mostly been near its current level during the lake's history. Unambiguous evidence of former highstands above 1883 m has not been reported. In order to explain the occurrence of the drowned beaches and their relatively narrow depth range, leakage through the caldera walls must vary with depth and cannot occur just at the lake bottom or at the modern lake level. A reasonable model is that leakage is proportional to elevation above the bottom of the lake. Recognition that there is a thick layer of relatively permeable debris resting on glaciated lava in the northeast caldera wall above an elevation of 1845 m suggests a variant of this model where leakage is proportional to elevation above 1845 m. Climate studies indicate that Crater Lake began to fill during a dry period. Assuming that precipitation at that time was 70% of modern and that the beach at 1853 m (the deeper beach is somewhat suspect) corresponds to this amount of precipitation, a combination of the above leakage models is necessary to match these values. The history suggested by the combination model estimates that the lake filled to 1853 m in around 800 years. The lake filling model provides a chronology for postcaldera andesitic volcanism because volcanic landforms, 98% of their volume hidden beneath the lake's surface, document eruptions at several prior lake levels ending when the lake reached ∼1805 m elevation.

J. V. Gardner et al. 2001, USGS Water Resources Investigations Report 01-4046; http://walrus.wr.usgs.gov/pacmaps

V42C-1041 1330h POSTER

Crater Lake Revealed: Using GIS to Visualize and Analyze Postcaldera Volcanoes Beneath Crater Lake, Oregon

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Crater Lake, Oregon, partially fills the caldera that formed ∼7,700 years ago by the eruption of 50 km^3 of mainly rhyodacitic magma and collapse of Mount Mazama. Prior to the climactic event, Mount Mazama had a 400,000-year eruptive history, much of which was like those of other Cascade volcanic centers such as Mount Shasta. Since the climactic eruption, there have been several less violent, smaller eruptions within the caldera itself. Until a recent bathymetric survey, relatively little was known about the character and timing of these eruptions because their products are obscured beneath Crater Lakes surface.

In the summer of 2000, the lake bottom was mapped with a high-resolution multibeam echo sounder (Gardner et. al., 2001), providing a 2m/pixel view of the lake floor from its deepest basins virtually to the shoreline. Using Geographic Information Systems (GIS) applications, the bathymetric data has been visualized and analyzed (aided by images and samples obtained with the manned submersible *Deep Rover*, sediment cores and dredged rocks, and detailed geologic mapping of Mount Mazama) to determine a geologic map of the lake bottom, a history of lake filling (Nathenson et. al., 2001), and volumes, times, and rates of postcaldera eruptions. These calculations have been used to assemble a geologic history for Crater Lake from the time of caldera formation to present day.

Postcaldera eruptions have been both subareal and subaqueous, and were well underway within about 90 years after the climactic eruption, beginning with andesitic lava flows from the Wizard Island and central platform volcanoes. The eruptive history of the Wizard Island volcano is divided into three periods defined by former shorelines where subaerial flows entered the lake, quenched rapidly, and fractured, forming lobate deltas and breccia slopes. The shorelines are visible in slope and shaded-relief images of the lake floor created with GIS. The lake filling model suggests that these shorelines formed at ∼90, 250, and 480 years after the lake began to fill. Combining volume calculations determined with GIS and age information from the lake filling model, oldest to youngest Wizard Island minimum eruption rates are $8.4x10^6$ m^3/yr, $6.5x10^6$ m^3/yr, and $3.6x10^6$ m^3/yr. These are comparable to rates calculated for the central platform volcano using the same approach. The minimum eruption rate for the entire 4 km^3 of postcaldera andesite erupted from ∼90 to 480 years after caldera formation is $8.4x10^6$ m^3/yr, which is comparable to historic rates of lava effusion at arc volcanoes. The cessation of postcaldera volcanic activity at Crater Lake, ∼4,900 years ago, is marked by subaqueous extrusion of a 0.074 km^3 rhyodacite dome on the east flank of Wizard Island..V. Gardner et. al., 2001, USGS Water Resources Investigations Report 01-4046; http://walrus.wr.usgs.gov/pacmaps. Nathenson et. al., 2001, Models for the Filling of Crater Lake, Oregon (this meeting)

URL: http://walrus.wr.usgs.gov/pacmaps

V42C-1042 1330h POSTER

An Early Holocene Eruptive Period at Mount Rainier, Washington

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Tephrochronologic studies indicate that the Cowlitz Park eruptive period at Mount Rainier began about 7500 years ago and continued intermittently until about 6800 years ago. Stratigraphic evidence suggests that Cowlitz Park time comprises four distinct eruptive episodes, each of which occurred during a relatively brief interval. The eruptions produced subplinian falls, several small ash falls, pyroclastic flows, and lahars, the largest of which swept down the White River valley to Puget Sound lowland. Tephra layers are of two types: vesicle rich (chiefly pumice lapilli, scoria, and ash) and vesicle poor (chiefly fine-grained glass and lithic fragments). Pumice and glass shards in vesicle-rich deposits are microlite-poor and derive from larger explosive eruptions. Glass shards in vesicle-poor ashes have variable microlite contents and derive from smaller explosions, or from ash clouds that billow up from block-and-ash pyroclastic flows. Although the Pleistocene record indicates considerable effusive activity at Mount Rainier, no record remains of lavas that might have erupted during Cowlitz Park time.

The oldest eruption, ca 7500 cal yr BP, produced vesicular tephra "A," distributed to the east, with a volume of 5 x 10^6 m^3. Layer A is pumiceous, but fine-grained, glassy layers, suggestive of ash-clouds derived from pyroclastic flows, bracket it stratigraphically. About 7300 cal yr BP, within a short interval of time, a more complex eruptive episode occurred that produced a subplinian fall, at least 3 minor ash layers and an avalanche of hydrothermally altered rock on the south flank of the volcano that generated a lahar. The subplinian layer, "L," was among the most voluminous in the Holocene 30 x 10^6 m^3 at Mount Rainier. This tephra occurs to the southeast and chiefly contains pumice along with subordinate, juvenile, lithic clasts. Related fine-to-coarse-grained ash layers derive from small explosions that occurred shortly before and after the eruption of layer L.

Another subplinian eruption occurred ca 7000 cal yr BP and deposited tephra layer "D" to the east, 50 x 10^6 m^3. Near the volcano, ballistic "D" scoria bombs are common. The presence of both mafic scoria and silicic pumice lapilli within the tephra indicate that magma mingling at depth influenced the D eruption. About 6800 cal yr BP, the last eruption of the period produced a 2-3 x 10^6 m^3 tephra (layer N) that was distributed east to northeast. Layer N is pumiceous, but, as with layer A, it occurs stratigraphically between fine-grained, glassy layers, suggestive of ash-clouds derived from pyroclastic flows. Radiocarbon age control suggests that large ca 10^8 m^3 lahars occurred in the White River drainage during both of these last two eruptive episodes and that the largest flowed at least 70 km downstream.

V42C-1043 1330h POSTER

Late Holocene Eruptions of Mount Rainier, Washington

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Detailed stratigraphy, more than 20 radiocarbon ages, and paleomagnetic secular variation measurements indicate that eruptions of Mount Rainier clustered in three major periods during the past 3000 years. Products include a plinian fall deposit, several vulcanian falls, several fine ash falls that are associated with block-and-ash flows, and lahars that descended all major drainages that head on the volcano. Tephra layers are of two types: vesicle rich (chiefly pumice lapilli, scoria, and ash) and vesicle poor (chiefly fine-grained glass and lithic fragments). Pumice and glass shards in vesicle-rich deposits are microlite-poor and derive from explosive eruptions. Glass shards in vesicle-poor ashes have variable microlite contents and derive from minor explosions, or from ash clouds that billow up from block-and-ash pyroclastic flows. These findings contrast with those of previous studies that document only two eruptions, each associated with a pumiceous tephra layer, during the last 3000 years.

The oldest eruptive period, called Summerland, began after 2700 cal yr BP with a vesicle-poor tephra and a collapse of hydrothermally altered rock on the west flank of the volcano that generated the Round Pass mudflow. Lava flows, fine ash falls and a pyroclastic flow erupted ca 2400 to 2500 cal yr BP. Intermittent eruptions produced more fine-grained ash falls, a possible pyroclastic flow and more lahars, then culminated in the plinian "C" fall to the NE and large lahars that flowed south, southeast, and west about 2200 cal yr BP. The Summerland period ended before 1600 cal yr BP with minor fall deposits and lahars.

About 1000 cal yr BP, the Deadman Flat eruptions produced large lahars that contain distinctive prismatically-jointed glassy clasts, interpreted as juvenile components from pyroclastic flows, and co- ignimbrite ash in the headwaters of the White River. The lahars descended valleys to the NE and flowed 100 km to Puget Sound. Aggradation shortly after emplacement of the lahars filled lowland valleys to depths of 1 to more than 10 meters in the Duwamish, White and Puyallup River valleys and buried tidal flats in what are now the South Seattle suburbs near Boeing Aircraft Co.

Between 600 and 400 cal yr BP, numerous lahars of the White River period, including the alteration-bearing Electron Mudflow, descended the NE, S, and W sides of the volcano. No tephra layers are known for this period, but a lahar in the White River drainage contains distinctive, moderately inflated, glassy clasts, interpreted as juvenile, and eruptions are a likely cause of the edifice-wide lahars during this time period. The last eruptions at Mount Rainier were minor events that occurred between AD 1830 and AD 1850 (X tephra) and in AD 1892.

V42D MC: Hall D Thursday 1330h

Explosive Volcanism: Flows and Falls

Presiding: **C Wilson,** Oxford University

V42D-1044 1330h POSTER

Fractal Spectrum Technique for Quantitative Analysis of Volcanic Particle Shapes

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The shapes of volcanic particles reflect numerous eruptive parameters (e.g. magma viscosity, volatile content, degree of interaction with water) and are useful for understanding fragmentation and transport processes associated with volcanic eruptions. However, quantitative analysis of volcanic particle shapes has proven difficult due to their morphological complexity and variability. Shape analysis based on fractal geometry has been successfully applied to a wide variety of particles and appears to be well suited for describing complex features. The technique developed and applied to volcanic particles in this study uses fractal data produced by dilation of the 2-D particle boundary to produce a full spectrum of fractal dimensions over a range of scales for each particle. Multiple fractal dimensions, which can be described as a fractal spectrum curve, are calculated by taking the first derivative of data points on a standard Richardson plot. Quantitative comparisons are carried out using multivariate statistical techniques such as cluster and principal components analysis. Compared with previous fractal methods that express shape in terms of only one or two fractal dimensions, use of multiple fractal dimensions results in more effective discrimination between samples. In addition, the technique eliminates the subjectivity associated with selecting linear segments on Richardson plots for fractal dimension calculation, and allows direct comparison of particles as long as instantaneous dimensions used as input to multivariate analyses are selected at the same scales for each particle. Applications to samples from well documented eruptions (e.g. Mt. St. Helens, Tambora, Surtsey) indicate that the fractal spectrum technique provides a useful means of characterizing volcanic particles and can be helpful for identifying the products of specific fragmentation processes (volatile exsolution, phreatomagmatic, quench granulation) and modes of volcanic deposition (tephra fall, pyroclastic flow, blast/surge).

V42D-1045 1330h POSTER

Small-Volume, Highly Mobile Pyroclastic Flows Formed by Rapid Sedimentation From Pyroclastic Surges on Montserrat: An Important Volcanic Hazard Around Lava Domes

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Gravitational collapses at the Soufriere Hills Volcano (Montserrat, Antilles) on 25 June and 26 December 1997 generated pyroclastic surges that spread out over broad sectors of the landscape and laid down thin, bipartite deposits. In each case, part of the settling material continued to move upon reaching the ground and drained into valleys as high-concentration granular flows of hot (120-410 ^{o}C) ash and lapilli. These surge-derived pyroclastic flows travelled at no more than 10 m s^{-1}, but extended significantly beyond the limits of the parent surge clouds (by 3 km on 25 June and by 1 km on 26 December). The front of the 25 June flow terminated in a valley about 50 m below a small town that was occupied at the time. Despite their small deposit volumes (5-9 x 10^4 m^3), the surge-derived pyroclastic flows travelled as far as many of the Soufriere Hills block-and-ash flows on slopes as low as a few degrees, reflecting a high degree of mobility, and L/H and A/V$^{2/3}$ were 6-15 and 130-360 respectively. An analysis of the deposits from 26 December suggests that sediment accumulation rates of at least several mm s^{-1} were sufficient to generate pyroclastic flows by suspended-load fallout from the surge clouds.

Surge-derived pyroclastic flows are an important, and hitherto under-estimated, hazard around active lava domes. At Montserrat they formed by sedimentation over large catchment areas and drained into valleys different from those affected by the primary block-and-ash flows and pyroclastic surges, thereby impacting areas not anticipated to be vunerable in prior hazards analyses. The deposits are finer-grained than those of other types of pyroclastic flow at the Soufriere Hills Volcano; this may aid their recognition in ancient volcanic successions but, along with valley-bottom confinement, reduces the preservation potential.

V42D-1046 1330h POSTER

Compressible Pyroclastic Gravity Currents

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The behavior of gravity-driven pyroclastic flows is analyzed. It is shown that compressibility can be important in the flow of these gas-particle mixtures, where the presence of particles greatly reduces the density scale height; therefore variations in density due to compressibility are significant over the thickness of the flow. A pressure-dependent density has been incorporated into a shallow-water model of these gravity currents, including the contribution of particles to the density and thermodynamics. Analytical similarity solutions and numerical solutions of the model equations are derived. The mixture of compressible flows is shown to decompress upon gravitational collapse (unlike incompressible flows). As a result, such flows have faster propagation speeds than incompressible currents of the same dimensions because the internal energy of compression, together with some buffering thermal energy from the particles, becomes available upon decompression to be transformed into kinetic energy of motion. A simple 'box-model' approximation is developed to determine the effects of particle settling during the decompression stage. The major effect is that only a small fraction of particles settles in the decompression stage because the small mass loss leads to a more rapid decompression.

V42D-1047 1330h POSTER

New Observations on a Classic Eruption: Mount Pele Martinique, May 8, 1902

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Mount Pele in Martinique W.I. is the type locality where pelean eruptions were first described during the catastrophic eruption of 1902 which destroyed the city of St-Pierre, killing ∼28,000 people (Alfred Lacroix, 1904). The continuing expansion of a pre-existing quarry by the company Sablière de Fond-Canonville to the south of the Tombeau des Caraibes (but north of Rivire Claire), has exposed a new rock-face, which, during February of 2001, was more than 275 meters long. More than 35m of vertical stratigraphy was exposed, comprising deposits of the nue ardentes from both the 1902 and 1929 eruptions. In total, ∼15m of 1902 and ∼20m of 1929 deposits were newly exposed (separated by a well-defined orange-brown paleosol). Extensive photographic work was done to record the exposed surface during February/March of 2001. The major units were recorded and correlated within vertical cross-sections from previous studies.

The oldest unit exposed in the outcrop (U1) is a 2-meter thick black scoriaceous agglomerate altered to pink material in its upper part. This unit corresponds to the deposit from the destructive May 8, 1902 eruption. Compared with the 1929 dome material, U1 has, respectively, less SiO2 (57.5 vs. 62.1), less K2O (0.78 vs. 1.02) and more Fe2O3 (8.1 vs. 6.45) all in wt. %.

Microscopic observations of the major rock types, the 1902 black scoria of May 8, and the grey andesite of 1929, provide evidence for magma mixing. Mixing textures are present in both the 1902 and 1929 deposits (two different types of volcanic glass were found coexisting in the same sample). Preliminary observations made on etched surfaces of plagioclase phenocrysts using the Nomarski Differential Interference Contrast technique show that the plagioclase crystals are intricately zoned (oscillatory, normal) and indicate a complex mixing history.

V42D-1048 1330h POSTER

Debris Avalanches and Debris Flows Transformed from Collapses in the Trans-Mexican Volcanic Belt, Mxico.

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Volcanoes of the Trans-Mexican Volcanic Belt (TMVB) have yielded numerous sector and flank collapses during Pleistocene and Holocene time. Sector collapses associated with magmatic activity have yielded debris avalanches with generally limited runout extent (e.g. Popocatpetl, Jocotitln, and Colima volcanoes). In contrast, flank collapses (smaller failures not involving the volcano summit), both associated and unassociated with magmatic activity and correlated with intense hydrothermal alteration in ice-capped volcanoes, commonly have yielded highly mobile cohesive debris flows (e.g. Pico de Orizaba and Nevado de Toluca volcanoes).

Collapse orientation in the TMVB is preferentially to the south and north-east, probably reflecting the tectonic regime of active E-W and NNW faults. The different mobilities of the flows transformed from collapses have important implications for hazard assessment. Both sector and flank collapse can yield highly mobile debris flows, but this transformation is more common in the case of the smaller failures. High mobility is related to factors such as water and clay content of the failed material, the paleotopography, and the extent of entrainment of sediment during flow (bulking).

Both debris-avalanches and debris-flows are volcanic hazards that occur from both active volcanoes, as well as those that are inactive or dormant volcanoes, and may by triggered by earthquakes, precipitation, or simple gravity. There will be no precursory warning in such non-volcanic cases.

V42D-1049 1330h POSTER

Hydrous Speciation Cooling Rates in the Bishop Tuff: Application of Heat Conduction Modeling to Constrain Emplacement Conditions

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Hydrous speciation in rhyolitic melt inclusions from quartz phenocrysts in the Bishop Tuff indicate a broad range of cooling with rates from 10 C/s to 1.0e-8 C/s based upon the calibrated Zhang et. al. geospeedometer and extrapolations to slower cooling rates (1). In general, faster cooling rates correspond to plinian fall deposits while cooling below 1.0e-4 C/s is confined to pyroclastic flow deposits. Cooling rates within pyroclastic flows also vary considerably with stratigraphic position with faster cooling rates closer to the pre-eruptive ground surface.

Cooling rates in pyroclastic flows vary with height and time, and are governed by boundary conditions as well as by flow thickness, emplacement temperature, and the thermal diffusivity of the pyroclastic material. A semi-analytical heat conduction computer model was developed to highlight the effect of varying these parameters, and to aid in the interpretation of Bishop Tuff hydrous speciation data. The interpretation of cooling rates inferred from hydrous speciation is complicated by non-uniform cooling in natural deposits. Hydrous speciation records a very specific portion of the cooling history: speciation has been calibrated to indicate the last temperature (Tae) and cooling rate at which hydroxyl and molecular water are in equilibrium (1). The model monitored the constantly changing cooling rates and temperatures of each stratigraphic position in the flow to record the moment that the predicted Tae and final speciation cooling rate were reached.

Investigation of the parameter space has yielded some counter-intuitive results. Examination of two hypothetical 15m flows, one emplaced at 450C and one at 600C, reveals that a higher emplacement temperature can yield lower recorded cooling rates from hydrous speciation in the basal part of the pyroclastic flow. The distinctive cooling signatures produced by the model provide an opportunity to constrain the emplacement conditions of observed pyroclastic flows. Comparison between modeled and observed cooling rates suggest that one 50m Bishop pyroclastic flow was emplaced at approximately 500C. Further refinement of this technique could prove especially useful in delineating the thickness of flows that have been substantially eroded.
1. Zhang et. al. (2000), Geochim Cosmochim Acta, 64, 3347-3355.

V42D-1050 1330h POSTER

Physical and Thermal Structure of the Bishop Tuff, California

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The 0.76 Ma Bishop Tuff, California, includes an ignimbrite constructed from a series of overlapping packages of material erupted sequentially and simultaneously from multiple sources around the ring fracture of Long Valley caldera (Wilson, C.J.N., Hildreth, W., 1997, Journal of Geology 105, 407-439). Exceptionally good continuous exposures of the ignimbrite in the walls of Owens Gorge to the east of Long Valley provide a cross-section through the east-side packages (Ig1E and Ig2E). We have measured 10 sections up the gorge walls to draw up a cross section of the ignimbrite down Owens Gorge, using lithic abundances and lithologies to define the physical eruptive packages and their subdivisions, and measurements of tuff bulk

density (as an easily measured proxy for welding intensity) to define the thermal eruptive packages. The physically emplaced bodies of ignimbrite represent an overlapping, shingling suite of material such that successively later ignimbrite occurs most prominently farther away from source. Two major and two lesser zones of maximum density (welding) are present, the lower two (in Ig1Ea and lower Ig1Eb) in upper Owens Gorge, and the two most prominent (upper Ig1Eb and Ig2Eb) in middle and lower parts of the gorge. Welding fluctuations are controlled by bulk temperatures of individual batches of hotter and cooler material, but the intensity of the welding also depends on deposit thickness (i.e. load stress). Physically defined contacts between ignimbrite packages show that time breaks inferred to be of hours may not result in formation of any visible parting or flow unit boundary. Furthermore, positions of density (welding) minima between zones of higher density tuff do not coincide with horizons of stratigraphic significance. These observations lead to two conclusions. (1) The absence of clear partings or flow unit boundaries in an ignimbrite sequence is not diagnostic either of the material representing a single flow unit, or of the material being continuously progressively aggraded. (2) Use of the density (welding) minimum to locate the boundaries of cooling units and in measuring and modelling the emplacement and thermal history of compound cooling units may lead to errors.

V42D-1051 1330h POSTER

Volume Estimation of the 1998 Flank Collapse at Casita Volcano, Nicaragua a Comparison of Photogrammetric and Conventional Techniques

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In October 1998 a precipitation-triggered flank collapse occurred at Casita volcano, Nicaragua, which led to a devastating lahar that killed over 2,500 people. In this study the failure volume, a critical parameter for flow modelling, hazard assessment and sedimentological work, was calculated using a range of methods. Several pre- and post-failure DEMs were created, based on photogrammetric, cartometric and surveying data. The resulting wide range in volumes prompted an assessment of the accuracies and potential problems associated with each of the datasets and techniques used.

The best estimate for the failure volume is 1.6 x $10^6 m^3$. It is based on a vegetation-corrected pre-failure DEM, generated using automated digital photogrammetry in ERDAS Imagine's OrthoMAX, and a post-failure surface based on a field survey carried out with a Total Station. The volume figure is approximately an order of magnitude higher than values reported in previous publications, all of which are based solely on estimates in the field. This demonstrates that such volume figures reported in the literature, if they are not based on rigorous quantitative analysis, must be regarded with caution.

V42D-1052 1330h POSTER

The Upper Toluca Pumice (10.5 kyr): Product of the last major Plinian eruption of Nevado de Toluca volcano, Central Mexico

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The last Plinian eruption at Nevado de Toluca volcano occurred 10.5 kyr ago producing the Upper Toluca Pumice (UTP). The UTP consists of four widespread fallout layers, interbedded with pyroclastic flow and surge deposits. The UTP event occurred under open vent conditions starting with hydromagmatic explosions that emplaced a hot pyroclastic flow (F0) on the east and northern flanks of the volcano. This explosion decompressed the magmatic system allowing almost immediately the formation of a 21 km high Plinian column that was dispersed by predominant winds 5° to the NE (PC0), which waned after some time. The eruption recommenced with the establishment of three Plinian columns that were dispersed in a NE-E direction, reaching heights of 39, 42, and 28 km, and deposited fall layers (PC1, PC2, and PC3) respectively. These Plinian columns were interrupted several times by phreatomagmatic and collapse events that emplaced pyroclastic flows (F1, F2, and F3) and surges (S1, and S2), mainly on the eastern and northern flanks of the volcano. The juvenile components of the UTP sequence are white, gray and banded pumice and gray juvenile lithic clasts both of dacitic composition (63-66wt% SiO_2), and minor accidental lithics. The fallout deposits (PC1 and PC2) covered a minimum area of 2000 km^2 with a total volume of 14 km^3 (ca. 6 km^3 D.R.E.); a mass eruption rate ranging from 3×10^7 to 5×10^8 kg/s and a total mass of 1.2×10^{13} kg. The UTP emplaced 1.5 m of gravel-sized pumice in the modern City of Toluca region and ca. 20 cm of fine sand in the Mexico City region. A future event of this magnitude might represent a major catastrophe to the 30 million people living in these cities and their surroundings.

V42D-1053 1330h POSTER

The Geochemistry of Feldspar, Fresh Glass, and Melt Inclusions Within Feldspar as Potential Tools for Correlating Fresh and Altered Tuffs at Olduvai Gorge, Tanzania

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Olduvai Gorge, Tanzania, preserves a 100-m sequence of Plio-Pleistocene volcaniclastic sediments interbedded with at least 10 predominantly trachytic tephra layers. These tephra were deposited in environments including a saline-alkaline lake, volcaniclastic alluvial fan, and wetlands, and hence degrees of alteration vary. Fresh glass is sometimes preserved, but is usually altered to zeolite, limiting its use for geochemical analysis for stratigraphic correlation. In the absence of fresh glass, feldspar and melt inclusion compositions can be used.

Samples of five major Bed I tuffs (Tuffs IB through IF) were collected from sites up to 15 km apart in various environments. Major and minor element analyses of glass shards, feldspar, and melt inclusions within feldspar from each tuff (electron microprobe) were supplemented by trace element analysis of feldspar and shards from select samples (Synchrotron XRF microprobe). At least two samples (20-60 grains) of each tuff were analyzed.

Tuffs IB through IE can be distinguished using feldspar composition (mean compositions: IB= An4Ab63Or33, IC= An11Ab67Or22, ID= An30Ab61Or9, IE= An12Ab64Or24). Tuff IF feldspars are more variable and partially overlap the composition of Tuff IC, but 28% of the grains analyzed from IF contain significant Ba (1 to 4%) and Sr (up to 900 ppmw). These high Ba feldspars may suggest multiple eruptive sources for Tuff IF.

Where glass shards were altered, fresh glass was preserved as inclusions in feldspar. The shard composition varies more within each sample than the feldspar composition, though most of the tuffs can be distinguished based on the concentrations of Ca and Al in the fresh shards (CaO% IB < 1, ID > 1.4 , IE $= 1.2$; Al2O3 % IB, ID, IE <17, IF > 18.5). The inclusions within the feldspars of Tuffs IB and IE are consistent with the compositions of the associated shards and cluster together tightly (especially in Ti and Ca), suggesting that inclusions could be used to correlate these tuffs. The compositions of the inclusions from Tuffs IC and ID are more widely variable and overlap, limiting their usefulness for identification. At Olduvai, feldspar composition currently provides the best method for identifying each tuff, for inclusion composition is too variable in some tuffs.

V42D-1054 1330h POSTER

Mapping Ash Grain-Size Distribution From the August 18, 1992 Eruption of Mt. Spurr

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The August 18, 1992 eruption of Mt. Spurr, Alaska, produced tephra which was deposited south eastward from the vent with significant ash accumulations as far away as Cordova, AK. The USGS sampled this deposit within 48 hours of the eruption and dry mass per unit area was measured for each sample. A map of this data was made which showed a secondary maxima. Their sieve and sedigraph results from samples in the secondary maxima showed a bimodal grain-size distribution.

Though there are limitations in the spatial resolution of the data, the distal grain size data were hand-contoured as a mass flux (g/m^2) for each grain-size phi class. The contour pattern maxima for the 0-1, 1-2, and 2 -3 phi classes (500-125 microns) occur at distances from the vent consistent with individual particle settling velocities. The 2-3 and 3-4 phi size classes show proximal, bilobate distribution patterns consistent with plume bifurcation [Ernst et al., Bull. Volcanol. 56 (1994) 159-169]. The mass flux of 5-6 and 6-7 phi classes (8-31 microns) were highest in the location of Well's Bay (~250 km from the vent). The presence of these fines at this distance from the vent cannot be explained by settling as discrete particles. Similar anomalous patterns occur for elements of the 3-4, 4-5, 7-8 and 8-9 phi classes. The simplest interpretation of these data suggests a pattern consistent with fine ash falling radially from the plume as aggregates predominately composed of 8-31 micron sized particles. Fall out of these aggregates likely produced the observed secondary maxima, though no aggregates were found preserved in the deposits. These results are consistent with recent models that suggest 20 micron particles are most likely to form aggregates in eddies within the plume [Shaw et al., in press]. The technique employed provides valuable data concerning particle transport and fallout which can be combined with field and remote-sensing observations to better understand and model plume behavior. The anomalous mass of hazardous fines deposited near Anchorage emphasizes the need to understand the role of aggregation in fallout.

V42D-1055 1330h POSTER

An Archean Primary Pyroclastic Flow Erupted and Deposited Underwater, Ontario, Canada

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The volcano-sedimentary rocks of the Hurd Property, located in northeastern Ontario, are within the Kinojvis Group of the Abitibi Greenstone Belt. These Archean rocks are of tholeiitic affinity ranging from intermediate to mafic in composition. Despite a low greenschist grade overprint primary volcanic textures are well preserved. The study area consists of three lithofacies, which from oldest to youngest are: (1) an intermediate lava; (2) volcaniclastic deposit; and (3) mafic lava. The underlying intermediate lava is a dark grey and massive lithofacies that becomes flow banded and lobate within a few meters of the sharp, but undulatory contact with the overlying volcaniclastic lithofacies. The 10-15 m-thick volcaniclastic deposit is subdivided into lower and upper divisions based on flow characteristics and a sharp internal contact. The lower division is characterized by conspicuous m-wide columnar joints within the central part of the deposit, along with a possible gas segregation pipe. Observed fragments range from tuff to breccia in size, comprising glass shards, flow banded clasts, pumice, and fragments containing perlitic cracks and spherulites, all of which are non-sorted. The discontinuously exposed, subordinate upper division forms a graded unit composed of conspicuously large (up to 1m x 10cm in section) imbricated fragments that are massive to flow banded. The contact between the upper volcaniclastic lithofacies and the mafic lithofacies is sharp, but irregular, typically marked by pseudo-pillow like shapes within the mafic unit. Only the lower 25 m of this massive, amphibole-rich mafic lithofacies is exposed in the study area.

Lobate features, along with imbrication within the upper volcaniclastic lithofacies suggest a subaqueous environment of deposition consistent with observed pillows and interflow chert locally. Nonetheless, the succeeding volcaniclastic deposit appears to have been emplaced under high temperatures based on columnar joints, perlitic cracks, pumice, spherulites and a gas segregation pipe. Subsequent ingestion of water is limited to the upper part of this lithofacies, as indicated by imbricated fragments in a graded unit. Therefore, the volcaniclastic lithofacies represents a primary pyroclastic flow emplaced in a submarine setting. The complete sequence was protected/insulated by the mafic lava, which was brecciated and chilled due to escaping fluids from the underlying flow resulting in the formation of pseudo-like pillows at its base.

It is envisaged that eruption began with the continued extrusion and construction of an intermediate dome facies that probably collapsed due to a combination of internal pressure and mechanical failure. Such collapse could have formed a laterally directed explosion forming a small volume pyroclastic flow. A possible steam

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envelope may have insulated the main mass of the flow with turbulent mixing of water restricted to the upper flanks forming the upper imbricated zone. As such, the volcaniclastic sequence represents a primary Archean subaqueous pyroclastic flow.

V42D-1056 1330h POSTER

Ash Aggregates Found in Pyroclastic Surge Deposits Produced during the 1982 Eruption of El Chichon Volcano, Chiapas, Mexico: considerations on their Origins

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During the most violent phase of the 1982 eruption of El Chichon volcano, at 0135 (GMT) April 4, pyroclastic surges, S1, S2 and S3 (1,2), were produced. With the exception of S2, associated to a pyroclastic flow, the origin of the deposits is controversial.

Field studies up to 8 km from the source in different sectors of the volcano indicate that S1 exceeds the previously traced northern limit showing a distribution with a N-S largest axis. The depositional structures of S1 and S3 suggest emplacement from diluted pyroclastic density currents of hydromagmatic origin. Component analysis of samples from different horizons of S1and S3 showed the presence of ash aggregates of different types, most of which formed around cores of millimetric-sized vegetal fragments. The eruptive clouds were thus characterized by temperatures insufficient to burn wood. The granulometric distributions of different horizons of S1 and S3 layers have similarities suggesting that they derived from the same fragmentation mechanism.

SEM observations indicate the presence of structures like hydration cracks and hydration skin on glass shards characterized by blocky forms or low degree of vesicularity, corroborating that fragmentation was generated by the interaction between magma and external water.

1 Macias J.L., Sheridan M.F., Espindola J.M. (1997). Bull. Volc. 59 (6): 459-471.

2 Sigurdsson H., Carey S.N., Fisher R.V. (1987). Bull. Volc. 49: 467-488

V42D-1057 1330h POSTER

On the Freezing of Pyroclastic Flows

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Processes of sedimentation in pyroclastic flow are still poorly understood, although their massive deposits have been extensively studied. It is unclear whether the flows freeze en masse or gradually sediment particles, aggrading their deposits in a layer-by-layer fashion. Arguments for en masse deposition include the poorly sorted, structureless nature of deposits and the common presence of coarse-tail grading of lithics and/or pumices. Sedimentation by freezing of the flow implies that the deposit facies is directly representative of the dynamical state of the moving flow. Arguments for deposition by aggradation are the existence of compositionally distinct units within some massive deposits and the onlap structure of these units on the preexisting topography. The boundary between compositional units is interpreted as a timeline within the massive deposit.

Remarkable exposure of pyroclastic deposits at Toluca Volcano, Mexico, allows 3D reconstruction of the facies spatial distribution. Sections perpendicular to flow axes display a transition of facies from a thin marginal stratified deposit to a thick massive deposit to multiple massive units in the flow interior. While stratified deposits are cross-bedded, massive deposits feature coarse-tail reverse grading of lithics and coarse-tail normal grading of pumices. Multiple units are also coarse-tail graded and are separated by thin stratified veneers. In sections parallel to flow axes, the flow interiors show a gradual transition from massive facies proximally to crudely stratified facies to stratified facies distally, without significant changes in thickness.

Since perpendicular sections feature evidences of timelines in the middle of coarse-tail graded deposits, these massive deposits cannot be the result of en masse deposition. Parallel sections show a continuum between massive and stratified facies, implying the existence of multiple depositional units within a structureless deposit. Since these units can be traced into each individual layers of a stratified deposit, we interpret the Toluca pyroclastic deposits being entirely a product of deposition by aggradation. These results suggest that the aggradation process does not only produce massive and/or stratified deposits but is also able to generate coarse-tail grading.

V42D-1058 1330h POSTER

Compositional Homogenization, Silicic Replenishment, and the Zoned Ignimbrite of Aniakchak Caldera, Alaska

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The origin of compositional evolution and diversity at volcanic centers is commonly attributed to in situ crystallization differentiation of a parental magma with secondary contributions from open-system processes. The occurrence of zoned ignimbrites, often containing appreciable compositional gaps, in arc environments defies the expectation of gradual and continuous compositional change implied by the various self-differentiation mechanisms. Large compositional gaps often observed could not be preserved in a zoned magma chamber without the formation of an intermediate-composition diffusive boundary layer. As an alternative, we propose that subvolcanic magma chambers are more often sites of homogenization of initially chemically diverse magmas that develop independently of one another.

The caldera-forming eruption of Aniakchak Volcano on the Alaska Peninsula produced a zoned ignimbrite which provides insight into this process. The 3400 yBP ignimbrite comprises a rhyodacite and hybrid andesite. Geochemical and petrographic evidence indicates that the andesite is the product of successive inputs of rhyodacitic and high-alumina basaltic magmas into a crustal chamber. Detailed mass-balance models preclude progressive distillation from high-alumina basalt as the means for producing the rhyodacitic end-member, but partial melting of a young mafic pluton is allowed. Secondary fractionation processes in the shallow chamber have accompanied the primary effects of binary mixing of rhyodacite and basalt, resulting in an excess apatite component, manifested in large excesses of phosphorus as well as elevated rare earth concentrations.

It appears that prior to the caldera-forming eruption, an unusually large intrusion of rhyodacitic magma, extracted directly from a mafic plutonic source, rapidly overpressurized the shallow andesitic chamber, initiating an eruption before thorough mixing could occur, and allowing a large-scale dumping of the system. With the low-density rhyodacite exhausted, the now-destabilized roof collapsed into the chamber, leading to eruption of the resident andesite.

V42D-1059 1330h POSTER

The Complex History of a Caldera-Forming Magma: the Abrigo Ignimbrite, Tenerife, Canary Islands

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The 0.196 Ma Abrigo Member of the Diego Hernandez Formation is a widely-distributed, lithic-rich, dominantly phonolitic ignimbrite produced during the most recent caldera-forming eruption on Tenerife. It had a minimum original extent of $\sim$2,000 km^2. It represents the climax of a $\sim$40 k.y. magmatic cycle recorded in 12 underlying plinian pumice deposits that have strong chemical affinities to the Abrigo. The juvenile component of these plinian deposits consists solely of aphyric to weakly porphyritic phonolitic pumice, with no mixed or petrographically distinct clasts. In contrast, nine distinct types of fresh juvenile clasts occur in the Abrigo: light green aphyric pumice, dark green pumice with large tabular alkali feldspars, dark green crystal mush (>90% phenocrysts), nepheline syenite blocks with minor interstitial glass, black aphyric and porphyritic pumice (some bearing olivine phenocrysts), mafic crystal cumulates, grey hybrid pumice, and coarsely to finely banded pumices. Bulk compositions range from primitive (9.5% MgO) basanite to highly evolved phonolite. Hence, the complete range of compositions and crystallinities occurs among the Abrigo ejecta. Chemical variations among the phonolitic component indicate derivation from at least two distinct magma sources, and/or a role for assimilation within the Tenerife edifice. Our model for the Abrigo magma system invokes a crystallizing body of phonolitic magma, consisting of crystal mush beneath crystal-poor liquid that produced several eruptions over a 40,000 year period. Subsequently, the crystal mush was invaded by mafic magma which itself cooled and partly crystallized while heating, remobilizing and stirring the mush and supernatant liquid (and perhaps melting some wall-rock) to produce mingled, mixed and hybrid phonolite-intermediate-basanite magmas with a large range in crystallinity. Large-scale caldera collapse may be responsible for the seemingly near-complete evisceration of the magma system during the eruption.

V42D-1060 1330h POSTER

Ash? Particles Found Inside the NASA DC8 which Encountered Hekla's February 2000 Stratospheric Volcanic Cloud–a Needle in a Haystack.

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As part of our remote sensing efforts on the Hekla eruption (Rose et al, this session) we have performed an extensive SEM examination of particles provided us by Tom Grindle of NASA Dryden. These particles came from the engines and filters of the NASA DC8 that was damaged by its encounter with the Hekla volcanic cloud at 76N 0W at 0510 UT on 28 February 2000, about 35 hours after the explosive phase of the eruption. Finding definitive evidence of ash in these samples was difficult because other kinds of particles were also present, possibly the result of uncontrolled sampling times. Strong evidence for ash comes from the damage reflected in the aircraft (T. Grindle, 2000, personal communication) and from aerosol number density measurements in the volcanic cloud reported by T M Miller et al (2000, EOS Transactions 81 (48) F1277). The early, most explosive part of the Hekla eruption likely was gas-rich but contained some ash that was andesitic or basaltic andesitic in composition (A. Hoskuldsson, pers comm, 2001). The ash in this early component could not be detected by satellite remote sensing, perhaps because it was masked by the effects of abundant ice. Since ice masses were estimated at <100 kT in the cloud, it is likely that ash masses were even less. Because we are interested in aircraft hazard mitigation, it is important to establish clearly that ash was present in the aircraft and to try to estimate its concentration. We found large amounts of metal alloy particles in one of the engines and a dominance of angular feldspar and other silicates in the other engine and filter samples. We expanded our search of the silicate materials and obtained samples of the early, most silicic ash from Iceland for comparative analytical work. This was still inconclusive prior to abstract submittal.

V42D-1061 1330h POSTER

Events During the Complex Plinian Phases of the c. AD 1305 Eruption of Tarawera, New Zealand

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Plinian phases of the c.1305 AD Kaharoa eruption deposited a minimum of 5.1 km3 of tephra (2.3 km3 DRE) in two cycles involving 2 possibly 3 vents out of a total of 7 vents associated with the eruption. Each cycle is characterized by a general increase of column height and mass discharge rate in successive phases to a maximum, followed by a rapid decrease in both parameters. The 1st cycle produced six coarse pumiceous fall units (A through G, excluding C which is a co-pyroclastic flow density current), all dispersed to the southeast, under stable northwesterly winds. Thin (up to 6 cm) widely dispersed distinctive fine ash beds of uncertain origin are present between most of the coarse pumice beds. The initial eruptions of the 2nd cycle occurred during a sheared wind field thay may indicate an onset of a deviation from the normal weather pattern, producing the bi-lobate unit H. Four subsequent fall units (I - L) were deposited under variable wind fields predominantly from southerly directions predominantl. First-order comparisons with other plinian deposits suggests that the Kaharoa eruptions were of low to moderate intensities, with calculated column heights ranging from 16 to 26 km and wind speeds from 20 to > 30 m/s. Mass discharge rate varied by an order of magnitude from 8.8 x 106 to 9.8 x 107 kg/s and volumetric discharge ratefrom 4.0 x 103 to 4.4 x 104 m3/s. The minimum inferred durations for individual plinian events ranged from 2 to 5 hours with the exception of the widely spread unit K (25 hours), interpreted from its poorly sorted, mixed nature and anomalous dispersal. to have been deposited from a series of low intensity eruptions with slightly varying wind directions. Total minimum duration of the coarse plinian fall is 64 hours. The timing of the plinian phase, and thus the onset of the eruption, can be constrained by the change in the predominant northwesterly wind pattern to the less frequent southerly winds which occur mostly in austral winter season.

V42D-1062 1330h POSTER

Kizimen Volcano: An Unzen-like Magma System in Kamchatka

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Kizimen Volcano is a Holocene lava and dome complex from basaltic andesite to dacite composition situated on the eastern edge of the Central Kamchatka Depression (CKD) and midway between volcanoes of the eastern front (EVF) and of CKD. All lavas are horblende-bearing mid-potassic of the calcalkaline series. They differ from two-pyroxene basalts and andesites of ancestral, Pleistocene, Kizimenok Volcano in showing greater geochemical and petrological evidence of modification by crustal processes. Prominent characteristics of the rocks are large phenocrysts of plagioclase and hornblende co-existing with olivine and orthopyroxene as well as abundant cognate mafic enclaves of more primitive (basaltic to basaltic andesitic) composition. Trace element geochemistry is typical of island arc volcanism (IAB). Sr, Nd, Pb isotope systematics lie well within normal Kamchatka Volcanoes and close to MORB. Phenocrysts show extreme disequilibrium in terms of magnesium number of mafic phases (olivine, pyroxene), presence of quartz, and coexistence of apatite and sulfide. Enclaves are both fractionated compared to primary mantle melt and are contaminated by incorporation of more acidic material from the host. Similarly, the host is contaminated by basic debris from enclaves. This interaction likely occurs by frequent recharge of mantle magma to a mid to upper crustal chamber. Despite pervasive evidence of magma mingling, the fundamental geochemical signature of subduction origin remains clear. Thus, the apparently crustal admixed silicic component is likely of cogenetic plutonic origin. Kizimen exhibits some remarkable similarities to Unzen Volcano in Japan. 1. Repeated extrusion of hybrid dacite domes and more basic lavas from the summit region. 2. Thick block-and-ash aprons to domes but relative paucity of tephras, despite apparent high water content of the magma. 3. Close association with an active graben structure. 4. Nearly identical petrologic characteristics indicative of shallow interaction of contrasting magmas. An age of less than 1,000 years for the youngest flows (from lichenometry) and presence of vigorous superheated fumaroles indicate the likelihood of future, Unzen-like eruptions.

V42D-1063 1330h POSTER

Turbulence-Induced Ash Aggregation in Volcanic Clouds

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Size distributions of ash from the volcanic cloud produced by the 1992 Mount Spurr, Alaska eruption show a characteristic bimodal shape with modes at approximately 90 and 20 μm. Volcanic ash is unlike rain because the individual ash particles comprising aggregates that fall from the cloud make up the size distribution collected at the ground, rather than the aggregates themselves. We hypothesize that particles in the 20-μm mode are removed more efficiently than both larger and smaller particles through turbulence-induced collision and coagulation. The mechanism for this enhanced collision rate is the inertial response of particles to turbulent accelerations. Atmospheric observations suggest that the volcanic cloud was turbulent and estimated energy dissipation rates confirm that particles in the 20-μm mode were most susceptible to the inertial mechanism. These findings have implications for ash fallout and volcanic cloud lifetime, and serve as indirect evidence for the inertial collision mechanism.

V42D-1064 1330h POSTER

Role of Water and Ice in Ash Aggregation: Constraints from the Upper Scoriae 1 Deposit, Santorini, Greece.

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Volcanic eruption clouds can disperse ash over large areas, posing hazards on the ground and for air traffic. One distant goal is to develop much needed risk models of ash fallout. This however, is hindered by incompletely understood aspects, one of which is ash aggregation and especially the role of liquid water and ice. We analysed accretionary lapilli-rich fall deposits from Santorini, interpreted here to have formed from eruption clouds elutriated from energetic base surges rich in water, which condensed and froze during rise while interacting with ash. Investigation methods included fieldwork, hand sample binocular microscopy, lapilli and particle size analysis, SEM, EPMA and basic modelling of aggregate settling. Field data indicate both ductile and brittle deformation of aggregates during deposition. Lapilli size distributions peak sharply at 2.5 mm with few aggregates $\sim$10 mm, but most $<$4.5 mm. Lapilli display a volumetrically-dominant, poorly sorted, coarse-grained core and a thin, fine-grained rim. Particle size distributions in the core and rim peak at 45-70 microns and 10-30 microns (MALVERN and SEM data), with a sharp grain size break. This is consistent with growth by wet collection where aggregate size is limited by drop break-up. Fine ash rims imply freezing halts wet accretion, and lapilli $>$4.5 mm indicate accretion proceeds similar to hailstone growth. Insights from hailstone studies and experiments of Gilbert & Lane (1994) suggest that a liquid skin is needed to aggregate fine rim ash, thus constraining rimming processes to approximately 5-8 km asl. Multiple fine rims indicate recycling of frozen accretionary lapilli. Close association of fine vesiculated ash and large lapilli (i.e. contrasting Vt) in the deposit suggests that fallout of lapilli and mud rain was coeval, perhaps due to a settling-driven instability at the umbrella base. A new conceptual model accounting for all data observations is summarised. The new constraints will be useful for development of new numerical column models of ash aggregation with microphysics included.

V42D-1065 1330h POSTER

Marginal Stability of Atmospheric Eruption Columns and Pyroclastic Flow Generation

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Explosive volcanic eruptions frequently generate fall and flow deposits simultaneously, which can be attributed to a marginally stable atmospheric column in transitional conditions between the buoyant and collapse regimes. This behavior is reproduced by laboratory experiments and numerical simulations. Ten well-documented eruptions are used to test theoretical models of explosive eruptions. Three types of deposits, fall, flow, and composite deposits made of intercalated flow and fall units, are observed in these eruptions. Estimates of mass discharge rate and initial volatile concentration in the magma are available for each eruptive phase. Using the simple assumptions that (1) the mass fraction of gas in the mixture is equal to the initial volatile content of magma and (2) jet expansion outside the vent is unconstrained by crater dimensions, theoretical predictions are not consistent with the data. Agreement between data and theory may be achieved by appealing to imperfect degassing of pyroclasts, which lowers the gas content of the erupted mixture. The effective amount of continuous gas phase carrying pyroclasts in suspension depends on the size distribution of pyroclasts. In coarse pyroclast populations a large amount of magmatic gas remains trapped in bubbles within the pyroclasts and is not involved in the bulk volcanic flow. A new regime diagram based on estimates of the effective gas content in the erupted mixture allows good agreement with the observations. For given mass flux and initial dissolved volatile content, changes of the size distribution of pyroclasts may have a strong effect on atmospheric column behavior.

V42D-1066 1330h POSTER

Late-stage Pyroclastic Flow and Fall Deposits From Volcán Ceboruco, Mexico: Insights From a Small Volume Caldera-Forming Eruption

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Volcán Ceboruco, located in western Mexico, erupted 3 to 4 km^3 of rhyodacitic to dacitic magma, known as the Jala Pumice, forming a 3.7-km-wide caldera (approx. 1000 A.D.). Late-stage deposits differ significantly from early ones in eruption style, overall lithic content, pumice composition, accidental lithic types, and erupted volume. Detailed stratigraphic correlation between pyroclastic fall, surge, and flow deposits of the Jala Pumice indicate that a progressive shift occurred from an early convective region (Phase I), to a transitional regime feeding both a Plinian convective column and dilute density currents (Phase II), to an almost fully collapsing regime producing mostly dense pyroclastic flow deposits and lithic-fall deposits (Phase III). Phase I deposits contain less than 15 wt.% lithics. In contrast, the lithic content of Phase II deposits range between 20 and 60 wt.%, and between 65 and 90 wt.% in Phase III deposits. A systematic change in pumice composition is observed in the Jala Pumice sequence, where 95% of the juvenile component in Phase I deposits is rhyodacite pumice (white pumice) compared to 85% of the juvenile component in Phase III deposits being dacitic pumice (gray pumice). Banded pumice clasts, consisting of intermingling streaks of the two magma compositions, are found only in Phase II and III fall deposits. Accidental lithic type populations also vary through the Jala Pumice. Early deposits contain an abundance of surficial and granitic lithics, whereas late-stage deposits are entirely composed of surficial lithics and Sierra Madre Ignimbrite fragments. The erupted volume of Phase I deposits is dramatically different than the Phase III layers. Phase I deposits, composed of 2 pyroclastic fall layers, account for approximately 70% of the total erupted volume of the Jala Pumice, whereas late-stage deposits, composed of pyroclastic flow and small volume lithic-fall deposits, account for less than 2% of the total erupted volume. In addition, despite the abnormally high lithic content observed in the late-stage flow deposits, referred to as the Marquesado and North-Flank PFDs, they are clearly pyroclastic in origin due to their long run-out distance ($>$13 km), and dynamic facies changes with distance and topography. We conclude that foundering of the caldera produced an excessive amount of lithic material, some of which was incorporated into late-stage pyroclastic flows and block and ash falls, with collapse, subsequently choking the conduit and eventually shutting down the eruption.