# REVIEW OF NUMERICAL ANALYSES FOR MAGMA DRIFT INTERACTION AT THE PROPOSED YUCCA MOUNTAIN REPOSITORY

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*Prepared by*

**Debashis Basu[1]**
**Kaushik Das[1]**

**[1]Center for Nuclear Waste Regulatory Analyses**
**San Antonio, Texas**

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# ABSTRACT

The location for the proposed high-level nuclear waste repository at Yucca Mountain, Nevada, is in a small volume basaltic volcanic field in the western Great Basin. Based on the recent volcanic history of that field and region, if a future event occurred, it would begin with basaltic magma ascending through dikes 1 to 3 m [ 3.3 to 9.8 ft] in width. With continued ascent, a conduit up to 10 m [33 ft] in diameter might develop along the strike of the dike that reaches the surface, and eruptive activity, which includes effusion of lava flows and Strombolian–violent Strombolian eruptions, might ensue and construct a monogenetic, basaltic scoria cone. A range of models and data has been considered during the development of performance assessments conducted by the U.S. Department of Energy and as part of the U.S. Nuclear Regulatory Commission safety analysis for the proposed repository. A key component when abstracting these types of events is to understand how rising basaltic magma will interact with subsurface repository structures, such as tunnels (drifts), waste packages, and drip shields. Several past investigations have focused on numerically analyzing specific aspects of the intersection of a basaltic dike with the proposed repository drifts. Those analyses took into account the characteristics of the basalt lava (and hence magma) generally encountered in the Yucca Mountain region. Most of the analyses looked into the large uncertainties that existed in many key parameters, such as magma volatile contents, specific subsurface geometries of intersection between a basaltic dike and a repository drift, and the complex fluid dynamics nature of magma. Some of these analyses considered multiphase flow of fragmented magma into an open drift immediately after intersection, followed by rapid filling of the drift. Other analyses considered effusive flow of hot basaltic magma inside the drift neglecting gravity. However, most of the prior analyses (i) focused on the various aspects of dike–drift interactions that showed that a drift intersected by ascending basaltic magma will quickly fill with magma and (ii) concluded that the physical conditions, such as the velocity of the magma and the static and dynamic pressure inside the drift, will be significantly high. This report only considers analyses that have been published as technical papers, and it provides brief overviews of the different numerical analyses that have been carried out to simulate magma dynamics at the proposed Yucca Mountain repository. The report also summarizes one experimental study to analyze the potential interaction between rising magma and the proposed repository.

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# ACKNOWLEDGMENTS

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# QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

**DATA**: No original data were generated for this report.

**ANALYSES AND CODES**: No technical analyses or codes are presented or used in this report.

# 1 INTRODUCTION

This report is part of the knowledge management activities for the U.S. Nuclear Regulatory Commission high-level waste repository safety program. It summarizes several numerical studies and one experimental study that have been carried out to analyze the magma dynamics and the possible interaction between magma and the proposed repository at Yucca Mountain. This report documents the different scenarios (extrusive and intrusive) that have been considered in the previous analyses, the numerical techniques that have been used, and the major findings of the investigations.

## 1.1 Background

Yucca Mountain is located in southern Nevada in a region that has experienced sporadic basaltic volcanism since the late Miocene (Crowe, 1986; Fleck, et al., 1996; Valentine and Perry, 2006; Dartevelle and Valentine, 2008). It lies within one of many small volume basaltic volcanic fields that typify the western Great Basin (e.g., Faulds and Varga, 1998), the Crater Flat Volcanic Field (Valentine et al. 2006, Connor, et al., 2000). In this field and the surrounding area, more than 40 basaltic vents have formed in the past 11 million years. There are 6 cinder (or scoria) cones within 20 km [12.5 mi] of Yucca Mountain that formed in the last million years (e.g., Fleck, et al., 1996) and some dikes that may have fed older eruptions. Volcanic hazard assessment has been a major focus of study since Yucca Mountain was first proposed as a repository for high-level nuclear waste.

Most of the prior analysis of interaction between the proposed repository and rising basaltic magma (Dartevelle and Valentine, 2005, 2008; Woods, et al., 2002) accept a generalized conceptual model for basaltic volcanism near Yucca Mountain that would likely begin with an alkalic basalt melt ascending through the brittle crust in magma-filled cracks or dikes that are 1 to 3 m [3.3 to 9.8 ft] thick and on the order of 1 to 5 km [0.6 to 3 mi] in length (Detournay, et al., 2003). Studies of the Crater Flat basaltic magmatic system (Valentine, et al., 2005, 2006; Valentine and Perry, 2006) considered that if a future eruption occurred it would be similar to the most recent eruptions; the initial surface expression of the eruption would be a fissure, but within a few days, eruptive activity would quickly be focused into a central vent. The resulting volcano is likely to be a monogenetic cinder cone with a total volume on the order of 0.01 to 1 $km^3$ [$1.3 \times 10^3$ to $1.3 \times 10^9$ $yd^3$] (Detournay, et al., 2003). Because the most likely composition of the magma is potassic trachybasalt with up to 4.6 wt% pre-eruptive volatiles (Nicholis and Rutherford, 2004), the eruption style will likely be Strombolian to violent Strombolian, characterized by both explosively emplaced tephra and effusively erupted lava flows, the former as evidenced by the presence of ballistic fragments in the cones (classic Strombolian style) and by scoria and ash-fall deposits representing fall-out material from the plume (violent Strombolian).

The lack of direct physical evidence or analog cases for what might happen should magma intersect open drifts (sub-surface tunnels) makes it difficult to accurately quantify the impact of the magma dynamics on the proposed repository and its drifts (tunnels). The study by Dartevelle and Valentine (2007) of the explosive eruption of basaltic tephra through a geothermal borehole (Namafjall, Iceland) provides a unique perspective on the simulations of multiphase volcanic processes. The model results were consistent with observations, including development of complex compressible flow phenomena along with ejection of particles. Woods and Sparks (1998) performed initial scoping calculations to determine the potential behavior of magma flow inside a repository drift at Yucca Mountain. The work of Woods and

Sparks (1998) also led to a series of papers and reports that examined the potential consequences of basaltic magma intrusion into drifts (e.g., Lejeune, et al., 2002; Woods, et al., 2002, Connor, et al., 2009 ). Collectively these papers show that the drifts will quickly fill with magma once the basaltic dike intersects the repository. These models considered effusive flow of hot basaltic magma inside the drift and neglected gravity. Dartevelle and Valentine (2005) considered multiphase flow of fragmented magma into an open drift immediately after intersection, followed by rapid filling of the drift.

Additionally, in the last few years, a series of papers (Menand and Phillips, 2007a,b; Menand, et al., 2008; Phillips, et al., 2008; Woods, et al., 2002, Connor, et al., 2009) focusing on various aspects of dike–drift interactions have collectively shown that a drift intersected by ascending basaltic magma will quickly fill with magma and concluded that the physical conditions, such as the velocity of the magma and the static and dynamic pressure inside the drift, will significantly influence the integrity of a repository. These papers describe multiphase flow in a dike–drift configuration and experiments examining circulation patterns established in a drift after intersection under steady-state conditions.

In this report, the Center for Nuclear Waste Regulatory Analyses (CNWRA®) has summarized and documented the various computational studies that have been carried out to date to analyze the predicted magma dynamics and the complex interaction between magma and the proposed repository at Yucca Mountain.

## 1.2 Purpose and Scope

This report documents the important technical aspects and results of computational analyses carried out to study the magma dynamics at the proposed Yucca Mountain repository. Modeling and analyses for two possible scenarios have been considered here. The scenarios have a spectrum from gas-poor to gas-rich magma entering repository tunnels, corresponding to the range of volcanic eruption behaviors that can be broadly classified as effusive to explosive. The explosive eruption involves the intersection of a dike with a drift, the dike then reaching the surface, forming a conduit, and feeding a cone- and tephra blanket-forming explosive eruption. The effusive eruption is much less violent and is, beneath the surface, intrusive in nature. The different cases considered in this report primarily deal with intrusive flow of gas-poor magma within the drift and some cases of invasion of a drift by gas-rich magma during an explosive eruption. The different numerical models in the various analyses are explained, and the conclusions from each of these analyses are also documented in this report. This report provides a brief literature review of the several numerical and experimental studies carried out in the past on the analysis of the magma dynamics and the possible scenarios of magma–repository interaction. All these past analyses were carried out from a fluid dynamics perspective.

# 2 NUMERICAL SIMULATIONS: DISCUSSIONS AND OBSERVATIONS

This section details prior numerical simulations that several groups have carried out. Most of these studies deal with flow of magma in empty drifts (subsurface tunnels) and none of the analyses, except that by Basu, et al. (2008), have modeled drifts with waste containers.

## 2.1 Woods, et al. (2002)

The work by Woods, et al. (2002) was one of the first analyses carried out to evaluate the consequence of a rising basaltic dike intersecting a horizontal repository. It was a quasi-two-dimensional numerical analysis. Simulations were carried out for a homogeneous flow model with magma, gas, and particles all moving at the same speed. Woods, et al. (2002) assumed a one-dimensional flow of a homogeneous multiphase mixture where all the phases (magmatic melt, volatile water vapor, and exsolved gas) are in thermal and dynamical equilibrium. The simulations were carried out with a water content of 2 percent in the basaltic magma. Woods, et al. (2002) assumed a compressible flow inside the repository. The shock-capturing Lax scheme was used in conjunction with an essentially non-oscillatory scheme (Bokhove, et al., 2005). The simulations assume that the magma originated at a depth of 30 km [18.6 mi] at the base of the crust. Calculations show that the density difference between the magma and the crust result in a net buoyancy to drive the dense basaltic magma through the lower density rocks. The work also assumed that the dike remains open after breaking into the horizontal repository and magma continues to rise into and flow along the repository. In the simulations, the dike has a total pressure on the order of 10–20 MPa [210,000 $\text{lbf/ft}^2$–420,000 $\text{lbf/ft}^2$], which is the total lithostatic pressure plus overpressure.

The model results revealed that initially there is a rapid expansion of the magma mixture as a rarefaction wave propagates back into the dike with exsolved volatiles. The resulting mixture expands and accelerates along the repository length. A complex shockwave structure forms inside the repository with multiple shock reflections. The analysis focused on two situations: closed or open drift. The analysis found that if one end of the drift is closed, then on reaching the end of the drift, the shock is reflected and its amplitude increases by an order of magnitude. Subsequently, recompression of the magma-volatile mixture takes place, accompanied by shock waves. Woods, et al. (2002) also found that in this case, a region of high pressure and density develops between the end of the drift and the shock. On the other hand, for an open-ended drift, the calculations suggested that the explosively intruding magma will fill the repository within a few hours after intersection and the magma pressure in the repository drifts will increase steadily toward values comparable to the driving pressure.

The analysis concluded that the precise nature of magma dynamics and magma pathways will depend on many factors, including any heterogeneity or fractures in the overlying rock strata, proximity of the repository to the surface, and any damage to the rock structure prior to the intersection of the dike with the repository drift(s). The analysis of Woods, et al. (2002) also found that once a flow path to the surface develops, a quasi-steady eruption would be established. However, their primary conclusion on the magma dynamics is that the intersected horizontal repository will be quickly filled by magma at an early stage of eruption and ascent. They further postulated that a steady flow system from the repository depth to the atmosphere would be established with three possible cases: (i) circular conduits that extend from the points of dike-repository intersection to the surface; (ii) magma flow through part of the repository and then eruption through secondary dikes; and (iii) magma flow through the intersected repository, followed by further magma flow through access tunnels and then to the open atmospheric surface.

The simulation by Woods, et al. (2002) assumed homogeneity within the gas-particle mixture, which may be a reasonable assumption for confined flow of a fragmented magma within a tunnel, but this assumption has not been rigorously tested. The analysis provided a starting point for simulating gas particle flows associated with interaction between rising basaltic magma and horizontal repository.

## 2.2 Dartevelle and Valentine (2005)

Dartevelle and Valentine (2005) carried out simulations to investigate the interaction between the horizontal repository emplacement tunnels and hawaiitic magma (alkaline basalt). They primarily investigated the intersection of a single feeder dike with the intersected repository tunnels and subsequent extension of the dike above the repository. Their results indicated that the dynamic pressure waves generated within the repository from the expansion of the rising magma and subsequent pyroclastic flows is on the order of $10^7$ Pa [210,000 lbf/ft$^2$]. The analysis by Dartevelle and Valentine (2005) did not assume homogeneous multiphase flow (as assumed by Woods, et al., 2002). Instead Dartevelle and Valentine (2005) considered separated flow of the melt (in the form of pyroclasts) and gas. They carried out two-dimensional unsteady simulations using the multiphase code GMFIX (Dartevelle, 2004) that relies on the implicit multiphase formulation in which each phase is modeled as a continuum. GMFIX solved the Navier-Stokes equations as well as the partial differential equations of energy for each phase with appropriate turbulence models and interfacial coupling between phases.

In the first set of simulations, the geometry consisted of a single opening above the main dike and at the inlet. A gas-dominated magmatic mixture (40 volume percent pyroclasts and 60 volume percent of water vapor) is generated by the sudden decompression and fragmentation of an overpressurized rising magma into the repository that has an initial pressure of 0.1 MPa [2,100 lbf/ft$^2$]. The simulations revealed that about 60–65 percent of the gas-pyroclasts mixture flows vertically up the dike and that swift decompression of the mixture causes a gas shock that propagates through the repository drift with very high horizontal speed {~200 m/s [660 ft/s]} and a dynamic pressure of $7 \times 10^4$ Pa [1,500 lbf/ft$^2$]. The remaining 30–35 percent of gas–pyroclasts mixture formed a hot, buoyant pyroclastic flow-like density current that propagated along the roof of the repository with a horizontal speed of 125 m/s [410 ft/s] and a dynamic pressure of $10^7$ Pa [210,000 lbf/ft$^2$ ]. Reflection of the shock takes place from the end of the drifts toward the dike. The reflected gas shock was found to create a quasi "zero-dynamic pressure front" that moved upstream as pre-shock- and post-shock-reflection gas velocities. The gas velocities change between pre-shock and post-shock.

Simulations by Dartevelle and Valentine (2005) with a secondary dike found that some of the within-drift "pyroclastic flows" are diverted into the secondary dike. However, the horizontal speed and the dynamic pressure were identical to the case without the secondary dike (closed drift). Figure 2-1 shows the contours of the solid volume fraction for both cases. Dartevelle and Valentine (2005) concluded that the drift will eventually fill up through a process of recirculating flow with a continuous supply of new pyroclastic material. However, the analysis did not predict what happens in the adjacent drifts.They determined that flow will be inhibited when the concentration of pyroclasts becomes sufficiently high.

In summary, the computational results by Dartevelle and Valentine (2005) showed that the initial interaction between the rising magma and the repository results in a complex transient,

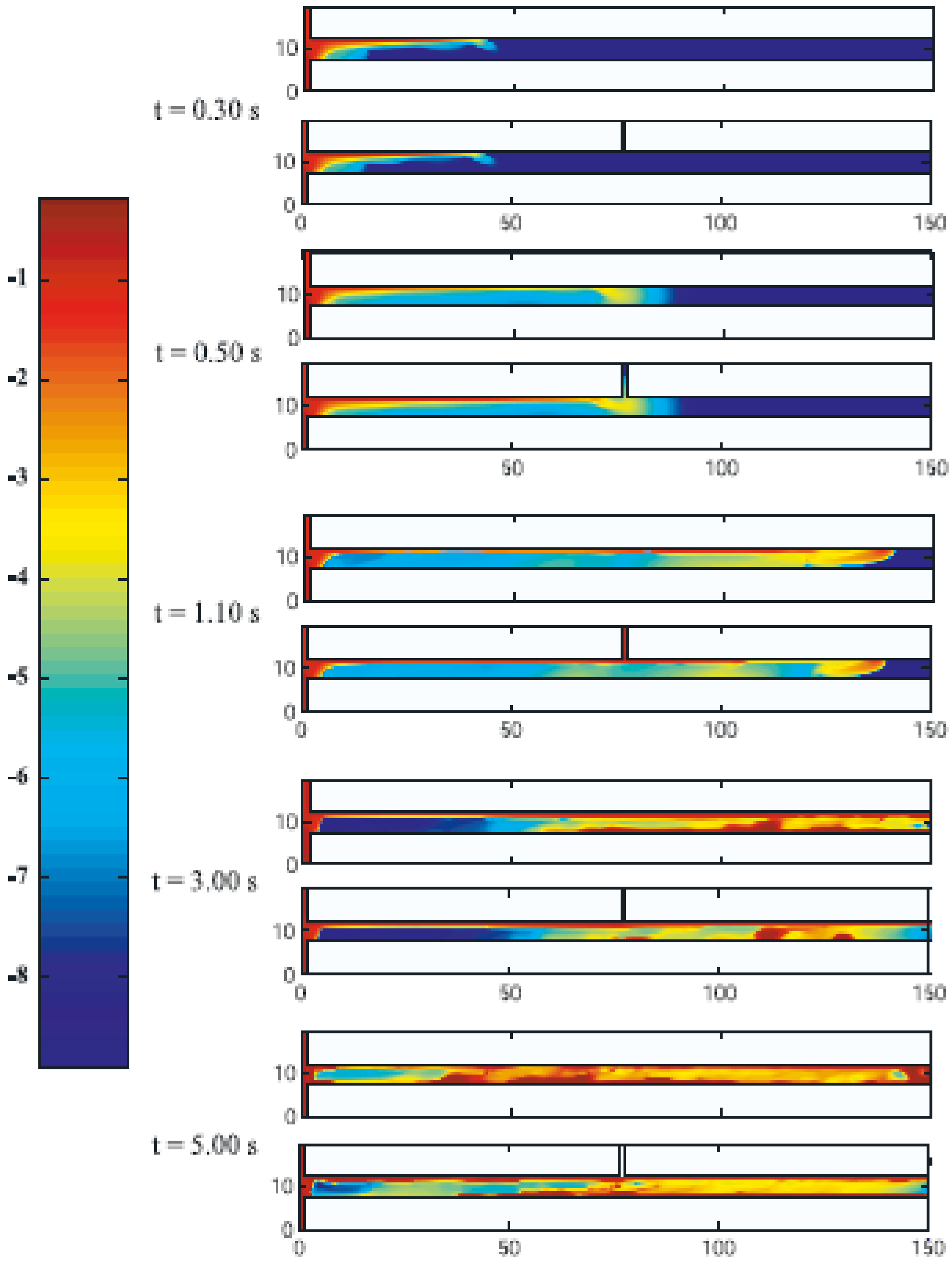

Figure 2-1. The Dartevelle and Valentine (2005) Model of Pyroclastic Flow Inside the Drift. Volumetric Solid Fraction Shown in Colors. The Pyroclastic Flow Turns Downward and Forms a Dense Flow on the Drift Floor That Moves Backwards Towards the Main Dike (t = 3.00 Seconds)
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explosive, multiphase flow (density current) where the speed of the pyroclastic (fragmented magma) mixture varies between subsonic and supersonic regimes. The simulations revealed that this gas–particle mixture enters a horizontal repository drift along the ceiling of the drift due to the upward momentum of the mixture at the dike–drift intersection. The mixture then flows along the roof for some considerable distance before it begins to settle downward, acting like a density current. If the current reaches the closed end of a drift before it settles to the floor, it turns and travels back toward the dike–drift intersection point along the drift floor, setting up a transient return flow. This sets up a circulation pattern within the repository drift.

This work by Dartevelle and Valentine (2005) was one of the earliest simulations that considered multiphase magma dynamics for the proposed Yucca Mountain repository. Their simulation was the first for explosive violent eruption and subsequent interaction with drifts that considered a multiphase approach. Subsequently, Dartevelle and Valentine (2008), discussed in the next section, carried out more simulations and comparisons with, and incorporation of data derived from, analog sites.

## 2.3 Dartevelle and Valentine (2008)

Dartevelle and Valentine (2008) carried out numerical simulations to understand the range of processes and dynamic parameter values where a repository would be intersected by volatile-rich trachybasaltic magma as it ascends in a vertical dike. The analysis focused on a fragmented magmatic mixture (explosive disruption) under pressure interacting with an underground cavity, which forms a density current or flow. The simulations were two dimensional and time dependent and were carried out with the multiphase hydrodynamics code GMFIX. The numerical simulations indicated that when gas–particle mixtures rising from below interact with horizontal repository drifts, complex flow patterns involving varying degrees of recirculation develop in the density current, along with deposition of pyroclasts in the repository.

The analysis was primarily based on three assumptions: (i) the geometry of the dike and the conduit was chosen based on studies from older volcanoes in the regions; (ii) the fragmented gas-pyroclastic flow (density current) is considered as an end-member for interaction between magma and repository (the other end-member is the flow of viscous, effusive (unfragmented) magma); and (iii) a multiphase approach is the most suitable where a continuous gas phase and a dispersed particle phase are treated as an overlapping continuum with each phase satisfying the mass, momentum, and energy equations.

Initial conditions for most of the simulations had atmospheric pressure inside the repository drift and a temperature of 25 °C [77 °F]. The inlet pressure was taken as 12.5 MPa [261,000 $\mathrm{lbf/ft^2}$]. This consists of an overpressure of 6 MPa [125,000 $\mathrm{lbf/ft^2}$] and a lithostatic pressure of 6.5 MPa [136,000 $\mathrm{lbf/ft^2}$]. Simulations were carried out for two values of water content for the gas–particle mixture: 4.6 WT% (high water content) and 1.2 weight percent (low water content). Total mass flux at the inlet was $7.4 \times 10^5$ kg/s [1,630,000 lbm/sec]. The average vertical inlet velocity for the gas–pyroclast mixture at the dike entrance was 3.9 m/s [12.8 ft/sec]. Temperature of the gas-pyroclast mixture at the inlet was 1,273 °K [1,832 °F].

Computed results demonstrated that the nature of the gas–pyroclast mixture flow inside the repository after intersection with the dike and the circulation pattern is strongly influenced by repository geometry. Simulations with a closed drift geometry (without any exit) generated the highest absolute dynamic pressure and the flows are more dilute if there is an opening. Also, the dynamic pressure is higher for the high-water-content gas–pyroclast mixture compared to the low-water-content gas–pyroclast mixture.

The dynamic pressure generated inside the repository is also found to be influenced by the diameter of pyroclastic particles considered in the simulations. Simulations showed that the least inertial particles with a diameter of 100 mm [0.33 ft] have the fastest motion and produce the highest dynamic pressure. On the other hand, the particles with the most inertia are those with a diameter of 1 cm [0.033 ft], which generated the least dynamic pressure. As the flow moves downstream in the horizontal direction within the repository drift, the 1-mm [0.0033-ft] and 1-cm [0.033-ft] particles settle rapidly on the floor to form a denser concentrated granular flow, while the finer particles maintain a diluted flow.

Simulations reveal that apart from the geometric configuration, the water (vapor) content of the magma in dike is also important for the flow dynamics. Higher water (vapor) contents in the magma will lead to more dilute flows in terms of pyroclastic mixtures. A more dilute flow can maintain a slower flow on the roof of the drift and a more turbulent gas–particle mixture over the whole length of the repository drift. Hence the dilute flow is able to generate higher dynamic pressures because of the higher vapor content.

Overall, magma dynamics and interaction of the ascending magma with the horizontal drift is found to be sensitive to the geometry of the interaction (closed or open repository), particle size of the pyroclasts, the volatile content of the pyroclasts, and the pressure boundary conditions. Table 2-1 provides a summary of the different geometrical configurations and magma dynamics.

## 2.4 Menand, et al. (2008)

All three previous simulations considered one end-member of the intrusive scenario; namely, fragmental (“explosive”) flow into the repository drifts. A study by Menand, et al. (2008) considered the other end member: effusive eruption and associated magma dynamics within the horizontal repository drifts. Many basaltic volcanoes that have Strombolian eruptions have phases during which a relatively stationary column of liquid magma remains in the volcanic conduit and sub-surface plumbing system for a period of time (Dartevelle and Valentine, 2008), so this could be a realistic scenario for a disruptive event at future repository drift.

Under this situation, bubbles are formed by slow exsolution of volatiles from the magma. These bubbles tend to rise and set up circulation patterns in shallow magmatic systems. Many classical Strombolian eruptions are found to be caused by large bubbles bursting at the surface

**Table 2-1. Geometry Configuration and Magma Dynamics for Different Experiments**

| Construct | Value |
|---|---|
| Closed repository drift | Generated the highest absolute dynamic pressure<br>Granular concentration increases with time because there is no exit<br>Strong pyroclastic current generated in the recirculating zone |
| Repository drift with one opening | Less dynamic pressure compared to the closed repository<br>More turbulence compared to closed repository drift<br>Opening creates much more complex circulation pattern within the repository drift compared to the closed repository drift |
| Repository drift with two openings | Flow field is similar to the closed repository with one opening |

of magma columns with exsolved volatiles. Menand, et al. (2008) studied the physics associated with gas segregation in a magma-filled drift through analogous experiments. This analysis deals with the effusive sustained magma (lava-like) flow in a repository drift intersected by a vertical dike. The experiments revealed how gas segregation is dominated by exchange flow between the vertical dike and the horizontal repository drift due to the presence of exsolved gas bubbles. Menand, et al. (2008) showed that circulation would develop in the tunnel, with

the primary vortex closest to the entrance of the cavity being the strongest and the strength of the successive vortices decreasing down the tunnel. They also showed that foam, which developed from degassing (bubble growth), could change the flow style in the tunnel.

The experiment shown in Figure 2-2 demonstrated that if a horizontal pipe or sill is connected to the vertical feeding conduit of such a volcano, a flow pattern can be set up in which some bubbly magma is diverted into the horizontal body (in this case the horizontal repository drift). As the magma flows horizontally away from the main conduit/dike, bubbles continue to rise and form a foam at the top of the horizontal repository drift, while the bottom of the horizontal repository drift becomes enriched in denser, degassed magma. The interaction of the foam and degassed magma sets up an exchange flow between the vertical conduit (or dike) and the horizontal repository drift. This constitutes the gas segregation mechanism.

Experimental results determined that the time for gas segregation is controlled by the rate of rise of the bubbles in the drift. The time required for steady-state gas segregation in an effusive eruption will range from hours to hundreds of years depending on the average size of the exsolved gas bubbles and the viscosity of degassed magmas. The amount of degassing will be determined by the degree of water exsolution, cooling, and crystallization.

The mass flux associated with gas segregation was found to be dependent on the viscosity of the magma. It is less for most viscous degassed magmas. The mass flux is also found to be strongly dependent on the average exsolved bubble diameter. If the magma supply rate is higher than the flux associated with gas segregation, then the eruption will be of a violent Strombolian nature. For a magma supply rate that is lower than the flux associated with gas segregation, the eruption characteristics will be those of milder episodic Strombolian explosions. These explosions are generated by the repeated collapse of the foam accumulated at the top of drifts.

## 2.5 Basu, et al. 2008

CNWRA staff carried out a computational analysis to investigate the flow of magma into a horizontal subsurface tunnel, including obstacles, after intersection during initial ascent in a dike (Basu, et al., 2008). These models were not designed to simulate the conditions of initial intersection or investigate possible changes to the properties of the first magma to arrive at the drift, but rather the conditions after intersection as the drift is effusively invaded and filled with magma. The numerical model provided some ideas about the flow patterns that might develop in a dry subsurface tunnel intruded and transected by a dike of degassed (single-phase) basaltic magma, where the tunnel contains obstacles. This showed that the tunnel will fill with magma and provides a glimpse of the complex flow patterns that might develop in the tunnel near the dike under various conditions of magma supply rate and obstacle position. The two-dimensional simulation results show that magma flow patterns that develop within the tunnel are affected by the location of the dike intersection, relative to obstacles present in the tunnel. Under the conditions modeled in this study, low viscosity, nonexpanding magma ascending along a dike that intersects a repository drift will fill the drift under the influence

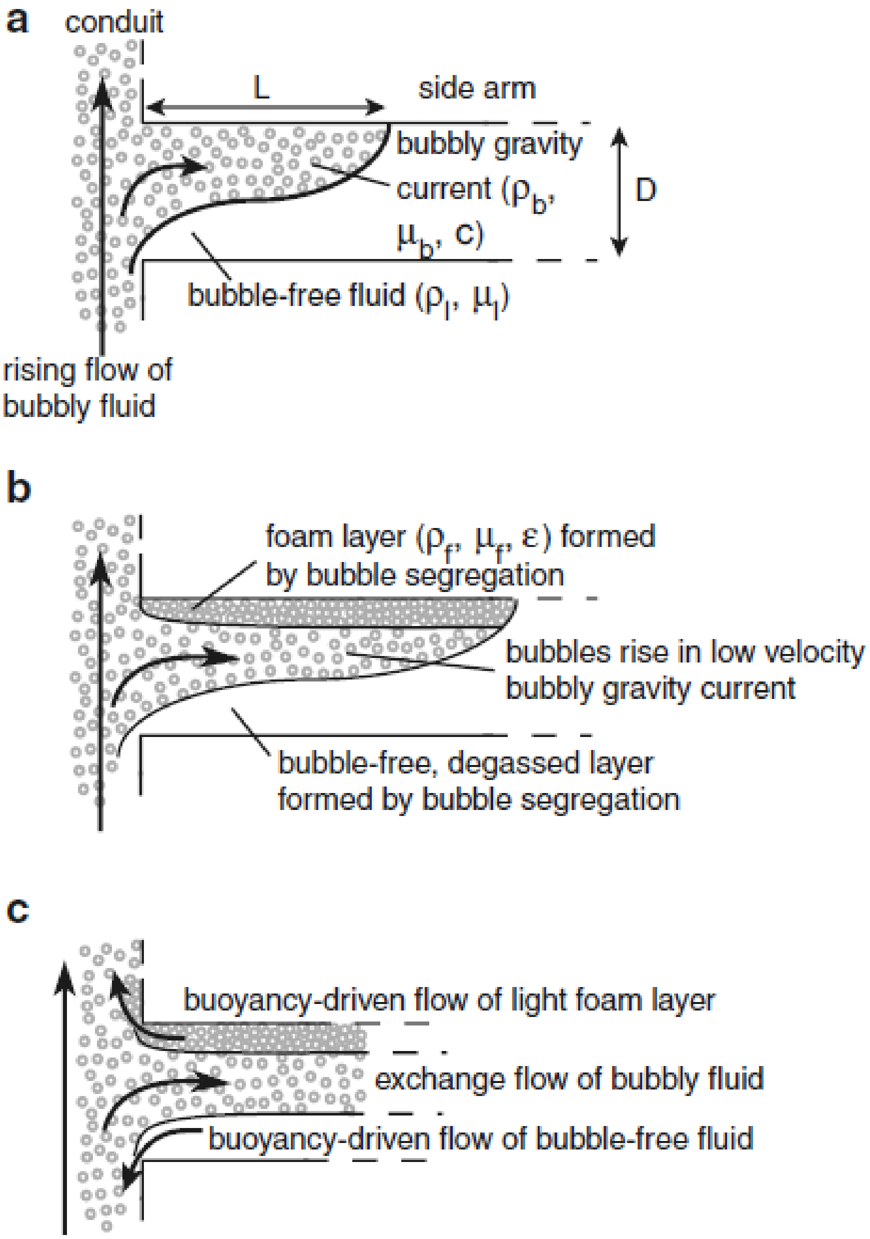


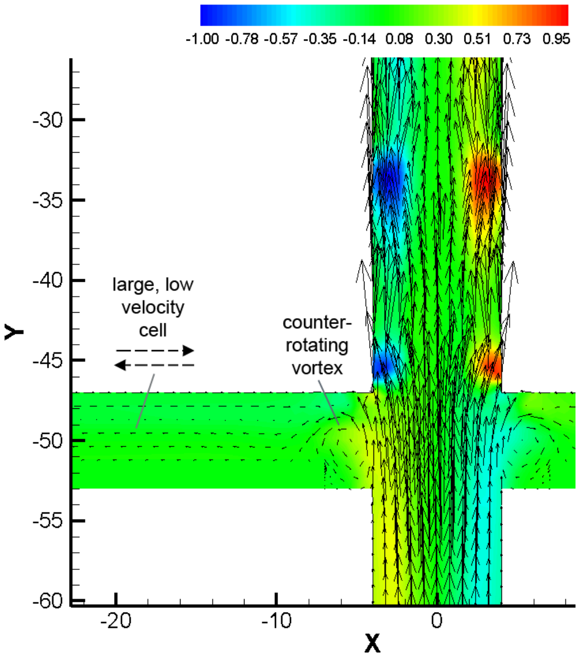
**Figure 2-2. Schematic Showing the Interaction of the Magma With Bubbles and Gas Segregation (Menand, T., J.C. Phillips, and R.S.J. Sparks. "Circulation of Bubbly Magma and Gas Segregation Within Tunnels of the Potential Yucca Mountain Repository." *Bulletin of Volcanology*. Vol. 70, No. 8. pp. 947–960. 2008. Reproduced With Kind Permission of Springer Science+Business Media).**

of gravity from the base to the top and then continue upwards along the dike. Counterrotating vortices in magma adjacent to the dike that extend into the tunnel are driven by viscous coupling between the magma rising in the connected dike and the magma in the tunnel. In the tunnel beyond these primary vortices, a larger, low velocity circulation cell is established with magma flowing away from the dike along the base of the tunnel and toward the dike along the tunnel ceiling.

This same pattern develops in the presence of an obstacle in the tunnel. Flow patterns that develop in a magma-filled tunnel can be affected by the location of dike intersection, specifically relative to obstacles in the tunnel. Slight changes in the modeled distance between the dike and the obstacles produced additional vortices adjacent to the primary vortices (i.e., those located directly next to dike position) that extended higher velocity circulating magma further down the tunnel, as shown in Figure 2-3. In addition to the strength and size of the primary

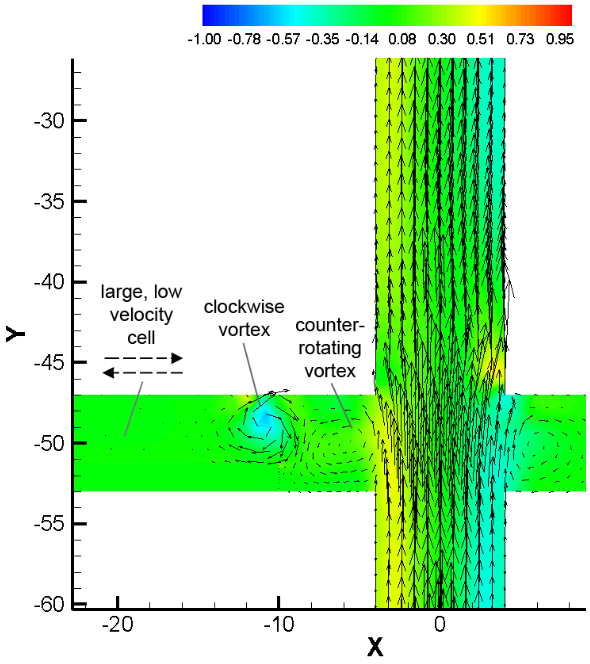
vortices, the shape and distribution of the vortices that develop are affected by the ascent rate of the magma in the dike. At higher ascent rates, vertically coupled counterrotating vortices develop in the space between the dike and the obstacles. In all cases, some pattern of circulation developed in the tunnel, and the pattern was largely influenced by the interplay between the ascending magma and location of the obstacles.

(a)



Distance Between Dike and Obstacle: 4 m

(b)



Distance Between Dike and Obstacle: 7 m

**Figure 2-3. Effect of Distance Between Dike and Obstacles on the Flow Field. Color Contours Show Vorticity Superimposed With Velocity Vectors (Basu, et al., 2008). Magma Inlet Velocity = 1 m/sec [3.28 ft/sec]; Length Is in Meters.**

# 3 CONCLUSIONS

This report presents and summarizes the results of several numerical studies and one experimental study that analyze magma dynamics in the case where a rising dike may intersect the drifts at the proposed Yucca Mountain repository. The analyses focused on different scenarios of an ascending basaltic dike intersecting a horizontal repository drift and its significance.

The analyses considered in this report have taken into account both end-member types of flow into (and out of) repository drifts: (i) flow of gas-poor magma as an incompressible viscous fluid and (ii) compressible flow of fragmented magma and a continuous gas phase (i.e., a pyroclastic flow-like density current). Basu, et al. (2008) considered the flow of gas-poor magma, while the analyses of Woods, et al. (2002) and Dartevelle and Valentine (2005, 2008) considered the compressible flow of fragmented magma and a continuous gas phase. In between these two end members are flows that are bubbly in nature; however, in these flows, the continuous phase is treated as incompressible basaltic melt. Menand, et al. (2008) and Phillips, et al. (2008) considered such flows and conducted experiments to study the role of a horizontal body on the mass transfer processes in a vertical conduit with bubbles.

The analyses showed that the interaction of rising basaltic magma and the horizontal repository drift is controlled by the geometry of the repository drift, the conditions inside the drift, and the presence of obstacles (Basu, et al., 2008). Flow features encountered in compressible fragmented magma flow are different from the flow features observed in effusive incompressible magma flow inside the repository drift. For degassed magma, gas segregation may occur. However, that possibility is controlled by the rate of bubble formation in the magma and the magma viscosity.

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