Volcanology, Geochemistry and Petrology

V11A MC: 305 Monday 0830h

Experimental Volcanology: Sturtevant Memorial I *(joint with G, P, T, MR, HG)*

Presiding: **E Brodsky,** University of California Berkeley**; H Mader,** University of Bristol

V11A-01 0830h INVITED

Onset of Caldera Collapse During Ignimbrite Eruptions: Scaling Analysis and Experimental Constraints

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We investigate the onset of caldera collapse during the rapid depressurisation and discharge of volatile rich silicic magma, using combined experimental and theoretical approaches. We first present a scaling analysis of the force balance on the roof of a depressurising magma chamber for the collapse of a coherent piston. This analysis provides a failure criterion for the chamber roof and shows that the chamber underpressure required to trigger coherent (piston) collapse along a vertical or steeply outward-dipping reverse ring fault increases with the roof aspect ratio (R = thickness/width).

A series of laboratory experiments, using granular material and silicone as the analogue chamber roof and magma respectively, validate the analysis. They reveal a transition, with increasing roof aspect ratio, between regimes of piston collapse to either (1) no collapse (low reservoir underpressure) or (2) non-coherent collapse (high reservoir underpressure). Coherent collapse occurs along outward-dipping faults, which propagate from the reservoir edges through the roof. In non-coherent collapse, the first reverse faults form at deeper levels, then join underground, and collapse proceeds in a chaotic fashion; underground collapse then triggers surface subsidence (thin residual or mechanically weak roof) or creates a cavity overlain by a stable roof (thick and strong residual roof).

Then, taking into account the failure criterion obtained with the scaling analysis, we develop a theoretical model which allows calculation of the erupted chamber volume fraction required to trigger caldera collapse. We consider a two stage model, with an initially overpressured chamber that becomes progressively underpressured as the eruption proceeds. The main input parameters are the chamber depth, vertical extent and ellipticity in plan view, the magma water content, the cohesion and coefficient of internal friction of the roof, and the ring fault dip. The results show that in the case of a mechanically homogeneous roof and a single, large and rapid eruption, the erupted volume fraction required to trigger piston collapse increases with the roof aspect ratio until the chamber is totally emptied (before initiation of any collapse) at R∼1-1.4, the exact value depending mainly on the ring fault dip and to a lesser extent on the coefficient of internal friction of the roof. As shown by experiments, collapse into reservoirs with R>1-1.4 probably cannot collapse as a piston and, if a surface caldera forms at all, collapse is more likely to occur non coherently. Data for the onset of caldera collapse during seven well documented major ignimbrite eruptions are in broad agreement with the model.

V11A-02 0845h

Numerical and Experimental Study of the Controls on Growth and Geometry for Pyroclastic Ejecta Cones

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Pyroclastic ejecta cones, the most frequent type of which are cinder cones, are the most common form of volcanic landform. Cinder cones have only been modelled as the result of accumulation of ballistic ejecta. First we systematically review observations and data on cinder cones and other ejecta cones and eruptions producing them. This demonstrates that: 1.) very few cinder cones contain much material of ballistic size so that they could not have formed by ballistic ejecta; 2.) many cinder cones initially grow rapidly, commonly to 160 m high just in the first week of activity; 3.) thick ejecta cones are also produced during plinian eruptions; 4.) cinder-cone eruptions typically produce eruption columns up to 20km high extending above high lava fountains (up to 1600m high), i.e. they are much more explosive and hazardous than previously recognised. We then present new numerical modelling of controls on cinder and spatter cone growth. The cones grow by fallout of material from turbulent eruption jets dominating the eruption column region where there is most of the mass and which leads to deposition producing the cinder cones. We compare the results to numerical predictions of cone growth from ballistic ejection and find that only fallout from eruption jets can account for the observed geometry of spatter cones. Jet fallout modelling predicts that mass per unit area decreases exponentially fast with distance from vent, although for cinder cones the material quickly redistributes by surface grain flows to maintain the cone slope at the angle of repose. Effects of contrasting erupted grain-size distributions, vent radius and eruption velocities are evaluated. This model can account for the rapid initial growth of cinder cones in the first week of activity. We then present results of grainpile laboratory experiments to elucidate the origin of the 10 degrees steeper inner crater slope compared to the outer cone slope and investigate the mechanics of crater formation by slumping. This work accounts for the crater and cone slopes, shows how this is related to the observed constant crater rim to cone diameter ratio (=0.4) in young cinder cones, and contrasts inner crater slopes of cinder cones with the near-vertical slopes of cones containing much fine ash. Implications of this work for volcanic hazards are briefly discussed.

URL: http://www.geophysik.uni-kiel.de/∼criedel/volcind.htm

V11A-03 0900h INVITED

Solidification in Channel Flows: Lava Tubes or Open Channels?

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The solidification of channel flows as a result of surface cooling is studied in experiments in which polyethylene glycol wax flows under cold water down a 3m long, sloping, rectangular channel. All flows were laminar, with Reynolds numbers of 0.2-70, based on flow depth and centre-line speed. For a constant source flux we find two steady-state regimes, depending on the flow velocity and the temperatures of the wax and the water relative to the freezing temperature of the wax. One regime is characterised as 'open-channel' flow with mobile crust, the other as 'tube' flow beneath a stationary, solidified roof. For sufficiently high flow speeds and temperatures a solid surface crust develops in the centre of the channel at some distance from the source. The crust is rafted down the centre of the channel. Compression or extension of the crust is sensitive to variations in the source flow and to downstream changes in channel width or slope. Under these conditions, in a uniform channel, the crust remains separated from the walls by shear regions in which solid phase is continually forming but fragmented into small pieces by the shear. This solidification occurs along the length of the channel, including very close to the source, in the slowly moving sidewall boundary layers. The fragmented solid down-wells due to convection down the side walls and across the base of the flow. Thus cross-stream convection, driven and organised by a non-uniform surface heat flux and in concert with the shear, maintains the width and surface temperature of the shear regions independent of distance down channel. It also leads to cooling of the interior. In contrast, at lower flow speeds and temperatures, the rate of solidification in the shear regions overcomes the actions of side wall shearing and convection, and creates a stationary roof. The roof develops over the whole flow, and flow continues through an insulated tube beneath. We find the condition for tubes $U_0 t_s/W < 0.75 \pm 0.2$, where U_0 is the surface speed without cooling at the centre-line, t_s is the predicted time for onset of solidification in an idealised situation and W is the channel width. Time-dependent behavior can occur under conditions near the open channel-to-tube transition.

V11A-04 0915h

Solidification in Channel Flows: Effects of Channel Irregularities on Transitional (Time-Dependent) Flow Behavior

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The surfaces of basaltic lava channels evolve in both space and time from crust-free to crust-dominated. The presence or absence of stable lava crusts, in turn, dictates the rate of heat loss from the lava core and controls the mechanisms of lava flow advance. For this reason, we extended experimental studies of the cooling and solidification of channel flows to investigate unsteady behavior observed near the transition from open channel flow to tube flow in both uniform and irregular channels. The experiments used polyethylene glycol wax flowing at moderate Reynolds numbers under cold water down a 3m-long, sloping, rectangular channel. For a straight uniform channel, flows at conditions of $0.4 < U_0 t_s/W < 1$ initially developed a strong crust that spanned the entire width of the channel but continued to move downstream. With time, the crust backed up from the downstream end of the channel, and was repeatedly over-run by newly crusted flow from upstream. Hence the flow became progressively deeper in the distal regions, and the effects of the downstream end of the channel (a free fall into a reservoir) propagated towards the source. The result was a complex flow that evolved toward fully developed tube flow under a stationary, insulating roof. Up-flow propagation of lava tubes is observed at Mt. Etna, Italy (Calvari and Pinkerton, 1998) and Kilauea, Hawaii (Peterson et al., 1994) when slopes flatten and flows widen, or at channel bends and constrictions. We explored several configurations of channel geometry to examine their effect on time-dependent flow behavior. When a flow encountered an 80% expansion in channel width (at 1.2m from the source), the flow speed decreased at the expansion. This promoted the formation of rigid crust and shifted the onset of tube flow to larger values of $U_0 t_s/W$. When the flow encountered a decrease in channel width (at 0.6m from the source), acceleration of the flow caused disruption of the surface crust inside the constriction. However, rotating pieces of crust sometimes blocked the entrance to the narrow region and thus promoted tube formation upstream. Flow over small obstructions placed within the channel acted to disrupt the central crust and inhibit tube formation. Flow through a sloping zig-zag channel (with an amplitude to wavelength ratio of 1:5) showed no significant differences from flow in a straight channel, except that conditions for the formation and upstream propagation of stationary crust were again shifted to larger flow speeds and higher temperatures. Together these observations suggest that stable crust formation in channelized lava flows may be very sensitive to changes in flow surface velocity generated by either irregularities in channel morphology or variations in lava flux.

V11A-05 0930h

Rheology of Phonolitic and Trachytic Melts: the Effect of Fe_2O_3 and Al_2O_3

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The Na_2O-Al_2O_3-SiO_2 system is used to model a large number of petrological processes. But even in this simple system there are anomalous changes in rheology as a function of composition. It has been previously shown for sodium-aluminosilicate melts that, at a constant temperature and constant SiO_2 content, there is a shallow maximum in viscosity in the vicinity of the subaluminous join. This maximum occurs within the peraluminous field, suggesting the presence of triclusters consisting of one aluminate and two silicate tetrahedra.

The viscosity of trachyte and phonolite composition melts with 67 mol% SiO_2, has been determined using the micro-penetration technique in the $8 < \eta$ ($\log_{10}$ Pa s) < 14 range. For these composition melts, at a temperature of 1050K, viscosity increases by 6.5 $\log_{10}$ Pa s as the composition is changed from peralkaline to subaluminous [0.60>Na/(Na+Al)>0.47], and then appears to reach a plateau as the melt compositon becomes increasingly peraluminous. The viscosity decreases by 0.4 $\log_{10}$ Pa s with the continued addition of network-forming Al_2O_3 and the removal of network-modifying Na_2O as Na/(Na+Al) is decreased from 0.47 to 0.40. The activation energy for viscous flow also changes dramatically as a function of melt composition; increasing from ∼480 kJ mol^{-1} for the peralkaline compositions, to ∼630 kJ mol^{-1} for the peraluminous compositions.

This suggests that the change in melt structure due to the change in Na:Al composition has a dramatic effect on the flow mechanism of the melt.

The structure of the melt is further altered by the addition of Fe_2O_3. The substitution of Fe_2O_3 for 20% of the Al_2O_3 in this system results in a decrease in viscosity of at least an order of magnitude. The activation energy for viscous flow for the peraluminous and subaluminous composition melts is decreased by 20% upon the substitution of Fe_2O_3 for Al_2O_3; but no change in activation energy is observed for the peralkaline compositions.

V11A-06 1005h

The Rheology of a Bubbly Liquid

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A semi-empirical constitutive model for the visco-elastic rheology of bubble suspensions with gas volume fractions $\phi < 0.5$ and small deformations ($Ca \ll 1$) is developed. The model has its theoretical foundation in a physical analysis of dilute emulsions. The constitutive equation takes the form of a linear Jeffreys model involving observable material parameters: the viscosity of the continuous phase, gas volume fraction, the relaxation time, bubble size distribution, and an empirically-determined dimensionless constant. The model is validated against observations of the deformation of suspensions of nitrogen bubbles in a Newtonian liquid (golden syrup)subjected to forced oscillations. The effect of ϕ and frequency of oscillation f on the elastic and viscous components of the deformation are investigated. At low f increasing ϕ leads to an increase in viscosity whereas at high f viscosity decreases as ϕ increases. This behaviour can be understood in terms of bubble deformation rates and we propose a dimensionless quantity, the dynamic capillary number Cd, as the parameter which controls the behaviour of the system. Previously published constitutive equations and observations of the rheology of bubble suspensions are reviewed. Hitherto apparently contradictory findings can be explained as a result of Cd regime. A method for dealing with polydisperse bubble size distributions is also presented.

V11A-07 1020h

Determining Flow Type and Shear Rate in Magmas From Bubble Shapes and Orientations

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To compare bubble geometries in obsidian to bubbles deformed under known conditions, we measure the deformation of air bubbles in corn syrup in simple shear. We use these experimental data and results of theoretical, numerical and experimental studies to interpret the shear environments that formed the textures preserved in obsidian samples. In particular, we use the shapes and orientations of bubbles in obsidian to estimate shear rates and assess flow type (simple vs. pure shear). This technique can be used to determine shear rates in volcanic conduits, the origin of pyroclastic obsidian, and the emplacement history and dynamics of obsidian flows.

The deformation of a bubble is governed by the competing stresses from shearing that deforms, and surface tension that rerounds. The ratio of these stresses is the capillary number, Ca. An initially spherical bubble placed in a low Reynolds number, steady flow field deforms with a time-dependent shape and orientation until it reaches a steady geometry or breaks into smaller bubbles. A useful measure of the magnitude of flow-induced bubble deformation is the dimensionless parameter, $D = (l - b)/(l + b)$ where l and b are the semi-major and semi-minor axes of the sheared bubble. For small deformations (Ca$\ll$ 1), low Reynolds number flow and bubble viscosity $\ll$ suspending fluid viscosity, $D \sim 2$Ca in pure shear and $D \sim$ Ca in simple shear. In pure shear flow, bubble elongations are parallel to the shear direction regardless of the magnitude of bubble deformation. However, in simple shear flow, the angle between the bubble elongation and the flow varies with Ca, which is proportional to bubble radius and shear rate. Because the relationships between Ca and bubble orientation and shape for pure and simple shear differ, we can distinguish between these flow types using bubble geometries preserved in obsidian. Furthermore, because Ca is a function of shear rate, we can use relationships between Ca and D to calculate shear rates when melt viscosity and surface tension are known.

To demonstrate the potential of the technique, we examine three obsidian samples chosen for diversity in origin and texture. Two of the samples have low crystallinities and banding defined by layers of different vesicularity. Bubble geometries indicate that a sample from a spatter-fed obsidian flow was deformed by pure shear whereas a juvenile obsidian clast from a pyroclastic fall deposit records predominantly simple shear. There is no significant shear localization, but the component of pure shear in the pyroclastic sample is inversely related to layer vesicularity. A third sample from an obsidian flow shows banding marked by variable concentrations of microlites. For the same bubble radii, bubbles in the higher crystallinity bands are more deformed than in the lower crystallinity bands. We attribute this to higher effective viscosities (melt +crystals) surrounding bubbles leading to greater deformation.

V11A-08 1035h INVITED

The Influence of Bubble Nucleation Mechanism on Eruptive Degassing: Experiments with Dacite and Rhyolite Melts

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Recent decompression experiments using water-saturated rhyolite melts (>70 wt% SiO_2) at magma chamber conditions (~ 800-900°C; 150-200 MPa) illustrate how bubble nucleation mechanism affects the pressure-depth interval for eruptive degassing and the resulting development of porosity in ascending magma. A slight pressure drop of ΔP < 5-20 MPa triggers vesiculation in heterogeneous melts where crystals or other discontinuities offer favorable collection sites for nascent bubble nuclei [1,2]. Volatile supersaturation is low at the onset of heterogeneous nucleation (C(actual)−C(equilibrium) < 0.3 wt% H_2O) and the nucleation rate depends on the number of crystals present. Spontaneous bubble nucleation in homogeneous, crystal-free melt is difficult by comparison, requiring ΔP of ~ 150 MPa [3,4]. In this instance, extreme supersaturations develop (C(actual)−C(equilibrium) > 2.0 wt% H_2O) and the homogeneous nucleation rate is dictated by ΔP. Collectively, [1-4] suggest that systems dominated by heterogeneous nucleation undergo continuous near-equilibrium gas evolution, whereas a disequilibrium, low-pressure vesiculation burst is characteristic of those constrained by homogeneous processes. Although real systems are probably never truly crystal-free, results in [4] show that rhyolite magmas containing up to 10^4 crystals/cm^3 and perhaps as high as 10^6 crystals/cm^3 are controlled by homogeneous, rather than heterogeneous nucleation, during ascent.

New experiments suggest that the extreme supersaturations seen in homogeneously-nucleating rhyolite may not hold for other compositions. Water-saturated, crystal-free dacite melt (65 wt% SiO_2) containing 5.9 wt% H_2O at 1000°C and 200 MPa begins to vesiculate under isothermal decompression (dP/dt ~ 1 MPa/s) at ΔP = 50 MPa and C(actual)−C(equilibrium) ~ 1.0 wt% H_2O. As might be expected by the relatively low degree of supersaturation, the homogenous nucleation rate at the triggering ΔP is less than in similarly-conducted rhyolite experiments, 7 x10^2/cm^3s compared to 1 x$10^5/cm^3$s. The relative ease of homogeneous nucleation in dacite melt appears to be a consequence of lowered surface tension. As shown theoretically in [1], a small decrease in surface tension dramatically decreases the ΔP required to trigger homogeneous nucleation. A fit of our empirical data to nucleation theory suggests an effective surface tension for dacite melt at 1000°C and 5.9 wt% H_2O of 0.05-0.06 N/m. Similar calculations give 0.10 - 0.11 N/m for rhyolite at 900°C and 5.2 wt% H_2O [4].

[1] Hurwitz, S., Navon, O., 1994, EPSL, 122, 267-280. [2] Gardner, J.E., Hilton, M., Carroll, M.R., 1999, EPSL, 168, 201-218. [3] Mourtada-Bonnefoi, C.C., Laporte, D., 1999, GRL, 26, 3505-3508. [4] Mangan, M., Sisson, T., 2000, EPSL, 183, 441-45

V11A-09 1050h

Bubble growth during decompression of magma: Experimental and theoretical investigation

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We examined the physics of growth of bubbles during decompression of volatile-supersaturated melts and constructed a bubble growth model that accounts for the interplay of three dynamic processes that control the growth. These coupled processes are decompression rate, deformation of the viscous melt, and diffusion of the volatile species from the supersaturated melt into the bubble and the corresponding equations must be solved simultaneously by numerical computation. However, when one of the processes dominates, asymptotic solutions may be obtained for the specific growth regimes. We present four asymptotic solutions for the following regimes: viscous controlled with fast diffusion, viscous controlled with no diffusion, diffusion controlled and decompression controlled growth. The characteristic time scales of the different processes determine the transition between the different growth regimes. A close match between analytical and numerical solutions is obtained as long as the approximations that allow the analytical solution hold. The model fits new and published experimental data of bubble growth in hydrated silicic melts during decompression.

The model is used in order to follow the evolution of volume and pressure in a conduit underneath a dome that contains magma with a finite yield strength (i.e. - visco-elastic). Following an initial drop of pressure, gas pressure is higher than ambient pressure and the pressure difference overcomes the static strength of the magma . Then, the bubbles expand in order to equate gas pressure with the ambient pressure, the magma flows in the conduit and the dome grows. Eventually, the driving pressure falls to a threshold where it can no longer overcome the dynamic yield strength of the magma, the magma halts and behaves elastically and another cycle of pressurization begins. This process can continue for several cycles of pressurizing and dome growth.

V11A-10 1105h

The Effect of Conduit Inclination on Eruptive Style

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The eruptive style of volcanoes is influenced by the behavior of the phases in the erupting fluid. Bubbles present in high-viscosity magmas have very low relative rise-velocities. Consequently the timescales of bubble collision and coalescence are long and the generation of large bubbles becomes unlikely. Bubbles in low-viscosity magmas are more likely to interact on the timescale of magma residence time in the conduit. There is, therefore, considerable scope for bubble collision and coalescence processes to generate a few large bubbles from the many small bubbles originally generated as dissolved gaseous species exsolve.

We have carried out some exploratory experiments in which air bubbles are generated at the base of a straight circular-section tube. Flow patterns were observed as the variables of gas flow rate (0.3 - 10 l/min), liquid viscosity (water and sugar solutions 0.001 - 10 Pas) and tube inclination (0 - 45° from vertical) were varied.

Bubbly flow (bubble diameter < tube diameter) occurred in a vertical tube at low gas-flow rates. A foam layer was generated at the top of the flow. In higher-viscosity liquids, where the timescales for film drainage become significant, the foam layer built up and emerged from the top of the tube. Increasing the gas flow rate forced the pattern into slug flow (bubble diameter = tube diameter) as small bubbles collided and coalesced more frequently. The foam layer did not establish itself during slug flow.

When the tube was inclined the transition to the slug flow pattern occurred at much lower (order of magnitude) gas flow rates than for vertical tubes. For instance, at a gas flow rate of 2 l/min bubbly flow occurred in vertical tubes, while tilting the tube by 20° produced a well developed slug flow pattern.

We discuss the processes taking place in the experiments and the effect that conduit inclination could have on eruptive style for volcanoes with similar degassing rates.

V11A-11 1120h

Gas-Driven Eruptions, and Speculation for Methane-Driven Ocean Eruptions

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Brad Sturtevant was a central player in experimental simulations of various types of eruptions, including those driven by the exsolution of gas initially dissolved in a liquid (referred to as gas-driven eruptions, including explosive volcanic eruptions, lake eruptions and eruption of Champagne), and those driven by the evaporation of a liquid (such as geyser eruption, or evaporation waves). The experimental simulations helped to bring together the general understanding of different eruptions. Among gas-driven eruptions, explosive volcanic eruptions are the most familiar and spectacular type. Lake eruptions were recognized only in the 1980s. The underlying principles of the two types of eruptions are similar although there are some difference in the role of the conduit and buoyancy.

The main purpose of this report is to speculate on a possible but yet unrecognized type of gas-driven eruptions, methane-driven water eruptions in oceans. In marine sediment, huge amount of CH4 is stored either as gas or as methane hydrate. (The gas pockets might burst, resulting in mud volcanos.) Under some unusual circumstances such as marine landslides or earthquakes, a large amount of CH4 may be released from sediment to seawater. Depending on the local pressure-temperature conditions, and depending on the kinetics of the various chemical reactions, the released methane gas might lead to gas-driven explosive eruptions. This type of eruptions would be similar to CO2-driven lake eruptions, except that the gas is CH4 instead of CO2. Although no such eruptions have been reported and they are expected to be rare, theoretically they are possible. Because CH4 gas is less dense than air, erupted CH4 gas cloud is expected to rise high into the atmosphere instead of forming ground-hugging flows for CO2 gas flows. Hence the danger to life on the ground is smaller. Satellite imaging might be able to detect such eruptions.

V11A-12 1135h

Dry Particle Aggregation in Volcanic Plumes

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Understanding the deposition of fine grained silicate particles from volcanic plumes is key to interpreting ash fall deposits and predicting hazards for future eruptions. The importance of particle aggregation for the 'premature' deposition of ash grade tephra was demonstrated in the 1980 eruption of Mount St. Helens during which delicate, dry aggregates were collected 390 km from the volcano. This type of aggregate is thought to be bound mainly by electrostatic forces and consequently has little or no preservation potential in a deposit. The generation and physical characteristics of dry aggregates have not been previously investigated. We have carried out laboratory experiments with small, dry silicate particles produced by repeatedly colliding two samples of Mount St. Helens pumice. Extensive aggregation was observed in the column of falling particles below the samples and, in the absence of any liquid phases, this process was driven solely by fall velocity differences and the electrostatic charges generated on particles during fragmentation. For particles falling distances of $\sim$1 m, images of in-flight aggregates show that they commonly have irregular shapes and are up to $\sim$800 μm in size. Fall velocity measurements suggest that most aggregates have densities of $\sim$100 to 200 kg m^{-3}. During experiments in which falling particles and aggregates were horizontally dispersed within a gentle airflow, bimodal particle size distributions were produced, similar to those observed in the May 18, 1980 Mount St. Helens deposits. These particle size distributions suggest that aggregates were comprised mainly of particles $<$70 μm in diameter. The dispersal experiments confirmed the earlier aggregate density measurements and suggest that the plan view of landed aggregates represents a reasonable aerodynamic area from which the fall velocity of equivalent spheres can be estimated. Our experimental data are in agreement with aggregate size and density estimates previously used within several theoretical plume sedimentation models in order to explain some features of natural ash deposits. The results have consequences for remotely sensed data, numerical models of plumes and for the interpretation of ash fall deposits.

V11B MC: 304 Monday 0830h

Trench to Subarc: Diagenetic and Metamorphic Mass Flux in Subduction Zones (GERM/MARGINS Subduction Factory Session) I *(joint with OS, T, MR)*

Presiding: **G E Bebout,** Lehigh University**; H Becker,** University of Maryland

V11B-01 0835h

Mass Flux of Continental Material at Cenozoic Subduction Zones–New Global and Trench-sector Calculations Using New Geological and Geophysical Observations

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INTRODUCTION: A decade ago, then available geophysical and geological data implied that more than 65 percent of ocean floor sediment entering most subduction zones (SZ) accompanied the oceanic crust to the mantle (= sediment subduction or SS). The underthrusting slab also eroded the margin's crustal framework and conveyed this material to the mantle (= subduction erosion or SE). Globally, the mass of continental material recycled to the mantle was estimated at 1.3-1.8 km^3 / yr (SS. = 0.7 km^3 + SE = 0.6-1.1 km^3). SEDIMENT SUBDUCTION: New and enhanced seismic reflection data, new drilling observations, and reevaluation of older information stress that the efficacy of SS is higher than earlier assessed. In detail, it appears that 100 percent SS occurs at non-accreting margins (19,000 km), at least 80 percent at accreting margins (16,000 km) where small to moderate size accretionary prisms (width=5-40 km) are forming, and 40-45 percent where larger prisms are accumulating (8,000 km). At Cenozoic SZs (43,000 km), it is now estimated that the long-term (i.e., $>$10 Myr) rate of SS is at least 1.0 km^3 / yr (solid volume).
SUBDUCTION EROSION: New and reassessed seismic, drilling, submersible, coastal mapping and arc-retreat observations suggest a higher long-term rate of SE than formerly estimated at 30 km^3 / Myr / km of trench. We now estimate that, except perhaps where large accretionary bodies are forming, the long-term rate of forearc erosion averages at least 40 km^3 / Myr (range = 28-62), which corresponds to a global recycling rate of 1.4 km^3 / yr. The matching average rate of landward truncation of the submerged forearc is 2.5 km / Myr (range = 1.8-4.2).
SUMMARY: The late Cenozoic rate at which continental crust is recycled at SZs is currently estimated at 2.4 km^3 / yr (ss=1+ se=1.4) +/- 25 percent, which is basically that now approximated for arc magmatic additions. It can thus be inferred that at Cenozoic SZs rates of crustal addition and recycling have been in general balance. This quasi-stasis may be applicable to the Phanerozoic.

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Production and Fluid Flow at Shallow to Intermediate Forearc Depths: An Overview

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A variety of physical and chemical processes lead to the production and eventual expulsion of fluids from subduction forearc regions at shallow to intermediate depths. Many processes, such compaction and some of the stress (in the case of smectite) and thermally induced dehydration reactions, are relatively well understood, at least at a general level. However, much remains uncertain about the depth and temperatures at which water comes to be released, expulsion mechanisms, and pathways to the surface. For example, because most/all systems have a highly heterogeneous permeability distribution it is not known what proportion of the input fluids come to be expelled laterally either along the subduction thrust or through the oceanic basement, or by more vertical pathways through the forearc itself (via faults, diapirs, and diffuse flow). Indeed, a recent bethnic flux meter study of the Costa Rican forearc suggests that diffuse flow may account for a significant proportion of the expulsion flux, with the potential that there is only limited lateral focused expulsion along the decollement.

Predicting the depth at which fluids originate is also difficult because even though the consolidation behavior of sediments can be determined experimentally, the development of overpressures in low permeability systems can result in a considerable extension of the depth range over which consolidation proceeds. Another factor that has to be considered in predictions of fluid origination and expulsion patterns is that even where mechanical compaction proceeds to near completion, a significant residual fluid volume (5-20 %) can remain trapped within sediment pores and in the fractured but still relatively ridged upper oceanic basement. Ultimately, however, studies of exhumed materials do suggest, that the bulk of the remaining pore fluids in sediments do come to be expelled (at least into local fracture systems) during the onset of late stage diagenesis and as pressure solution reactions pick up at seismogenic depths. The fate of pore fluids trapped within basement is less clear, however, and this region may not be a significant net source of fluids at shallow to intermediate depths. Indeed, there is the potential that much fluid remains trapped in the basement until temperatures have risen sufficiently for it lead to the additional development of hydrous minerals such as chlorite. Thus, while fluid production/expulsion within the sediments is probably intimately associated with aseismic/seismogenic processes it seems reasonable to assume that it is the basement that forms the principal source of H20 involved in magma generation.

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Pore pressure development and progressive sediment compaction at the toe of the Costa Rican margin wedge: Mechanical and hydrologic implications

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At subduction zones, the fate of pore fluids within underthrust sediments has important effects on the evolution of mechanical strength and structural development. Results from Ocean Drilling Program (ODP) Leg 170, offshore Costa Rica, documented the complete underthrusting of a regionally uniform sediment section, with the important implication that observed changes in sediment thickness and void ratio directly reflect the evolution of effective stress. Combining logging-while-drilling (LWD) data, down-hole physical properties data, and laboratory consolidation tests, we track the development of effective stress and pore pressure within underthrust sediments with progressive loading beneath the margin wedge. High-quality drilling data, combined with numerous laboratory consolidation tests, allows a spatially detailed investigation of down-section pore pressure evolution with progressive loading. Effective stresses inferred from laboratory experiments and those projected from observed reductions in void ratio are in excellent agreement. In both cases, the results indicate essentially undrained conditions at site 1043 (located $\sim$0.5 km landward of the trench). At site 1040 (located$\sim$1.6 km from the trench), our results suggest that the lower, pelagic underthrust sediments remain nearly undrained, whereas the upper, hemipelagic sediments are partially drained. An inferred minimum in effective stress developed near the base of the hemipelagic section between sites 1043 and 1040 is consistent with observed down-stepping of the decollement at $\sim$2-3 km from the trench, and illustrates the important effects of pore pressure distribution on structural development. In comparison, pore pressures within underthrust sediments at the Nankai and Barbados subduction zones inferred from porosity data indicate that dewatering at these locations occurs more slowly than at Costa Rica. These differences can be attributed to the higher permeability and larger compressibility of near-surface sediments underthrust at Costa Rica.