# Scientific Analysis
# Administrative Change Notice

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|---|---|---|---|---|---|
| **1. Document Number:** | ANL-MGR-GS-000001 | **2. Revision:** | 02 | **3. ACN:** | 01 |
| **4. Title:** | Characterize Framework for Igneous Activity at Yucca Mountain, Nevada | | | | |
| **5. No. of Pages Attached:** | 15 | | | | |

**6. Approvals:**

| | | |
|---|---|---|
| Preparer: | Alex Sánchez Alex Sánchez<br>Print Name and Sign | July 5, 2005<br>Date |
| Checker: | Cheryl Hastings Cheryl Hastings<br>Print name and sign | 7/11/05<br>Date |
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| 7. Affected Pages | 8. Description of Change: |
|---|---|
| 6-6 | Editorial Correction – text and section callout updated for DIRS 170028 associated with TBV-6057 resolution<br>Page 6-6, third paragraph, first sentence - text updated from:<br>"Although an ascending dike could be influenced by topographic or thermal-mechanically induced stress, the model described here assumes that the dike propagates through the repository (BSC 2004 [DIRS 170028], Section 6.3.9.2.2.2)."<br>to now read:<br>"The model described here assumes that the dike propagates through the repository, consistent with results of an analysis of topographic and thermal mechanically-induced stress effects on an upward propagating dike (BSC 2004 [DIRS 170028], Section 6.2)." |
| 6-6 | Section callout added for DIRS 170028 associated with TBV-6057 resolution<br>Page 6-6, third paragraph, second to last sentence – Section callout added as shown:<br>Because the entry of magma from the dike into the drift is not necessarily instantaneous with intersection, it is unlikely that dike intersection will result in an abrupt explosion into the drift (BSC 2004 [DIRS 170028], Section 1.3.2). |
| 6-7 | Section callout added for DIRS 170028 associated with TBV-6057 resolution<br>Page 6-7, paragraph 2, sentence 1 – Section callout added as shown:<br>The rate and degree to which an intersected drift fills with magma depends on variables, such as magma rise rate, magma viscosity, and the nature (effusive or pyroclastic) of the flow into the drifts (BSC 2004 [DIRS 170028], Section 1.3.2). |
| 6-8 | Section callout updated for DIRS 170028 associated with TBV-6057 resolution<br>Page 6-8, paragraph 5, last sentence – Section callout updated as shown:<br>Thermal energy from the cooling magma would also be transferred into the host rock (BSC 2004 [DIRS 170028], Section 6.7 ~~Section 6.9~~). |

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**4. Title**: Characterize Framework for Igneous Activity at Yucca Mountain, Nevada

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|---|---|
| 6-18, 6-19, 6-30, 6-31 | Typographical correction associated with TBV-6057 resolution<br>Corrected typographical error in year for DIRS 135969 reference citation as follows:<br>Page 6-18 (3 references): Connor et al. ~~1997~~ 1996 [DIRS 135969]<br>Page 6-19 (2 references): Connor et al. ~~1997~~ 1996 [DIRS 135969]<br>Page 6-30 (1 reference): Connor et al. ~~1997~~ 1996 [DIRS 135969]<br>Page 6-31 (1 reference): Connor et al. ~~1997~~ 1996 [DIRS 135969] |
| 6-20 | Reference citation deleted and text added associated with TBV-6057 resolution<br>Page 6-20, first paragraph last sentence:<br>Intersection probabilities near $10^{-7}$ intersections per year (Ho and Smith 1998 [DIRS 140152], pp. 507 and 508~~; Reamer 1999, p. 61 [DIRS 119693]~~) reflect unusually small volcanic source zone areas or unusually long event lengths (Table 6-5). Section 6.3.2. discusses differing characterizations of a volcanic event and the effect of such differences on probability calculations. |
| 6-20 | Text clarification<br>Page 6-20, paragraph 2, sentence 1 - Table and section callout added to enhance transparency, as shown:<br>Most of the published intersection probabilities (shown in Table 6-5) and the mean intersection probability estimated in the PVHA (discussed in Section 6.3.1.5) cluster at values slightly greater than $10^{-8}$ per year, indicating that this probability estimate is robust, given the range of alternative temporal and spatial models, and the different event geometries considered in the probability calculations.<br>This is a self-identified text clarification |
| 6-63 | Correction for typographical error in DTN (associated with CR 4231)<br>Page 6-63, last paragraph, last sentence:<br>The final footprint polygon used for calculation information is contained in output DTN: ~~LA0303BH831811.001~~. LA0303B**Y**831811.001. |
| 6-71 | Correction for typographical error in DTN (associated with CR 4231)<br>Page 6-71, First paragraph, third sentence:<br>The joint distributions are listed in three output files (Output DTN: LA0302BY831811.001 ~~LA0303BY831811.001~~): file CCSM-LA.CMP provides the joint distribution for length and azimuth of dike intersection |
| 7-3 | Correction for typographical error in DTN (associated with CR 4231)<br>Page 7-3, 3rd paragraph, second sentence:<br>Output DTN: ~~LA303BY831811.001~~ LA**0**303BY831811.001 contains the repository footprint polygon developed in Appendix B and data used to generate figures and tables in Section 6 of this report. |

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| 7-3 | Correction for typographical error in DTN (associated with CR 4231)<br>Page 7-3, 3rd paragraph, third sentence:<br>Output DTN: LA**0**307BY831811.001 ~~LA307BY831811.001~~ contains additional data used to generate figures and tables in Section 6 and 7. |
| D-1 | Text clarification<br>Page D-1, paragraph 1, sentence 3 – Section callout added and text clarified as shown:<br>~~Section 1.5.2 of the *Yucca Mountain Review Plan, Final Report*, and Section~~ Sections 1.5.2 and 1.5.3 of NUREG-1804 (NRC 2003 [DIRS 163274]), the *Yucca Mountain Review Plan, Final Report*,~~ provides~~ provide the acceptance criteria that apply to the description of site characterization activities.<br>This is a self-identified correction |
| D-1 & D-2 | Corrected text formatting and renumbered bullets to address condition identified in CR 4734-004.<br>Page D-1 **-** Reformated 3rd paragraph under bolded subsection heading beginning with “Section 1.5.3 Acceptance Criteia…” as new subsection as shown:<br>**Section 1.5.3 Acceptance Criterion 2: The “General Information” section of the License Application contains an adequate description of site characterization results.**<br>Renumbered subsequent bullets as shown:<br>~~2~~. 1. A sufficient understanding is provided of current features and processes present in the Yucca Mountain region.<br>~~3.~~ 2. An adequate understanding is provided of future events and processes likely to be present in the Yucca Mountain region that could affect repository safety.<br>~~4.~~ 3. The description of the reference biosphere is consistent with present knowledge of natural processes in and around the Yucca Mountain site, including the location of the RMEI. |
| D-3 | Renumbered subcrieteria to address condition identified in CR 4734-004.<br>Page D-3, Subcriteria “5” and “6” following bolded header renumbered as “1” and “2” as shown:<br>**Acceptance Criterion 1: Events Are Adequately Defined**<br>~~5.~~ 1. Events or event classes are defined without ambiguity …<br>~~6.~~ 2. Probabilities of intrusive and extrusive igneous events are … |
| D-18 | Renumbered subcriteria to address condition identified in CR 4734-004.<br>Page D-18, 1st paragraph, 1st sentence, renumbered Subcriteria “2” as “3”<br>~~2.~~ 3. Consideration of conceptual model uncertainty is consistent with available site… |
| D-18 | Corrected formating<br>Page D-18, 2nd paragraph, 2nd sentence, corrected “title style” formatting for the referenced Analysis Report for DIRS 170001. The words “Number of” are part of the Analysis Report title and have been italicized as shown:<br>Modeling of the volcanic disruption of waste packages is addressed in *Number of…* |

#### 6.1.1.2 Igneous Processes

The formation of a volcanic event in the Yucca Mountain region begins with ascent of magma from the mantle source as a dike (magma-filled crack). During magma ascent and decompression, volatile gases, such as $H_2O$ and $CO_2$, escape, increasing the volume of the magma. This resulting volume expansion drives the basaltic magma upward through the upper few kilometers of crust. Because volatiles are concentrated near the crack tip of the ascending magma, the start of volcanism is typically characterized by pyroclastic eruptions (volcanic explosions and aerial expulsion of clastic rock from a volcanic vent) of gas-rich magma. Based on analogue studies, the concentration of volatile species in basalts of the Yucca Mountain region is likely to range from 1 to 3 wt %, or more (BSC 2004, [DIRS 169980], Section 7). This range is higher than in most alkali (sodium or potassium-rich) basalt magmas, possibly because the volatile species originated in small percentages of partial melt of a hydrous lithospheric mantle source. The incompatible-element-enriched nature of these alkali basalts relative to other alkali basalts in the western United States is consistent with this conclusion (BSC 2004 [DIRS 169980], Sections 6.3.2 and 6.3.3).

Basaltic magma is transported from a region of melting in the mantle to the surface through dikes. In the Yucca Mountain region, dikes are typically 1 to 2 m in width and have an average length of 4 km (CRWMS M&O 1996 [DIRS 100116]). The longest expected dike length in the Yucca Mountain region is about 10 km. Based on the regional stress field of the upper crust, dikes are expected to have an orientation that centers on N30°E, although other orientations are possible and are observed within the region (BSC 2004, [DIRS 169980], Section 6.3).

The model described here assumes that the dike propagates through the repository, consistent with results of an analysis of topographic and thermal mechanically-induced stress effects on an upward propagating dike (BSC 2004 [DIRS 170028], Section 6.2). As the dike approaches the level of the drifts, the crack tip advances ahead of the magma front and will intersect the repository drifts first. When the magma front within the dike reaches the level of the repository, magma will be available to flow into drifts. There are two possibilities for the behavior of the magma as it approaches the drifts. One is that the magma steadily releases gas into the host rock as it approaches the drifts so that a relatively gas-poor magma flows effusively into the drifts. A more likely scenario, based on analogue studies of historic eruptions, is that the initial magma encountering the drifts will be gas-rich, resulting in pyroclastic flow into the drifts. In either case, the dike tip will precede the magma by several seconds to a few hours. Because the entry of magma from the dike into the drift is not necessarily instantaneous with intersection, it is unlikely that dike intersection will result in an abrupt explosion into the drift (BSC 2004 [DIRS 170028], Section 1.3.2). At the analogue Parícutin volcano, the initial crack broke the surface several hours before the first manifestation of weak pyroclastic eruptions began (BSC 2004 [DIRS 170028]).

The most likely scenario following dike intersection of repository drifts is that the dike continues to follow the path established by the dike tip and erupts to the surface without being influenced by the presence of the repository. An alternative scenario is that the lateral diversion of magma into drifts results in sufficient pressurization of drifts to propagate a dike to the surface at a location some distance from the site of the initial dike intersection. This scenario could potentially lead to more waste entrained during an eruption compared to the case of conduits developed only above the site of initial dike intersection. The amount of waste potentially entrained in this scenario would depend on the length of drifts that transport magma to the site of the down-drift dike, assuming the magma is able to incorporate and transport waste.

The rate and degree to which an intersected drift fills with magma depends on variables, such as magma rise rate, magma viscosity, and the nature (effusive or pyroclastic) of the flow into the drifts (BSC 2004 [DIRS 170028], Section 1.3.2). Magma rise rates are assumed to range between 1 and 10 m/s, while viscosities are assumed to range between 10 and 100 Pa·s (BSC 2004 [DIRS 169980]).

The potential ascent of dikes and the formation of conduits at Yucca Mountain has been analyzed relative to the configuration of the repository, which consists of approximately one hundred waste-emplacement drifts of 5-m diameter, spaced about 80 m apart and encompassing a total area of approximately 5 $km^2$. The number of waste-emplacement drifts intersected would depend on the orientation of a dike system intersecting the repository, the number of dikes in a dike swarm, and the lengths of the dikes lying within the repository footprint.

Formation of a volcano begins with a fissure eruption as a dike or dike swarm intersects the surface (BSC 2004 [DIRS 169980]). The formation of a basaltic volcano is complex with total eruption durations typically ranging from weeks to months and possibly years. During the eruption, activity includes effusion of gas-poor lava flows and explosive, gas-rich pyroclastic eruptions. Both types of eruptions can occur simultaneously or in alternating cycles that include periods of inactivity (BSC 2004 [DIRS 169980], Section 6.4). Intrusive processes simultaneously occur in the subsurface. Analogue studies of shallowly eroded volcanoes in the Yucca Mountain region demonstrate that subsurface intrusive processes may include the formation of multiple dikes (dike swarm) and sills (horizontal emplacement of magma into the host rock). Evolution of the intrusion beneath an erupting volcano can also lead to changes in the location or migration of eruptive vents during the period of eruption (BSC 2004 [DIRS 169980], Sections 6.3.1 and 6.3.3).

At a relatively early stage of the eruption, the fissure eruption localizes to one or more conduits that transport magma to the surface for the remainder of the eruption. Conduit formation provides a mechanism to transport waste to the surface. The physical processes that would influence the exact location of a conduit within the repository (e.g., at drifts or within pillars) depend on multiple complex factors. Conduit localization is assumed to be random along the length of a given dike (BSC 2004 [DIRS 169980], Section 6.3.1.1). Conduit diameters are typically a few tens of meters. A value of 150 m is used in the TSPA-LA as an upper bound for conduit diameter. Basalt conduit depths probably reach several hundred meters and are assumed in this model to reach the depth of the repository to allow interaction with waste emplacement drifts (BSC 2004 [DIRS 169980], Sections 6.3.3 and 6.3.1).

Magma flux through the conduit during explosive phases of the eruption typically varies from approximately $10^4$ kg/s for normal Strombolian (eruption of ballistic magma fragments) activity to approximately $10^6$ kg/s for violent Strombolian (sustained eruption column producing an ash plume) activity (BSC 2004 [DIRS 169980], Section 6.3). Commonly, high magma flux and explosive eruptions occur during the early stage of the eruption, with an increase in effusive (lava flows) activity as the eruption proceeds. At Lathrop Wells, however, field observations indicate that early volcanism was Strombolian, followed by violent Strombolian eruptions.

Lathrop Wells is one of eight small-volume (about 0.01 $km^3$ to 0.1 $km^3$) basaltic volcanoes that formed during the Quaternary within 50 km of Yucca Mountain (Figure 6-1). Based on observations of preserved eruptive deposits, these volcanoes share a similar eruptive history of a pyroclastic phase that led to the formation of a main scoria cone and effusion of *aa* lava flows. The scoria cone and lava flow deposits, excluding tephra fall from violent eruptions, typically cover a few square kilometers. The fundamental similarity of all Quaternary volcanoes in the YMR suggests that a future volcano that could potentially disrupt the repository will share these same characteristics (BSC 2004 [DIRS 169980], Section 6.3.3).

A violent Strombolian eruption is the most energetic eruption expected in the Yucca Mountain region (BSC 2004 [DIRS 169980]; BSC 2004 [DIRS 170026]). These eruptions involve a sustained, vertical eruption column (a gas-particle jet) that propels the tephra to heights of several kilometers above the scoria cone. The tephra plume eventually reaches a level of neutral buoyancy in the atmosphere, spreads laterally as an anvil cloud, and is transported downwind. Tephra particles fall out of the vertical eruption column and the anvil-shaped cloud. The atmospheric dispersal and deposition of the fine tephra forms a sheet-like deposit of volcanic ash characterized by decreasing thickness and grain size with distance from the volcano. Tephra deposits might extend 10 km or more from the volcano and cover several hundred square kilometers (BSC 2004 [DIRS 169980], Section 6.3.3). In the TSPA-LA, only the violent Strombolian phase of volcanism is modeled for atmospheric dispersal because this is the only mechanism for the ash column to reach the heights necessary to deposit ash 18 km downwind from the volcano to the location of the RMEI (BSC 2004 [DIRS 169980], Sections 6.3.3.4.1 and 6.3.3.4.3).

If a dike intersects the repository, waste packages can be disrupted by magma entering the emplacement drifts and contacting the waste packages (intrusion case), or by direct entrainment of waste packages within conduits to the surface (eruption case). In the intrusion case, the number of packages disrupted depends on the number of emplacement drifts filled by magma, which is conditional on the number of drifts intersected by dikes. For the eruption case, the number of packages disrupted depends on the diameter and number of conduits that form within the repository footprint (BSC 2004 [DIRS 170001], Section 6.4).

If magma fills a drift, post-emplacement processes become important (BSC 2004 [DIRS 170028]). Magmatic volatiles are expected to degas from the cooling magma within the intruded drift and infiltrate the tuff host rock. Thermal energy from the cooling magma would also be transferred into the host rock (BSC 2004 [DIRS 170028], Section 6.7).

### 6.1.1.3 Post-Igneous Processes

After the deposition of a violent Strombolian tephra sheet, volcanic ash is subject to redistribution by normal sedimentary processes (erosion and deposition) (BSC 2004 [DIRS 170026]). A hypothetical violent Strombolian eruption through the repository would produce tephra dispersed to the northeast, blanketing part of the Fortymile Wash drainage system with particles less than 2 mm in size (BSC 2004 [DIRS 170026], Section 6). Redistribution of

New data that could potentially change the assessment of the number of volcanic events by the PVHA experts include an analysis of existing aeromagnetic data for the YMR (Earthfield Technology 1995 [DIRS 147778]) and new ground magnetic surveys of aeromagnetic anomalies (Connor et al. 1996 [DIRS 135969]; Magsino et al. 1998 [DIRS 147781]). A map presented by Earthfield Technology (1995 [DIRS 147778], Appendix II) indicates the presence of as many as 40 to 60 aeromagnetic anomalies within approximately 35 to 40 km of Yucca Mountain that are interpreted as intrusive bodies; six of these lie within approximately 5 km of the proposed repository site. The Earthfield Technology (1995 [DIRS 147778]) results were based on the merging of three aeromagnetic data sets: the Timber Mountain, Lathrop Wells, and Yucca Mountain surveys. Subsequent to release of the Earthfield Technology (1995 [DIRS 147778]) report, it was discovered that the report "was flawed by an incomplete and mislocated Timber Mt. Survey" (Feighner and Majer 1996 [DIRS 105078], p. 1). Inspection of the flight survey map in Earthfield Technology (1995 [DIRS 147778], Figure 2) and a corresponding map enclosed in *Results of the Analysis of the Timber Mt., Lathrop Wells, and Yucca Mt. Aeromagnetic Data* (Feighner and Majer (1996 [DIRS 105078], Appendix I) indicates that the Timber Mountain Survey, which encompasses about 50 percent of the coverage area and the majority of the aeromagnetic anomalies, was mislocated approximately 20 km to the south-southwest of its correct location. For this reason, further analysis of the anomalies that were presented by Earthfield Technology (1995 [DIRS 147778], Appendix II) and that lie within the Timber Mountain survey is not warranted. The six anomalies located within 5 km of the proposed repository site (the Yucca Mountain survey) are associated with mapped faults and are probably due to magnetic variation resulting from fault-controlled juxtaposition of rock masses with differing magnetic properties (Feighner and Majer 1996 [DIRS 105078], p. 2; Reamer 1999 [DIRS 119693], p. 32).

The most reliable and detailed data available for magnetic anomalies in the YMR is presented in Connor et al. (1996 [DIRS 135969]) and Magsino et al. (1998 [DIRS 147781]). These data were obtained using ground magnetic surveys of fourteen selected aeromagnetic anomalies located to the north, east, west, and south of the proposed repository site (Magsino et al. 1998 [DIRS 147781], Figure 1-1). Collectively, these surveys represent a comprehensive assessment of aeromagnetic anomalies nearest the proposed repository site and provide confidence that the geologic record of basaltic volcanism near Yucca Mountain is adequately understood. Of the fourteen surveys, seven provide no evidence of buried basalt and three were conducted over areas with known surface exposures of basalt, partly to enhance understanding of the relationship between volcanism and geologic structure (Magsino et al. 1998 [DIRS 147781], Section 4). Four of the 14 surveys provide evidence of buried volcanic centers. Two of these (Anomalies A and F/G of the PVHA) were known to the PVHA experts as possible buried basaltic volcanic centers (from the data of Langenheim et al. 1993 [DIRS 148622]; Crowe et al. 1995 [DIRS 100110], Figure 2.5), but the data presented in Connor et al. (1996 [DIRS 135969]) and Magsino et al. (1998 [DIRS 147781]) provide increased detail and confidence of their volcanic origin. Of the two remaining surveys, anomalies in the Steve's Pass area on the southwest margin of Crater Flat are interpreted as buried basalt. Interpretation of a buried, reversely magnetized body of rock southwest of Northern (or Makani) Cone is less certain and may be either a basalt body or Miocene tuff (Magsino et al. 1998 [DIRS 147781], Sections 4.4 and 4.11). Each of the four anomalies representing probable buried volcanic centers occur within volcanic source zones previously specified by the PVHA experts (CRWMS M&O 1996 [DIRS 100116],

Appendix E), except for the anomalies in the Steve's Pass area, which lie slightly to the southwest of most experts' volcanic source zones in a direction away from Yucca Mountain.

On the basis of evidence for buried volcanic centers presented in Connor et al. (1996 [DIRS 135969]), Brocoum (1997 [DIRS 147772]) conducted sensitivity analyses to assess the potential impact on the PVHA results of increased event counts in Amargosa Valley and Crater Flat. Considering the experts' method for assessment of event counts, particularly for northeast alignments of vents (as in the case of Amargosa anomaly F/G), the mean value for the number of buried volcanic centers was increased from the original PVHA value of 4.7 events to 6.1 events (Brocoum 1997 [DIRS 147772], Enclosure 1, p. 5). The mean annual frequency of intersection of a dike with the repository footprint was recalculated using the revised event count distributions, resulting in an increase in the mean annual frequency of intersection of 4 percent (Brocoum 1997 [DIRS 147772], Enclosure 1, p. 5). Given the uncertainty factored into the PVHA by assessment of alternative event counts and hidden event factors, small changes in the PVHA event counts have a minor impact on the annual frequency of intersection distribution derived from the PVHA. A later sensitivity analysis presented by *Synthesis of Volcanism Studies for the Yucca Mountain Site Characterization Project* (CRWMS M&O 1998 [DIRS 105347], Chapter 6, pp. 6-83 and 6-84) conservatively assumed that all known aeromagnetic anomalies in Crater Flat and the Amargosa Valley were of Quaternary age, instead of Pliocene. Using this assumption, the most likely number of Quaternary volcanic events near Yucca Mountain based on PVHA event counts was increased from 3.8 to 8 events. This increase in the Quaternary event count resulted in a disruption probability of approximately $2.5 \cdot 10^{-8}$ per year (CRWMS M&O 1998 [DIRS 105347], Chapter 6, p. 6-84), a result not significantly different from the mean PVHA result of $1.5 \cdot 10^{-8}$ per year (CRWMS M&O 1996 [DIRS 100116], pp. 4-10, 4-14).

The data presented by Connor et al. (1996 [DIRS 135969]) and Magsino et al. (1998 [DIRS 147781]) provide stronger evidence that Anomalies A and F/G (as defined in the PVHA) represent buried volcanic centers, and that at least one anomaly not considered by the PVHA experts represents a probable buried volcanic center. Sensitivity studies (Brocoum 1997 [DIRS 147772]; CRWMS M&O 1998 [DIRS 105347], Chapter 6) show that the addition of several volcanic events located within already defined volcanic source zones does not significantly impact the results of the PVHA. Significantly, the four anomalies east of Yucca Mountain (Magsino et al. 1998 [DIRS 147781], Figure 1-1) show no evidence of buried volcanic centers and provide confirmatory evidence that the volcanic source zones specified by the experts to the south and west of Yucca Mountain are a valid representation of the spatial distribution of post-Miocene volcanism in the YMR.

In 1999, the USGS conducted a regional aeromagnetic survey for the purpose of assessing potential hydrologic pathways in the Yucca Mountain/Death Valley region (Blakely et al 2000 [DIRS 151881]). Subsequent interpretation of these data indicated that 20 to 24 aeromagnetic anomalies present to the west and south of Yucca Mountain could potentially represent buried basalt (O'Leary et al. 2002 [DIRS 158468]; Hill and Stamatakos 2002 [DIRS 159500]). Section 6.5.4 of this report documents an assessment of how the potential presence of additional buried volcanoes in the YMR could impact the frequency of intersection.

#### 6.3.1.8 Alternative Estimates of the Intersection Probability

Several alternative estimates of the intersection probability (the annual probability of a volcanic event intersecting the repository footprint) were presented between 1982 and 1998 (Table 6-5). As discussed in the following section (6.3.2), volcanic events in hazard calculations have been represented as both points and lines (Table 6-5). For point events, volcanic source zone areas or the repository area have generally been increased to account for the fact that volcanic events have dimension due to the length of associated dikes. The shorter the event length, the more comparable intersection probability results are for calculations representing volcanic events as points. Intersection probabilities near $10^{-7}$ intersections per year (Ho and Smith 1998 [DIRS 140152], pp. 507 and 508) reflect unusually small volcanic source zone areas or unusually long event lengths (Table 6-5). Section 6.3.2 discusses differing chararacterizations of a volcanic event and the effect of such differences on probability calculations.

Most of the published intersection probabilities (shown in Table 6-5), and the mean intersection probability estimated in the PVHA (discussed in Section 6.3.1.5), cluster at values slightly greater than $10^{-8}$ per year, indicating that this probability estimate is robust, given the range of alternative temporal and spatial models, and the different event geometries considered in the probability calculations.

Table 6-5. Published Estimates of the Probability of Intersection of the Proposed Repository at Yucca Mountain by a Volcanic Event

| Reference | Intersection Probability (per year) | Comment | Event Representation |
|---|---|---|---|
| Crowe et al. (1982 [DIRS 102741]), pp. 184 through 185 | $3.3 \cdot 10^{-10} – 4.7 \cdot 10^{-8}$ | Range of alternative probability calculations. | point |
| Crowe et al. (1993 [DIRS 100026]), p. 188 | $2.6 \cdot 10^{-8}$ | Median value of probability distribution. | point |
| Connor and Hill (1995 [DIRS 102646]), p. 10121 | $1–5 \cdot 10^{-8}$ | Range of 3 alternative models. | point |
| Crowe et al. (1995 [DIRS 100110]), Table 7.22 | $1.8 \cdot 10^{-8}$ | Median value of 22 alternative probability models. | point |
| Ho and Smith (1998 [DIRS 140152]), pp. 507 through 508 | (1) $1.5 \cdot 10^{-8}$,<br>(2) $1.09 \cdot 10^{-8}$,<br>$2.83 \cdot 10^{-8}$,<br>(3) $3.14 \cdot 10^{-7}$ | 3 alternative models; 3rd$^{rd}$ model assumes a spatial intersection ratio (using a Bayesian prior) of 8/75 or 0.11, approximately one order of magnitude higher than other published estimates, because volcanic events are forced to occur within a small zone enclosing Yucca Mountain. | point |
| CRWMS M&O (1998 [DIRS 105347]), Chapter 6, p. 6-84 | $2.5 \cdot 10^{-8}$ | Sensitivity analysis that conservatively assumes all aeromagnetic anomalies in Amargosa Valley are Quaternary age. | point |

link between the two fields is anomalously hot mantle, the lower volume, eruption rate, and recurrence rate of the Crater Flat field indicates that the underlying mantle is not as hot or prone to melt as mantle beneath Lunar Crater. The low activity of the Crater Flat field compared to nearly every other volcanic field in the western U.S. indicates that the underlying mantle is not particularly hot. Therefore, there is no evidence to indicate that the recurrence rate of volcanism near Yucca Mountain will ever reach values equivalent to those at Lunar Crater.

- Neodymium isotopic compositions of basalts in the Lunar Crater and Crater Flat volcanic fields are significantly different, indicating fundamentally different mantle sources or fundamental differences in processes that produced the basalts. Smith et al. (2002 [DIRS 158735]) recognized the isotopic differences between the two volcanic fields and speculated that the unusual Nd isotopic compositions of basalt near Yucca Mountain are due to (1) contamination of asthenospheric melts passing through lithospheric mantle or (2) modification of asthenospheric mantle by fluids or melts derived from subducted crust. Either mechanism would not be expected to affect the basalts near Yucca Mountain selectively, but would instead operate on a much larger scale. For example, because subducted crust existed beneath most of the western United States for tens of millions of years, modifying fluids of melts derived from subducted crust would be expected to modify asthenospheric mantle on a continental scale, not just the small region surrounding Yucca Mountain. Basalts from Lunar Crater have isotopic compositions similar to ocean island basalts, indicating a source in relatively warm and convecting asthenospheric mantle. The unusual Nd isotopic composition of basalts in the Crater Flat field indicate derivation from a lithospheric mantle source that is old, stable, and cold (nonconvecting) compared to asthenospheric mantle (Perry et al. 1987 [DIRS 162311]; Farmer et al. 1989 [DIRS 105284]; Livaccari and Perry 1993 [DIRS 162310]). Wernicke et al. (1987 [DIRS 107250]), citing tectonic evidence, suggested that the relative lack of volcanism in the YMR until 15 m.y. ago left the lithosphere cold and difficult to extend, compared to more volcanically active and earlier extended regions of the Basin and Range province. The preponderance of evidence indicates that the small volume of basalt and limited volcanic activity near Yucca Mountain reflect an underlying mantle source that is cold and unable to produce significant volcanic activity.

On a more local and shallow crustal scale, most researchers conclude that (1) volcanism is correlated with zones of past or present crustal extension, and (2) once dikes feeding volcanoes enter the shallow upper crust, their location and orientation is influenced by the orientation of the local stress field and the presence of faults that may locally control vent location and alignment. The evidence cited for these two conclusions includes several northeast-oriented vent alignments in the YMR and the association of eruptive centers with known or inferred faults (Smith et al. 1990 [DIRS 101019], p. 83; CRWMS M&O 1996 [DIRS 100116], Appendix E, p. AM-4; Connor et al. 1996 [DIRS 135969], p. 78; Reamer 1999 [DIRS 119693], Section 4.1.3.3.3; Fridrich et al. 1999 [DIRS 107333], p. 211).

A mechanistic model relating mantle melting and lithospheric extension has recently been proposed for the YMR by Connor et al. (2000 [DIRS 149935]) and additionally, is used as the geologic basis for weighting spatial density models based on crustal density variations across the

YMR (Reamer 1999 [DIRS 119693], Section 4.1.6.3.3). The conceptual basis of the model is that crustal density variations across the YMR control variations in lithostatic pressure at the base of the crust. These pressure variations in turn control the location of decompression melting within the mantle, which, in turn, controls the location of future igneous activity within the YMR (Connor et al. 2000 [DIRS 149935], pp. 419 through 422).

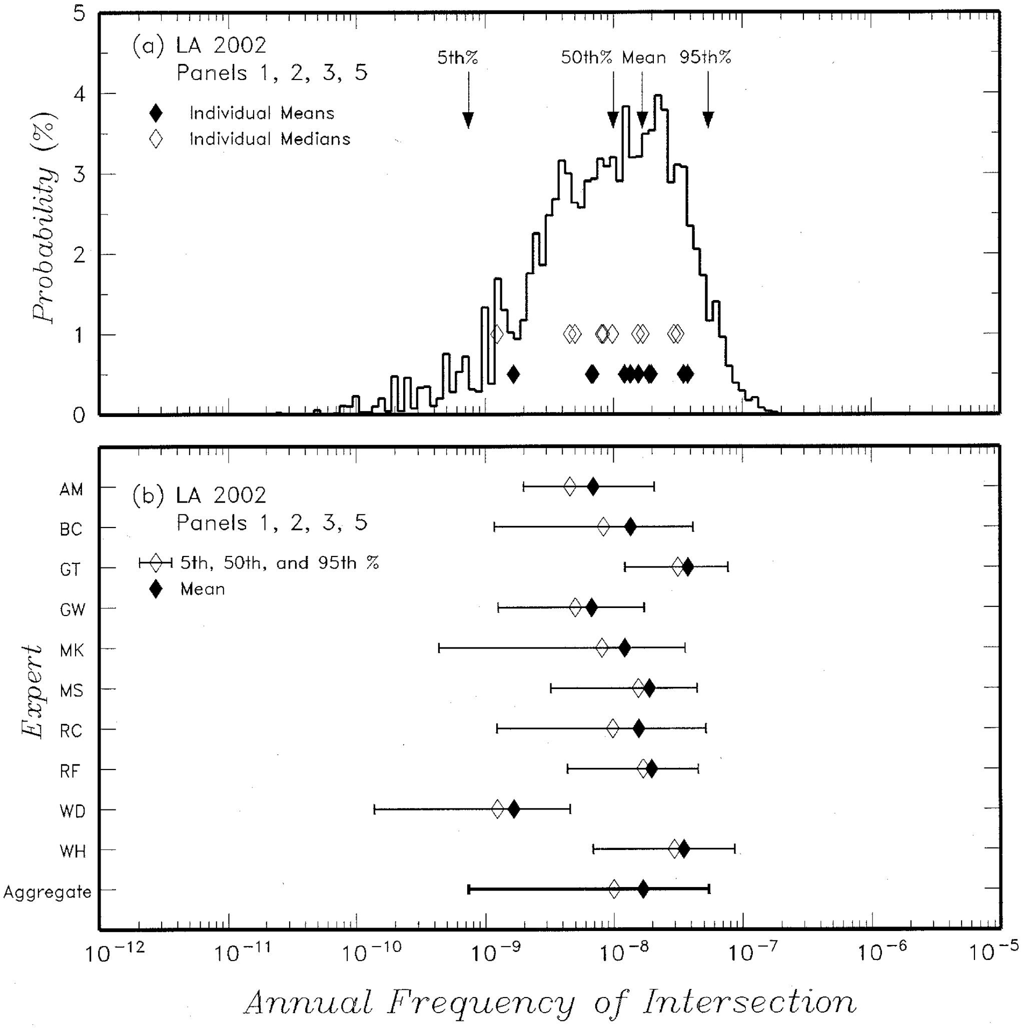
As formulated, a finite-element model that calculates lateral pressure changes in the YMR based on upper crustal density variations (Connor et al. 2000 [DIRS 149935], p. 420) is a poor predictor of volcano distribution in the YMR. The model predicts that maximum melting (and, hence, more frequent occurrence of volcanism) will occur farthest from the region of high crustal density (Connor et al. 2000 [DIRS 149935], Figure 3). But this model prediction is the opposite of what is observed for the occurrence of post-Miocene volcanism in the YMR because volcanism is concentrated near high-density crust of the Bare Mountain domain, rather than farther to the east (Figure 6-5).

A map of apparent crustal density variation (Connor et al. 2000 [DIRS 149935], Plate 1) shows that low average crustal density extends fairly uniformly for a distance of at least 50 km east of the Bare Mountain Fault. Within the context of the conceptual model proposed by Connor et al. (2000 [DIRS 149935]) (i.e., crustal density exerts a primary control on location of volcanism), post-Miocene volcanism should occur somewhat randomly across this broad region. Instead, all post-Miocene volcanism near Yucca Mountain is located within 5 to 10 km of the Bare Mountain fault or near the southern ends of the Windy Wash and Stagecoach Road faults (Fridrich et al. 1999 [DIRS 107333], p. 211), indicating that local zones of extension and upper crustal faulting may exert more direct control on the location of volcanism than the effect of shallow crustal processes on mantle processes (CRWMS M&O 1996 [DIRS 100116], Appendix E, e.g., pp. AM-5 and MS-2; Fridrich et al. 1999 [DIRS 107333], p. 211; Reamer 1999 [DIRS 119693], Section 4.1.5.3.3). This does not mean that areas of low crustal density and volcanism do not often coincide, but instead means that both are independently influenced or caused by upper crustal faulting and extension.

Connor et al. (2000 [DIRS 149935]) use crustal density as a primary “tectonic” or “geologic” control on volcano distribution (Reamer 1999 [DIRS 119693], Section 4.1.6.3.3), even though volcanoes are not randomly distributed over broad areas of low crustal density as predicted by this model. An alternative method of weighting spatial density models would be to weight by estimated percent of extension within the Crater Flat basin (e.g., Fridrich et al. 1999 [DIRS 107333], Figure 5), thereby tying probability models more directly to a geologic process (faulting and extension) that many researchers agree exerts an important geologic control on volcano location (Smith et al. 1990 [DIRS 101019], p. 83; CRWMS M&O 1996 [DIRS 100116], Appendix E, pp. AM-5 and MS-2; Connor et al. 1996 [DIRS 135969], p. 78; Reamer 1999 [DIRS 119693], Section 4.1.3.3.3, p. 47). The strong southward and westward increase in extension rate across the Crater Flat basin corresponds well to sites of most recent volcanism in the basin (Fridrich et al. 1999 [DIRS 107333], Figures 1 and 5), as opposed to crustal density variations that are hypothesized to control volcano location, but do not correspond well with volcano location (Reamer 1999 [DIRS 119693], Figure 22). In terms of alternative conceptual models, models based on observable geologic features in the YMR provide a more defensible framework and technical basis for probability calculations than models relying on unobservable intersection and the distribution in the frequency of intersection in output files for use in the final step of the computation. Separate output files are created for all of the alternative sets of source model parameters and for the alternative parameters that describe the associated dikes.

**Step 4**: The results from Step 3 are combined over the distributions for both the source model parameters and the associated dikes (see Figure 6-12a and Figure 6-12b) to compute the full distribution for frequency of intersection specified by an individual PVHA expert's interpretations. The results for each expert are then combined with equal weights to obtain the composite distribution. These calculations are performed using software routine VHTREE V1.0 (LANL 2000 [DIRS 148544]). Complete enumeration of all of the alternative parameter sets is achieved by a series of nested DO loops. The mean value and various percentiles of the distribution for frequency of intersection of the repository footprint by a dike are computed from the discrete distribution for frequency of intersection defined by the alternative end branches of the volcanic hazard model logic trees.

The 2003 repository footprint used for the calculations in this report is shown on Figure 6-17a (BSC (2003 [DIRS 162289]), but this footprint has been superseded by a more recent design (BSC 2004 [DIRS 164519]). The calculations performed in the PVHA (CRWMS M&O 1996 [DIRS 100116]) used the repository footprint shown in Figure 6-17b. The 2003 repository design (BSC 2003 [DIRS 162289]) calls for a longer and narrower emplacement area compared to the design used at the time of the PVHA (Figure 6-17b). Appendix B presents the coordinates of the drifts in the 2003 repository footprint and their transformation to UTM kilometers. The repository footprint polygon used for calculations in this report uses values obtained from *Repository Design, Repository/PA IED Subsurface Facilities* (BSC 2003 [DIRS 162289]) and modified to provide a clearance of approximately 55 m around the drift coordinates (see Figure 6-17a) to account for the effect of the size of eruptive centers in the calculations (see Appendix B). The final footprint polygon used for calculation information is contained in output DTN: LA0303BY831811.001.



Output DTN: LA0303BY831811.001.

NOTE: (a) Aggregate distribution and median and means for individual PVHA expert interpretations. (b) Range for 5th to 95th percentiles for results from individual PVHA expert interpretations compared to range for aggregate distribution. Two-letter code indicates initials of experts from Table 6-3.

Figure 6-18. Annual Frequency of Intersecting the Repository Footprint

### 6.5.3.2 Conditional Distributions for Intersection Length, Azimuth, and Number of Eruptive Centers within the Repository Footprint

The Latin hypercube sampling process described in Section 6.5.2.2 was used to compute joint distributions for length and azimuth of dike intersection at the mean, 5th, and 95th percentile frequencies of intersection. At each of these frequencies of intersection, distributions for the number of eruptive centers within the repository footprint were developed, conditional on the length and azimuth within the repository of the intersecting dike system. The joint distributions are listed in three output files (Output DTN: LA0302BY831811.001): file CCSM-LA.CMP provides the joint distribution for length and azimuth of dike intersection and conditional distributions for the number of eruptive centers corresponding to the mean frequency of

2. A discrete probability distribution for the annual frequency of disruption of the repository emplacement area footprint by one or more eruptive centers. This distribution is obtained by multiplying the first column of output file PVHA-4PA.DST (Output DTN: LA0307BY831811.001) by 0.782, the conditional probability of disruption by at least one eruptive center, given intersection of the repository. As discussed in Sections 6.5.3.2 and 7.1, it is considered appropriate to use the conditional probability obtained for the mean frequency of intersection to define the full distribution for frequency of extrusive disruption.

3. Conditional joint probability distributions for length and azimuth of an intersecting dike and number of eruptive centers within the repository footprint, output files CCSM-LA.CMP, CC05-LA.CMP, and CC95-LA.CMP (Output DTN: LA0302BY831811.001). As discussed in Sections 6.5.3.2 and 7.1, it is considered appropriate to use the distributions obtained for the mean frequency of intersection (output file CCSM-LA.CMP) to evaluate consequences at all frequencies of intersection.

In addition, there are a number of other data sets associated with this analysis report. Output DTN: LA0303BY831811.001 contains the repository footprint polygon developed in Appendix B and data used to generate figures and tables in Section 6 of this report. Output DTN: LA0307BY831811.001 contains additional data used to generate figures and tables in Section 6 and 7. Output DTN: LA0009FP831811.001 contains the data files for PVHA 1996 volcanic hazard model and data used to generate some figures in Section 6 and Appendix C. Output DTN: LA0009FP831811.004 contains additional data from Appendix C. See Section 6.1.3 for a fuller description.

## 7.3 UNCERTAINTIES

The data and parameter inputs to the PVHA, as well as their uncertainty, were defined as part of the expert elicitation process. All of the uncertainties defined by the elicitation process were fully propagated through the probability models and are reflected in the final probability distribution. Selection of particular parameter values, ranges, and bounding assumptions for conceptual models were arrived at through the process of expert elicitation. The contributions to uncertainty from each of the PVHA components are described in *Probabilistic Volcanic Hazard Analysis for Yucca Mountain, Nevada* (CRWMS M&O 1996 [DIRS 100116], Section 4.2) and Section 6.3.1.5 of this scientific analysis report.

The probability of intersection of the repository by an ascending basaltic dike has been estimated to be $1.7 \times 10^{-8}$ per year. Therefore, to meet the requirements of 10 CFR 63.114(d), the probability of intersection has been identified as an event that must be evaluated as part of the analysis of repository postclosure performance. Sections 1.5.2 and 1.5.3 of NUREG-1804 (NRC 2003 [DIRS 163274]), the *Yucca Mountain Review Plan, Final Report*, provide the acceptance criteria that apply to the description of site characterization activities. NUREG-1804, Section 2.2.1.2.2.3 contains Acceptance Criteria related to the integrated subissue of identification of events with probabilities greater than $10^{-8}$ per year. NUREG-1804, Section 2.2.1.3.2.3 contains the acceptance criteria related to the integrated subissue of mechanical disruption of waste packages. NUREG-1804, Section 2.2.1.3.10.3 contains the acceptance criteria related to the integrated subissue of volcanic disruption of waste packages. The following information identifies sections of this report that contain information relevant to future igneous events at Yucca Mountain. The applicable acceptance criteria may also be addressed in other analysis and model reports and are considered fully addressed when this report is considered in conjunction with those reports.

**Section 1.5.3 Acceptance Criterion 1: The "General Information" section of the License Application contains an adequate description of site characterization activities**

1. An adequate overview is provided of the site characterization activities related to geology; hydrology; geochemistry; geotechnical properties and conditions of the host rock; climatology, meteorology, and other environmental sciences; and the reference biosphere.

   Section 6.1.1 describes the conceptual model for igneous activity, and Section 6.2 describes the volcanic history of the Yucca Mountain region. Section 6.3 describes the PVHA (CRWMS M&O 1996 [DIRS 100116]), including the process used (Section 6.3.1), the definition of a volcanic event, and the technical basis for the definition ( 6.3.2). Section 6.4 describes the Crater Flat structural domain and its relationship to volcanism.

**Section 1.5.3 Acceptance Criterion 2: The "General Information" section of the License Application contains an adequate description of site characterization results.**

1. A sufficient understanding is provided of current features and processes present in the Yucca Mountain region.

   FEPs associated with igneous activity and addressed by information in this report are identified in Section 6.1.2. The analysis report describes the volcanic history of the YMR and separates the Miocene eruptions of huge volumes of silicic tephra from the Pliocene and Quaternary eruptions of very modest amounts of basalt that ended with the eruption(s) at the Lathrop Wells cone about 80,000 years ago. Internal structure and boundaries of the Crater Flat structural domain are described in Section 6.4.1. The correlation of volcanism with features of the structural domain is described in Section 6.4.1.5. The relationship of volcanic source zones described in the PVHA) to the structural domain is described in Section 6.4.2.

The PVHA established that the annual probability of intersection of the repository by a basaltic dike is very low but still large enough that volcanism must be considered in the TSPA-LA. The estimate of the annual probability of intersection of the repository by an ascending basaltic dike was done using an expert elicitation process described in the PVHA. Topics of special interest include (a) discussion of PVHA results and uncertainty (Section 6.3.1.5), (b) consideration of alternative conceptual models (Section 6.3.1.6), (c) discussion of the significance of buried volcanic centers on PVHA results (Section 6.3.1.7), (d) discussion of alternative estimates of intersection probabilities, (e) discussion of the definitions and parameters of a volcanic event and implications for alternative probability calculations (Section 6.3.2), and (f) discussion of conceptual models of volcanism and formulation of probability models (Section 6.3.3).

2. An adequate understanding is provided of future events and processes likely to be present in the Yucca Mountain region that could affect repository safety.

   The PVHA established that the annual probability of intersection of the repository by a basaltic dike is very low but still large enough that volcanism must be considered in the TSPA-LA. The estimate of the annual probability of intersection of the repository by an ascending basaltic dike was done using an expert elicitation process described in the PVHA. Topics of special interest include (a) discussion of PVHA results and uncertainty (Section 6.3.1.5), (b) consideration of alternative conceptual models (Section 6.3.1.6), (c) discussion of the significance of buried volcanic centers on PVHA results (Section 6.3.1.7), (d) discussion of alternative estimates of intersection probabilities, (e) discussion of the definitions and parameters of a volcanic event and implications for alternative probability calculations (Section 6.3.2), and (f) discussion of conceptual models of volcanism and formulation of probability models (Section 6.3.3).

   For TSPA-LA, volcanic disruption of the repository will be modeled by two disruption scenarios. The first is a direct release scenario, which features a basaltic eruption through the repository and ejection and dispersal of contaminated ash to the location of the RMEI. The second is an indirect release scenario, which features intrusion of a basaltic dike into the repository without eruption, damage to waste packages, and exposure of the waste to transport by normal groundwater mechanisms. In each case, the dose is multiplied by the annual probability to provide a probability-weighted mean annual dose. The annual probability is documented in this report and other reports document the other parameters needed to complete the models for the two scenarios.

3. The description of the reference biosphere is consistent with present knowledge of natural processes in and around the Yucca Mountain site, including the location of the RMEI.

   This report does not address the characteristics of the reference biosphere or the location of the RMEI.

## Section 2.2.1.2.2.3, Identification of Events with Probabilities Greater Than $10^{-8}$ Per Year

### Acceptance Criterion 1: Events Are Adequately Defined

1. Events or event classes are defined without ambiguity and used consistently in probability models, so that probabilities for each event or event class are estimated separately.

   For the PVHA (CRWMS M&) 1996 [DIRS 100116]), an expert panel was convened in 1995 to review all pertinent data relating to volcanism at Yucca Mountain and, based on these data, to quantify both the annual probability and associated uncertainty of a volcanic event intersecting a proposed repository sited at Yucca Mountain. The data the experts reviewed was comprehensive, consisting of two decades of data collected by volcanologists who conducted studies to quantify the probability that a future volcanic eruption would disrupt the proposed repository. PVHA results and uncertainties are summarized in Section 6.3.1.5. Section 6.3.2 describes how the experts defined a volcanic event and the implications of the definition for alternative probability calculations. Based on the description in Section 6.3.2, although the experts defined a volcanic event differently, the product of the expert elicitation process was an unambiguous definition of a volcanic event and the descriptions in Sections 6.3.2 and 6.3.3 show how the definitions were consistently used in the development and evaluation of probability models that supported the estimate of the probability of intersection of the proposed repository by a future igneous event.

2. Probabilities of intrusive and extrusive igneous events are calculated separately.

   Section 6.5.3 describes the results of the estimation of the probability of intersection of the repository footprint by an ascending basaltic dike. The section also describes the results of the estimation of the number of eruptive centers that could occur within the repository footprint. Probability values, presented in Table 6-14, show the annual frequency of intersection of the repository by a dike, the conditional probability of at least one eruptive center (given intersection), and the annual frequency of occurrence of one or more eruptive centers within the proposed repository.

### Acceptance Criterion 2: Probability Estimates For Future Events Are Supported By Appropriate Technical Bases

1. Probabilities for future natural events have considered past patterns of the natural events in the Yucca Mountain region considering the likely future conditions and interactions of the natural and engineered system. These probability estimates have specifically included igneous events.

   Section 6.2 describes the volcanic history of the YMR. Section 6.3.1 describes the PVHA process and includes documentation of the measures used to include information about past patterns of igneous activity in the YMR were incorporated into alternative spatial and temporal distributions of potential future volcanic activity in the region (Section 6.3.1.3). Section 6.3.1.7 describes the methods used to evaluate the significance of buried volcanic centers on the PVHA results, and Section 6.3.1.8

3. Consideration of conceptual model uncertainty is consistent with available site characterization data, laboratory experiments, field measurements, natural analogue information and process-level modeling studies; and the treatment of conceptual model uncertainty does not result in an under-representation of the risk estimate.

   This report does not directly address the processes and associated models of volcanic disruption of waste packages. Modeling of the volcanic disruption of waste packages is addressed in *Number of Waste Packages Hit by Igneous Intrusion* (BSC 2004 [DIRS 170001]) and *Atmospheric Dispersal and Deposition of Tephra from a Potential Volcanic Eruption at Yucca Mountain, Nevada* (BSC 2004 [DIRS 170026]).

   Uncertainties in conceptual models used to estimate the probability of intersection of the repository, distributions of dike length and orientation, and the number of eruptive centers within the proposed repository are explained in Section 6.5.1, which describes the formulation of the analyses and 6.5.4, which describes studies of the sensitivity of the frequency of intersection to increases in the number of buried volcanic centers.

**Acceptance Criterion 5: Model Abstraction Output Is Supported By Objective Comparisons**

This report does not address model abstraction. Analysis outputs consist of the frequency of intersection of the repository (Section 6.5.3.1), and conditional distributions for intersection length, azimuth, and number of eruptive centers within the repository footprint (Section 6.5.3.2).