Multiscale parametric imaging of basaltic lava flows

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Basaltic volcanism is widespread on the terrestrial planets and recent orbital data from Mars have revealed excellent examples of flow morphology. On Earth, it is the most common form of extrusive activity, with over half of the volcanoes consisting largely of basalt. For example, the recent 2012 eruption of Tolbachik volcano in Russia was large enough to produce significant flows that were emplaced over snow/ice and observed with both ground and satellite based imaging. Larger outpourings of basaltic lava in the past have been coincident with mass bioextinction events, and even small eruptions can pose hazards to the local and regional populations. Therefore, understanding flow emplacement, cooling, and morphology is important, with one approach being the use of thermal infrared (TIR) data. Basaltic flows rapidly form a chilled glassy crust after emplacement, with a lower percentage of preserved vesicles than the lava directly below. With time, the crust will stretch, cool, thicken, fold, and possibly spall off due to vesiculation of the lava and continued flow. The crust can also remain intact to form the exposed primary flow surface, which can be later disrupted on a larger scale during the emplacement process and flow inflation. The thicknesses of a glassy crust directly affects the interpretation of the TIR temperature and emissivity data. The TIR wavelengths are particularly sensitive to silicate mineralogy because of the presence of the strong absorption bands formed by vibrational motions of the Si-O and Al-O bonds. However, there has been a debate on whether molten materials have dramatically lower TIR emissivities than their solidified counterparts. This unknown not only affects the derived compositional information, but also feeds into models of the radiative cooling efficiency and flow formation. Moreover, the crustal rheology of active flows can be directly estimated once the TIR data is corrected for the emissivity of the molten/glassy components. We have performed multiscale parametric imaging of basaltic lava flows over the past decade, including the development of a novel laboratory-based micro-furnace to acquire the first TIR emissivity measurements of molten silicates. Results confirm the dramatic lowering of emissivity following the phase change from a solid to a melt. We have also collected and analyzed field-based TIR and LiDAR data of active pahoehoe flows at Kilauea volcano, Hawaii. Spaceborne data of these flows in Hawaii and the new ones in Kamchatka are now being compared to laboratory and field data as well as to similar flow morphologies on Mars. The goal of all these studies is to accurately determine flow mineralogy/vesicularity, model crust formation, cooling, and inflation using TIR data at multiple spatial and topographic scales. The results are providing a better understanding of the morphology and emplacement dynamics of basaltic flows.

Investigating Lava Properties using Experiments, Video Analysis, Infrared Thermometry and Numerical Flow Models

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The thermal and mechanical properties of lava are primary controls on lava flow behavior and are critical parameters in flow simulations. However, these properties are difficult to measure at field conditions or correctly extrapolate from the scale of small-size samples. We address this challenge by conducting controlled experiments using lab-made, meter-scale basaltic lava flows and carefully monitoring their cooling and deformation using high spatial and temporal resolution video and infrared cameras.

Our experimental setup is part of the Syracuse University Lava Project (http://lavaproject. syr.edu) and includes a large furnace capable of melting up to 450 kg of basalt at temperatures well above the basalt liquidus. The lava is poured out of the furnace to produce meters-long flows. To date, we have poured lava on sand, gravel, steel, ice and snow, onto unconfined planes, confined channels, and planes with obstacles. This experimental setup is probably the only facility that allows such large scale controlled lava flows made of natural basaltic material. We record the motion of the lava using a high-resolution video camera placed directly above the flows, and the temperature using forward-looking infrared (FLIR) cameras and thermocouples.

After the experiments, we analyze the images for lava deformation and cooling behavior. To extract a surface velocity field from the videos, we employ the technique of differential optical flow, which uses the time-variations of the spatial gradients of the image intensity to estimate velocity between consecutive frames. An important benefit for using optical flow, compared with other velocimetry methods, is that it outputs a spatially coherent flow field rather than point measurements. We demonstrate that the optical flow results agree with other measures of the flow velocity, and estimate the error due to noise and time-variability to be under 30 percent of the measured velocity.

We compare the observations with numerical forward-models to constrain the thermal and rheological parameters and laws which best describe the lava. Our forward flow models are obtained by solving the Stokes flow equations using the finite- element method. The model domain is an unstructured mesh defined by the geometry of the observed flow. We explore a range of rheological parameters, including the lavas apparent viscosity, the power-law exponent m and the thermal activation energy. We find that for the high-temperature portion of the flow a weakly shear-thinning or Newtonian rheology (m>0.7) with an effective activation energy of B=5500J gives the best fit to the data. These results agree well with predictions of the composition-based Shaw (1972) and GRD model (Giordano, Russell and Dingwell, 2008).

In summary, we demonstrate that our experimental lava flows allows for a careful documentation of flow evolution and control over flow variables, which leads to understanding of lava flow dynamics in unparalleled detail.

Topographic and stochastic influences on pāhoehoe lava lobe emplacement

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Basalt is the most common rock type on the surface of terrestrial bodies throughout the Solar System and—by total volume and areal coverage—pāhoehoe flows are the most abundant form of basaltic lava on Earth. Models of flow field development are important for understanding the hazards imposed by terrestrial lava flows and for interpreting the significance of lava morphologies on Earth and other planetary surfaces. However, at present, such models are limited by the availability of dynamic dimensional measurements of active flows and the characterization of random influences on flow emplacement. This study addresses this issue by characterizing topographic and stochastic influences on active pāhoehoe lobes from Pu‘u ‘Ō‘ō on Kīlauea, Hawai‘i, during 21–26 February 2006 using oblique time-lapse stereo-photogrammetry and differential global positioning system (DGPS) measurements. At this time, the local discharge rate supplying lava to a distal lobe was 0.0061 $\pm$0.0019 m^3/s. This rate was generally constant during the period of observation, but every 4.13 $\pm$0.64 minutes there was a 2- to 6-fold increase in the areal coverage rate. This periodicity is attributed to the time required for the pressure within the liquid lava core to exceed the cooling-induced strength of its margins. The pāhoehoe flow advanced through a series of down-slope and cross-slope breakouts, which began as 0.2 m-thick units (i.e., toes) that coalesced and inflated to become approximately meter-thick lobes. The lobes were thickest above the lowest points of the initial topography and above shallow to reverse-facing slopes, defined relative to the local flow direction. The flow path was typically controlled by high-standing topography, with the zone directly adjacent to the final lobe margin having an average relief that was a few centimeters higher than the lava-inundated region. This suggests that microtopography (i.e., cm-scale relief) can exert strong controls on pāhoehoe flow paths by impeding peripheral toes and confining the interior portions of flow. This study also develops models to explore the effects of random and correlated growth processes during the emplacement of pāhoehoe lobes. Results show that cycles of enhanced areal spreading and inflation can be reproduced by simulating the preferential growth of lava lobes in the direction of new breakouts using a probability distribution that governs the possibility of the correlated emplacement of lava parcels from the flow margins. These examples demonstrate the value of time-series observations of active pāhoehoe emplacement processes. It further clarifies the need for future observations of dynamic topography coupled with surface temperature distributions to determine how thermo-rheological parameters affect the location and frequency of new breakouts as well as the balance between areal spreading and inflation.

Investigating the formation and evolution of channel networks in Hawaiian lava flows with airborne LiDAR analysis

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New ways of imaging lava flow morphology are providing important new insight into lava flow dynamics and emplacement conditions. Here we focus on airborne LiDAR data for recent lava flows at Mauna Loa and Kilauea, Hawaii, USA, which highlight both the complexity and diversity of lava channel networks. Importantly, the form of the channel network geometry — broad and distributary or narrow and confined — appears to exert a primary control on both the rate of flow advance and the final flow length.

We map channels using flow morphology, LiDAR intensity, and aerial and satellite imagery. Extracted channel cross-sections provide data on the final state of individual channels. Analysis of lava channels as interconnected networks, with tools developed for studying brain connectivity, can be used to determine the best-connected channels, most important junctions, and simplified flux distribution. To quantify the influence of pre-eruptive topography, we have constructed DEMs using aerial photographs calibrated by LiDAR data outside the extent of the flows. From these data we can measure both pre-eruptive slopes and the scales of obstacles in the flow path. Subtraction of the pre and post-emplacement DEMs also provides whole-flow thickness maps.

Our analysis of Hawaiian channel networks reveals that regions of higher slope tend to generate multiple parallel channels. The ratio of the flow height to obstacle height, as well as the size and geometry of the obstacle, determines whether the flow will surmount or split around the obstacle. From this we infer that obstacles are more likely to influence the flow path on steep slopes where flows thin and speed up. We have also combined our flow thickness maps with the results of channel network analysis to show that the most built-up parts of the channels occur at major bifurcations along high-flux channel reaches. These results have important implications for understanding lava flow emplacement, developing predictive models of flow advance, and designing flow diversion barriers. By controlling the distribution of lava flux from the vent through the flow, the channel network governs both the final flow length and advance rate. Channel bifurcations cause flows to slow down and shorten; conversely, topographic focusing may allow flows to travel further and faster than in distributary networks. For this reason, understanding the relationship between the topology of the channel network and the underlying topography that produces it, are critical for developing accurate models of lava flow field development. The scale and geometry of underlying topography that can split or confine the flow could also inform the size and placement of diversion barriers. Finally, understanding the relationship between eruption parameters and channel network morphology facilitates the interpretation of these features in planetary flows, where observations are limited to those made by remote sensing.

Detection of subtle lava flow morphology in densely forested areas by airborne LiDAR survey and Red Relief Image Map

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The vast increase of the volume of three dimensional topographic data acquired by Airborne LIDAR extends the possibility of the visualization method. High resolution three dimensional topographic data potentially holds useful information which can not be expressed by ordinal visualization method. We have developed Red Relief Image Map (RRIM) for an interpretation of micro topography. This new visualization method is based on multi-layered topographic information computed from gridded three dimensional data (DEM). RRIM can visualize the topographic slope, concavities and convexities at the same time. In this study, we will show a microtopographical image of lava flow at Fuji volcano in Japan. We executed detailed surveys and analysis for the micro topography of Aokigahara lava flows erupted in 864 to 868 on the north western slope of Fuji Volcano using airborne LiDAR survey and Red Relief Image Map. New crater at the 864 to 866 eruptions named "Kudariyama crater" was found to the WNW of "Ishizuka crater" by this analysis. "Kudariyama to Ishizuka craters" and "Nagaoyama to Koriike craters" were formed at the northwestern slope of the volcano in the 864 to 866 eruptions. The linear graben structures on the lava flows ranging, 2-5 km in length must have been made by the collapse of the roof of lava tunnels. These structures suggest several lava tunnels must have been existed beneath the flows. These lava tunnels play an important roll to transport molten lavas from source craters to the front of flows, especially in large scale eruptions. We are not able to obtain this information from a clasic photointerpretation and topography map reading technique. Therefore, airborne LiDAR survey and Red Relief Image Map are indispensable for a volcano topography investigation in densely forested area.The application of RRIM is not only LiDAR data but also wide variety three dimensional data such as SRTM3, GTOPO30 and ETOPO2.

Longitudinal variation of the morphology of the Geomunoreum lava cave system in Jeju Island, Republic of Korea

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Morphology and dimension of lava tubes change continuously because of accretion and erosion of lava during the course of lava tube system formation. In this study, we investigate the pattern and cause of lava accretion and erosion from the morphological changes inside the Geomunoreum lava cave system extending ca. 13 km from source to shoreline in the northeastern part of Jeju Island, Korea. We used an electronic total station and 3D laser scanning device for a detailed and quantitative survey of six lava caves of the cave system from upstream to downstream.

The survey shows that (1) the upstream portion of the cave system has three- or four-story passages with severe collapse of the ceilings and walls above the floors that have larger slope gradients than the other portions, (2) the relatively long midstream portion typically has two-story passages with little collapse of the ceilings and walls and very gentle floors, and (3) the downstream portion is smaller and has simple and single-story morphology with several lava falls and gentle floors.

The longitudinal variation of lava cave morphology suggests that thermal erosion by lava was an important process in the upstream portion of the cave system whereas lava accretion was more important than erosion in the downstream portion. The longitudinal variation of lava accretion and erosion is attributed to 1) longer duration of lava flows in the upstream reach, resulting in more erosion of the bottom of tube, and 2) sluggish movement or stagnation of lava in the downstream reach, allowing more time for lavas to accrete on the ceilings and walls. We infer that the longer lava storage in downstream tube is related primarily with the profile of a shield volcano, which commonly becomes gentler downstream and can cause deceleration of lava flow. The detailed and quantitative documentation of the morphological changes reported in this study can help understand the development and evolution for other lava cave systems common in gently sloping shield volcanos worldwide.

Using pillowed flows to locate effusive centers and explore for volcanogenic massive sulfide deposits: an example from the Archean Abitibi Greenstone Belt of Canada

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There is a well established relationship between the locations of submarine effusive centers and volcanogenic massive sulfide (VMS) deposits. The fluids that create the Cu-Zn-Pb-Ag-Au VMS deposits rise along synvolcanic faults in extensional environments; these faults can also control the location of dikes feeding felsic to mafic lavas. Therefore, locating effusive centers can help target mineral exploration in prospective districts. Pillow lavas are well suited for this purpose due to their relatively consistent lateral facies and thickness variations. In the absence of pre-eruptive topography, the maximum thickness of such lavas should be found near the vent. Mafic to intermediate flows tend to be massive to pillowed in proximal areas; the proportion of hyaloclastite and pillow breccia increases, whereas the proportion of massive rocks decreases, away from the source. Pillow size can decrease in distal areas. For ancient successions, such variations can be documented in outcrop but also in exploration drill cores. Furthermore, if it can be assumed that a stratigraphically and geochemically consistent package of flows emanated from a single vent area, then facies variations can be compiled for this entire package rather than individual flows. This approach is illustrated for a 132 m-thick package of tholeiitic basaltic andesite flows in the Hebecourt Formation (Blake River Group) from the 2.7 Ga Abitibi Greenstone Belt in Quebec, Canada. These non-vesicular variolitic rocks are part of a submarine lava plain, perhaps in a back-arc basin. The proposed effusive centre for the basaltic andesite unit, identified using thickness and facies variations, is just above replacement-style VMS mineralization in an underlying rhyolite flank breccia.

Emplacement of continental flood basalt lava flow fields

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We examine the conditions required to explain the great length (up to 1000 km) and the large volume (perhaps up to 10,000 cu km) of continental flood basalt lava flows. Two simple requirements for a long lava flow are 1: sufficient magma held in a chamber to supply a large volume of lava, and 2: an emplacement system that can transport the liquid lava from vent to flow front without the lava freezing. For the common lava composition in many provinces, including the Columbia River basalt (CRB) flood basalts, this is a cooling range of only approximately 150 plus or minus 50 C. During flow-field emplacement, a combination of cooling and degassing promotes groundmass crystallization that is crucial in determining the resulting flow characteristics. All large lava flows in flood basalt provinces are exclusively pahoehoe, or closely related varieties. This is mandated by the fact that aa lava flows are too thermally inefficient, cooling by approximately 2 to 5 C per km in the feeder channels and rapidly developing groundmass crystals, to attain lengths much in excess of 100 km on Earth. Only the insulated flow model for pahoehoe flow fields, where the dominant lava body is the inflated sheet lobe, fits all the quantitative criteria required to explain the great extent of flood basalt flows: effusion rates are on the order of 1000s cu m per sec, lava travels from the vent to the flow front in days to weeks, heat losses are restricted to as little as 0.001 to 0.1 C per km, and eruption durations are years to centuries. These values dictate that eruptive volumes must be 100s to 1000s of cu km, a condition met by only by lava flow eruptions in flood basalt provinces. Such enormous mean output rates from fissure vents (100s-1000s cu m per s) would feed numerous inflating sheet lobes (each containing 0.05-0.5 cu km of lava), into which most of the lava output is emplaced. However, each lobe need only have local injection rates of a few to 10s of cu m per second in order to thicken within plausible time-frames (months to a few years). Significantly higher mean output rates (equating to much shorter eruption duration rates) do not provide sufficient time to explain the growth of inflated lobes with the observed crustal thicknesses and show that, compared with almost all historic basaltic volcanism, rates at which typical CFB lavas formed were at times spectacularly high, especially for certain parameters. New results explaining the details of internal lava transport within simple flow fields from the CRB suggest that there is only time to emplace the observed number of sheet lobes if several are forming at once. Vent systems for flood basalts are poorly understood, and maps of vents on the 180-km-long CRB Roza fissure system will help us understand the nature of venting and eruption columns, important for assessment of the environmental impact of flood basalt volcanism.

Lava architecture and vent distribution in an active rift (Manda-Hararo, Afar, Ethiopia)

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The Manda-Hararo rift segment in Afar (Ethiopia) has been actively undergoing a period of dyke injection, extension and volcanism since an initial fissure event in 2005. We present the results of a detailed mapping, remote sensing, geochemistry and geochronology project to characterise the spatial and temporal distribution of volcanism in this rift segment and the interplay between tectonism and magmatism in this active extensional setting at the continental-oceanic crust transition.

Characterisation of the morphology of individual lavas and the architecture of stacking multiple lavas within a province requires a unique indentifying feature for each individual flow field. In the absence of a unique chemostratigraphic, palaeomagnetic, or petrologic fingerprint, field investigation and good exposure may be the only way of tracing a single lava flow from its source to the distal reaches of a flow field. High-resolution mapping at the scale of individual lavas in Afar, a poorly accessible region, required the development of a mapping methodology. The mapping approach involved remote sensing and three-dimensional image analysis of topography and surface rock chemistry based on mineral maps generated from false colour composites of Landsat ETM+, ASTER and hyperspectral (Eagle and Hawk) imagery together with aerial photographs. We combined the datasets with DEMs derived from LiDAR, SPOT5 and ASTER within GeovisionaryTM software for interpretation within an immersive visualisation suite enabling simulation of a fieldwork-based investigation. Interpretations derived from this approach were ground-truthed by targeted field studies and samples were acquired for 40Ar-39Ar dating.

Results from the mapping establish the eruption history of the Manda-Hararo rift at the scale of individual eruption units and enables identification of the structures, textures and spectral signatures of volcanic complexes that can be combined with fieldwork to ground validate the composition, character and age of lavas. The investigation shows a spread of eruption sites, vent character, and young volcanic ages (<10 ka) dispersed around the axis of the rift segment suggesting that crustal accretion may not be limited to the central spreading centre. Linear basaltic fissure vents dominate the topographic rift axis whilst point source basaltic vents are located up to 7 km away from the rift axis. Recent volcanism and observation (from high-resolution geophysics and satellite geodesy) of dyke emplacement in the last 7 years suggests focused magmatic accretion in the rift axis. However, our mapping reveals that abundant cinder cones and vents are also located off-axis suggesting past activity of this segment has included the development of oblique and off-axis magmatic plumbing systems. This observation is similar to models of slow-spreading magmatic mid-ocean ridge (MOR) segments, and contrasts with repetitive eruptions from central fissure vents in fast-spreading MORs.

Dynamics of rhyolitic obsidian flow evolution at Cordón Caulle, Chile

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The 2011-2012 rhyolitic eruption of Cordón Caulle (Chile) has provided an unprecedented opportunity to observe an evolving obsidian lava flow. The eruption began explosively on June 4th 2011, with lava first reported on June 15th 2011. By January 2013 the lava had reached >6 km^2 area and >0.3 km^3 volume, and continued to locally advance, despite effusion at the vent halting in April 2012.

We present observations, images and samples of the lava flow carried out in January 2012 and January 2013, plus satellite imagery. The flow field comprises two major branches (NW and SE), each 2 km long, 1 km wide, 35 m thick and emplaced onto shallow topography. These branches exhibit 500-700 m-wide central channels of blocky lava with distinctive surface folding (ogives), bound by near-linear, nested levees. The outer portion of the flow consists of many dozens of breakout lava lobes, typically 50-100 m across, which originate from the outermost levees and create an indented flow margin. By contrast, there is a third, minor flow branch that extends down steep slopes 2 km to the NE. This is considerably narrower (100-300 m), thinner (20 m) and morphologically simpler. Blocky lava facies dominate the lava flow surfaces, comprising metre-scale blocks of vesicle-poor, glassy lava, with local coarsely vesicular pumice. By contrast, lava breakouts consist of darker, more continuous lava spines and slab tens of metres across, with abundant crease structures and highly deformed vesicles.

An automated photo-reconstruction technique (SfM-MVS, a combination of structure from motion and multi-view stereo algorithms) was used to create 3D models of portions of the lava flow front on repeated visits, allowing precise quantification of morphological changes over timescales of 3 hours, 6 days and 1 year. Evolution of the margin of the NW flow branch over 6 days in 2012 involved spreading of 1-2 m/day of blocky lava facies, perpendicular to the channel axis, with more rapid advance of breakout lava (3 m/day) in a discrete, non-perpendicular direction. Zones of rapid advance correspond with the loci of most frequent rockfall events, which occurred from active breakouts at 1-10 minute intervals in both 2012 and 2013.

Our observations reveal the striking similarity between the dynamics of the Cordón Caulle rhyolite and far better-understood compound basaltic flow fields, whose late-stage evolution involves the breakout of lava lobes from stalled lava margins. We emphasise the importance of bedrock slope on controlling lava structure and evolution. The localized persistence of lava advance eight months after ceased vent supply indicates efficient thermal insulation, which serves to significantly prolong the duration of hazardous activity. Finally, endogenous growth can clearly play a major role in obsidian lava flow advance, which demands the reappraisal of the architecture, longevity, and emplacement mechanisms of rhyolitic lavas.

Dynamical regime and advance rate of lava flows using its deposit characteristics: 2 cases from the Lonquimay and Villarrica volcanoes, Southern Andes of Chile

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The advance of lava flows is controlled by the effusion rate, rheology, topography and cooling effects. Consequently, the deposits of lava flows would reflect the interplay between these factors. We tested a methodology to estimate the variations of flow rate and velocity of ancient lava flows using its deposit dimensions, textural characteristics and petrography. We studied the deposits of two lava flows with contrasting styles generated during historical times in the Southern Andes of Chile: the 1971 eruption of Villarrica volcano and the 1988-89 eruption of Lonquimay volcano. Both eruptions have a record of its duration and advance rate, so we can test different dynamical models in order to fit better the available data.

The Villarrica eruption lasted a couple of days and the resulting lava flow reached a length of 16.5 km, with thicknesses of 3-15 m, depending mainly on the channelling of the flow. The morphology is transitional between Pahoe-hoe and Aa. Clasts morphologies are mainly rubbly and slabby, ranging from a few cm to a couple of meters in diameter. The lava has a basaltic andesitic composition, with a porphiric texture and a vitric groundmass.

The Lonquimay eruption, on the other hand, lasted a year and the lava flow reached a length of 10.2 km, with increasing thicknesses from 10 m near the vent to more than 40 m at the front. The morphology is transitional between Aa and blocky. Major structures include levees, crease structures, compressional ridges and spines more than 5 m height towards the front. Surface blocks could be rubbly or fragments with angular and planar surfaces. The lava has an andesitic composition, with an aphanitic texture but with a very crystalline groundmass.

We used 3 simplified, 2-D models, assuming different dynamical regimes in each case, to estimate the advance of the flows: a viscous regime, a crustal yield strength or an internal yield strength. The rheology of the flows is modelled as a Herschel-Bulkley fluid and was estimated with samples taken at different locations through the flows, using glass composition (to calculate the liquid viscosity) and crystal content.

The modelling of the advance of these flows, together with field observations, suggests that the Villarrica flow was controlled by the internal viscosity of the lava with a viscosity of 10^4-10^5 Pa s, while the Lonquimay flow was controlled by the crustal yield strength, with a value of $2x10^5$ Pa.

Our results show that it is possible to estimate the dynamical regime, velocity and flow rate variations of ancient lava flows, and not only the mean effusion rate, combining the dimensions, morphology and petrography of the deposits.

Generation of pillow basalts in Iceland, submarine to subglacial.

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Pillow basalt formations are common in Iceland, most examples formed by subglacial eruptions during the last major glaciation. These formations are concentrated within Iceland volcanic zone and formations younger than 2.8 MA. In this talk I present an investigation of basalt pillow lava formations from several places in Iceland, among others Surstey, Kverkfjoll, Langjokull, Reykjanes and Kirkjubajarklaustur. Presenting not only the youngest pillows formed in Iceland but also show difference between subaquatic and subaerial to subaquatic pillows. Frequent occurrence of pillows in Iceland is due to the ice sheet during the last major glaciation. The geological features of the pillows can be used in order to constrain the eruptive and environmental conditions. Vesicular cores in many of the pillows, are relate to a depressurization event during eruption caused by jokulhlaup. Pillows occur in three main types of settings in Iceland, ridges and hillocks entirely made up of pillows, such formations only being found within the centre of Iceland, the lower most part of hyaloclastite formations in tuya-mountains and hyaloclastite ridges, these formations being observed in the centre of Iceland as well as towards the coastal areas, and as products of initially subaerial lava flows that have subsequently flowed into water. The sharp division between pillows and hyaloclastites observed in many subglacial volcanic formations reflects eruptive pressure conditions. Morphological studies of pillows, viscosity considerations, analogue experiments, and numerical calculations suggest that pillow size and shape variations are primarily controlled by eruption rate and viscosity. The cooling history of a pillow pile can be divided into two main stages. In the first stage the pillow is erupted into water. In the second stage the pillow is buried beneath later pillows and becomes part of the pillow pile. Any pillow is then surrounded by other, still hot pillows and cooling is now by water or steam through the pillow pile. After burial the cooling rate is expected to slow. Aspect of subglacial eruptions is heat loss from the pillow basalt results in rapid melting of the surrounding ice. The resulting large bodies of water are unstable and can escape from the ice in catastrophic outbursts or jokulhlaups. Sudden changes of environmental pressure can feedback into the eruptive activity, causing vesiculation and a switch to explosive activity. Confining pressure influences magma degassing. At low pressures the most abundant magmatic volatile is water, since the much less soluble carbon dioxide starts degassing at much greater depths. The rapidly quenched glassy rims of pillows provide information on the preeruptive volatile content of the magma. Since water solubility in magmas is pressure dependent it can be used to estimate erupting pressures, provided the magma is volatile saturated. The pressures can be used to estimate the thickness of water or ice.

Dynamics of pillow-dominated subglacial eruptions recorded in Undirhlíðar quarry, Reykjanes Peninsula, southwest Iceland

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The dynamics of pillow-dominated subglacial eruptions have been investigated in Undirhlíðar quarry, southwest Iceland, which exposes an almost complete cross-section of a subglacial pillow ridge. Quarry walls are dominated by pillow basalts ranging in size from 0.5 m to 3 m in diameter. Two stratigraphically and lithologically distinct lenses of volcanic tuff-breccia are interbedded with pillow lava units in the eastern half of the quarry. One of the units, comprising a poorly sorted range of clasts, appears to be made predominantly of broken fragments of pillow lava. The other unit shows somewhat better sorting and has clasts with intact vitric rims, interpreted to be volcanic bombs. Thin (<30 cm) laterally continuous layers of indurated yellow vitric lapilli tuff separate some pillow units. Three dikes have been observed, at least one of which feeds an overlying pillow unit. The Undirhlíðar units define two mineralogical and chemical populations: (1) incompatible element enriched (Nb/Zr ~0.15) rocks comprising the olivine-free lower (older) pillow units, and (2) less enriched (Nb/Zr ~0.125) units including the olivine-phyric dikes, west wall pillows, and the upper (younger) pillow units. The combined lithostratigraphic, petrographic, and geochemical relationships suggest a 4-stage emplacement model. (Stage 1) An initial effusive phase erupts the incompatible element enriched, olivine-free pillow lavas, building the bulk of the subglacial ridge. (Stage 2) An explosive phase generates the lens of tuff-breccia on the eastern side of the ridge. (Stage 3) A second effusive phase on the west side of the quarry intrudes the initial effusive deposits and erupts pillow lavas that drape over the western edge of the existing ridge. This effusive phase is distinguished from the first as a distinctly olivine-bearing batch of magma less enriched in incompatible elements. (Stage 4) A final effusion on the east side of the quarry intrudes tuff-breccia formed by partial collapse of a pre-existing pillow unit, and erupts a capping layer of pillow lavas. This effusion is compositionally similar to the previous effusive phase (Stage 3), but large olivine phenocrysts are absent. Our model for the formation of Undirhlíðar adds to the observations of previous workers by documenting two important relationships: (1) the specific stratigraphic sequence of vitric tuff-breccia cut by dikes that feed pillow lava flows emplaced immediately above the tuff-breccias (TDP lithofacies association), and (2) the chemical transition that coincides with the TDP lithofacies association from olivine-free incompatible element enriched rocks to olivine-bearing rocks that are less enriched in incompatible elements. These observations suggest that explosive volcanism may play an important role in pillow-dominated subglacial eruptions, and that the formation of subglacial pillow ridges can record complex magma supply dynamics.

Morphometry and morphology of lunar mare domes from SELENE terrain camera

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A number of smooth low domes with gentle convex-upward profiles are distributed in lunar maria. They are called lunar mare domes, and have long held the interest of the planetary and volcanological communities.

Lunar mare domes are characterized by circular to somewhat irregular outline, a generally convex shape, relatively low slopes (generally less than 10 degrees), and diameters ranging up to 30 km. Some show summit craters, and occur in groups on mare plains. Lunar mare domes have been detected during telescopic study of the Moon since 18 century. Previous studies were used Lunar Orbiter, Apollo, Clementine, and Lunar Reconnaissance Orbiter data, and almost agree that most lunar mare domes are volcanic origin. But the details of mare domes are still not well understood, because of shortages of spatial resolution, favorable light condition, and limited coverage of imaging area.

In this research, we use Terrain Camera (TC) data of SELENE. The TC carried on SELENE is a panchromatic push-broom imager with two optical heads (TC1 and TC2) to acquire stereo data for the entire surface of the Moon when the sun elevation is higher than 30 degrees. The slant angles of TC1 and TC2 are +15 and -15 degrees, relative to the spacecraft flight direction for the nadir vector. Each head has a linear CCD sensor of 4096 pixels. They have 10-m cross- and along-track resolutions respectively, and 5-m vertical resolution at the SELENE nominal altitude of 100 km. The TC also acquired non-stereo data when the sun elevation was lower than 30 degrees. These low sun-elevation data is powerful tool to analyze mare domes with very low slopes.

We analyze the morphometry and morphology of mare domes in Hortensius, Milichius, Cauchy, and Argao areas by the TC data, and compare with terrestrial small shield volcanoes of Hawaii, Mexico, Iceland, and NW USA. We will discuss the formation of lunar mare domes.

Petrological characteristics of Takayubaru lava flow extruded immediately before the catastrophic Aso–4 pyroclastic eruption in central Kyushu, Japan

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Takayubaru lava flow was extruded during the formation of Omine pyroclastic cone which is located 5 km from the western caldera rim of Aso. Short interval time between Takayubaru and Aso–4 volcanic products was estimated by the lack of intercalating soil formations and nearly identical K–Ar ages for the two.

Observation of drilling core samples shows that Takayubaru lava has upper clinker part, massive part and lower clinker part. Lack of weathering and clinkers are not observed inside the massive part indicating that Takayubaru lava is a single flow unit.

Takayubaru lavas contain about 20 vol.% phenocrysts incluring clinopyroxene, orthopyroxene, plagioclase and opaque minerals. Most of plagioclase phenocrysts show characteristic fractured texture, indicating melting along cleavage and fractures. They also contain hornblende microphenocysts (<0.3 mm) varing from fresh to complete opacites.

There is no correlation between phenocryst abundance and chemical composition of Takayubaru lava. Takayubaru lava and Omine scoria show no clear difference in phenocryst abundance and in chemical composition. They both have greater abundance of phenocryst than Aso–4 pumice. Silica content varies from 63 to 66 wt.% for Takayubaru lavas, and 61 to 66 wt.% for Omine scoria samples. The upper to middle part of drilling core is homogenous(<1wt.% SiO_2). In contrast, the samples from the lowest part and the farthest part have less silica than others, with about 2% variation. Aso–4 pyroclastic deposits contain a wide variation of basalt to basaltic andesite scoriae (SiO_2=49–56 wt.%) and dacite pumice (SiO_2=65–72 wt.%). In contrast, Omine scoria and Takayubaru lava do not contain mafic magma as observed in Aso–4 eruption. The compositional trend of Takayubaru lava is different from that of the silicic member of Aso–4 deposit. It seems that neither the injection of mafic magma nor the over spill of Aso–4 acidic magma were observed in the eruption of Omine cone and Takayubaru lava.

Petrological characteristics of Miocene basalts from Ootsu district, back-arc area of SW Japan arc

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Cenozoic basalts are widely distributed in the Chugoku district, SW Japan. These basalts are considered to be produced by asthenosphere upwelling in back-arc area, because most of the basalts are OIB (Ocean Island Basalts) in character. However, subduction signatures, such as Nb depletion, are also observed among basalts from this area. We report geological and petrological characteristics of basalts from Ootsu district, a back-arc area of SW Japan arc.

Miocene basalts of Ootsu district (hereinafter called Ootsu basalts) are composed of large amounts of lava flows and following pyroclastic fall deposits. Ootsu basalts usually contain olivine phenocrysts, which have tiny euhedral spinel inclusion, and clinopyroxene and plagioclase occasionally. Based on petrography, Ootsu basalts are divided into two types, magnetite-rich type basalts (MRBs) and magnetite-poor type basalts (MPBs).

MRBs and MPBs also have different contents of major and trace elements, and show several chemical compositional trends in each types. They are characterized as follows: (1) SiO2 content and FeO*/MgO ratio of MRBs and MPBs range from 46-52 wt.% and 1.00-2.42, 49-56 wt.% and 0.82-2.11 respectively, and (2) MRBs are rich in FeO* and TiO2 contents, and MPBs are rich in Al2O3 contents. In terms of SiO2 versus (Na2O+K2O), MRBs are plotted in the alkaline basalt field, and MPBs are plotted near the boundary between alkaline basalt and tholeiite fields. In the Nb-Zr-Y discrimination diagram, MRBs are plotted in within-plate alkaline basalts field, on the other hand, MPB are plotted in the fields of within-plate alkaline basalts and within-plate tholeiite. In the N-MORB normalized spider diagrams, these basalts show Nb depletion and Pb enrichment.

In the Cr-Al-Fe3+ ternary diagram, chromian spinels coexisting with olivine phenocrysts show crystallization trends convex from Cr to Fe apex, which are typical characters of alkaline basalts. Most pyroxene of Ootsu basalts are augite, and increasing in Fe2+ and Ca during crystallization. Some pyroxene of Ootsu basalts contain pigieonite in the groundmass. Assuming that the Fe-Mg exchange partition coefficient between basaltic melt and olivine is 0.3. Some of these rocks have the primary features of high NiO/MgO and low FeO*/MgO ratios of the bulk rock compositions, and Mg value and NiO content of olivine phenocrysts range from 87.9-87.2 and 0.34-0.28 relatively. The estimated compositions of primitive magmas for MRBs and MPBs suggest that they were derived from different sources. Having subduction signatures is potentially believed to be due to two possible models for these magma generation process: (1) the magma reacts with surrounding crustal rocks during its migration upward, and (2) subduction components enrichment from Philippine Sea Plate dehydration.

Petrological comparison between the earliest product of Aso-4 pyroclastic flow and its precursory lava extrusion, in central Kyusyu, Japan.

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Oyatsu pumice flow represents the earliest stage of Aso–4 pyroclastic eruption (89 Ka) that produced Aso caldera, and shows an interesting contrast with precursory extrusion of Takyubaru lava flow (90 Ka). The petrological comparison of the two magmas will provide important information of the magma supply system that lead to an ultra–Plinian eruption.

Both Oyatsu white pumice flow deposit and Takayubaru lava have phenocryst assemblage of plagioclase, clinopyroxene, orthopyroxene, hornblende and opaque minerals. However, Takayubaru lava contains opacitized hornblende and fractured plagioclase.

Both Oyatsu white pumice and Takayubaru lava show short but well–defined fractionation trends in the compositional plots. However, the former does not plot on the extension of the latter trend. This indicates Oyatsu and Takayubaru magmas do not show genetic relationship by fractional crystallization.

Bulk distribution coefficients estimated from the logarithm plots of trace elements (e.g. log(Rb)–log(Sr), log(Rb)–log(Zr), log(Rb)–log(Ba)) are different between Oyatsu pumice and Takayubaru lava. Thus although the phenocryst assemblage is the same, the proportion of subtracted phases seem to be quite different.

We conclude that the precursory Takayubaru magma did not form a part of huge Aso–4 magma supplying system which erupted Oyatsu pumice.

The evolution of the dimensions and morphology of lava flows from a volcano: A case study on the Lonquimay Volcanic Complex, Southern Andes of Chile

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The morphology, dimensions and petrography of ancient lava flows can be used to extract the flow conditions during an eruption. Consequently, the study of a set of lava flows from a volcano can give important clues about the variations through time of such parameters as the effusion rate and the factors controlling it.

Lonquimay Volcanic Complex (LVC) is located in the Southern Volcanic Zone of Chile, and has been active mainly during the Holocene. Its eruptive products are mainly andesitic in composition. The LVC is composed by a main stratocone with an estimated volume of 20 km^3 and a fissure system with pyroclastic cones and craters with a NE orientation and extending 10 km to the east from the main cone (Cordon Fisural Oriental, CFO).

The main cone is divided into 5 units ranging from late Pleistocene to the present. Lava flows from the older units reach up to 15 km from the vent and morphologically are mainly Aa flows, with minor amounts of pahoe-hoe. On the other hand, lava flows from Unit 5 (the youngest unit) are only up to 3 km length with a blocky morphology. All the lavas from the volcano have a similar chemical composition and crystal contents are very uniform.

The CFO zone is where most of the historic activity of the LVC has taken place. Lava flows are up to 10 km with compositions ranging from andesite to dacite with a blocky morphology. Crystal contents are slightly less than in the main cone.

Lava flows from the main cone show a progressive shortening in length and a decrease in total erupted volume as lavas get younger. Lava morphologies and petrography suggest a crustal control on lava dynamics of younger lava flows, opposed to a viscous internal control for older lava flows. Our observations indicate that the oldest lava flows were erupted with higher effusion rates than the younger ones. This can be attributed to the construction of the edifice with the consequent increment in lithostatic pressure. Last eruptions from the volcanic complex are being erupted laterally from the CFO as magmas are unable to ascend through the main cone.

Our results indicate that the construction and growth of a volcanic edifice auto-impose the effusion rate, location of vents, morphology and final length of the lava flows erupted.

Emplacement processes of off-axis large submarine lava field in the Oman Ophiolite

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Large submarine lava with thicknesses >100 m and volumes exceeding a few km^3 are not uncommon volcanic constructs of mid-ocean ridges and around Hawaii Islands, yet details of the physical processes of eruption of these large lava flows are poorly understood. The V3 flow of the Oman ophiolite extruded at 90 Ma far off the paleospreading axis as thick lava flows with a minimum areal extent of >11 km by 1.5 km and the maximum thickness >270 m, yielding an estimated volume >1.2 km^3.The V3 flow was fed by a thick feeder dike in the SW of the flow field and buried off-axial fault-bounded basins with a thick sedimentary cover. The upper V3 flow field consist of compound lobes that merge upstream into larger and thicker sheet-like lava. Welding of flow lobes formed domal structures of columnar joints with narrowing joint spacing and banded lava crust with erosive coarse-grained lenticular dolerite embedded in fine-grained convex dolerite. Cooling rate determines the relationships among joint spacing, crystal number density and the degree of flow-lobe welding/coalescence. Faster cooling prohibits welded flow lobes to merge into an inflating single larger lobe but formed superposed welded flow lobes with well developed columnar jointing. On the contrary, higher supply rate of lava and slower cooling enabled flow lobes to merge and subsequently inflate to form a larger sheet flow or to become a part of the major lobe, which are now preserved as massive core.

Low-T hydrothermal alteration and weathering slightly modified the bulk compositions as indicated by moderate albitization of plagioclase and partial replacement of titanomagnetite and clinopyroxene by titanite and chlorite, respectively. However, strong positive correlations among incompatible HFSEs and REEs and relatively good correlations with major elements besides LILEs and Pb show that these elements were less mobile and preserve primary characteristics. MgO varies from 8 to 4 wt% with a moderate enrichment and a decrease in FeO. Modelling by MELTS demonstrates that fractionation of olivine, clinopyroxene and plagioclase, the major phases in the groundmass of the lava, at a pressure of the paleowater depth is responsible for the major and trace element variations of the flow. Stratigraphic variation in the bulk compositions show a notable enrichment in MgO and depletion in incompatible elements in the lowermost core, consistent with accumulation of olivine phenocrysts. Enrichment in incompatible elements in the uppermost core of the flow is in accordance with the model that the last solidified, residual melt resided in this horizon. The V3 flow shows 20-50 times enrichment in Th and depleted HREEs compared to primitive mantle, similar to differentiated EMORBs.

Reconstructing lava flow emplacement process at the hotspot-affected Galapagos Spreading Center, 92 and 95W

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Volcanic eruptions at mid-ocean ridges (MORs) control the permeability, internal structure, and architecture of oceanic crust, thus establishing the foundation of the evolution of the ocean basins. To better understand the emplacement of submarine lava flows at MORs, we have integrated submersible-based geologic mapping with remote sensing techniques to characterize the lava flow morphology within previously mapped lava flow fields produced during single eruptive episodes at the Galapagos Spreading Center (GSC). Detailed attributes describing the surface geometry and texture of the lava flows have been extracted from high-resolution sonar data and combined with geo-referenced visual observations from submersible dives and camera tows. Based on signatures contained in these data, a fuzzy logic-based classification algorithm categorized the lava flow morphology as pillows, lobates, or sheets. The resulting digital thematic maps offer an unprecedented view of GSC lava flow morphology, collectively covering 77km2 of ridge axis terrain at a resolution of 2m x 2m. Error assessments with independent visual reference data indicate approximately 90

Reconstruction of paleo-volcanoes in the back-arc region of northeast Japan that formed during the opening phase of the Japan Sea

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In northeast Japan, many basaltic volcanic rocks that formed during the opening of the Japan Sea in the Early Miocene are widely distributed. Most of basaltic rocks are found on the Japan Sea side of northeast Japan. They are thought to be related to back-arc rifting during the opening of the Japan Sea (Sato and Amano, 1991). Although the magma geneses of these basalts have been studied (Tsuchiya, 1988; Yagi et al. 2001), the precise location of the paleo-volcanic edifices and a detailed description of the type of volcanism is lacking. In this study, we identified the pale-volcanic edifices and reconstructed the subaqueous volcanoes themselves based on detailed facies analysis of outcrops in the Dewa Mountains in Sakata, Yamagata Prefecture. The paleo-submarine volcanoes were found to be about several kilometers in diameter, over one hundred kilometers high and mainly composed of resedimented hyaloclastites including fluidal-clast breccias, with minor amounts of massive and pillow lavas. The rising velocity of the magma determines the intensity of the eruption if the tectonic setting and magma composition are same (Mangan and Cashman, 1996). We estimate that the hyaloclastites that make up the main part of these volcanoes were formed when the rising velocity of the magma was high, whereas, massive lavas and pillow lavas were formed when the rising velocity was low. The characteristics of the paleo-submarine volcanoes identified in this study are very similar to volcanic deposits formed by submarine fire fountains (Fujibayashi and Sakai, 2003; Head and Wilson, 2003; Simpson and McPhie, 2001). Many dikes that were feeders of these basaltic rocks intrude the study area. Since the palaeo-stress field during the eruption stage was tensional (Sato and Amano, 1991) the reconstructed submarine volcanoes probably formed by fissure eruptions during the opening of the Japan Sea.

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Soufrière Hills Volcano, Montserrat, Phase V 2009-10: Interpretation of thermal imagery of the lava dome

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Phase V of the Soufrière Hills Volcano (SHV) andesitic lava dome eruption lasted from October 2009 to February 2010. This phase was entirely exogenous and ended with a series of Vulcanian explosions and a partial dome collapse. Activity was cyclical with most of the extrusion occurring during periods of elevated seismicity several hours apart. On 30 December 2009, an unusually cloud-free day, a series of thermal images of the upper part of the lava dome were obtained from a helicopter with a FLIR SC-640 handheld, high-resolution thermal infrared camera. Thermal images of the lava dome were superimposed on simultaneously acquired visible images for analysis and correlation.

At the time of the survey flight there was a distinctive vent, partly surrounded by an ash rampart on the south side of the lava dome summit, and a flow lobe extending from the vent to the northeastern edge of the summit platform. The active face of the extruding shear lobe was located above the north and northeast sides of the lava dome, generating numerous rockfalls and block-and-ash flows in those directions. A large inactive flow lobe covered the south flank of the dome.

On thermal images the inactive south lobe had surface temperatures of 40-60 ℃, with fracture temperatures up to 355 ℃. The small spiny dome occupying the crater had a maximum observed temperature of 380 ℃. The active lobe flowing east-northeastwards towards the edge of the dome was bounded on the south side by a levee and appeared to be several tens of meters thick immediately above the active rockfall and block-and-ash flow source areas. Temperatures in freshly exposed headwalls above chutes leading into the drainages below had temperatures up to 420 ℃. Interestingly the highest temperatures observed were not associated with active extrusion but with fumaroles. A particularly vigorous fumarole was located immediately above the saddle between the 2006-07 and the 2009-10 lobes. Its maximum temperature was 550 ℃. Another fumarole midway between the saddle fumarole and the crater rim reached 495 ℃. Older parts of the SHV dome not active during Phase V such as the 2006-2007 Phase III lobe had surface temperatures of 25-30 ℃.