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Modeling magma-drift interaction at the proposed high-level radioactive waste repository at Yucca Mountain, Nevada, USA

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[1] We examine the possible ascent of alkali basalt magma containing 2 wt percent water through a dike and into a horizontal subsurface drift as part of a risk assessment for the proposed high-level radioactive waste repository beneath Yucca Mountain, Nevada, USA. On intersection of the dike with the low pressure, horizontal drift, the ascending magma will be diverted into the drift. The fragmenting mixture expands down the drift to reach speeds of order 100–300 m/s. After this initial disruptive activity, parts of the repository can be filled with magma within a matter of hours until a pathway is found to allow the magma to vent. Magma flow through the drift network will cause intense heating of any waste canisters located along the pathway between the dike and the surface conduit. The assessments suggest a greater number of waste packages may be adversely affected than previously recognized. *INDEX TERMS:* 8414 Volcanology: Eruption mechanisms; 8434 Volcanology: Magma migration; 8499 Volcanology: General or miscellaneous

1. Introduction

[2] Increasingly, geologists and geophysicists are called upon to develop and use models of geophysical processes to evaluate volcanic hazard and risk. This is particularly evident for the siting of nuclear facilities, which must be located in areas of very low geologic risk [*International Atomic Energy Agency*, 1997]. Because of the requirement to assure long-term public health and safety, risk assessments are made for rare phenomena, such as volcanic eruptions, which require development of realistic physical models. A striking example is the need to model the potential impacts of volcanic activity on the proposed high-level radioactive waste repository beneath Yucca Mountain, Nevada, USA. Probabilistic volcanic hazard assessments indicate that the likelihood of a basaltic volcanic eruption occurring in the repository during the next 10^4 yr, the proposed compliance period of the repository, is 10^{-8}–10^{-7} per year [*Connor et al.*, 2000]. This hazard is sufficient to require that the potential impact of volcanic activity on repository performance be evaluated.

[3] Any assessment involves evaluating the interaction of natural volcanic processes with a complex engineered system. Large uncertainties in the assessment are related to variations in engineering design, natural variations in the geologic system, and epistemic uncertainty in the mechanisms of basalt eruption. Here we develop a model of magma intrusion and flow into the repository. We consider the initial transient flows that occur when magma first intersects repository drifts, and then longer-term steady-state flows that develop once eruptive pathways to the surface have been established. In a basaltic eruption lasting several days or weeks the interactions between moving magma and the waste canisters will control the amount of radioactive waste ultimately released. Three alternative scenarios for effects of the repository on pathway development are postulated and discussed. These three scenarios are predicated on the assumptions that: (a) tangential and thermal stresses around the drift do not prevent dike intersection with the drifts; (b) the structure and geometry of the repository and drifts are preserved until the dike intersection; (c) the drifts are not back-filled with sufficient material to impede flow; (d) following intersection of the dike with the drift, the magma will be diverted into the drift, because the drift provides the path of least resistance; and (e) interactions with other engineered components, such as ventilation shafts or drift supports, have minor effects on magma flow processes. While further studies are being conducted to test these assumptions, our current assessments suggest a greater number of waste packages may be adversely affected than previously recognized [*U.S. NRC*, 1999].

[4] Volcanic hazards at the proposed repository site result from its location within a geologically active basaltic volcanic field. Six Quaternary pyroclastic basaltic volcanoes are located within 20 km of the site, including Lathrop Wells volcano, formed by eruptions approximately 80 ka ago [*Heizler et al.*, 1999]. These mildly alkaline cinder cones are characterized by relatively wet basaltic magmas, with olivine and amphibole assemblages indicating about 2 wt percent water in the magma [*Vaniman et al.*, 1981; *Knutson and Green*, 1975]. Such magmas produce relatively small volume ($\sim$0.1 km^3) but explosive eruptions [*Doubik and Hill*, 1999; *Wilson and Head*, 1981], which may have substantial impact on waste packages stored in the subsurface repository drifts.

[5] In the proposed design, repository drifts would be located 200–300 m below the surface and have a cross-sectional area of order 20 m^2. Given the roughly E-W trend of the repository drifts [*CRWMS M&O*, 2000] and NNE trend of maximum horizontal compressional stress [*Ferrill et al.*, 1999], magma ascending beneath the repository is expected to form a dike that cuts across numerous drifts. Each intersected drift will drain magma from a section of the dike of order 80 m in length (Figure 1), corresponding to the drift spacing. The drifts may accommodate a large fraction of the ascending magma, as the cross-sectional area of each drift equals that of a 20 m section of a dike, 1 m wide. Prior to magma intrusion, the drifts will have a pressure close to atmospheric [*Rosseau et al.*, 1999] and the magma at the leading edge of the dike will have a pressure of order 10 Mpa, based on lithostatic pressure and the fluid pressure required to initiate a vertical fracture [*Pollard*, 1987; *Lister and Kerr*, 1991]. Therefore, on intersection with the drift, there will be a very rapid decompression of the magma. If the alkali basalt contains a typical amount of water, of

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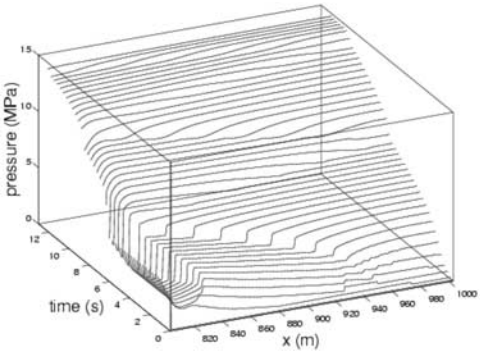

Figure 1. 1D flow calculations of pressure as a function of position and time along a basalt dike during the initial few seconds after the dike intersects the drift. Magma has 2 wt percent water. In the figure, the drift lies in the region 800 < x < 1000 m, and the upper 800 m of the dike lies in the region 0 < x < 800 m. The initial shock wave propagates to the end of the drift and is then reflected at the drift end and amplified by an order of magnitude. Subsequently the pressure in the drift builds up towards that in the dike at the point of intersection with the drift.

order 2 wt percent, this decompression will be explosive [*Blackburn et al.*, 1976].

2. Physical and Mathematical Modeling

[6] We present a series of flow models assuming a 1m wide vertical dike intersecting a 5m diameter horizontal tunnel. As a consequence of magma decompression and volatile exsolution, the magma in both the dike and the drift will expand and accelerate. The magma may then break up to produce a high speed mixture of vesicular fragments of magma and gas in regions of low pressure (e.g., near the Earth's surface or on encountering an empty drift). This flow speed typically can be very high and may exceed the slip velocity between the gas and many of the liquid fragments. As a first quantitative model, we examine the possible magnitude of such a flow, when the magma in the dike first intersects the drift. We examine the intensity of a homogeneous flow with liquid, particles and gas moving at the same speed. We also assume the dike and drift walls exert a viscous and turbulent drag on the flow [*Wilson and Head*, 1981]. The motion may be described by the averaged speed u and density ρ of the magma-gas mixture in terms of position x, pressure p, and time t along the drift or dike, leading to the equation for momentum conservation,

$$\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x}\right) = -\frac{\partial p}{\partial x} - fu - \rho g H(x), \tag{1}$$

where $H(x)$ has value 1 in the vertical dike, and value 0 in the horizontal drift. Here, f is the drag coefficient, which has value $f = \frac{\alpha\mu}{d^2} + \frac{2C\rho|u|}{d}$,where the viscosity μ = 10 Pa s, α = 12 and 8 for flow in the dike and cylindrical drift, d denotes the dike width or drift radius, and C denotes the turbulent drag coefficient, which depends on the wall roughness, but which is taken to have the representative value 0.01. We couple equation (1) with the equation for conservation of mass in the dike or drift, with cross-sectional area $A(x)$,

$$\frac{\partial(A(x)\rho)}{\partial t} + \frac{\partial(A(x)\rho u)}{\partial x} = 0. \tag{2}$$

The model is completed with an equation describing the bulk density of the magma-gas mixture

$$\frac{1}{\rho} = \frac{n(p)RT}{p} + \frac{(1 - n(p))}{\sigma}, \tag{3}$$

where R is the gas constant of H_2O, T the constant temperature, σ the basalt magma density, and $n(p)$ the exsolved gas mass fraction, which decreases with pressure according to the solubility law

$$n(p) = n_0 - sp^{1/2}, \tag{4}$$

where the solubility coefficient s has value 3×10^{-6} Pa$^{-1/2}$ and n_0 is the total gas mass fraction [*Holloway and Blank*, 1994]. For this process, we assume that the mixture remains isothermal owing to the large thermal inertia of the liquid phase.

[7] The cross-sectional area of the dike or drift, given by the function $A(x)$, is assumed to vary smoothly from the dike cross-section to that of the drift over a distance of about 5 m around the point of intersection of the dike and the drift. This provides a parameterized model of the three-dimensional flow at the dike-drift intersection using the stream-tube approach. The model system of equations has been solved numerically. Shock-capturing second- and third-order Local Lax Friedrich and Essentially Non-Oscillatory numerical schemes have been used and tested extensively for accuracy [*Bokhove and Woods*, 2002].

3. Model Calculations

[8] We assume that the magma originates at a depth of around 30 km at the base of the crust and has an unvesiculated density of 2600 kg/m^3 and has lithostatic pressure. The crust is assumed to have a linear density variation with depth, from 2940 kg/m^3 at 30 km depth to 2400 kg/m^3 at the surface [*U.S. NRC*, 1999]. Integrating from the source depth to the surface, we find that the mean density contrast between magma and crust is 70 kg/m^3, resulting in a net buoyancy to drive the dense basaltic magma through the lower density rocks in the upper ten kilometers of the crust. In these circumstances, then in the upper crust, the dike has a total pressure of order 10–20 MPa, that is the local lithostatic pressure plus an overpressure, which is easily sufficient for propagation of the dike tip into the crust [*Stasiuk et al.*, 1993; *Lister and Kerr*, 1991]. Apart from the waste canisters, the drift is assumed to be empty, and since the drift cross-sectional area is much larger than that of a 1.8-m-diameter canister, $A(x)$ is taken to be the total drift cross-sectional area in equation (2). We assume that the dike remains open after breaking through into the drift, so that magma continues to rise into and flow along the drift. These simplifications lead to an upper bound on the magnitude of flow in the drift, since in this model we do not account for any closure of the dike.

[9] Figure 1 indicates the evolution of pressure and velocity in the dike-drift system over the first ~12 s following break-through into the drift. Initially, there is a rapid expansion of the magma-volatile mixture as a rarefaction wave propagates back into the dike through the magma, and volatiles are exsolved. This expanding mixture accelerates along the drift reaching speeds of tens to hundreds of meters per second, with the density decreasing as the pressure falls. Air is displaced and compressed ahead of the magma-volatile mixture and as a result, a shock forms in the air and moves down the drift at speeds of several hundreds of meters per second. The subsequent flow behavior depends on whether the drift is closed at both ends or open at one end to a larger diameter access drift. If closed, then on reaching the end of the drift, the shock is reflected and its amplitude increases by an order of magnitude. The shock then propagates back upstream, moving into the magma-volatile mixture and back towards the dike at speeds of 20–30 m/s. As the shock moves through the magma-

volatile mixture, the mixture is recompressed. A region of higher pressure, of order several MPa, and hence higher density, develops between the end of the drift and the shock (Figure 1). The calculations suggest that, if the dike intersects the drift 200–300 m from the end of a closed drift, then the pressure within this drift will build up to about the initial level in the dike in a time of order 10 s [*Bokhove and Woods*, 2002]. If the flow then continues up the dike and breaks out at the surface, the pressure adjusts to one of a range of steady states described below.

[10] Alternatively, in an open-ended drift, the explosively erupting magma will begin to fill the access drift as well as the drifts it has directly intersected. After a period of a few hours the available underground space will be filled and the magma pressure in the repository will increase towards values comparable to the driving pressure. In addition to initial fracture propagation ahead of the dike, development of large magma pressures in the repository or individual drifts could drive open a fracture in the overlying crust and produce a conduit to the surface for the erupting magma. Calculated estimates of the fluid pressure required to initiate a vertical fracture range from 2–6 MPa, depending upon the fracture orientation [*Pollard*, 1987]. Hydrofracturing stress measurements, in borehole G-1 at Yucca Mountain, indicate pressures of 5.1–5.5 MPa are required to reopen existing fractures in the unsaturated zone near proposed repository depths at Yucca Mountain [*Stock et al.*, 1985].

4. Steady Flow Regime

[11] The precise location of the preferred magma pathways from the drift to the surface will depend on many factors, including any heterogeneity or fractures in the overlying rock strata, proximity of the drift to the surface, and any damage to the rock prior to intersection of the dike and the drift. Since we have no basis for preferring a particular pathway, we compare three different cases which might bound the range of possibilities (Figure 2): (Case 1) that the deep dike path continues to the surface without any major perturbation by the repository system, (Case 2) that the pathway to the surface is shifted to a new position, 500 m along a drift with an area of 20 m^2, and (Case 3) that the magma uses the main access drift to the repository for flow to the surface. The access drift is taken to be 4 km long, with a gentle incline to the surface and area of 50 m^2. Breakout from the access drift, which is likely be closed at each end, may occur at a variety of locations (e.g., structural weaknesses, ventilation shafts).

[12] Once a flow path to the surface develops, a quasi-steady eruption may become established (Figure 2). In order to quantify the potential impact of such a steady flow regime on the canisters, we have extended the flow model, described by equations (1)–(4), to include a conduit from the drift to the surface. We then calculated steady flow solutions for the three different cases, assuming magma is supplied to the dike from a reservoir located 30 km below the surface. To complete the model, we apply the condition of choked flow as the magma-volatile mixture erupts at the surface [*Wilson and Head*, 1981]. This condition ensures that on issuing from the vent, the flow has speed smaller than or equal to the speed of sound of the decompressed magma-volatile mixture. On solving the governing equations, in each case we find flow speeds of a few metres per second 1–2 km below the repository. These increase to values of order 90 m/s as the flow decompresses, exsolves volatiles and erupts at the surface. For flow limited to the dike (case 1), the pressure falls below lithostatic except near the exit to the surface, where the flow accelerates and expands so as to reach choked conditions. The pressure falls below lithostatic in case 1 owing to frictional drag on the magma during ascent deeper in the system; note that the adjustment from the initial break-through and pressurization of the tunnel to this steady state may lead to some transport of material back into the dike. We find that in the case in which the flow is diverted along a drift, the flow pressure is elevated relative to lithostatic in the upper kilometer or so as the flow advances along the drift (case 2) and main drift (case 3) towards the surface. These flow rates are somewhat smaller than in case 1, in which the magma flows directly along the dike to the surface. Calculated flow pressures for case 3 exceed the minimum fracture strength of the overlying rock [*Pollard*, 1987]. If a conduit formed initially in response to flow down a 4-km-long access drift, these large flow pressures would be likely to cause significant widening of the conduit or the formation of additional conduits. The flow calculations for cases 2 and 3 may be used to estimate the drag force acting on the waste canisters in the drift, $\rho C_d u^2 A_c$, where A_c is the area of the end face of the canister and $C_d \sim 1$ is the drag coefficient of a canister. For the above model calculations, the ratio of drag force to canister weight is typically of order or smaller than 0.1–1.0. This suggests that the canisters may be displaced down the drift, although the flow is much too weak to keep the canisters in suspension and any canister motion is likely to be relatively slow.

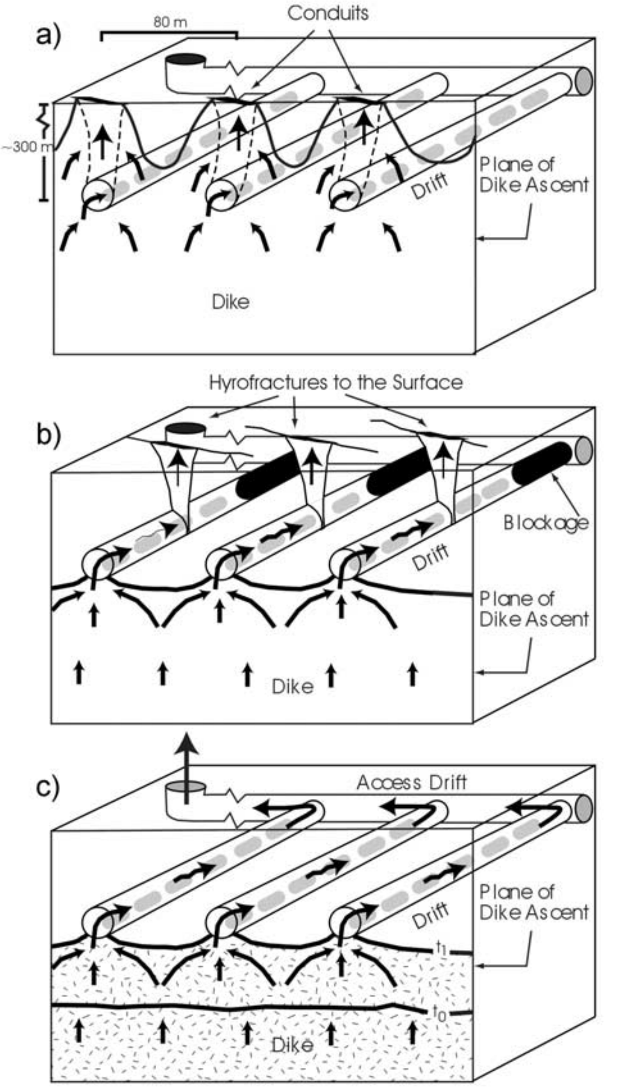

Figure 2. Schematic of the steady flow geometry that may enable a steady basaltic eruption to develop: (a) with flow along the original dike; (b) with magma being diverted along the drift before surfacing along a new fissure; and (c) with magma being diverted along the drift and into the main access drift from where it vents to the atmosphere.

[13] As well as mechanical damage, waste canisters will experience considerable thermal stress from the magma. For example, if

the steady-flow regime becomes established, then heat transfer from the molten magma to the containers may lead to ductile deformation of the containers [*Rebak et al.*, 1999]. If we assume that the magma flows past the canisters with a steady speed of order 10 m/s, as indicated by our solutions of the governing equations, then the canister will gradually heat by thermal conduction from this quasi-steady magmatic heat source. To a good approximation, the time-scale required to heat the 7 cm walls of the canister above a likely deformation temperature of 800°C is given by the time for thermal diffusion $d^2/\kappa \sim 10^3$ s, where the effective thermal diffusivity of the composite shell of the canister, $\kappa \sim 10^{-6}$ m^2/s. For times greater than $\sim 10^3$ s, the canisters will become deformable, and may then break open. The time required for thermal damage is short relative to the duration of most basaltic eruptions, and so canister failure is anticipated for these magmatic conditions.

5. Implications

[14] Our calculations point to the potential damage that an alkali basaltic volcanic eruption might have on the proposed subsurface repository at Yucca Mountain. Although our models are a considerable simplification of the complex processes involved with magma-repository interaction, the models are consistent with general observations of explosive basaltic eruptions and current knowledge of the underlying physics. The models indicate that intersected drifts will be quickly filled by magma at an early stage in an eruption, with potential disruption of the drift contents. The repository drifts may then provide a possible flow path to the surface. These results indicate that, although magma injection is a very low probability event, it can potentially affect a large number of waste canisters in the proposed repository. Heating of the waste packages to magmatic temperatures is expected to lead to their failure, and prolonged magma flow through the repository drifts over periods of days to months may then provide a mechanism to transport contaminants to the Earth's surface. Although there are large uncertainties inherent in these conceptual models, the risk significance of these models should be determined for the proposed subsurface repository at Yucca Mountain. Important areas for future work include investigation of the effects of magma-volatile separation, especially in the repository drifts, mechanisms of waste package disaggregation and waste entrainment, and the coupling between magma flow and the evolution of the dike, drift, and conduit geometry.

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