997; Arce et al., 2003; Capra et al., 2006). The eruptive sequence is topped by a surge deposit dated at ~3.3 ka B.P.

By comparing the occurrence of the eruptive events during late Pleistocene–Holocene with a high–resolution paleoclimate record from Guatemala, no eruptive activity is recorded in the stratigraphic record of the volcano during the Last Glacial Maximum (22,000–18,000 cal BP, LGM). During this period, extensive moraine deposits have been documented on the volcano slope, up to 3400–3600 m a.s.l. Because the last eruptive activity previous to this period was the Lower Toluca Pumice, a plinian eruption that originated a 20 km–high column, and no large dome collapse activity is found afterward (only the 13 ka El Refugio block–and–ash flow, limited to the NE flank), we assume that the volcano shape was similar to the present, with an open crater but probably at a higher altitude, since the actual shape is due to the ~10.5 ka catastrophic Upper Toluca Pumice plinian eruption that emitted more than 8 km3 of magma. Under this scenario, and considering the stratigraphic record, it is clear that during the LGM the volcano was quiescent or only suffered very minor eruptions that deposited material on the glacier and was subsequently eroded and remobilized. The stratigraphic record of the volcano shows very large eruptions whose deposits are spread all over the slopes up to 30 km from the vent. Therefore, even with the presence of an extended glacier, a large eruption with such characteristics should have been preserved on distal areas. We suggest a correlation between a very low eruptive phase of the volcano and the presence of a glacier during the LGM. An important issue to resolve would be to estimate the glacier thickness and evaluate how it could have affected the magmatic pressure on the conduit up to the magma chamber. This is an ongoing project and some preliminary results will be presented, including a stratigraphic record of epiclastic sedimentation during the LGM at Nevado de Toluca Volcano.

Viscous flow behavior of tholeiitic and alkaline Fe-rich Martian Basalts

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The chemical compositions of Martian basalts are enriched in iron with respect to terrestrial basalts. Their rheology is poorly known due to the lack of experimental data. Therefore, empirical models for the calculation of viscosity from composition are a priori not applicable a priori to these silicate melts. Here, we experimentally determine the viscosity of five synthetic silicate liquids having compositions representative of the diversity of Martian volcanic rocks over time including primary Martian mantle melts and alkali basalts. The concentric cylinder method has been employed between 1500 °C and the respective liquidus temperatures of these liquids. The viscosity near the glass transition has been derived from calorimetric measurements of the glass transition. Fitting parameters were obtained for the non-Arrhenian behavior of the melts viscosity over a wide temperature range. Comparison with empirical models reveals that Giordano et al., 2008 offers the best match with experimental results, whereas the model proposed by Hui and Zhang, 2007 is inappropriate for the compositions considered.

Melts thought to represent primary melts in the Amazonian period (<3.0 Ga) exhibit a slightly lower viscosity in comparison to those of the Hesperian period (age <3.7 Ga), but this difference is not deemed sufficient to produce an overall shift of Martian lava flow morphologies over time. Rather, the details of the crystallization sequence (and in particular the ability of some of these magmas to form spinifex texture) is proposed to be a dominant effect on the viscosity during Martian lava flow emplacement and may explain the lower range of viscosities (10^2 - 10^4 Pa ·s) inferred from lava flow morphology for the Amazonian period flows. In contrast, differences between the rheological behavior of tholeiitic vs trachy-basalts are significant enough to affect their emplacement as intrusive bodies or as effusive lava flows. The upper range of viscosities (10^6 - 10^8 Pa ·s) suggested from lava flow morphology may be explained by the occurrence of alkali basalt. Andesitic lavas are not required to explain these values. At superliquidus conditions, the Martian basalt viscosities are as low as those of the Fe-Ti-rich lunar basalts, similar to the lowest viscosities recorded for terrestrial ferrobasalts, suggesting fast ascent rate of magma. These low viscosities may be one of the key parameters to understand the abundance of primitive magmas at the surface of Mars (see Baratoux et al., this session).