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Title: Aspects of Igneous Activity Significant to a Repository at Yucca Mountain, Nevada

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Los Alamos
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ASPECTS OF IGNEOUS ACTIVITY SIGNIFICANT TO A REPOSITORY AT YUCCA MOUNTAIN, NEVADA

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ABSTRACT

Location, timing, volume, and eruptive style of post-Miocene volcanoes have defined the volcanic hazard significant to a proposed high-level radioactive waste (HLW) and spent nuclear fuel (SNF) repository at Yucca Mountain, Nevada, as a low-probability, high-consequence event. Examination of eruptive centers in the region that may be analogueues to possible future volcanic activity at Yucca Mountain have aided in defining and evaluating the consequence scenarios for intrusion into and eruption above a repository. The probability of a future event intersecting a repository at Yucca Mountain has a mean value of 1.7 X 10^{-8} per year. This probability comes from the Probabilistic Volcanic Hazard Assessment (PVHA) completed in 1996 and updated to reflect change in repository layout. Since that time, magnetic anomalies representing potential buried volcanic centers have been identified from magnetic surveys; however these potential buried centers only slightly increase the probability of an event intersecting the repository.

The proposed repository will be located in its central portion of Yucca Mountain at approximately 300m depth. The process for assessing performance of a repository at Yucca Mountain has identified two scenarios for igneous activity that, although having a very low probability of occurrence, could have a significant consequence should an igneous event occur. Either a dike swarm intersecting repository drifts containing waste packages, or a volcanic eruption through the repository could result in release of radioactive material to the accessible environment. Ongoing investigations are assessing the mechanisms and significance of the consequence scenarios.

Lathrop Wells Cone (~80,000 yrs), a key analogue for estimating potential future volcanic activity, is the youngest surface expression of apparent waning basaltic volcanism in the region. Cone internal structure, lavas, and ash-fall tephra have been examined to estimate eruptive volume, eruption type, and subsurface disturbance accompanying conduit growth and eruption. The Lathrop Wells volcanic complex has a total volume estimate of approximately 0.1 km^3. The eruptive products indicate a sequence of initial magmatic fissure fountaining, early Strombolian activity, and a brief hydrovolcanic phase, and violent Strombolian phase(s). Lava flows adjacent to the Lathrop Wells Cone probably were emplaced during the mid-eruptive sequence.

Ongoing investigations continue to address the potential hazards of a volcanic event at Yucca Mountain.

INTRODUCTION

The U. S. Department of Energy (DOE) is preparing a license application to be submitted to the U. S. Nuclear Regulatory Commission (NRC) for the construction of a geologic repository for the disposal of high-level radioactive waste and spent nuclear fuel at Yucca Mountain, Nevada. The NRC [1] requires the applicant (DOE) to conduct site characterization activities to assess potential natural hazards that may be significantly affect the performance of a geologic repository. For those hazards with a probability greater than 1 X 10^{-8}, the consequences of that hazard or disruptive event must be evaluated. Six known volcanic centers occur within the Yucca Mountain region (See Figure 1). The DOE has conducted site characterization activities to evaluate the potential volcanic hazards and associated consequences. The following discussion summarizes the volcanic history, potential hazards and associated consequences, and describes ongoing activities to enhance DOE's technical basis for volcanic hazards.

OVERVIEW OF VOLCANIC HISTORY

Two major types of volcanism, explosive silicic volcanism followed by basaltic volcanism, have occurred in the Yucca Mountain region (See Figure 1). The early period of Miocene silicic volcanism in the southwestern Nevada volcanic field (SWNVF) culminated between 11.8 and 12.4 Ma with the eruption of four voluminous ash-flow tuffs of about 1,000 km^3 each [2]. One of the silicic ash-flow tuffs that erupted from the Timber Mountain caldera complex is the Topopah Spring Tuff, which makes up much of Yucca Mountain is planned to be used for waste emplacement. Yucca Mountain is an uplifted fault-bound block comprised of both ashflow and ashfall tuff deposits. The absence of silicic activity in the Yucca Mountain region during the past 6 to 8 Ma suggests the potential for it is negligible [3].

The earliest episode of basaltic volcanism in the Yucca Mountain region occurred between approximately 9 and 11 Ma and was associated with the waning of silicic, caldera-forming volcanism. Post-caldera basalts in the Yucca Mountain region can be divided into two episodes: Miocene (eruptions between approximately 9 and 7.3 Ma) and post–Miocene (eruptions between approximately 4.8 and 0.08 Ma). The time interval of about 2.5 million years between these episodes is the longest eruptive hiatus of basalt in the Yucca Mountain region during the last 9 million years [4]. This eruptive hiatus also marks a distinct shift in the locus of post-caldera basaltic volcanism in the Yucca Mountain region to the southwest [4]. The Miocene basalts and post–Miocene basalts are both temporally and spatially distinct. The assessment of the volcanic hazard significant to a repository at Yucca Mountain has focused on the volcanism that has occurred within the past 5 million years, and especially the last 1 million years [5].

The total eruption volume of the known post–Miocene basalts is about 6 km^3. The volume of individual episodes has decreased progressively through time, with the three Pliocene episodes having volumes of approximately 1 to 3 km^3 each and the three Quaternary episodes having a total volume of only approximately 0.5 km^3 [4]. The Quaternary volcanoes are similar in that they have volumes equal to or less than approximately 0.1 km^3 [4,13,14] and typically consist of a single main scoria cone surrounded by a small field of basalt lava flows that commonly extend approximately 1 km from the scoria cone.

There are seven known Quaternary volcanoes that occur to the south, west, and northwest of Yucca Mountain in a roughly linear zone defined as the Crater Flat Volcanic Zone [6]. Five of seven Quaternary volcanoes are in or near Crater Flat and lie within 20 km of the Yucca Mountain site (Figure 1). Models that attempt to relate volcanism and structural features in the Yucca Mountain region have emphasized the Crater Flat basin because of the volcanic centers within Crater Flat and its proximity to the repository [7,8].

STRUCTURAL CONTROLS ON BASALTIC VOLCANISM

Basaltic centers in the southern Great Basin are fed by dikes that ascend from source regions within the upper-mantle (subcontinental lithospheric) [9]. The location, length, and orientation of these dikes are influenced by local and regional structures. Observations of basaltic volcanism within the Great Basin suggest that 75 percent of Pliocene and Quaternary volcanic centers in the Yucca Mountain region occur in alluvial basins, 12.5 percent occur along range fronts, and 12.5 percent occur in range interiors [4]. The distribution of past events indicates that a future volcanic event in the Yucca Mountain region is about six times more likely to occur along structures within or along the edge of the basin than in a range interior such as the repository location in Yucca Mountain.

Regional Structure

Yucca Mountain lies within the southern Great Basin in the Basin and Range province, which is undergoing active ESE–WNW extension [10]. Magma-filled fractures (dikes) tend to strike orthogonal to the direction of the least compressive horizontal stress, and parallel to the direction of the greatest compressive horizontal stress [11]. Most investigations indicate the orientation of the greatest compressive horizontal stress in the Yucca Mountain region as N30E ±15 degrees

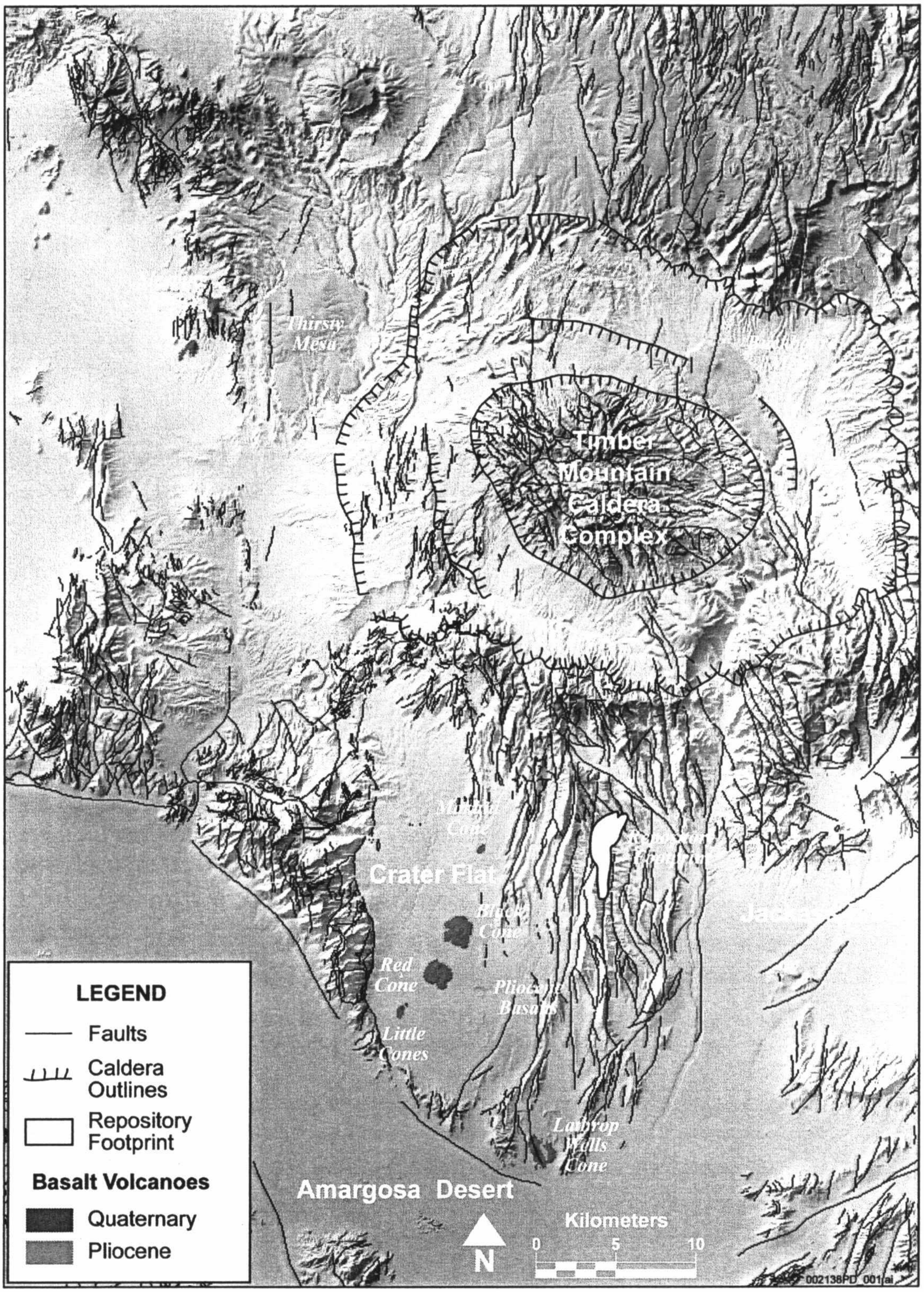

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Figure 1. Locations and Ages of Post–Miocene (Less than 5.3 Ma) Volcanoes (or Clusters Where Multiple Volcanoes Have Indistinguishable Ages) in the Yucca Mountain Region

Crater Flat Structure Structural Domain

Post–Miocene volcanoes in the Yucca Mountain region are spatially clustered (Figure 1) and occur within what is referred to as the Crater Flat structural basin [12,8]. This structural basin is a part of the Crater Flat structural domain which is weakly defined by the structural basin or graben [15]. It includes the Crater Flat topographic basin on the west and Yucca Mountain near the center of the structural domain. It is bounded on the west by the Bare Mountain fault and on the east by inferred fault buried beneath Jackass Flats. Seismic reflection surveys show that the Crater Flat basin is deepest to the west [16]. The northern boundary consists of a gradational termination at the perimeter of the Timber Mountain caldera complex [15]. The southern margin is inferred from gravity and magnetic data and from discontinuous outcrops to be a fault structure buried beneath young alluvium. The boundary is typically drawn in a northwestern direction along the Amargosa Valley [15]. Fundamental changes in the style, timing, magnitude of extension, and other deformation occur across all of the boundaries of the Crater Flat structural domain with the greatest extension occurring in the southern part of the basin [15].

CONCEPTUAL MODEL FOR BASALTIC IGNEOUS ACTIVITY

The behavior of basaltic magmas that could intrude or erupt through a repository provides important constraints on the consequences associated with igneous or volcanic activity. This section describes the properties of basaltic magmas and the mechanisms that determine the style and energy of intrusive or extrusive events.

The general conceptual model is shown in Figure 2. It depicts the key features and processes involved in the formation and construction of the small volcanic centers typical of the Yucca Mountain region. It shows the dikes that feed lava flows and Strombolian eruptions, as well as the ash clouds that deposit air-fall ash (tephra) downwind of the cone.

The basalts in the Yucca Mountain region come from alkali-basaltic magma that is generated by partial melting of ancient lithospheric mantle beneath the Yucca Mountain region [8]. Driven by buoyancy, the magma ascends through the lithosphere and continental crust of the southern Great Basin. In the brittle crust above approximately 15 km depth, batches of melt ascend as magma-filled cracks or dikes. The dikes are intruded with azimuths approximately N30E, a direction that is perpendicular to the direction of least compressive stress in the upper crust of the Yucca Mountain region. Within a few hundred meters of the surface, dikes in the Yucca Mountain region are generally 1 to 2 m thick, average 4 km in length, and nearly always erupt to form basaltic volcanoes. As dikes reach the surface, fissure eruptions are focused into central vents within hours or days. The conduits feeding such vents are estimated to be tens of meters in diameter. Conduits may shift in location and change in their subsurface configuration, vent locations may correspondingly change during the course of an eruption, multiple vents may be simultaneously active, and single vents may simultaneously produce lava and tephra.

The petrographic features of the erupted lava and experimental data on similar magma compositions indicate eruption temperatures near 1,170°C, the presence of 2 to 4 percent by weight water as the dominant volatile constituent and viscosity of approximately 10^2 poise. Experimental and theoretical data indicate that alkali basaltic magma of the Yucca Mountain region begins to exsolve gas at about 6 to 7 km depth. Volatile exsolution is a continuous process during the ascent of magma through the upper crust. The resulting volume expansion is a significant factor in driving the basaltic dikes upward through the final kilometer or so of brittle, fractured rock. The inception of basaltic volcanism is typically characterized by pyroclastic eruptions of gas-rich magma.

The unsaturated zone beneath Yucca Mountain is approximately 550 m deep. Together with magma properties, the high permeability and unsaturated condition of the tuffaceous host rocks of the repository play a major role in determining the style and dynamics of volcanic eruptions and the nature of potential interaction between basaltic magma and the repository drifts. Future hydrovolcanism is unlikely at Yucca

Mountain because of the elevated terrain, the great depth of the water table, and the high permeability and low porosity of the unsaturated host tuffs.

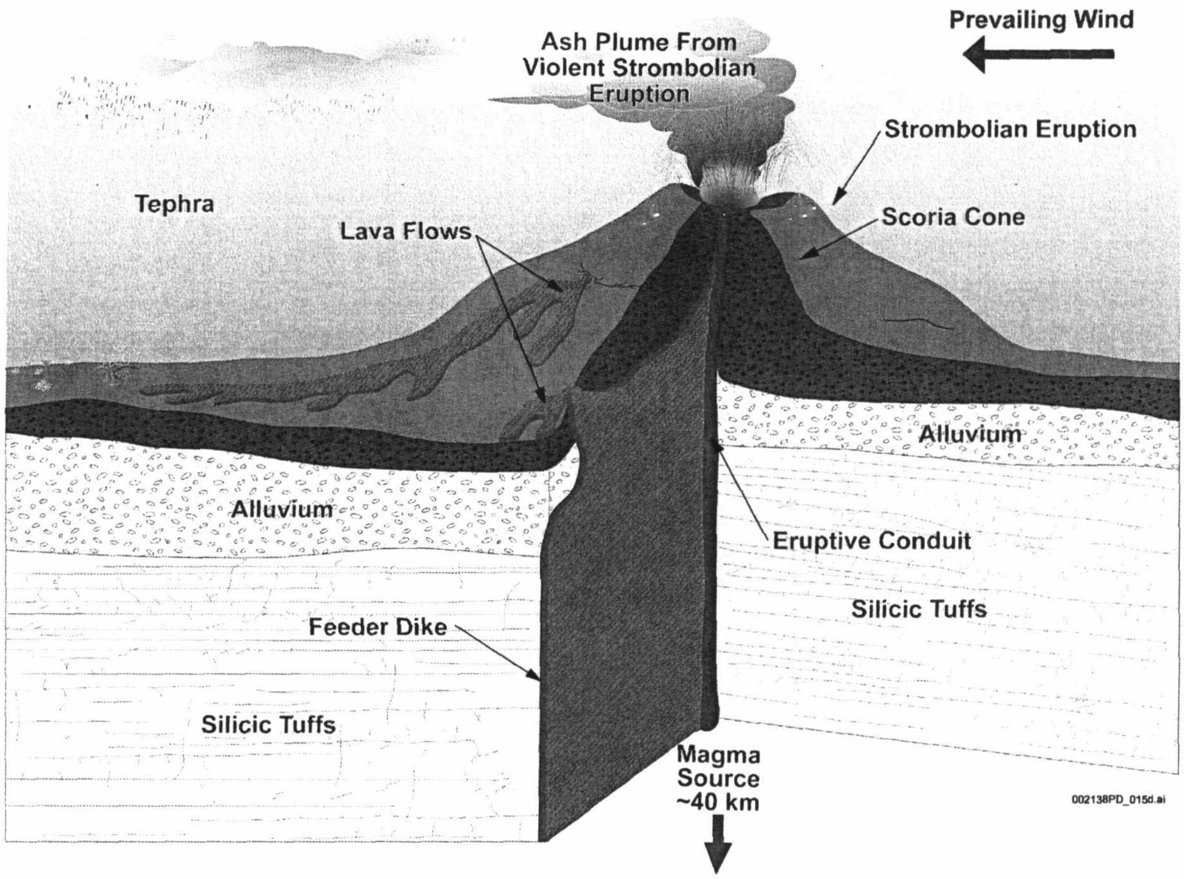

Figure 2. General Conceptual Model of Basaltic Volcanism in the Yucca Mountain Region

Based on historical observations of similar eruptions in analogue regions, the duration of single igneous events in the Yucca Mountain region is estimated to have been weeks, months, or perhaps a few years. The estimated durations and volumes of the basalt volcanic centers in the Yucca Mountain region suggest peak mass-eruption (discharge} rates of 10^3 (Strombolian} to 10^6 kg/s (violent Strombolian).

PHYSICAL VOLCANOLOGY OF BASALT VOLCANOES

Regional Volcanoes

Quaternary and Pliocene volcanoes near Yucca Mountain (See Figure 1) are composed of scoriaceous tephra cones, with associated *aa* lava flows [17, 4, 18]. Exposed deposits at most of the centers cover less than 2 square km. The cones are typical scoria cones with a 300 - 700 m basal diameter, and up to 220 m but generally less than 100 m in height, composed predominantly of frothy bombs and lapilli that were produced during Strombolian eruptions. For a number of the centers, several conduits were apparently active along a fissure or set of eruptive fissures, as at Red Cone (Figure 1). Most of the cones produced *aa* lava flows from their flanks or bases. The 1-Ma Crater Flat volcanoes (See figure 1) are deeply eroded and are in places covered by alluvial and eolian deposits, particularly the lava flows, but the proportion of lava to cone tephra deduced from mapping and interpretation of associated aeromagnetic anomalies appears to be generally greater than 1. The tephra-fall deposits from these eruptive centers have been largely removed by erosion or buried by younger sediments and are therefore unmappable. Even at the 80-ka Lathrop Wells volcano, primary tephra-fall deposits are not found at distances greater than about 2.5 km from the vent [19].

Lathrop Wells Volcano

The Lathrop Wells volcano (located in southern part of Figure 1) has an eruption age of approximately 77.3 ± 6.0 ka, based on seventeen $^{40}Ar/^{39}Ar$ ages on the stratigraphically oldest lava flow [18, 14]. The most probable interpretation for the Lathrop Wells eruptive center is that of a complex monogenetic volcanic center that erupted through the underlying volcanic tuff (similar sequence to that exposed at Yucca Mountain) and that produced a cone, lava flows, and tephra deposits. The eruption duration appears to have spanned a few months or years [19]. The center also exhibits some features that support other interpretations of age and eruptive history [18]. The estimated erupted volume is approximately 0.086km^3 [16]; 0.029 km^3 in lava flows, 0.018 km^3 of scoria cone, and 0.039 km^3 of tephra fall deposits. The history of eruption phenomena of the Lathrop Wells volcano is described in the *Characterize Eruptive Processes at Yucca Mountain, Nevada,* Rev. 01 analysis report [19]. The Lathrop Wells Cone has been quarried on its south flank for over a decade The cone consists of agglutinated masses representative of early fissue fountaining, and coarse lapilli grading to ash representing a Strombolian phase. Exposures in the lower quarry wall exhibit an abrupt transition from coarse lapilli to overlying fine lapilli and ash. This transition is inferred to mark an increase in eruption energy from Strombolian to violent Strombolian. The cone is surrounded on the northwest, west, and southwest by a tephra sheet. The tephra sheet consists of an ash blanket representative of a violent Strombolian phase and a smaller thin-bedded ash deposit representative of hydromagmatic phase. Lava flows appear to have originated on the northern side of the cone and moved to the east around the cone then south.

It is the opinion of Project scientists that the Lathrop Wells volcano represents an appropriate analogue for any future eruptions that may occur within the Yucca Mountain region. This position is further support by the Igneous Consequence Peer Review Panel [23]. Studies continue in the Crater Flat structural domain to enhance the understanding of the relationships between the volcanoes and their eruptive mechanisms and histories.

CHARACTERISTICS OF DIKES AND ERUPTIVE CONDUITS

Understanding the characteristics of dikes, dike swarms, and the formation of volcanic conduits including their width and depth is very important to any consequence analyses. The number of dikes and the size of the volcanic conduit intersecting a repository can be significant in evaluating the consequence of a potential future volcanic eruption through the repository. Natural analogue studies continue to enhance the understanding of dike emplacement and conduit formation.

Dike Widths and Swarms

Basaltic dikes intruded into tuff at eroded volcanic centers of the Yucca Mountain region have been measured [3]. Observed dike widths ranging from 0.3 m to 4 m, with most dikes between 1 and 2 m wide. The typical dike-width dimension assigned by the PVHA experts was 1m [5].

Most basaltic volcanoes in the Yucca Mountain region are mono-genetic, small in volume, and probably fed by a single dike or a small dike swarm. The Lathrop Wells volcano may be underlain by as many as three dikes [18]: (1) the dike that fed the main cone and small spatter vents in a chain to the north and south of the cone; (2) a dike that fed spatter and scoria mounds in a parallel chain just to the east of the main dike; and (3) a possible dike that fed scoria vents near the northern edge of the volcano, although these could be an extension of (2) above.

Analyses of basaltic volcanic fields in the southern Great Basin indicates that the spacing between multiple dikes can vary from about 100 m to approximately 1 km. Based upon field observation and map measurement, the estimated dike spacing at Lathrop Wells volcano is approximately 320 m between the two inferred NW-trending dikes that fed the cone and the linear set of scoria mounds (vents) immediately east of the cone. Spacing is approximately 700 m between the mounds and an inferred third dike related to scoria mounds on the eastern lava flows. Map measurements taken from a population of about 100 dikes, gives an average of 410 m (standard deviation equal to 430 m) for a N-trending dike set and 690 m (standard deviation equal to 482 m) for a NW-trending dike set. Based on a limited data set, dike spacing in the Yucca Mountain region ranges from about 100m to 690 m [19].

Eruptive Conduits

Most observed basaltic eruptions begin as fissure eruptions, discharging magma where a dike intersects the Earth's surface, and soon focus into roughly cylindrical conduit eruptions. The best data to constrain conduit diameters and depths to which conduits extend would come from basaltic volcanic necks exposed by erosion, where direct measurements could be made of conduit diameter and variation with depth. Although many volcanic necks have been mapped as part of regional studies, few have been examined in detail for basaltic compositions or complexity (e.g., if observed conduits represent single or multiple events). Without direct measurements of conduit diameter in the Yucca Mountain region, estimates are based on analogue volcanoes.

The transition from magma flow in a sub-planar dike to flow in a cylindrical plug has been inferred at many field locations [24,25]. From a continuum-mechanics view, a planar dike is the preferred form for propagation of magma through brittle and elastic host rock, whereas a cylindrical conduit is the preferred form for magma flow and delivery to the surface [26]. Several processes have been put forward to explain this transition, including (1) magma viscosity variations induced by the solidification of magma at dike margins [27]; (2) brecciation and erosion of the dike wall rocks, as in the Shiprock NE dike [24, 26] and the San Rafael dikes [28]; and (3) progressive melting of the host rocks, enhancing localized flow [29].

Once a zone of widening and flow focusing has initiated, the evolving conduit may continue to widen. Several hypothetical processes, similar to those for the initial dike enlargement, have been described to explain this: (1) erosion from shear stress of flowing magma below the fragmentation level [30]; (2) thermo-elastic stressing of wall rock [31, 32]; (3) erosion from particle collision above the fragmentation level [32, 30]; (4) conduit-wall collapse due to variations in magma pressure or shock/rarefaction waves) [30]; (5) hydromagmatic processes involving the interaction of magma with groundwater or saturated sediment [31, 32]; (6) conduit-wall collapse due to offshoot dikes [32]; and, (7) pore-pressure buildup [32, 31].

Volcanic conduits are features that integrate magma paths over the duration of a volcanic eruption. Although a conduit may be large, only a fraction of it may be active at any given time during an eruption. The entire cross-sectional area of a conduit may transfer magma to the vent [33, 34], or to only a fraction of its cross-sectional area within a localized flow annulus, due to variations in flow velocity or viscosity [35, 23].

Basaltic conduits vary greatly in diameter, depth and geometry. Well-established sedimentary stratigraphy beneath the tephra deposits of Alkali Buttes, Lucero Volcanic field, New Mexico were used to evaluate the variations in conduit size beneath a mono-genetic alkali-basalt center [32]. Based on xenolith data and assuming a 1.5-m-thick feeder dike, the conduit that formed in the sedimentary country rock is calculated to range in diameter from 3.5 to 10 m. The upper 500 m of country rock at Alkali Buttes consists of mudstones and shales that provided a wet host rock, as indicated by lithic-rich hydromagmatic deposits. Conduit-size calculations, based on the proportion of lithics in these hydromagmatic deposits, indicate that a cylindrical conduit up to 40 m wide may have formed in the uppermost strata. A flared conduit could also have developed, varying in size from 6 m at depth to 300 m at the surface, which is a diameter equivalent to the mapped extent of the hydromagmatic deposits [32].

PROBABILISTIC VOLCANIC HAZARD ASSESSMENT

A probabilistic volcanic hazard analysis (PVHA) was conducted to assess the probability of a future volcanic event intersecting the repository at Yucca Mountain, and to explicitly characterize the uncertainties in the hazard analysis [5]. The expert panel consisted of Project scientists and independent scientists, all with expertise in the fields of geology and volcanology. The panel considered existing information and previous hazard assessments. Panel members were elicited to get a wide range of views and to capture the range of uncertainties. The experts acted as informed technical evaluators of data and were asked to present interpretations to facilitate discussion and to consider alternative interpretations. A primary purpose of the process was to identify and understand uncertainty. The experts provided weighted alternative models and parameters, expressing their degree of belief that these were appropriate models and values. Their evaluations were then combined to produce an integrated assessment of the volcanic hazard, an assessment representing the range of alternative scientific interpretations and uncertainties from the informed scientific community. The analysis expresses the volcanic hazard as the annual probability (1.5 X 10^{-8}) of intersection of the repository by a basaltic dike. The mean probability from this analysis This result provides input to the assessment of volcanic risk, which is the product of hazard and consequence.

Subsequent changes in the repository design have necessitated re-calculation of the hazard. With each change in design the mean probability of intersection has slightly increased. For the Site Recommendation design the mean probability increased to 1.6 X 10^{-8} [4]. For the preliminary license application design the mean probability increased 1.7 X 10^{-8} [36].

Anomalies suggestive of buried volcanic centers have been observed in aeromagnetic and ground magnetic data from surveys conducted by the U.S. Geological Survey [37, 38] and the Center for Nuclear Waste Regulatory Analyses [39]. These surveys were completed after PVHA. They suggest that a number of basaltic volcanic centers could be buried beneath alluvium in Crater Flat and northern Amargosa Desert areas. Interpretation of these data indicates that 20 to 24 magnetic anomalies occur within Crater Flat and the northern Amargosa Desert that could represent buried basaltic volcanoes [38, 39].

The potential impact of the aeromagnetic and ground magnetic data on the probability of igneous disruption of the repository was assessed by developing distributions for the number of volcanic events represented by the anomalies, assigning these events to the volcanic source zones defined in the 1996 PVHA., and calculating the annual frequency of intersection of the repository footprint [36]. The distributions for the number of volcanic events were developed using the groupings the PVHA experts tended to use. Two cases were developed. The distributions for the number of volcanic events for Case 1 were developed using the qualitative likelihood that the anomalies represent buried volcanic centers and using each expert's tendency for including anomalies with various levels of confidence into their distributions for volcanic events. In Case 2, all anomalies were assumed to be buried volcanic centers, and the distributions for the number of volcanic events were developed on the basis of each expert's tendency for grouping aligned volcanic centers into events.

The volcanic-event-count distributions developed for sensitivity Case 1 show an increase in the mean annual frequency of intersection of 22% (1.9X10^{-8}) and 40% increase in Case 2 (2.2 X10^{-8}). These cases represent increases in the PVHA mean probability of 1.6 X 10^{-8} [36].

IGNEOUS ACTIVITY CONSEQUENCE ANALYSES

Crustal extension in the Yucca Mountain region is accommodated through a combination of faulting and magma intrusion. There is a strong tendency for basaltic dikes of the Yucca Mountain region to preferentially ascend and erupt through upper crust that is undergoing extension; therefore most of the dikes have a preferred orientation approximately parallel with the least compressive horizontal stress. Crater Flat is the location of most of the Quaternary volcanoes in the Yucca Mountain region and is identified as the major volcanic source zone that may impact the repository. Based on the geologic and volcanic history of the Yucca Mountain region, it is expected that any future igneous activity would be similar to the basaltic activity that formed the scoria cones in southern Crater Flat. The Lathrop Wells Cone is the largest and youngest of these. These small volcanic systems are fed by narrow basaltic dikes that ascend from depths of 40 km or more, and are typically a few kilometers in length and 1 to 2 m in width [36]. The intersection of such a dike with the repository could impact repository performance.

The igneous processes and the effect of these processes on the repository are represented in two consequence scenarios and are reflected in Figure 3. The first scenario is an enhanced waste package corrosion scenario caused by a dike intersecting the repository and magma flowing down the repository drifts compromising the integrity of the waste packages. Under this scenario all waste packages that come into contact with the magma are compromised allowing corrosion to accelerate due to water coming into contact with the degraded waste packages after the magma cools. The second scenario is related to the dispersion of radioactive waste with volcanic ash from a hypothetical eruption through the repository. The waste packages intersected by the volcanic conduit are destroyed and their contents are dispersed into the atmosphere via the conduit. The volcanic conduit initiates at the feeder dike and passes through the repository to the surface. After deposition of the contaminated ash, sedimentary processes begin redistributing the contaminated ash. This may result in greater or lesser concentrations of post-eruption contaminated volcanic ash at any location.

The igneous processes and associated scenarios are represented in a simplified set of schematics in Figure 3. The upper left panel in Figure 3 shows the magma-filled dike propagating upward toward the repository and surface. The second panel (upper right) shows the magma filling the drifts that are intersected by the dike as it continues to propagate to the surface. The third panel (lower left) shows the dike erupting breaching the surface and initiating a volcanic eruption. The fourth panel (lower right) shows the dike cooling and degassing in place. In this depiction of an igneous event, waste packages would be entombed in the magma within the drifts and waste would also be dispersed onto the surface from the volcanic eruption. The extent of consequences of a dike intersection and/or volcanic eruption would depend on the characteristics of the basaltic magma, the geologic and hydrologic conditions in the repository during and after the intrusion, and the configuration and design of the repository and its engineered barrier systems.

The consequences of an igneous event intersecting Yucca Mountain are significant to the performance of a repository. The mechanisms of dike propagation, the behavior of the magma moving upward and intersecting the repository are described in the *Dike/Drift Interactions* model report [40]. The behavior of the magma as it moves into the repository drifts and then upward to the ground surface is also described in this report. The analysis report *Number of Waste Packages Hit by Igneous Intrusion* [41] calculates the number of drifts intersected by dikes with various emplacement orientations and thereby the number of waste packages affected by the magma moving down the repository drifts. The result of this analysis is a distribution of the number of waste packages impacted by magma flowing down drifts, a product of the number of drifts intersected by the dikes and the assumption that all waste packages in a drift intersected by a dike are compromised. The number of waste packages disrupted by a hypothetical eruption through the repository are also analyzed in this report. The number of waste packages affected by the eruption is controlled by the size of the conduit. Information from this analysis is treated as input to modeling the hypothetical eruption through the repository in the *Atmospheric Dispersal and Deposition of Tephra from a Potential Volcanic Eruption at Yucca Mountain, Nevada* model report [42]. This model report addresses the concentrations of radioactive waste in the tephra sheet from the eruption and the post eruption redistribution of the tephra sheet from sedimentary processes. The scenarios are expressed as conceptual and mathematical models described in these documents. The models and their analyses are then abstracted into mathematical relationships for inclusion in a probabilistic risk assessment (total system performance assessment). The total system performance assessment then calculates the risk (annual radioactive dose) to a hypothetical individual at some distance from the repository disrupted by the igneous event.

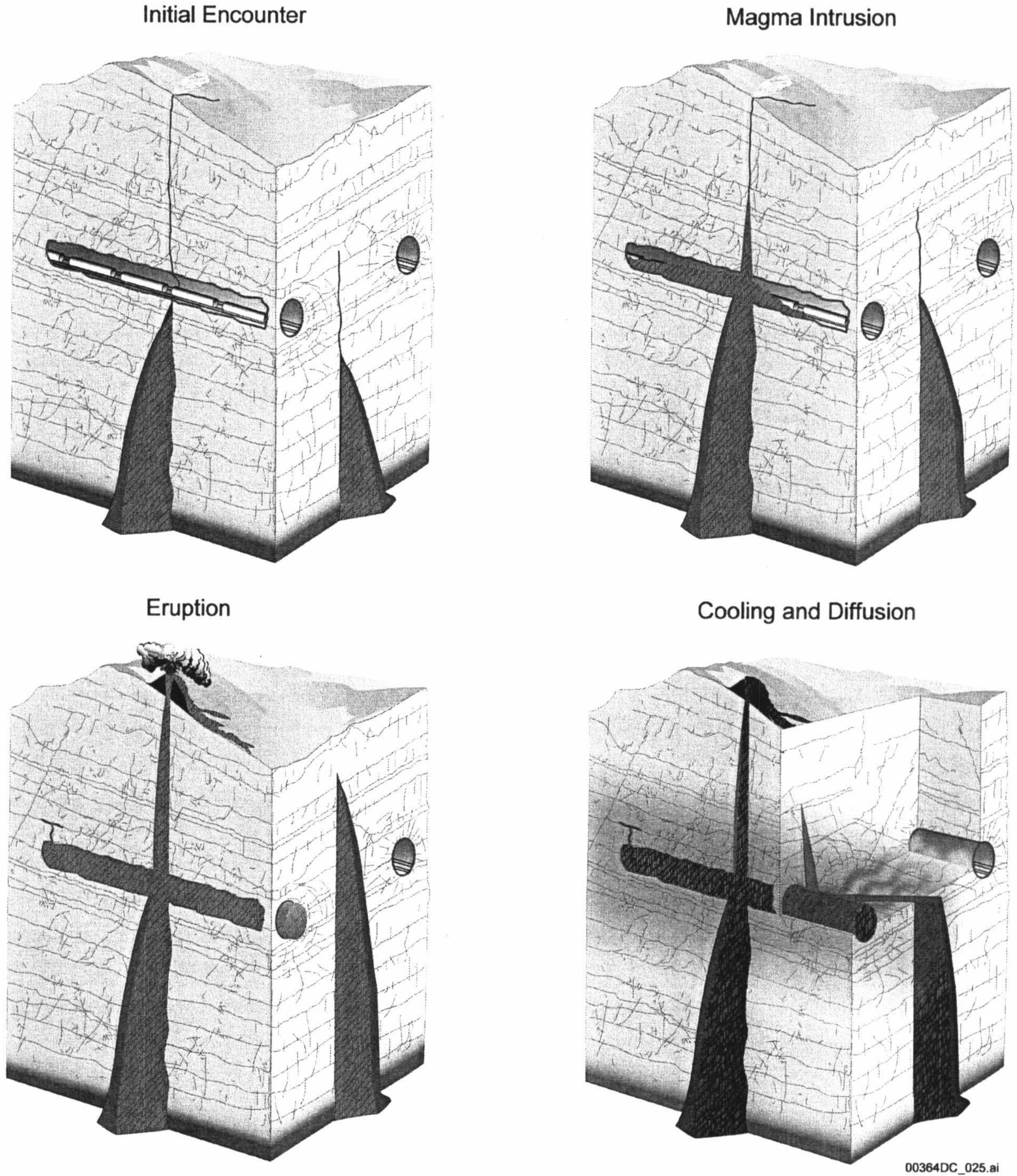

Figure 3. Schematic Drawing of the Processes Associated with a Dike Intrusion into or Eruption through a Repository

SUMMARY

Two major types of volcanism, explosive silicic volcanism (11.8-12.4 Ma) followed by basaltic volcanism, have occurred in the Yucca Mountain region. The early period of Miocene silicic volcanism culminated with the eruption of four voluminous ash-flow tuffs including the Topopah Spring Tuff, which is planned to be used waste emplacement at Yucca Mountain. After a 2.5 m.y. hiatus, Plio-Pleistocene basaltic volcanism occurred primarily in what is known as the Crater Flat area west of Yucca Mountain.

The youngest (approximately 78 ka) of these basaltic volcanic centers is the Lathrop Wells volcanic center. It is an appropriate analogue for the type of eruptive event that could occur in the future because it is the youngest volcano in the region and is similar of the type of eruptions that have occurred at other locations in the Yucca Mountain region during the Quaternary.. The type of eruption represent by Lathrop Wells is therefore considered to be an appropriate basis for conceptual models for consequence analyses of a hypothetical eruption through the repository.

The probability of an igneous event intersecting a repository at Yucca Mountain has been estimated to be slightly greater than one chance in 10,000 over 10,000 years (a mean value of 1.7×10^{-8} per year; therefore the consequences of potential future volcanic activity must be evaluated. The scenarios defining the consequences are based on the geologic record of Quaternary volcanism near Yucca Mountain. Two igneous scenarios with multiple sub-scenarios have been developed. The initial scenario is that of a dike intersecting the repository allowing magma to enter the drifts and affect the waste packages. The second scenario is that of a volcanic eruption that disperses contaminated volcanic ash into the atmosphere and onto the ground surface. The contaminated ash within the tephra sheet is then redistributed via sedimentary processes. These scenarios will be abstracted into mathematical relationships for a risk assessment (total system performance assessment).

The DOE continues to conduct investigations related to the probability of intersection and the potential consequences of an igneous event on a repository at Yucca Mountain to enhance the technical basis for quantifying the risk and the associated uncertainties.

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