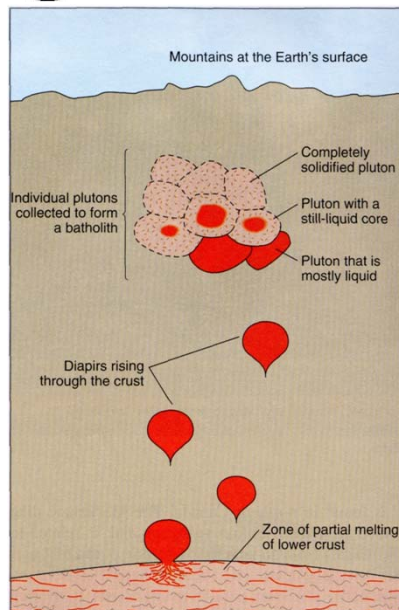


EASC 421 - Volcanology

Effusive volcanism



Physical Changes in Magma as it rises EASC 421



Temperature Drops

- ❖ Increase in viscosity
- ❖ Crystallization begins
 - Increase in viscosity
 - Composition becomes more silicic (more polymerized)
 - Increase in viscosity
- ❖ Gases concentrated in melt

Pressure Drops

- ❖ Gases exsolve
- ❖ H_2O concentration drops
 - Increase in viscosity
- ❖ Bubbles form
 - Increase in viscosity

Initial fluid is pure melt that segregates from its source region

- ❖ becomes an increasingly viscous, crystal-rich & bubble rich fluid as it approaches the surface.



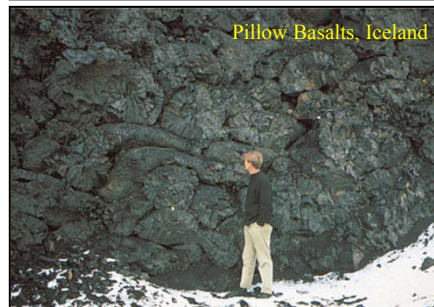
Form & Morphology

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- ✦ Lava flows take on a variety of forms:
 - ❑ 'A'a flows
 - ❑ Pahoehoe flows (subvarieties)
 - ❑ Coulées
 - ❑ Domes
 - Plugs, Spines
- ✦ What are some key differences?
 - ❑ Aspect ratio & Surface roughness
- ✦ **RHEOLOGY** – fluid dynamics of lava flows. Viscosity & Yield Strength are the 2 most important factors influencing:
 - ❑ Surface morphology (flow type)
 - ❑ Size and shape of the flow
 - ❑ Flow thickness
 - ❑ Effusion Rate (m^3/s)
 - ❑ Flow Velocity (m/s) & Length (m)
 - ❑ Flow Direction - controlled by topo.
 - ❑ Laminar vs Turbulent?



Pahoehoe & Aa, Hawaii



Pillow Basalts, Iceland



Morphology of Mafic Lavas

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- ✦ Pahoehoe
 - ❑ shiny, smooth, glassy flow surfaces
 - ❑ flow advances by budding new toes in bulldozer fashion
 - ❑ thinner flows (typically 1-3 m)



Kilauea

✦ 'A'a

- ❑ Very rough, clinkery, brecciated surface composed of irregular cindery blocks with razor sharp asperities
- ❑ Form as crust breaks & is ground during flow
- ❑ slower & thicker flows (typically 3-20 m)



Kilauea

✦ Blocky

- ❑ Similar to 'A'a, but surface blocks are bigger (meters vs. cm to 10's cm)
- ❑ thicker flows (>20 m) with a blocky rather than rubbly surface.
- ❑ andesites, dacites & some rhyolites



Paricutin, Mexico

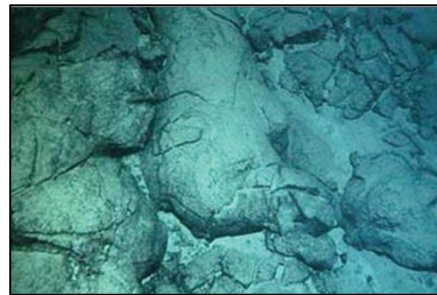


Formation of Pillow lavas

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- ✦ Restricted to submarine & subglacial flows.
- ✦ where water rapidly quenches a skin or crust -> forms a 'balloon' containing liquid lava.
- ✦ New pillows form by budding from cracks of parent pillows.
- ✦ Restricted to relatively low effusion rates.
 - Pahoehoe-like sheet flows form at high effusion rates



Pahoehoe

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Pahoehoe Toes



Ropey Pahoehoe

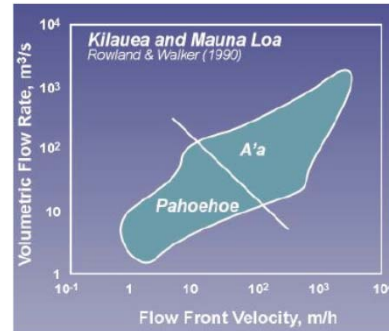
Entrail Pahoehoe



Pahoehoe vs. A'a

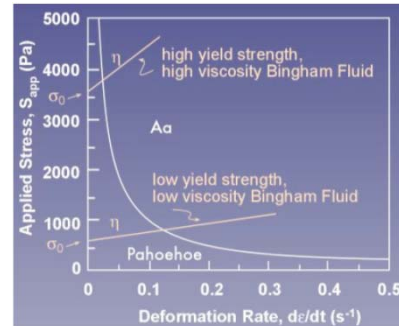
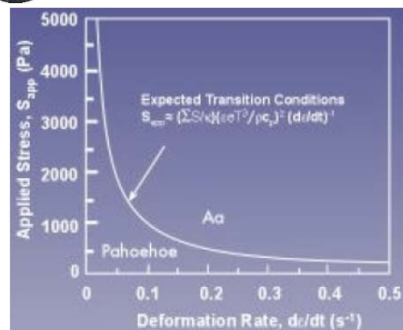
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- ✦ In Hawai'i, pahoehoe lavas form at low volumetric flow rates & low flow front velocities
 - ✦ Depends on discharge rate and slope.
- ✦ Pahoehoe only observed in relatively low viscosity lavas
 - ✦ Basalts & rarely andesites, never dacites or rhyolites
 - ✦ Suggests viscosity is a factor
 - ✦ Pahoehoe & a'a lavas often occur on same volcano - pahoehoe flows can transition to a'a
 - ✦ But a'a **never** transforms to pahoehoe.
- ✦ What factors dictate the surface morphology?
 - ✦ Obviously, composition & viscosity can't be the sole factors

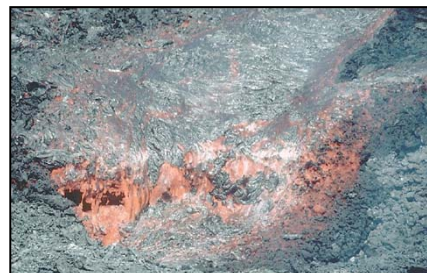


Pahoehoe transition to A'a

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- ✦ Some argue that energy supplied to break crust vs. rate at which crack can be healed is critical factor
- ✦ Above a certain critical rate of energy supply and cracking, an a'a crust develops.



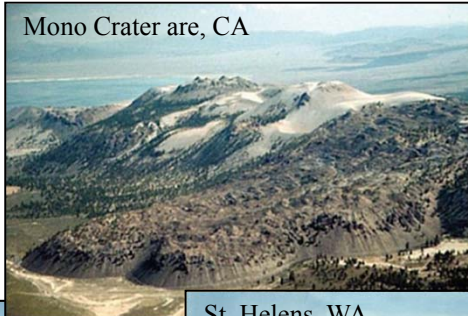


Silicic lavas

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- ✦ Coulées & Obsidian flows

Mono Crater are, CA



- ✦ Domes

Katmai, Alaska



- ✦ Spines

St. Helens, WA

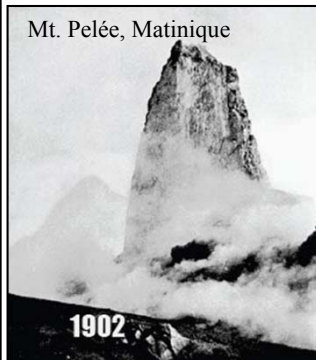


Formation of Silicic Lavas

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- ✦ High viscosities lead to very high aspect ratios
 - ✦ Rhyolitic lava coulées typically have thicknesses > 50 m.
 - ✦ Highly viscous lavas effectively do not flow horizontally at all, forming vertically extruded domes.
 - ✦ “Spines” represent perhaps the most viscous lavas.

Mt. Pelée, Martinique



1902



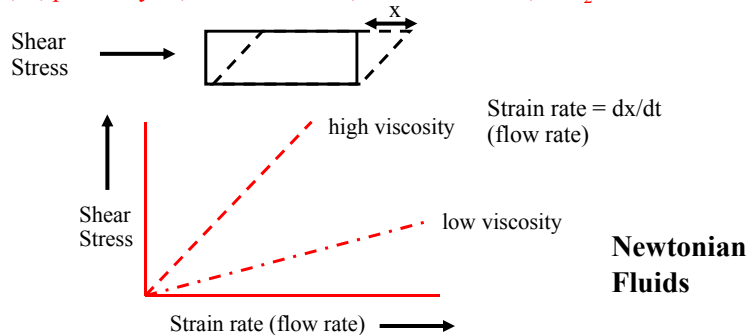
Soufrière Hills, Montserrat



Viscosity (η) = Shear Stress/Strain Rate

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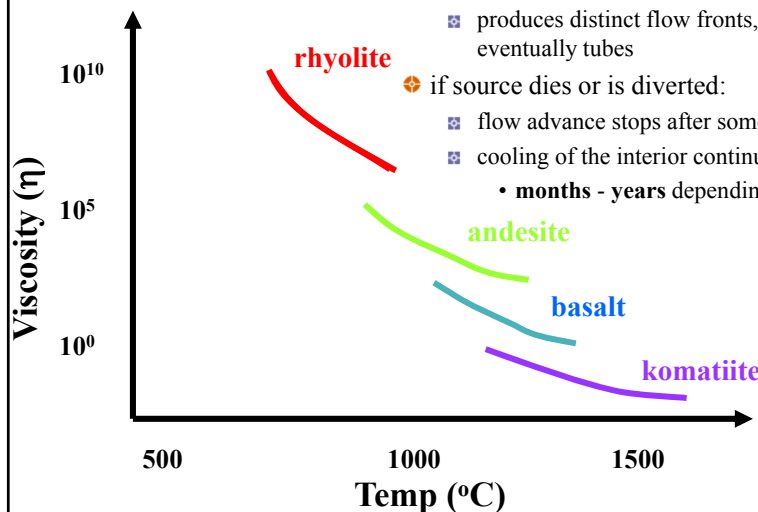
- ✦ internal resistance to flow (strain) by a substance when subjected to shearing (stress) - i.e., the “sluggishness” of a fluid
 - basalt = $10^2 - 10^3$ Pa*s, water = 10^{-3} Pa*s, olive oil = 10^{-1} Pa*s
- ✦ dependence of stress on strain
 - an applied stress produces a resulting strain through some proportionality (viscosity)
 - the definition of the proportionality depends on the material!
 - **what factors would affect the viscosity of a magma/lava??**
 - T, P, phenocrysts, bubble content, volatile content, SiO_2



Viscosity (η)

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- ✦ dissolved water/inc. pressure **reduces** viscosity
- ✦ cooling quickly produces a darker surface crust
 - increases viscosity & decreases velocity
 - produces distinct flow fronts, channels & eventually tubes
- ✦ if source dies or is diverted:
 - flow advance stops after some lag period
 - cooling of the interior continues
 - months - years depending on flow thickness





Thermal properties

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3 methods of cooling flows

Conduction - transfer of heat by direct contact

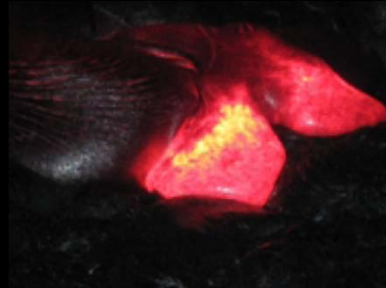
- dependant on interior T, so the dominant heat flow mechanism during entire cooling process (after crustal formation)

Convection - transfer of heat by movement of another medium (water, air) over surface

- very dominant early (prior to crust) but negligible later on

Radiation - transfer of heat by vibrational motion of atoms

- also very dominant early, declines with crustal formation, but still remains measurable



Laminar vs Turbulent

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Two kinds of flow

- Laminar:** particles in fluid all move with a constant velocity & direction
- Turbulent:** particles become highly disorganized with variable speeds & directions

For a Newtonian fluid, turbulent or laminar flow depends on Reynolds #:

$$Re = UR\rho/\eta$$

- U = velocity, R = hydraulic radius, ρ = density, η = viscosity
- Flow is turbulent when $Re > 500-2000$
- velocity, channel depth & viscosity: $Re = Uh/\eta_k$
 - h = channel depth

For a Bingham Fluid (has strength) the critical ratio is the Hampton #:

$$H = \rho U^2/k$$

- k = strength; Critical value (H) is 1000

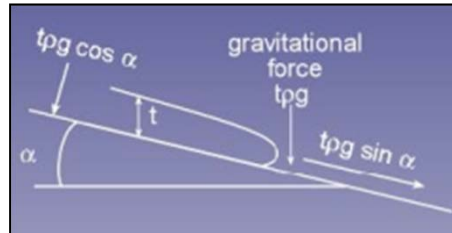
Turbulent vs. Laminar is probably not a factor as almost all lavas should flow laminarly, except perhaps some **Komatiites & Carbonatites**



Yield Strength & Flow Thickness

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- ✦ For a Bingham fluid to flow at all, a minimum force, the *yield strength*, τ_0 must be applied.
- ✦ Available force is gravity. Need the gravitational force to exceed τ_0 .
 - ✦ Vertical gravitational force is simply $t\rho g$
 - ✦ t = thickness, ρ = density, g = acceleration of gravity
- ✦ For flow to occur:
 - ✦ $t\rho g \sin \alpha \geq \tau_0$
 - ✦ $t \geq \tau_0 / \rho g \sin \alpha$



✦ Critical thickness, t_c

$$t_c = \tau_0 / (\rho g \sin \alpha)$$

- ✦ So all else being equal, lavas w/ high yield strengths produce thicker flows.
- ✦ Flows will be thinner on steep slopes!

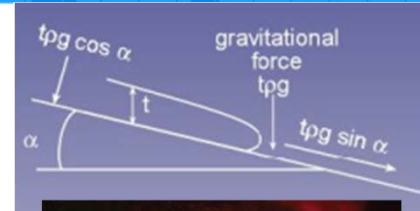


Viscosity & Flow Velocity

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- ✦ Once thickness exceeds critical thickness, flow will proceed at velocity, V (Jeffery's equation):

$$V = \rho g t^2 / B \eta \sin \alpha$$
 - ✦ Where $B \approx 3$
- ✦ Note inverse dependence of η and t^2
 - ✦ Assumes uniform viscosity
- ✦ Viscosity (η) = $\rho g t^2 / B V \sin(\alpha)$
 - ✦ Estimated from flow rate!



- ✦ Flow fronts generally advance very slowly, usually < 1 km/hr.
 - ✦ So minimal hazard to human life - most of the time.
- ✦ Interesting exception: lava flows from Mt. Nyiragongo, Congo (1977) flowed at velocities 30-100 km/hr killing ~2000 people.



Aspect Ratio

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- ✦ Define aspect ratio as: t/l
 - ✦ t = thickness; l = length
 - ✦ Also as ratio of thickness to area
- ✦ Depends on physical properties

$$t/l = \tau_0(F\eta)^{-1/4}(g\rho)^{3/4}$$
 - ✦ F = effusion rate

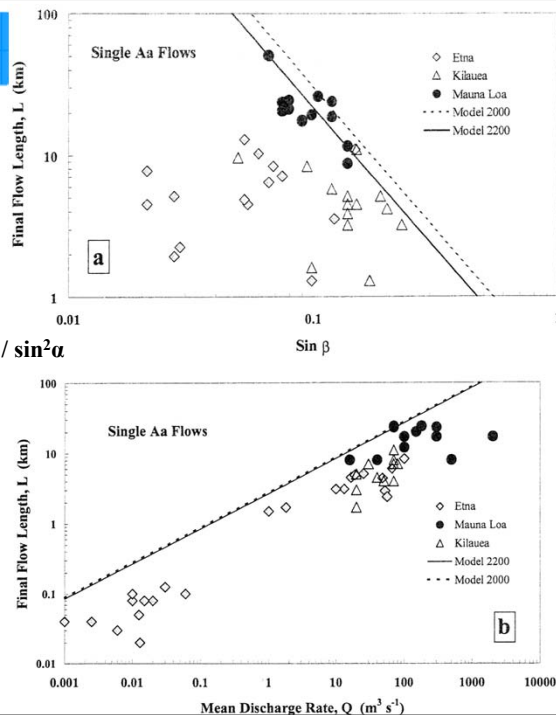


Length

- ✦ Predicting **length** of flow is complex
 - ✦ For an 'a'a flow
 - ✦ discharge rate, thermal diffusivity, thermal radiance, strength of the crust, slope & density

$$L = [(1.5\varepsilon S / \rho g)^2 (\Sigma \sigma T^4) / (T \kappa \rho c_p)] / \sin^2 \alpha$$

- ✦ Σ = surface emissivity, σ = Stephan-Boltzmann constant, ε = extension before failure of crust, S = tensile strength of crust





Simple & Compound lava flows

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✦ effusion rate (rate of discharge)

- ❑ probably single most important factor on the form of flow
- ❑ higher the effusion rate, the greater the distance traveled before cooling

✦ effusion rates

- ❑ basalt lavas - 0.5 to 5000 m³/s
- ❑ andesite to dacite lavas - 10 to 0.05 m³/s
- ❑ low effusion rate basalts
 - number of small flow units extruded closely in time that overrun each other in anastomosing channels => compound flows.
- ❑ high effusion rate basalts
 - extensive flows, often extruded as large-volume flowsheets
 - composed of a single cooling unit & called simple flows.
 - high effusion rates associated with flood basalt provinces suggest that they contain large-volume simple flows.



Compound flow: Saudi Arabia.

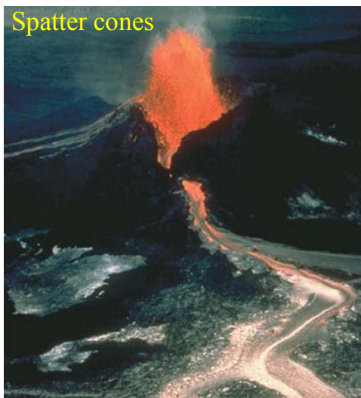
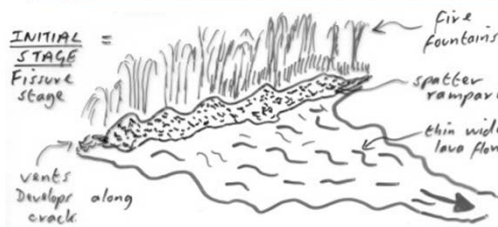


Simple flows: CRB province Palouse falls, WA



Development of a lava flow

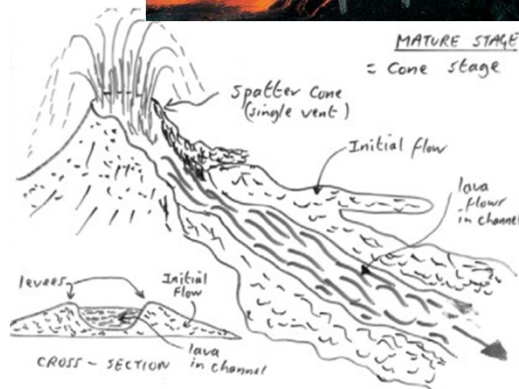
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Spatter cones



Fissures





Lava Channels

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- ✦ Fluid lavas will create own channels on gently sloping terrains, or by flowing down pre-existing stream channels
 - ❖ can develop in both pahoehoe and 'a'a
 - ❖ provides efficient transport for lava



NERZ, Mauna Loa

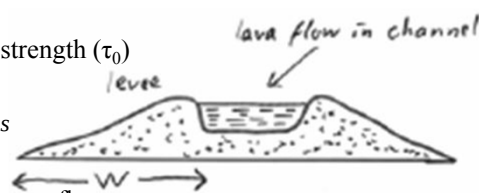


Flow Levees

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- ✦ Periodic overflow of lava causes buildup on banks of channel to produce natural lava levees
- ✦ Levee width (w) can be related to yield strength (τ_0)

$$W = \tau_0 / (2\rho g * \tan(\alpha)^2)$$
 - ❖ NB. this is also proportional to thickness



- ✦ pahoehoe - form as the channel periodically overflows
- ✦ a'a - can also occur by bulldozing effect of moving lava



Villarica, Chile



Kilauea, Hawaii



Lava channel formations

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- ✦ **Kipuka** – produced when several small lava channels may flow around subdued hills or high ground

- ❖ Hawaiian term for "island."
- ❖ noted by their mature vegetation



- ✦ **Accretionary Lava ball** - nearly spherical masses characteristic of a'a channels

- ❖ Diameters of few cm to > 3 m.
- ❖ spiral structure within from rolling of small fragment of solidified lava rolls along the surface of flow
- ❖ lava adheres to rolling mass like a rolling snowball!



Lakes & Falls

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- ✦ **Lava Lake** – accumulation of lava in volcanic craters

- ❖ common oscillation in lake levels
- ❖ if effusion rate is constant & high, lava may rise & overflow crater rim

Kupaianaha, 1986



Mauna Ulu, 1969-71



- ✦ As lava flows down an irregular topographic surface, can flow over an abrupt escarpment to produce **lava cascades** or **lava falls**

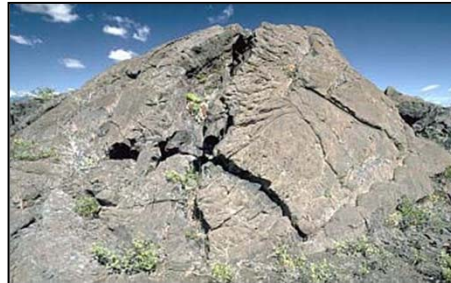
- ✦ With decrease in effusive rate & cooling, basalt may solidify in place to cover the escarpment in a **lava drapery**



Tumuli

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- ✦ Elliptical domed structures formed on flat or gentle slopes, on surfaces of pahoehoe flows & best developed on flows ponded in depressions (e.g., craters or calderas)
 - ✦ from 2-10 m high
- ✦ When slow-moving lava beneath a solidified crust wells upward
- ✦ Brittle crust buckles to accommodate inflating core of flow, creating a central crack along the length of the tumulus
- ✦ Variety of causal mechanisms:
 - ✦ obstruction of lateral flow downstream behind a slow-moving lava front
 - ✦ diversion of flow upward against an irregular topographic surface
 - ✦ local upheaval from the volatilization of groundwater
 - ✦ deflation of *inflated pahoehoe* sheet flow causing differential sagging & buckling
 - ✦ can grade into elongate forms or *pressure ridges*
 - subparallel to flow direction at flow margins
 - perpendicular to flow direction in center of flow



Rootless eruptions

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- ✦ From eruptions on pahoehoe surfaces not connected at depth to a magma chamber
- ✦ When crust thickens & underlying lava cools, viscous gas-poor lava can squeeze up through axial fracture of tumulus
- ✦ creates a protrusion = a *squeeze-up*.
- ✦ If lava stays hot & fluid, local extrusions through the cracked lava can produce rootless cones of **spatter**, called **hornitos**
- ✦ these can erupt through axial cracks of tumuli as well as through cracks & openings overlying active lava tubes





Lava Tubes

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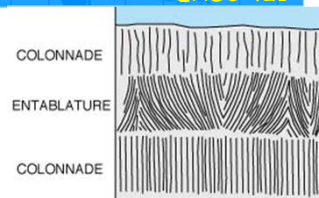
- ✦ insulate lava, prevent cooling & allow flow to travel great distances
- ✦ Cooling & crystallization of basaltic lava around sides, bottom, and top of lava channels
 - ❑ conduit that remains relatively hot & insulates lava
 - ❑ morphology efficient for flow without significant heat loss
 - ❑ typically < 1 km long but may exceed several km (e.g., >100 km, Queensland)
 - ❑ diam. (< 1 m to 15 m) & lateral extent highly variable
- ✦ High lava T (~1150°C) sustained throughout system
- ✦ Fast, hot turbulent lava *thermally erode* tube interior downward & laterally
- ✦ As eruption ceases, lava drains downslope, exposes hollow, inactive lava tube
 - ❑ flat floor & show high-lava marks on walls
 - ❑ thin coating of *agglutinated spatter* found on walls
 - ❑ *lava stalactites* hanging from roof & mound-like *lava stalagmites* from spatter dripping onto floor
 - ❑ most tubes remain buried but many delineated on surface by linear or curvilinear series of collapse depressions, *skylights*, along the axis of the tube.



Jointing Characteristics

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- ✦ lava flow cools & crystallizes, begins to contract
 - ❑ shrinkage causes formation of numerous **joints**
- ✦ Variety of patterns, but many thicker simple flows have 3-tiered character
 - ❑ *lower colonnade* (bottom)
 - ❑ *entablature* (middle)
 - ❑ *upper colonnade* (top)



- ✦ lower colonnade composed of **columnar joints**
 - ❑ develop perpendicular to cooling surface at base (top, sides?)
 - ❑ intersect to form a series of columns
- ✦ columns may vary in length (1-5 m) & diam. generally <1 m
- ✦ polygonal in cross-section (typically hexagonal) bounded by 4-8 joints
- ✦ *entablature* (if present) composed of array of closely spaced subvertical joints
 - ❑ forms more complex pattern of cracks: *hackly jointing*
- ✦ *upper colonnade* generally poorly developed or non-existent
 - ❑ crude columnar joints are vesicular & much shorter than those in the lower colonnade



Next class...

EASC 421

