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89.304 - IGNEOUS & METAMORPHIC PETROLOGY
INTRUSION OF MAGMA

1. The summit of Mauna Loa is 8192 m above the floor of the Pacific Ocean, but only 4169 m of this is above sea level. About 150 m of ocean-floor sediment covers the oceanic crust, which is 6.5 km thick in this region. The densities of the various materials, in kg m^{-3} are: seawater, 1000; sediments, 2000; oceanic crust, 2840; mantle, 3100; and magma, 2900. Calculate the depth of origin below sea level of an incompressible magma that rise buoyantly to the summit of Mauna Loa.

2. During the 1959 eruption of Kilauea Iki, a fountain of lava rose from the vent to a height of 450 m, and on one occasion, to 540 m. The ponding of this lava within the crater allowed for accurate monitoring of the volumes of erupted material in much the same way as a measuring cylinder is used to determine volumes of liquid in the laboratory. The flux of lava was estimated to have varied from 100 to 300 $m^3 s^{-1}$. Although there were periods of more violent eruption brought about by escaping gas, the steady fountaining is thought to have simply resulted from the velocity of ejection of magma fro the orifice.

   a. Using the height of 450 m and neglecting air resistance, calculate the maximum velocity of ejection of lava from the orifice. Assuming a parabolic velocity profile across the orifice (i.e., fully developed flow), determine the average velocity of ejection. HINT: a relationship from kinematics, $d = 1/2\ at^2$, may be useful in solving this problem.

b. Assuming a cylindrical feeder pipe, use the average velocity from part (a), along with the rate of ejection of 100 $m^3 s^{-1}$, to determine the diameter of the pipe.

c. If the magma had a density of 2750 kg m^{-3} and viscosity of 300 Pa s, would you expect turbulent or laminar flow in a feeder pipe with the diameter calculated in part (b)?

3. If the diameter of the Kilauea Iki feeder pipe was 1.65 m, what would the (a) maximum and (b) average velocities have been for the magma if it rose in response to a pressure gradient induced solely by the loading of solid basalt (ρ = 3000 kg m^{-3}) on the magma (ρ = 2750 kg m^{-3})? The viscosity of the magma is 300 Pa s.

4. What fraction of a 10-m-wide dike of dacite that behaves as a Bingham liquid would flow as a plug if the magma has a yield strength of 10^4 N m^{-2} and the magma is buoyantly emplaced in response to a density contrast between magma and country rock of 300 kg m^{-3}.

   The shear stress, τ, at any point in a vertical dike is given by

$$\tau = -(\rho_m g - \rho_c g)(\frac{W}{2} - x)$$

   where g = acceleration due to gravity, ρ_m = magma density, ρ_c = country rock density, W = dike width, and x = distance from the edge of the dike.

5. Jurassic basalts in eastern North America, associated with the initial opening of the Atlantic, are similar to those still being erupted today at the mid-Atlantic ridge in Iceland. In both areas erosion has exposed dikes that were feeders to fissure eruptions. In Iceland these dikes average 4 m in width, but in eastern North America many are as much as 60 m wide. Assuming that magma rose buoyantly in both areas and that the average density of the intruded lithosphere was 3000 kg m^{-3} in Iceland and 2900 kg m^{-3} in eastern North America, determine whether the flow was laminar or turbulent in these two areas, and calculate the average flow velocities for the respective dikes. The basaltic magma in both areas had a density of 2600 kg m^{-3} and a viscosity of 300 Pa s. The friction factor for the dikes is 0.01.

6. The Loch Ba granophyric (rhyolitic) ring dike on the island of Mull, Scotland, has an outside diameter of approximately 5.6 km and an inside diameter of 5.5 km.

   a. If intrusion of the ring dike resulted solely from the subsidence of the central block, what is the ratio of the average rate of intrusion to the average rate of subsidence. HINT: The area of a circle is key to answering this question.

   b. The radius of curvature of the ring dike is sufficiently great that at any point the dike can be treated as a planar sheet. The granophyric magma had a density of 2400 kg m^{-3} and a viscosity of 10^7 Pa s. The subsiding block consists largely of basaltic rocks with a density of 3000 kg m^{-3}. Assuming laminar flow, calculate the average intrusion velocity of the magma relative to the surrounding rocks and the rate of subsidence of the central block. Check to see if the assumption of laminar flow is valid.

   c. If growth of gas bubbles in the ring dike magma disrupted the magma, the viscosity of the magma-gas mixture would be 0.1 Pa s and the density would be 1800 kg m^{-3}. Under these conditions, calculate the average rate of intrusion of the magma and the rate of subsidence of the block. The friction factor for the ring dike is 0.06.

d. In light of your answers to parts (b) and (c), what role is magma disruption likely to play in the emplacement of rhyolitic ring dikes?

7. The following questions are most easily answered using a spreadsheet.

   a. Draw cross sections through two laccoliths (on a single graph), both having a radius of 2 km, one of which is intruded at a depth of 200 m and the other at 500 m into sandstone having a density of 2700 kg m^{-3}m Young's modulus of 3 x 10^{10} Pa and a Poisson's ratio of 0.1. The pressure on the magma is due solely to buoyancy resulting from a 10-km-long feeder column of magma with a density of 2400 kg m^{-3} intruding rocks with an average density of 2700 kg m^{-3}. P_m can be calculated from the hydrostatic equation using the difference in density between the magma and the country rock.

   b. Repeat the calculation for a laccolith intruded at a depth of 200 m but having a radius of only 1 km.

   c. Repeat part (a) for the case where intrusion is into limestone that has a Young's modulus of 6 x 10^{10} Pa, a Poisson's ratio of 0.2 and a density of 2700 kg m^3.

   d. In light of the results of your calculations, discuss the relative importance of the factors controlling the shape of a laccolith.